No dominion over nature

Why treating ecosystems like machines will lead to boom and bust in food supply

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Summary
Healthy ecosystems are essential for the long-term wellbeing of humans as they provide vital services such as food production, pollination, climate regulation and flood protection.

Global trends including population growth, changing diets and consumption patterns, urbanisation and climate change will exert increasing pressure on supplies of food and other products of ecosystems. Many experts predict that food production will need to increase by up to 100 per cent over the next forty years and some suggest that this can only be achieved through intensification of current industrial agricultural practices. This is the dominant narrative. Others suggest that low input agriculture (such as organic) and extensification provide the only alternative path to food security.

We reject both these approaches. A focus on intensification of production at the expense of all else appears to take trends in population growth, diet and consumption as preordained instead of open to challenge and change. We argue that greater conventional intensification will erode ecosystem stability and resilience leading to periods of boom and bust and ignores growing ecological and economic constraints on inputs. Similarly an over-emphasis on low input alternatives risks ignoring genuine and irresistible growth in aggregate human needs and the threats to remaining wild ecosystems from conversion to agriculture.

We suggest an alternative approach is necessary – a focus on maintaining ecosystem health through the management of terrestrial and aquatic environments as multifunctional mosaics. This approach envisages ecosystems managed to provide a range of services, with sites of intensive production supported by contiguous areas providing different services. This is compatible with modest average increases in productivity and with greatly enhanced

resilience in the face of natural and economic shocks. It recognises that ecosystems managed well can be both productive and resilient.

Four key changes in our current thinking and behaviour are required to deliver this more sustainable approach:

1) Governments, businesses and civil society should aim to counteract negative trends such as population growth, the impacts of climate change and unsustainable consumption patterns;
2) Ecosystems should not be viewed and treated as machines for the production of food or fibre, rather they are more like organisms with multiple needs and functions;
3) Technology and research are crucial in meeting the challenges ahead; making them open-source and combined with social learning (which shares relevant expertise from a wide range of sources) will benefit the greatest number of people, and;
4) Global markets in food and commodities need to recognise and value appropriately the positive services that ecosystems provide in addition to food production, and to incorporate features that reduce price volatility and shocks to ensure food security at all levels of society.

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Box 1. Definitions and key terms

An *ecosystem* consists of organisms and the non-living environment with which they interact. Ecologists view such systems in terms of *structure* (the species, the trophic links between them and their physical environment) and *functions* (the processes occurring within the ecosystem such as the cycling of nutrients and the flow of energy). Although the boundary of an ecosystem is often ambiguous and always permeable – with flows of energy and usually nutrients across it – ecosystems show persistence over time despite this permeability. Ecosystem functions are often performed by *functional groups* of organisms rather than single species. For example there may be a functional group of top predators that collectively regulate the populations of species lower in the food chain. Whilst the loss of the whole functional group is disastrous for ecosystem function (and may be *non–substitutable,* that is impossible for humans to replace) the loss of any individual species within it may or may not undermine function. Structure and function contribute to ecosystem *resilience* in ways we do not yet fully understand. Resilience describes the ability of a system to withstand, recover from, or adapt to, disturbance and to go on functioning. Ecosystems subjected to intense or persistent disturbance may undergo *regime shifts* which involve large, abrupt and persistent changes in structure and function.

Ecosystem services are the benefits people obtain from ecosystems. These may be *provisioning, regulating, cultural* or *supporting* (Watson et al., 2005) referring, respectively, to physical goods such as food and fibre, the regulation of natural processes such as erosion, flooding, climate fluctuations and pollination, the non-material cultural, aesthetic, psychological and spiritual benefits of the natural world and services that underpin and supply all the others, such as the formation of soil and photosynthesis. *Bioproductivity,* as used here, is a supporting service and food production is a provisioning one that depends on it.

We follow Smith (2003) in using the word *narrative* to imply a simplified and selective story that focuses attention on what is considered the core issue and that implies or states what needs to be done; it is an outlook that helps to frame a view of the world to the exclusion of alternatives. The narratives we discuss are supported by evidence and present plausible stories. However such accounts are partial and are normative as well as descriptive; they imply a particular world-view rather than a value-neutral objectivity. Narratives represent a particular *framing* of a problem that reflects the interests of particular groups of people (often the powerful); they carry the danger of 'lock-in' to the exclusion of alternative views (see STEPS (2010)).

Mixed-use mosaics are where the land or sea are managed for multiple services as opposed to just one (e.g. food provisioning). The practice can operate at a range of scales, and relates to ecosystems as functional self-regulating systems. It is similar to the term *sustainable intensification* as applied by the Royal Society (2009) and Pretty et al. (2011) to agriculture but is broader in embracing all types of bioproductivity. It implies managing landscapes and seascapes in a multifunctional mosaic, where production of food and other products is integrated with other services such as waste retention, watershed or climate regulation and large areas are not dominated by monocultures.

Sustainable intensification describes managing terrestrial agriculture to produce more food without adverse environmental impacts or the conversion of more land to agriculture. Sadly the term has been co-opted by some to imply business as usual intensive mono-culture with some limited greening. In this paper we use the term in its original intention.

Section one - the challenge ahead, delivering wellbeing without undermining essential ecosystem services

Introduction to the challenge

Bioproductivity is the ability of ecosystems – whether pristine or altered by humans – to capture energy in organic form. It is the basis of food production for humans and all other species and underpins all ecosystem functioning. This paper considers the near future of bioproductivity on Earth, in terrestrial and aquatic ecosystems. It shows how current trends and anticipated changes will lead to major challenges in ensuring human and ecosystem health for mid-century. Although we write as ecological scientists we also consider contributory social and economic factors; in an age where humans dominate ecological processes, a fastidious patrolling of disciplinary boundaries is unhelpful. Pressure is building to intensify current agricultural practises in response to these challenges. After considering the trends that underpin this argument we conclude that it is both too pessimistic (in assuming human behaviours cannot change) and too optimistic (in ignoring ecological limits and thresholds). Mixed-use mosaics, in which the land and sea are managed for multiple services, is a better option.

Productivity is only one function of ecosystems (although arguably the most important or foundational one). Other functions and services (see Box 1) include regulation of water and climate, provision of habitat for biodiversity, control of disease, recycling of nutrients and waste and production of soil. Healthy ecosystems are required to provide provisioning services (including food) for humans and for all other species and there are inevitable trade-offs between human and non-human uses of bioproductivity (Fig. 1). Ecosystems are both made by and support all living things, but a single species (*Homo sapiens*) now appropriates an estimated 32% of all terrestrial bioproductivity (Rojstaczer et al., 2001) using approximately 72% of Earth's ice-free surface to provide our food and shelter (Tilman et al., 2011). There are large areas of land, especially in India, China, the Middle East, Europe and the north east United States of America, where total human appropriation of bioproductivity exceeds the productive capacity of the local ecosystems (Imhoff et al., 2004). Human use exceeds 50% of all available freshwater runoff (with 75% of this used in agriculture), intensifying the magnitude and frequency of droughts (Wada et al., 2013). There is compelling evidence that a near future of maximising production will compound current problems and create new ones, presenting an enormous 'bioproductivity challenge for the world.

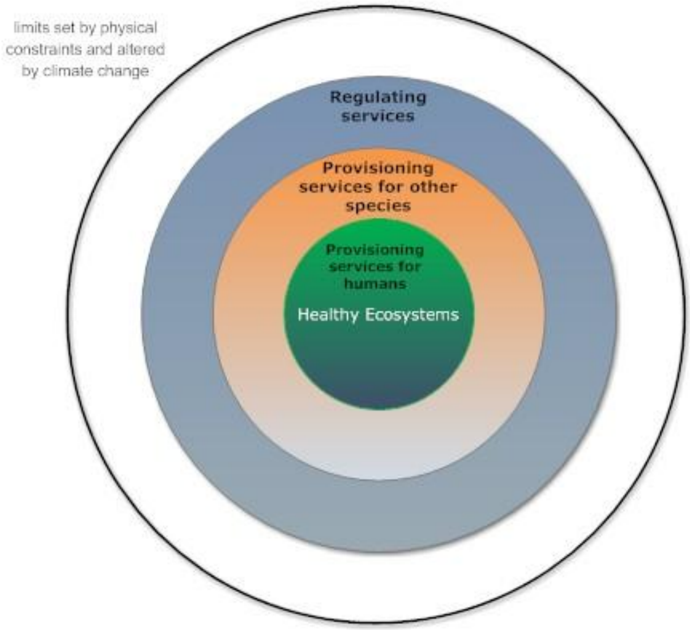

Figure 1. Ecosystem provisioning for humans and other species: provisioning services rely on ecosystems, with services for humans a necessary sub-set of those for all species. Provisioning can only occur if ecosystems also provide supporting services (such as soil production). The total 'space' for bioproductivity is constrained by physical limits such as energy from the sun, fresh water. It will be altered by climate change.

Dimensions of the challenge

1. Food supply - The median population projection by the United Nations Population Division is 9.6 billion by 2050, an increase from today of some 2.6 billion people, or 37%. Because global wealth is also projected to grow, the demand for food (for human and livestock consumption) is expected to grow faster than population. Hence many authors predict that global food production must be substantially increased in order to avoid mass starvation. For example the Royal Society states that 'even the most optimistic' projections assume 50% growth (Royal Society, 2009), the UN FAO estimates that a 60% increase in the availability of food calories will be required by 2050 (Alexandratos & Bruinsma 2012), whilst higher predictions include 100% from Tilman et al. (2011). Others (e.g. Garnett *et al.* 2013) argue that although food production will need to increase, the scale of increase can be significantly mitigated through action to reduce food waste, obesity and excessive meat and dairy consumption.

2. The more than human world - The International Union for the Conservation of Nature classifies 14% of species of bird, 22% of mammals, 29% of reptiles and 43% of amphibians as threatened with extinction. Recent documented rates of extinction exceed those in the fossil record by 100-1000 times and rates will accelerate further under business-as-usual. Hence human beings are responsible for initiating a mass extinction comparable to those caused by mega-disasters in previous geological eras. Many world views – whether based on religious or spiritual convictions or on secular ethical systems such as respect for sentience or for rights – consider this elimination of our fellow species as wrong in itself. And it impoverishes the human world by leaving less natural beauty and wonder for our ancestors to enjoy. We share the common view (e.g. (European Commission, 2007) that even though biodiversity is essential for future human wellbeing, the natural world and our fellow species are more than just 'natural capital' present for human benefit.

3. Loss of ecosystem services - Whilst ethical and aesthetic considerations may not be sufficient to motivate concern about biodiversity and ecosystems, material self-interest should be. Since ecosystem functions and services ultimately rely on species, reductions in biodiversity must eventually undermine the ability of ecosystems to maintain function, including bioproductivity. There is abundant evidence that this is already happening (Watson et al., 2011; Cardinale et al., 2012). It often follows the loss of groups of organisms that carry out important functions that are not substitutable such as pollination and trophic regulation. For example, Caribbean coral reefs suffered rapid change from healthy species-rich systems, complete with multiple services such as fisheries and high tourism value, to species-poor algal beds (Hughes, 1994). A threshold was crossed once the last species in the 'algal grazer' functional group was lost, resulting in rapid spread of algae. Continued loss of biodiversity will therefore accelerate the erosion of ecosystem services not only because of projected increases in the rates of loss but also because of these non-linear relationships between species loss and function. Critical thresholds will be revealed more frequently as ecosystems become increasingly homogenised (with dominant species being shared between many ecosystems) and denuded of species.

4. Social justice - Accidents of birth –country, gender and social class – are the largest determinants of what people eat, how they are educated and what prospects they have in life. Chronic under-nourishment (defined as regularly failing to obtain sufficient calories to lead an active life) is the most shocking outcome. A total of 842 million people in

2011–13, or around one in eight people in the world, were estimated to be suffering from chronic hunger. Many more (~2 billion; Micronutrient Initiative, 2009) suffer from deficiencies in micronutrients that undermine their development and health; malnutrition is not only a function of calories. The total number of undernourished people has fallen by 17 percent since 1990–92 (FAO, 2013). Hence progress is being made towards the 2015 Millennium Development Goal target of halving chronic hunger, but a major challenge remains to reach a basic level of shared food security. The increasing demands for food and sudden increases in food prices threaten to slow or reverse the progress in reducing chronic hunger, whilst food inequality is increasing with more people globally now suffering from obesity than from under-nourishment. In developed countries obesity, with its associated morbidity and stigma, is associated with poverty and is thus also an issue of social justice.

5. Climate change - Climate change is causing changes in patterns of precipitation, increases in extreme events, increases in average temperature, reductions in reliability of glacier meltwater, ocean acidification, sea level rise and diseases (IPCC 2014). Anthropogenic warming over the past century has been relatively modest compared with predicted additional changes in the coming century (0.7 °C increase compared with 1 – 3.7 °C predicted; see Box 2). However the changes already experienced are impacting global agricultural yields by slowing down the increases that are occurring in total productivity. For example global wheat production was lower by 5.5% over 1980-2008 compared with a modelled scenario without climate change; and the discrepancy was 14% in Russia where impacts of temperature change were particularly severe (Lobell et al., 2011). Even at 2 degrees of warming, often referred to as the threshold of ‘dangerous’ climate change, yields of major crops are expected to decline in both temperate and tropical climates, with more than 70% of models predicting global declines – in some cases by 25% or more – by 2050 (IPCC, 2014). In the oceans, many fish species are changing their distributions (by moving towards the poles) affecting fisheries resources (Sumaila et al., 2011). More worryingly, there are contested claims that global ocean productivity is already declining due to increasing stratification of warming waters (Behrenfeld et al., 2006; Boyce et al., 2010). Hence climate change will exert new pressures on bioproductivity. Since agriculture already directly accounts for over 10% of greenhouse gas emissions (IPCC, 2014) responding to the challenges of climate change, for example by intensification of production or investment in more fuel-intensive offshore fishing boats, could simply worsen the impacts in the long-term. The excessive use of bioenergy (fuels derived from biomass) to replace fossil fuels is another example of such ‘maladaptation’. Whilst bioenergy undoubtedly has a role in climate change mitigation, there will be strict limits on sustainable yields since in general land committed to biofuel production cannot be used to grow food. These limits will depend in part on other demands on bioproductivity, for example meat production. Smith *et al.* (2013) consider both ‘supply-side’ (such as better fertilizer use) and ‘consumption-based’ (especially reductions in meat consumption) measures for reducing greenhouse gas emissions from agricultural land. Whilst they argue that both are necessary, they show how consumption based measures offer a greater potential for greenhouse gas mitigation that supply side ones.

Box 2: Climate change predictions
From time to time, the Intergovernmental Panel on Climate Change (IPCC) assembles and evaluates recent observations of past climate change and recent predictions of future climate change. The predictions are based on simulations with 'multi-model, multiparameter, ensembles' and thus take account of known uncertainties to generate confidence envelopes. The simulations are driven by sets of 'representative concentration pathways (RCPs)' for emissions of greenhouse gases. Four main RCPs cover a range of scenarios (see below). The results for temperature rise are:

Global mean surface air temperature change, degrees Centigrade, 2081-2100 relative to 1986 - 2005, with likely range (roughly, the range that includes all but the lower 5% and the upper 5% of ensemble simulations): RCP2.6 mean 1.0 range 0.3 to 1.7; RCP4.0 mean 1.8 range 1.1 to 2.2; RCP6.0 mean 2.2 range 1.4 to 3.1; RCP8.5 mean 3.7 range 2.6 to 4.8.

The most optimistic scenario, RCP2.6, implies drastic reductions in emissions, such that, by 2050, net emissions are below 1990 levels, and are roughly zero by 2100, with sinks beginning to exceed sources and CO_2 concentration in the atmosphere by 2100 at 421ppm (it already exceeds 400ppm). RCP4.0 and RCP6.0 seem more likely but still require stabilisation of emissions; RCP8.5 implies that emissions continue to increase.

It is concluded that to achieve a 66% probability of keeping the global temperature rise to within 2 degrees C from the reference period 1861-1880, and taking account of other greenhouse gases, the maximum emissions of CO_2 should not exceed 790 GtC. About 50GT are currently emitted each year and "An amount of 515 (445 to 585) GtC was already emitted by 2011." Many experts believe that the target of keeping warming below 2 degrees, which is repeated in numerous governmental statements as a threshold beyond which 'dangerous' climate change will occur, will not be reached. For example Anderson and Bows (2011) state: 'There is now little to no chance of maintaining the rise in global mean surface temperature at below 2°C, despite repeated high-level statements to the contrary'.

Figures, and conclusions, taken from IPCC (2013)

Summary of Section one

Human demands on food, water, fibres and a range of ecosystem services are already enormous. They are causing rapid losses in biodiversity and threaten long term ecosystem health whilst failing to meet the basic needs of the world's poorest. Whilst economic and population growth will increase human demands, climate change will make meeting them harder, and increase the pressure on our fellow species. A focus on maximising production above all other ecosystem services implies the crossing of critical thresholds, including that of 'dangerous' climate change.

Section two – testing and rejecting the dominant narrative

The dominant narrative

Consideration of these pressures has led numerous crop scientists, national academies, agricultural lobby groups and agri-businesses to develop a powerful argument around future food security that emphasises the importance of applying technology and increasing inputs to increase yields, modelled in part on the green revolution of the 1960s and 1970s. This 'dominant narrative' can be summarised as:

> *Because of increasing population, increasing affluence, rapid urbanisation, changing diets with greater consumption of animal products and increasing pressure from climate change we need massive investment in agricultural technology – whether modern conventional breeding techniques or GM - and intensification in agricultural production to provide sufficient food for everyone by mid-century. This will inevitably involve trade-offs with other ecosystem services and result in a concentration of ecosystem use, with landscapes and seascapes divided into intensively productive, monocultural agricultural areas, spaces for residual wildlife and mega-urban centres'.*

This narrative rests on foundations stretching back to Adam Smith's *Inquiry into the Wealth of Nations* and including the remarkable successes of 20th Century agricultural technology, such as massive yield increases during the green revolution. Proponents argue that the lower outputs of organic farming, the need to protect remaining wildlands and forests and irresistible growth in demand for foodstuffs, fibres and biofuels mean we must invest in more intensification and in maximising production from monoculture farming. Whilst acknowledging the successes achieved to date by high input, high technology approaches, knowledge of the working of ecosystems and of ecological limits raises serious questions about the dominant narrative and its advocacy of substituting human technology for natural ecosystem services, which as Fitter (2013) demonstrates is not possible in most cases.

Testing the narrative

Here we raise four questions, the first asking whether the view of ecosystems implicit in the dominant narrative is correct and the others considering ways in which the projected demands on bioproductivity may be inaccurate.

Question 1: Are trade-offs inevitable? Ecosystems as machines or as organisms

Managing an ecosystem for maximum productivity may have a range of effects on the other functions and services that it provides. Two metaphors commonly applied to ecosystems imply different effects of attempting to maximise productivity. The 'ecosystem as machine' metaphor suggests trade-offs between contrasting ecosystem services. Cars can be built for speed or for safety, but not to maximise both. 'Ecosystem health' however implies a different interpretation; a healthy organism is better at a whole range of things than an unhealthy one, implying the possibility of synergies between functions (such as digestion and respiration); trade-offs may not be inevitable in these systems. Defining and understanding ecosystems is a central problem of ecology and one that remains contentious; ecosystems are neither machines nor organisms. However both organisms and ecosystems are complex systems with the capacity to regenerate and repair, a perspective with important implications for how we expect ecosystems to function. In particular, it means that by supporting the maintenance and creation of 'ecosystem health' we can benefit from the functions and services that healthy ecosystems provide.

So what does it mean to talk of a 'healthy' ecosystem? Abundant evidence supports the idea that ecosystems can show integrated and emergent properties that can be usefully considered under the umbrella metaphor of 'health'. Four key characteristics of ecosystem health were described by Tett et al. (2013) as:

1) Structure or organisation. This refers primarily to the trophic structure of the community (the way producers, herbivores and carnivores inter-relate in a food web) including the number of functional groups (such as organisms that can fix nitrogen, decompose cellulose or act as top predators). By analogy with an economy, a healthy ecosystem is one in which there is a good variety of different jobs or roles, and one where key jobs are not performed by only one or a few types or class of people. As with the other characteristics listed below, this definition of health is relative; some ecosystems are naturally more species rich (and contain more functional groups) than others.

2) Vigour. This refers to the fluxes of material and nutrients through an ecosystem, including carbon resulting from primary production, and the balance of these fluxes such as synthesis of organic material from carbon compared with respiration of CO_2. By analogy with an economy, a healthy ecosystem is one in which there is good communication and infrastructure and where energy and materials can flow easily between users along multiple routes.

3) Resilience. The capacity of the ecosystem to maintain its integrity when subjected to damaging impacts. This might refer to its ability to resist the effects of such impacts or to its ability to recover from them. By analogy with an economy, a healthy ecosystem is one which does not easily fall into an economic recession and which recovers fast if it does.

4) Hierarchy and heterogeneity. The existence of subsystems within the main system, which have some degree of independent function and which can help re-seed or stabilise other sub-systems that are damaged or under threat through efficient interconnections. By analogy with an economy, a healthy ecosystem consists of a number of different industries which may be connected but which have some degree of autonomy. Similarly, Nobel laureate Eleanor Ostrom has shown how subsidiarity can aid the sustainable management of 'common-pool resources' such as fish stocks or aquifers.

The dominant narrative leads to outcomes based on trade-offs between ecosystem functions and uses. It is undeniable that maximising one service or function, such as productivity, involves sacrificing others in some ecosystems and for some combinations of services. An important case involves the trade-off between resilience and productivity in many intensive agricultural and aquacultural systems. For example prioritising short-term productivity in intensive shrimp aquaculture notoriously leads to 'boom and bust' production with disease outbreaks and abandoned ponds following a few years of high outputs (e.g. Munasinghe et al., 2010). Paprocki and Cons (2013) describe how shrimp aquaculture in Bangladesh has left some areas in states of 'ecological crisis, bordering on ecological collapse', with mass landlessness and dispossession of peasant farmers and increased vulnerability to sea level rise and cyclones. However such trade-offs may not be inevitable, at least for healthy ecosystems that have not been so changed by human pressures that they have already transformed into different states. The regulating services of ecosystems, such as the abilities of a wetland to capture carbon and to buffer floods or extreme weather, often work in synergy; manage for one and the other comes as part of the 'bundle of services'. Whilst trade-offs between regulating and provisioning services may be more common they are not universal. In medium intensity farming, it is common for reductions in pesticide use to result in increases in productivity, as the regulating service of natural predators is restored as part of planned integrated pest management schemes (Pretty, 2008). Maximising the long term productivity of coral reef fisheries involves using a range of ecosystem management approaches which protect the habitat and place effective restrictions on short-term fishing effort (Bellwood et al., 2004). Many wild fisheries are currently overfished, both ecologically (meaning that they are in danger of collapse) and also economically (meaning that short term restrictions on fishing effort would result in higher value captures, including in many cases larger amounts, in the longer term). Hence long-term maximising of this provisioning service of reefs does not involve trade-offs with other services, but rather enhances the reef's ability to provide habitat for other biodiversity, protect the coastline, capture carbon and attract tourists. Such synergies are not limited to provisioning services in 'wild' marine ecosystems. In some regions of the world agricultural communities continue to make heavy use of 'wild' species in addition to those they cultivate; a recent review reported an average of 90-100 such species per agricultural and forager community in a sample from Africa and Asia (Bharucha and Pretty, 2010). Hence the distinction between wild and cultivated species may often be exaggerated, and managing for regulating services from wild species (such as pollination) can enhance food production from them too.

Box 3 gives three examples of how increasing one provisioning service can impact other ecosystem services; two of these involve synergies and one trade-offs. Trade-offs are possible in many types of ecosystems, but are likely to be particularly prevalent and likely to dominate over synergies in highly modified ecosystems such as intensive monoculture farmland. In our terminology, such examples have already been transformed away from healthy ecosystems and towards the status of 'machines', maximised for one function but vulnerable to regime shift and reliant on constant external inputs.

Box 3. Ecosystem service synergies or trade-offs?

Increasing the amount of a provisioning service (such as food) may involve enhancing the delivery of other services (a synergy) or reducing them (a trade-off). Here the first two examples illustrate synergies, the last a trade-off. The examples lie along a scale of intensification, from a largely unmanaged, natural system to an intensively managed and artificial one. Trade-offs are more likely at the intensive end of this scale.

Example 1: Increasing fisheries provisioning from mangroves

Mangrove forests provide a wide range of services, including provisioning of timber, medicines, fish and shellfish. Good catches of fish and shellfish (especially crabs and shrimp) rely on good ecosystem health, including proper flushing by seawater, dense and productive stands of trees and ecological connections with adjacent ecosystems such as seagrass meadows. Hence managing mangrove forests to enhance fisheries provisioning implies enhancing ecosystem health, with concomitant benefits for other services such as coastal protection and carbon sequestration. Positive interactions between individual trees raise the prospect of synergies for timber production and other services as well (Huxham et al., 2010).

Example 2: Increasing crop yields in mixed maize systems in Malawi

African agriculture suffers from a large ‘yield gap’ – the difference between potential production and achieved harvests. Productivity of maize farming in Malawi has recently been dramatically improved following a subsidy for N-fertilizer, allowing millions of farmers to boost yields. However increasing inorganic N inputs is expensive and vulnerable to future hikes in prices. In a large scale experiment Snapp et al. (2010) compared monoculture maize treatments with maize inter-cropped with nitrogen fixing shrubby legumes. They found the legume treatment produced the same (enhanced) crop of maize as a fertilized monoculture treatment, but with only half the amount of expensive fertilizer. In addition the yield was more stable and other ecosystem services, such as soil condition, biodiversity and carbon content showed signs of improvement. Agroforestry initiatives in Malawi and other African countries have shown how the use of nitrogen fixing ‘fertilizer trees’ can result in increased maize yields along with new services from the trees including honey and fuelwood (Asaah et al., 2011; Pretty et al., 2011).

Example 3: Increasing timber yields from monoculture plantations

Whilst forests may bring multiple ecological and social benefits plantations managed for maximum productivity often cause problems. Jackson et al. (2005) describe the trade-offs between monoculture tree plantations (often planted for fast production of wood) and hydrological services. Using a global data set they show how plantations reduce river flows; this may be a benefit in wet, flood-prone areas but a threat in many drier ones. They also tend to salinize and acidify soils. They report how these effects are less pronounced or absent in natural forests.

Question 2: How many mouths to feed?

The global human population will continue to grow over the next thirty years (assuming no unprecedented catastrophes). The United Nations Population Division recently revised their median prediction for 2050 upwards to 9.6 billion, further increasing to 10.9 billion by 2100 (Figure 3). Under this projection the total fertility rate (that is, the average number of children a woman will have during her lifetime) is 2.24 in 2045-2050; whilst large differences in fertility still exist between more and less developed countries, their fertility rates are converging rapidly, with 1.85 children per woman in the more developed regions and 2.29 children per woman in the less developed regions. However by 2050 there are already large differences in estimated total numbers depending on the assumptions concerning fertility, migration and mortality – Figure 3 concerns changes in fertility only, and assumes the same mortality and migration rates. The high fertility projection suggests 10.9 billion by 2050, compared with 8.3 billion under the low fertility scenario. This difference of 2.6 billion has widened to 9.9 billion by 2100 under the two scenarios, as the high fertility projection shows continued growth and the low projection sees population size peaking in 2049 and then starting to decline. In 2050, total fertility rates are 1.36 vs 2.35 children per woman in the more developed regions and 1.83 vs 2.76 children per woman in the less developed regions for the low vs high fertility projections respectively.

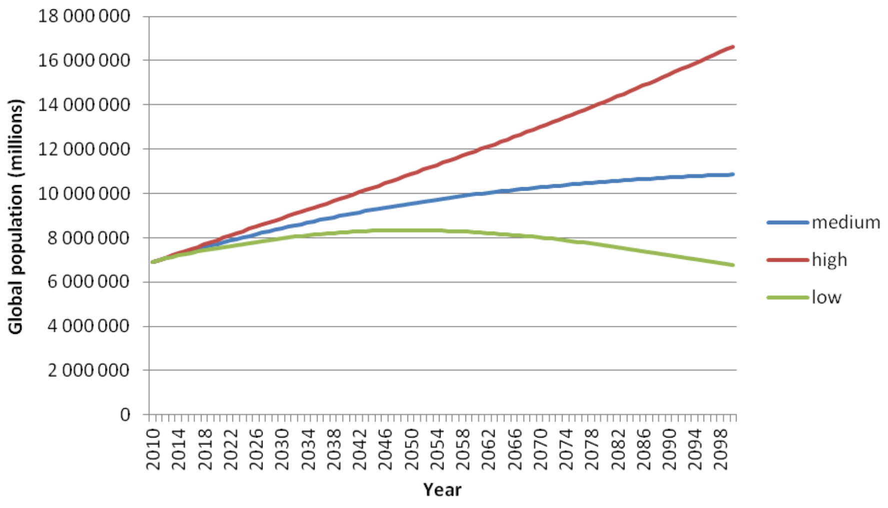

Figure 3. UN population projections until 2100. Reproduced from data taken from UN (2013)

Hence UN projections show that global population will increase, but that there are very large differences between projections; the 2.6 billion between high and low projections by 2050 is the same as the total global population in 1950. The differences are largely contingent on what happens to total fertility rates, particularly in less developed countries.

Question 3: How much wasted food?

Estimates of the total percentage of all food calories that are wasted – not consumed by humans or livestock – are difficult to produce, partly because of the multiple points in the provision of food from field to consumer at which waste can occur. Waste includes material that is not harvested, is harvested but then is lost in storage or before sale, is wasted during processing and at the slaughterhouse and is disposed of by households and businesses after purchase. Recent estimates in the UK suggest that households throw away around 19%, by weight, of the food that they buy (WRAP, 2014) and it is likely that US consumers are even more profligate; Fairlie (2010) suggests US consumers may waste up to 45% of their food. Considering all of these waste sources together suggests that at least one third of global food production is wasted, and that there are therefore very large opportunities to reduce food waste. In developing countries, public investment in transport infrastructure would reduce the opportunities for spoilage, whereas better-functioning markets and the availability of capital would increase the efficiency of the food chain, for example, by allowing the introduction of cold storage. Existing technologies and best practices need to be spread by education and extension services, and market and finance mechanisms are required to protect farmers from having to sell at peak supply, leading to gluts and wastage. There is also a need for continuing research in postharvest storage technologies, particularly to reduce the extensive losses to pests and diseases of stored crops and products. Improved technology for small-scale food storage in poorer contexts is a prime candidate for the introduction of state incentives for private innovation, with the involvement of small-scale traders, millers, and producers.

Question 4: How much will diets change?

The median UN population projection is for an increase of ~37% in global population by 2050. As summarised above, projected increases in food demand range from 60- 100%. This disproportionately fast increase is driven by assumptions about the growth in wealth and concomitant changes in diet, in particular increased consumption of meat

(Bonhommeau et al., 2013). Tilman et al. (2011) show that in 2000 *per capita* use of calories and of protein in their group of 15 richest nations (which includes Australia, Denmark, Japan, UK and USA) were 256 and 430% greater, respectively, than use in their five poorest nations (Central African Republic, Chad, Democratic Republic of the Congo, Niger and Sierra Leone). Whilst these differences partly reflect the need for greater *per capita* consumption amongst the very poor (to overcome chronic hunger) they also reflect much higher meat consumption, and higher consumption of relatively inefficient types of meat, among wealthy consumers than in poorer nations. Tilman et al. (2011) find strong correlations between wealth and *per capita* food consumption and use these to project future demand, with increases even in the wealthiest countries. There is a projected increase of 10% in *per capita* consumption in the wealthy nations by 2050, and of 34% in the second wealthiest group, taking their *per capita* rates to ~9200 and ~8800 Kcal day^{-1} respectively (these *per capita* rates look high because they include all the crops used for livestock and fish foods, as well as for direct human consumption). An estimated 1.4 billion adults globally are already overweight, with 65% of the world's population now living in countries with higher rates of mortality from being over rather than under-weight (WHO 2012). Given these rates of obesity and diet-related morbidity projections of even higher consumptions of calories are worrying; they are based on the extrapolation of business-as-usual rather than any suggested intervention to improve health or diets.

On a global scale consumption of meat and dairy products is strongly correlated with wealth. Assumptions of increasing meat consumption with growing global wealth are particularly important factors in generating the disproportionately large projected increase in food demand. This is partly because of the thermodynamic facts of energy loss along food chains, which makes less energy available for consumption as we move from primary producers to herbivores and then carnivores up a food chain. A ratio of 10:1 for energy in: energy out, implying 90% loss of useful energy between, for example, herbivores and plants, is often given in ecology texts and research (see e.g. Bonhommeau et al., 2013). In his careful analysis of the energetic efficiency of meat, Fairlie (2010) shows how the actual conversion efficiencies of plant materials to meat vary enormously depending on the species and agricultural systems involved. For example using waste materials as feedstock, and land unsuitable for crops for grazing, makes meat much more efficient. Many traditional agroecosystems such as the Asian steppes rely on grazing and represent sustainable uses of land. Pigs can provide an efficient way to store and recycle calories, eating food spurned or inedible by humans and converting low quality calories to high quality nutrients. However such efficiencies depend on using balanced low input systems. The least efficient approach is to take grains suitable for humans and feed them to cattle; here the conversion efficiencies are likely to be 14:1 or even worse. Whilst energy provides a useful general measure of agricultural efficiency other metrics may be more relevant to specific locations, for example water may be more limiting than energy in some cases. Substituting water for energy reinforces the wastefulness of grain fed cattle, with estimates from California suggesting 13.5 tonnes are required for each kg of beef (compared with 1.2 for wheat and 0.2 for potatoes; Hoekstra 2003). Because increasing meat consumption in recent decades has also correlated with decreasing energetic efficiency of meat production, the projected increases in meat consumption are based on assumptions of low energetic efficiency.

Fish have traditionally helped meet the demand for protein and are particularly important in poorer countries. Nearly 3 billion people globally rely on fish for 15% or more of their protein intake, and around 8% of the world's population are directly or indirectly supported by marine fisheries (Sumaila et al., 2011). However the total take from capture fisheries peaked at 87.7

million tonnes in 1996 and has since declined by around 10% (FAO 2012). 57% of marine fisheries are fully exploited (meaning that no more fish can be harvested without threatening long-term sustainability) and 30% overexploited (meaning that they are already fished above sensible ecological and economic limits; (FAO, 2012). Hence there is very limited capacity for any expansion in global fish catches, at least in the short term. Despite this, fish production is increasing because of the rapid growth of aquaculture, which now provides more than 50% of the world's fish. Small scale aquaculture provides numerous examples of mixed use mosaic, multifunctional approaches to achieving increased yields. For example Integrating Aquaculture with Agriculture (IAA) approaches in Africa can use low cost feeds and recycle wastes to grow protein and generate new businesses (Brummett and Jamu, 2011). In contrast most intensive production is currently unsustainable, relying as it does on habitat destruction (in the case of shrimp farming in mangrove areas) and inputs of food caught from the wild (exacerbating problems with capture fisheries). Box 4 illustrates the opportunities and challenges of aquaculture using salmon.

Box 4: Caging and eating the tigers of the sea

Cultivation of salmon is seen as an economically efficient way to feed people healthily and without overfishing wild populations. Furthermore, fish are better converters of feed into flesh than are cattle or pigs, because fish - cold-blooded and supported by the watery medium - expend less energy during growth. Of course, floating-cage aquaculture needs stringent regulation to avoid polluting the sea-bed or harming other marine creatures but, given this, what's the objection?

The key problem is that of ecological transfer efficiency. Grass- or grain- fed cattle use primary production, and, properly farmed, might convert at least 10% of this into meat. Predators, feeding on cattle or wild herbivores, convert at best 1% of primary production into predator biomass. Salmon are the marine analogues of large predators - or, to be accurate, of the super-predators that eat predators. In the wild, salmon prey on smaller 'forage fish' that eat animal plankton that eat phytoplankton, the marine primary producers. This implies an overall ecological transfer efficiency of one-tenth of 1%.

Why don't we try to feed lower down the marine food web? By fishing zooplankton, we could use up to 10% of primary production. The main difficulty is the energetic costs of capture: zooplankters are very small, and ships need powerful engines to haul large nets of a suitably fine mesh. It is more feasible to catch the planktonivorous forage fish. Forage fish include anchovies and herring. Prior to 1969 herring were caught in the North Sea for human consumption. Then the fishery crashed. Now it has been restored, but people in the UK no longer eat herring, and so it is mainly converted to feed for salmon (and chickens).

So it would be desirable to restore herring to our dining tables, or to use omnivorous fish such as carp in aquaculture. Alternatively - and this is an approach that is now being explored by some fish-farmers - salmon feed could be partly made from vegetable materials. Experiment has shown that it is possible to replace about three-quarters of the feed with plant material without harm to salmon well-being or altering the taste for humans. The long-chain omega-3 content of feed, currently supplied from fish oils, could be taken from genetically engineered oilseed crops. This would be using technology to increase the ecological transfer efficiency in marine aquaculture. And it would allow more forage fish to remain in the sea, where they provide food for creatures other than humans.

Sources:(Cury et al., 2012; Naylor and Burke, 2005; Ruiz-Lopez et al., 2013)

Summary and Conclusions for Section Two

The dominant narrative rests on projections of increased human population, increased average affluence, continued food waste and changes in average diet (and particularly increased consumption of grain-fed meat). As with any projections, these assumptions involve both quantified uncertainties (reflected in the differences between high and low projections) and uncertainties that cannot be quantified (including those relevant factors that are simply unknown and that cannot therefore be explicitly considered). The dominant narrative presents the main trends as essentially irresistible forces – torrents that will drive us remorselessly into a future which is more crowded, more urbanised, more fragmented – into urban, rural and vestigial wildlands - and more homogenised. However, accepting the direction of flow does not imply drifting – we can choose to steer in the current. For example there are huge opportunities to influence total global population, food waste and meat consumption in ways that will reduce pressures on ecosystems and improve human health. Hence a key challenge to the dominant narrative is to recognise how it conflates the virtually certain (such as increasing human population until 2050) with assumptions about human tastes, need and greed (such as increasing calorific consumption even in wealthy countries).

Linear thinking underpins the dominant narrative and reflects its broad acceptance of continuing global trends. Recognition of limits to these trends, combined with strenuous and informed efforts to avoid stepping over irreversible ecological thresholds, would suggest a different story. The metaphorical conception of ecosystems as more like organisms than machines is a key contribution from ecological science. It suggests that healthy ecosystems can combine multiple functions and services, particularly regulating ones, in ways that are synergistic and mutually supporting. But treating ecosystems as efficient machines, simplified to maximise the production of one or a few goods, makes them brittle and vulnerable to collapse – it makes them unhealthy. A useful distinction between a biological system (including an ecosystem) and a machine is that the former but not the latter is autopoietic: capable of long term self-maintenance. Maximising productivity may have the effect of converting a 'system' into a 'machine'; something no longer capable of sustaining itself and therefore relying on intensive inputs and management to avoid sudden deleterious change. There are many examples of regime shifts in ecosystems caused or exacerbated by humans that reduced local and regional bioproductivity; the collapse of the Newfoundland cod fishery in the 1990s, the desertification of the Sahel in the 1980s, the origins of the Dust-bowl in the USA in the 1930s and degradation of reefs in the Caribbean in the 1970s are just a few. Despite these disasters and the documented erosion of ecosystem services across the world (Watson et al., 2005) human welfare globally, as measured by indices such as the human development index, has continued to increase. This generates a paradox for ecologists and environmentalists: if ecosystems are so important for humans, how come some things are getting better even as ecosystems continue to degrade (Raudsepp-Hearne et al., 2010)? Of course how best to measure human well-being is contentious and there is evidence that it has remained unchanged over the past forty years in affluent countries even though GDP has increased several fold (Pretty, 2013). But even assuming genuine global improvement the dominant narrative provides a poor guide to the future; it assumes that the answer to this paradox is that ecosystems are not as important as environmentalists think, or at least that the services that ecosystems provide can be replaced by technology in wealthy societies. If this is true then linear thinking is appropriate. Abundant evidence, and prudent concern for the future, suggests that it is not, and that current practices and rates of exploitation are buying prosperity now at the expense of future generations.

Section three – a more sustainable route

Demography is not destiny

How do environmentalists avoid being 'on the wrong side of the fight against global hunger'? That is the challenge raised by Paul Collier in his analysis of the failure of economists and environmentalists to inform each other (Collier, 2011). The debate is often framed as a contest between powerful economic interests favouring more globalisation and intensification and greens eulogising organic localism; 'ostriches' and 'romantics' in Collier's terms. He warns that spikes in the global price of food hurt the urban poor most since these are the people without surplus money to buy food and without the land to grow it. Therefore policies promoted by 'romantics' – such as organic agriculture – that increase food prices will lead to hunger. It is surely correct that the rights of poor people to adequate nutrition should be paramount. It might also be right to claim 'there is nothing to be done about the increase in the demand for food' (Collier, 2011; p211); but a consideration of underlying causes suggests there is much that could be done about the *rate* of increase. Simply accepting high global population growth, increased obesity, increased consumption of meat and continued profligate food waste are inevitable is defeatist; demography is not (or at least is only partially) destiny. A good example of how cultural attitudes and beliefs can shape sustainable diets is provided by meat consumption in India. Despite rapidly rising GDP Indians eat only around 4kg of meat per year, ten times lower than their consumption 'predicted' on the basis of average income (Pretty, 2013). Other countries could follow that example of decoupling increasing demands for food (caused by increasing population) from increasing meat consumption; Sweden provides one example of where active government intervention has reduced meat consumption (Bonhommeau et al*.* 2013).

Taking a 'predict and provide' approach is not only defeatist, it is also dangerous. Collier's 'ostriches' are so called because they ignore looming environmental problems, in particular climate change. However his preferred scenario of intensifying production in simplified agricultural ecosystems ignores the potential existence thresholds, loss of ecosystem services and brittle, unhealthy ecosystems. An ecologically informed concern for bioproductivity needs to take thresholds seriously, and to focus on stability and resilience as much as on productivity.

Boundaries and thresholds

Rockström et al. (2009) sought to define 'a safe operating space for humanity'. This involves staying within nine 'planetary boundaries' beyond which dangerous thresholds will be crossed. They conclude that three such boundaries have already been breached: atmospheric greenhouse gas concentration, biodiversity loss and nitrogen use. Any bioproductivity policy that implies further trespass in the global impact beyond their boundaries therefore leads humanity closer to the danger of catastrophic collapses. For example, agricultural policies that posit increased global use of nitrogen fertilizers will lead to further incremental problems with eutrophication as well as increased chance of major ecosystem regime shifts (as in the Baltic sea following long term pollution; Österblom et al., 2007). They also ignore the contribution that the production and use of fertilizer makes to climate change and the probability that increasing costs of production – driven by the increasing price of natural gas, which typically constitutes 90% of the costs of production – will make fertilizer use impossible for poorer farms. In our terminology, healthy ecosystems are less likely to cross dangerous thresholds and policies directed at ensuring ecosystem health will remain within planetary boundaries. Three speculative scenarios for the near future of bioproductivity, expressed as food production, are described below and illustrated in Figure 4.

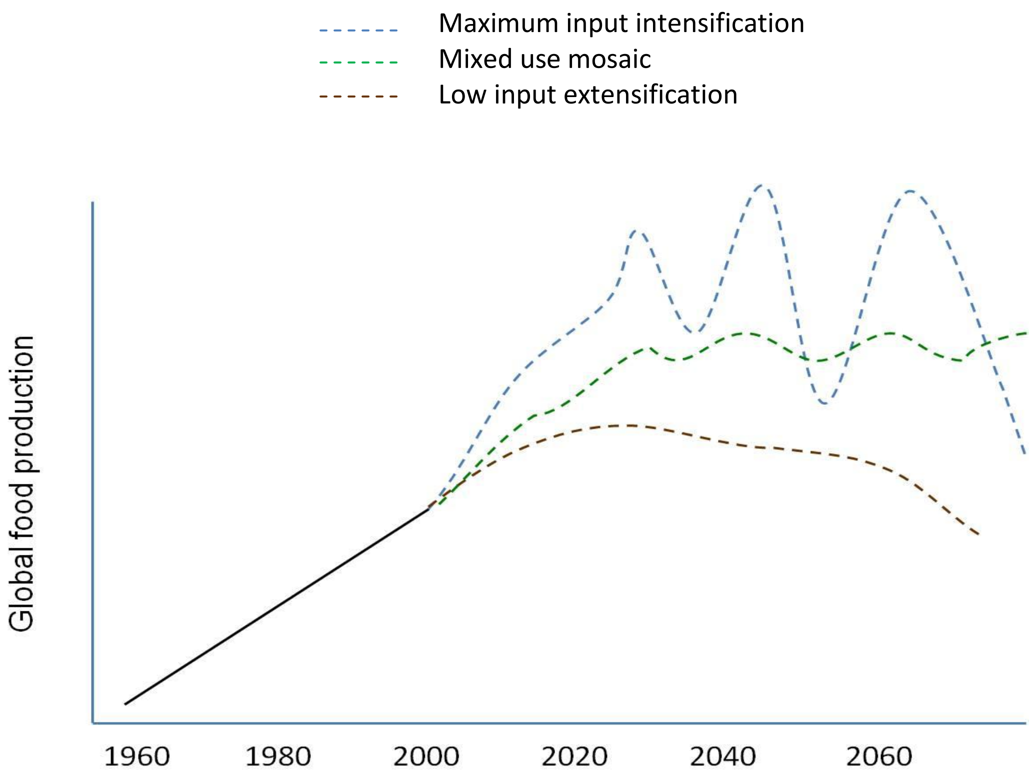

Figure 4. Bioproductivity futures.

The black line shows recent food production (Raudsepp-Hearne et al., 2010), relative to 1990. Dashed lines are three scenarios, differing in their approach to maintenance of ecosystem health.

'Maximum input intensification' (Figure 4) represents a scenario aimed at maximising bio-productivity on currently cultivated land. It assumes maximum application of technology and modern mono-culture farming methods and full integration of food into global commodity markets; a projection of the dominant narrative. For aquatic production this equates to maximum investment in global offshore fleets and intensive aquaculture. This is likely to result initially in the most rapid per unit area increase in food production, as it follows and accelerates existing trends. However it implies a loss of resilience and increasing exposure to the risk of sudden fluctuations for two reasons. First, this approach will degrade on-site regulating ecosystem services, implying greater and greater need for external inputs and reduced resilience in the face of climatic and other shocks. Second, it exposes food production to the full vicissitudes of the global market, making it vulnerable to sudden price hikes and slumps, protectionism and panics about global depletion of nitrogen and phosphorus.

'Low input extensification' assumes a continuing conversion of natural or semi-natural habitat into food production; this will occur mostly in low income countries (where the land and the need are greatest), consist largely of forest clearance and will use existing approaches and technologies (which are generally low-input and organic). Such an approach may see food production rise slightly, though probably not on a per-capita basis as suitable land for conversion to agriculture is limited, and the non-intensive practises may not imply severe local degradation of ecosystem services. However, it would result in accelerating losses of biodiversity (particularly as forests are destroyed), a gradual loss of landscape diversity, and risks degrading marginal areas such that they become unsuitable for even low-intensity agriculture. Eventually it is likely to result in sustained declines in productivity as major global services, including carbon sequestration, generation and provision of freshwater and climate regulation, are disrupted with the loss of biodiversity.

'Mixed use mosaic' represents management of bioproductivity whilst respecting ecosystem health; relating to ecosystems as functional self-regulating systems rather than machines and managing for sustained supply of regulating services. It is similar to the term 'sustainable intensification' as applied by the Royal Society (2009) and Pretty et al. (2011) to agriculture but is broader in embracing all types of bioproductivity and in emphasising the importance of the full suite of ecosystem services. It implies managing landscapes (and seascapes) in multifunctional mosaics, where areas of intensive production are supported by and integrated with contiguous areas providing waste retention, pollination, watershed, climate regulation and other services. Such mosaics may operate over a range of different scales, from less than an acre to many square kilometres, but exclude the zoning of entire regions or countries into mono-functional units. Indications of what such an approach might imply at a national level are provided in the UK National Ecosystem Assessment. This developed 'storylines', two of which ('Nature@Work' and 'Local Stewardship') emphasise ecosystem based and multifunctional management (Haines-Young et al., 2011). Globally this is compatible with modest average increases in productivity and with greatly enhanced resilience in the face of natural and economic shocks. It accepts the need for more food, at prices which are stable and predictable; although on average and initially prices are likely to be higher than under maximum input intensification there are many ways in which governments can and do intervene to ensure food security for the urban poor, whilst higher prices will benefit many of the rural poor. Crucially it acknowledges the risks posed by ecological boundaries; it is an attempt to learn from both 'romantics' and 'ostriches'. So what could make it possible? We suggest three key approaches:

Open Source Science – technology for all

Collier (2011) coins the formulation: *nature + regulation - technology = hunger*. This emphasises the crucial role technology must play in achieving sustainable bioproductivity; we would add that *nature + regulation - technology = hunger + instability.* This is because we need technology to avoid trespassing over planetary boundaries whilst feeding people. The recent history of agricultural technology represents an inspiring illustration of international co-operation and a telling rebuke to notions that efficient technological progress requires private rights and private capital. Beginning in the 1950s a series of international agricultural research centres (such as the International Rice Research Institute), funded by public and philanthropic money, helped to foster and develop a global commons in plant agricultural knowledge. Under the leadership of the World Bank, 17 member countries and organisations came together to form the Consultative Group for International Agricultural Research (CGIAR), which has since grown to encompass 67 countries. This co-operation was crucial in stimulating and disseminating the fruits of the 'green revolution' and in helping to avert mass hunger in the 1970s and 1980s. Free exchange of materials in the international breeding programmes, and regular field based training of young scientists in numerous countries, were both essential elements in this success (Byerlee and Dubin, 2010).

International co-operation and dissemination of new technology is threatened by sustained reductions over the past two decades in funding for the international breeding programmes and by the rise of private interests and patents. It is time to remember the proven success of CGIAR and to re-invest in publicly funded, open access bioproductivity science, with a shared goal of enabling sustainable food production in healthy ecosystems; recent new investments by the Gates Foundation into breeding programmes are welcome. A mixed use mosaic approach should draw on the best available approaches and technology. New innovations may present new risks as well as new opportunities; for example transgenic genetically modified (GM) varieties are more likely to lead to expression of novel proteins than cisgenic GM or conventional bred varieties, which broadly carry similar risks (EFSA Panel of Genetically Modified Organisms, 2012). However there is no good *a priori* reason to reject a whole technological approach, such as genetic modification, if risks are carefully assessed. Instead the systemic risks come from concentrations of power and a lack of democratic input and control which may have led, for example, to first generation GM crops doing more for the financial interests of large corporations than they have for world food security. The choice of appropriate technology will depend on the genetic resources available, the traits being considered within the whole farm system (including inputs being required) and the social context (see Box 5).

Box 5: Developing new crop varieties

Humans have been altering plant genomes through deliberate breeding for thousands of years. Recent advances in genetic science have massively improved the speed and efficiency with which traditional methods can be used and have opened possibilities for transfers of genes between unrelated species. The risks posed by applying these methods in specific cases need to be carefully balanced against their potential benefits and the opportunities for achieving those benefits without incurring the risks and costs involved. Here we contrast four important approaches:

- Hybridization. This involves crossing two strains or species. Because it has been used for millennia, and occurs in nature, examples are ubiquitous and it is uncontroversial. However it is imprecise, affecting thousands of genes at a time, and can typically require 5-30 years for the development of a new variety.
- Polyploids. This involves the duplication or addition of whole genomes. Examples in foods include wheat, strawberries and bananas. Polyploidy is common in nature but can be encouraged chemically during crop breeding, where it is often faster than hybridization. Because it involves changing large numbers of genes it is imprecise; the functions of the genes that are moved, and their location in the new genome, are usually unknown.
- Transgenic genetic modification (creating ‘GMOs’). Genes are transferred between often unrelated organisms. In principle this allows the precision ‘engineering’ of specific traits, with one or a few genes of known effect being moved to known locations on the genome.
- Cisgenics. This involves the deliberate transformation of plants with genetic material derived from the species itself or closely related species capable of sexual hybridization. It holds promise of speedy alteration of specific traits but without some of the issues around risk and public acceptance raised by transgenic methods.

Sources: (Holme et al., 2013)

Conventional breeding, aided and accelerated by recent advances in genomic techniques, could prove vital in helping to produce varieties of crops that can sustain harvests in the face of abiotic stresses such as floods, droughts and increased salinization, as predicted for many areas under climate change. Modern molecular methods have allowed a step-change in the speed at which we can detect and harness plant genetic variability for beneficial traits and so produce new cultivars with improved resilience to both climatic stress and to biotic threats, such as pest outbreaks and new crop diseases (also likely to be exacerbated by climate change). GM technology also has a role to play, particularly for crops where conventional breeding approaches are hampered by a lack of genetic resources or a difficult breeding system (e.g. banana). It raises the prospect (probably still distant) of revolutionary developments, such as successful incorporation of nitrogen fixing abilities into non-leguminous crops. Such a development could transform the productivity of low-input farming and bring us safely back inside the planetary nitrogen boundary.

Whilst some opponents of GMOs have sometimes based their opposition on poor science, proponents of conventional agri-business often fail to acknowledge the huge potential of alternative approaches. An extensive literature documents the potential of ‘ecological’ approaches to agriculture, including inter-cropping, mulching, agro-forestry, low tillage cropping and mixing aquaculture with rice production in increasing yields, particularly in developing countries which suffer significant ‘yield gaps’ – they generate less food per hectare than they should, given prevailing climatic and soil conditions. For example, Pretty et al. (2006) review more than 200 studies showing how careful agro-ecological approaches can both boost yields and sustain other ecosystem services. Successful application of these techniques usually involves an intimate knowledge of the local conditions and greater input of human labour than monoculture high input farming. The value of such local knowledge may be enhanced by new technology, such as the use of highly specific weather forecasts and detailed knowledge of local soil conditions to allow finely timed and sited sowing and fertilizing. Supporting traditional methods and disseminating new, fine-grained approaches is difficult since there is generally no commercial incentive – a large company is not selling its patented seeds. It requires investment in public science and extension services to farmers. This process – helping local producers to increase yields with technology that suits their sites whilst maintaining healthy ecosystems – should become the goal of a new generation of public spirited scientists and agriculturalists, standing on the shoulders of CGIAR’s and farmers success. Farmers working together can develop relevant research and innovation; the UN Food and Agriculture Organisation launched ‘farmer field schools’ in Indonesia in the 1980s to foster collaborative learning and implementation, and the approach has since spread to many millions of farmers in both developing and developed nations and has led to practical, fine-grained innovations (MacMillan and Benton, 2014; Pretty, 2003).

Similar applications of existing technologies and best practice, spread by extension services and education, promise major benefits in preventing food waste, particularly in developing countries. Public investment in transport infrastructure would reduce the opportunities for spoilage, whereas better-functioning markets and the availability of capital would increase the efficiency of the food chain, for example by allowing the introduction of cold storage. Market and finance mechanisms can also be improved, so that farmers are protected from having to sell at peak supply, leading to gluts and wastage. Improved technology for small-scale food storage in poorer contexts is a prime candidate for the introduction of state incentives for private innovation, with the involvement of small-scale traders, millers and producers.

Plunder or the public good? Good food needs good governance and social co-ordination

In its focus on meeting the physical needs and desires of a larger and more affluent human population the dominant narrative implies that the challenge of bioproductivity is primarily a physical one. However environmental justice – the just distribution of the costs of environmental degradation as well as the benefits of ecosystem services – is at least as much a function of social as of physical conditions. In *Poverty and Famines*, the Nobel Laureate economist Amaryta Sen described the problem of starvation in famines as arising from poverty (a lack of 'entitlements to food') rather than as a consequence of absolute food shortage. His prescription for the prevention of famines was democracy. Insisting on good governance, on transparency, on the rights of minorities and the rule of law, and reminding the world that the right to adequate food is enshrined in the Universal Declaration of Human Rights, are all important correctives to the Malthusian tendencies of both 'ostriches' and 'romantics'. His perspective can be broadened to include not only calories but nutrition, and to apply to ecosystem services beyond food. Public outrage at poor food, food fraud, food monopolies and the disease burden caused by poor nutrition is already an important force for good and can and should grow in the future. Public pressure for the conservation of healthy ecosystems and the maintenance of other ecosystem services (particularly cultural and aesthetic ones) will flourish with increasing empowerment and affluence; although sometimes dismissed as an indulgence of the affluent, such concerns are widespread in poorer nations too, since people there often rely to a far greater extent on ecosystem services; the low importance they are generally assigned may reflect a lack of democratic agency rather than any absence of concern.

A multi-functional mosaic approach to bioproductivity will rely on co-ordination and planning, at local and regional scales; free-market approaches assume that this is inefficient or impossible, and tend to look for technological solutions since they can be disseminated by the market. But examples of planned programmes towards better sustainability exist. In China a carefully designed and integrated programme called Shengtai Nongye or agroecological engineering, has established 'ecocounties' over some 12 Mha of land (Pretty, 2008). Policy for these 'ecocounties' is organized through a cross-ministry partnership, which uses a variety of incentives to encourage adoption of diverse production systems to replace monocultures. These include subsidies and loans, technical assistance, tax exemptions and deductions, security of land tenure, marketing services and linkages to research organizations. Although the programme covers only a relatively small part of China's total agricultural land, it does illustrate what is possible when policy is appropriately coordinated and prioritised.

An emphasis on environmental and social justice not only helps prevent crises but also changes some of the assumptions of the dominant narrative. Rights for women reduce birth rates and therefore the projected population. Increased rights for peasants – including fair access to land, clear property rights and fair land rental – helps to stem migration from the countryside into slums. Increased rights for consumers and campaigners helps to build pressure against food waste and pollution.

Mending the Markets

The global market in food provides essential buffering against local shortages, and many populations now rely on foodstuffs sourced and transported from around the world. Global markets also open financial opportunities for producers in low income countries, with the possibilities of developing ecologically sensitive products to sell to niche markets, such as fair trade food. Investing in smallholder agriculture and encouraging this kind of economic activity is recognised as a powerful route out of poverty (OECD, 2013). Short term failures in these markets – such as the sudden abolition of food exports from Russia and other producer countries during the grain shortage of 2011 – can cause sudden crises. Long term failures, however, are inherent in driving the world beyond safe boundaries and in degrading ecosystems.

Whilst environmentalists may see climate change as a moral or political failure, economists are more likely to regard it as a market failure – the misallocation of costs and benefits. According to The Stern Review of the Economics of Climate Change, the true costs of CO_2 emissions (which include all the economic damage caused by these emissions) lie in the range of $25 - $90 per tonne. Factoring this into the costs of energy, fertilizer and transport would radically alter the competitive status of current agricultural, aquacultural and fisheries businesses. Whilst increasing carbon costs may favour economies of scale in some situations, and hence benefit larger scale operations, in general they are likely to favour smaller-scale, less resource-intensive production which can serve local markets as well as higher value global ones; hence some of the currently damaging impacts of global markets in food may decline. Similarly, removal of the current perverse subsidies for environmentally damaging industries, such as fossil-fuel intensive deep sea fishing, would tip the balance in favour of smaller scale, more ecologically sensitive operations. Since increasing the costs for carbon pollution (either through the market or through command and control measures) is an essential prerequisite to avoiding dangerous climate change, it is a policy priority and its effects should be considered in any desirable scenario. This, coupled with the rising demand for food and increasing impacts of climate change, suggests that food prices are likely to remain high into the foreseeable future. We should capitalise on the opportunities this brings (such as raising greater revenue for poor farmers and increasing the returns on investment in local agriculture) whilst mitigating against possible negative effects, particularly on the urban poor.

Mixed use mosaics would manage areas for multiple ecosystem services and many of these can be encouraged through new policy and market interventions. For example there is a large and growing market in watershed services, with 'producers' (typically farmers on high ground) being paid to help ensure reliable supplies of clean water to downstream users; one example of the development of new applied valuation techniques for 'payment for ecosystem services' which can be a useful way of ensuring society values essential services provided they do not buttress current inequalities in land ownership or access (see e.g. Ring *et al.* 2010; Locatelli *et al.* 2014) Policy should develop ways of supporting ecosystem service provision with a clear focus on mixed use (to avoid the perversions of, for example, large scale afforestation of land of conservation importance with exotic species of tree in order to benefit from carbon credits). At the moment there are high transaction costs preventing small scale managers, producers and communities from obtaining information on markets and in meeting exacting standards of international certification. These costs could be reduced by providing appropriate educational and policy support. For example, training on market conditions and opportunities could become part of the mission of a new breed of 'public spirited' agricultural outreach scientists, farmers and educators.

Whilst food prices on the global market are likely to remain high (at least compared with recent decades), and this can bring important benefits, price volatility may also increase and this should be minimised; like healthy ecosystems, healthy markets should not be subject to massive phase shifts, crashes and structural uncertainty. Haldane and May draw explicit lessons from ecological science for a more stable financial system, including the importance of diversity amongst banks and institutions (with homogeneity breeding instability) and modularity (or in our terms 'hierarchy and heterogeneity') which helps protect against cascades of collapsing banks and institutions (Haldane and May, 2011). Hence there are many options for reducing volatility (including taxing transactions in the futures market on food) and it is time for the world community to reform global market governance to minimise volatility – a new Bretton Woods style agreement focused on stability and sustainability rather than on maximising trade and profits.

Conclusions

Four key conclusions emerge from our work. Achieving any of these require governments, civil society, business and citizens to take collective action.

- **Trends are mutable because predictions are different from destiny -** an impartial extrapolation of trends is an appropriate task for the scientist. But readers' must judge whether the predictions provided should be roadmaps or warning signs. There is a strangely passive (and dangerously circular) logic riding the dominant narrative; that we must simply predict what is coming, based on current trends, and then provide for it. Many trends are negative: increasing per capita calorie and meat consumption in wealthy nations, increasing food waste, accelerating degradation of ecosystem services and continuing poor access to reproductive health and education for millions of women all stand condemned in public and expert opinion. Preparing for the highly likely, such as some increased population, does not involve accepting the obviously bad; there is enormous potential to steer policy towards the lower ends of the plausible projections for population and food requirements and compelling social and ecological reasons to imagine different and better futures.

- **Healthy ecosystems are necessary for long term provisioning** - the notion of inevitable trade-offs between ecosystem services is simplistic and untrue. Regulating services often work together and underpin provisioning – so it is common to find synergies between them. Where trade-offs occur they often do so in ecosystems already pushed towards the maximisation of one particular provisioning service; they have lost health and are moving towards the status of 'machines' that wear out. Long term provisioning from natural or semi-natural ecosystems (such as marine capture fisheries) requires ensuring their health. Many ecosystems have been much altered by human agency, but managing them in multifunctional mosaics, with more than one service provided, will help ensure resilience and need not imply reductions in productivity. Extrapolations that rely on maximising productivity from ecosystems assume that past trends can be continued without taking sufficient notice of the real threat of systemic collapses once thresholds are exceeded.

- **Use the best science, technology and management, and make it public -** there is a proud history of public science, farmer informed research and international collaboration in food policy. We should celebrate and sustain this. There is enormous potential for increasing yields and improving resilience in lower income countries (particularly in Africa) through application of a wide range of approaches and technologies, both old and new. Private monopolisation of knowledge through patents and restrictive trade rules threatens to prevent this. Public and philanthropic investment in education, dissemination and co-development (with local stakeholders) of new and traditional technology, with the common goal of ensuring higher yields and healthier ecosystems, could build on past success and help achieve multi-functional management.

- **Use the market, but manage it too -** markets as they currently function lead to ecological degradation. Global food markets help feed the world and raise producer incomes, but also expose producers and consumers to the risks of price volatility and the under-cutting of health and environmental standards. Proper pricing of externalities, particularly of carbon and water, would help prevent this. Recognising the true costs of food production, storage and transport may tip the balance in favour of smallholders with more intimate local knowledge and lower ecological impacts. New markets for ecosystem services and high value environmentally sensitive products will also contribute to more sustainable agricultural ecosystems.

The recent history of improving global food security and nutrition shows how philanthropy, private and public funding of science & technology and markets can combine to improve the human condition. But we know that business as usual will not cope with the looming problems of this century. We can choose to recognise and mitigate the worst trends. By combining the best of old and new technology and respecting ecological limits a world of healthy ecosystems and food security is possible if we work together to achieve it.

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