



Review

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Author for correspondence:

H. Charles J. Godfray

e-mail: charles.godfray@zoo.ox.ac.uk

Food security and sustainable intensification

H. Charles J. Godfray¹ and Tara Garnett^{1,2}

¹Oxford Martin Programme on the Future of Food, and ²Food Climate Research Network, Oxford University, South Parks Road, Oxford OX1 3PS, UK

The coming decades are likely to see increasing pressures on the global food system, both on the demand side from increasing population and *per capita* consumption, and on the supply side from greater competition for inputs and from climate change. This paper argues that the magnitude of the challenge is such that action is needed throughout the food system, on moderating demand, reducing waste, improving governance and producing more food. It discusses in detail the last component, arguing that more food should be produced using sustainable intensification (SI) strategies, and explores the rationale behind, and meaning of, this term. It also investigates how SI may interact with other food policy agendas, in particular, land use and biodiversity, animal welfare and human nutrition.

1. Introduction

Food has always been a major policy focus for governments. Those who have failed to provide their populations with enough food—whether they are kings, dictatorships or parliaments—have often fallen [1]. But in the past few decades, agricultural production—one essential component of food provision—has received comparatively little attention compared with other policy goals, such as the pursuit of other forms of economic and social development. It is as if the apparent successes of the Green Revolution have convinced decision-makers that food security will look after itself [2].

In the past 5 years, all this has changed. Recent price volatilities have revealed the vulnerability of millions of people worldwide to hunger [3]. There is also a growing recognition that a more sophisticated understanding of what 'food security' actually means is needed [4]. In addition to the roughly billion people whose diets are deficient in energy, about the same number suffer the diseases of energy surplus, whereas, again in round terms, two billion suffer from the 'hidden hunger' of micronutrient deficiencies. Thus, a sizeable proportion of the world's seven billion people can be called malnourished. In addition, environmental problems caused by the way food is produced and distributed not only jeopardize our ability to produce the food we need now and into the future (notably by contributing to climate change, with global implications for our livelihoods and in some cases our lives) but also endanger the existence of much of the world's biodiversity [2]. Population growth and increases in *per capita* consumption, as people become richer, compound and exacerbate these problems [5].

This nexus of concerns (figure 1)—price volatility, hunger in all its forms, environmental damage and population and consumption growth—has prompted a refocusing of policy concern on food. It has also led to a plethora of calls for action—calls to increase agricultural productivity and output, to halt environmental damage, to change systems of governance, to alter consumption patterns, to address food losses and waste, and for more environmentally sustainable methods of farming [2,6–11].

Different stakeholders prioritize and evaluate these goals differently, depending on their interests, their underlying motivation and values. In our view, action is needed on all fronts—there are many dangers in assuming the challenges of achieving sustainable food security can be met by a focus

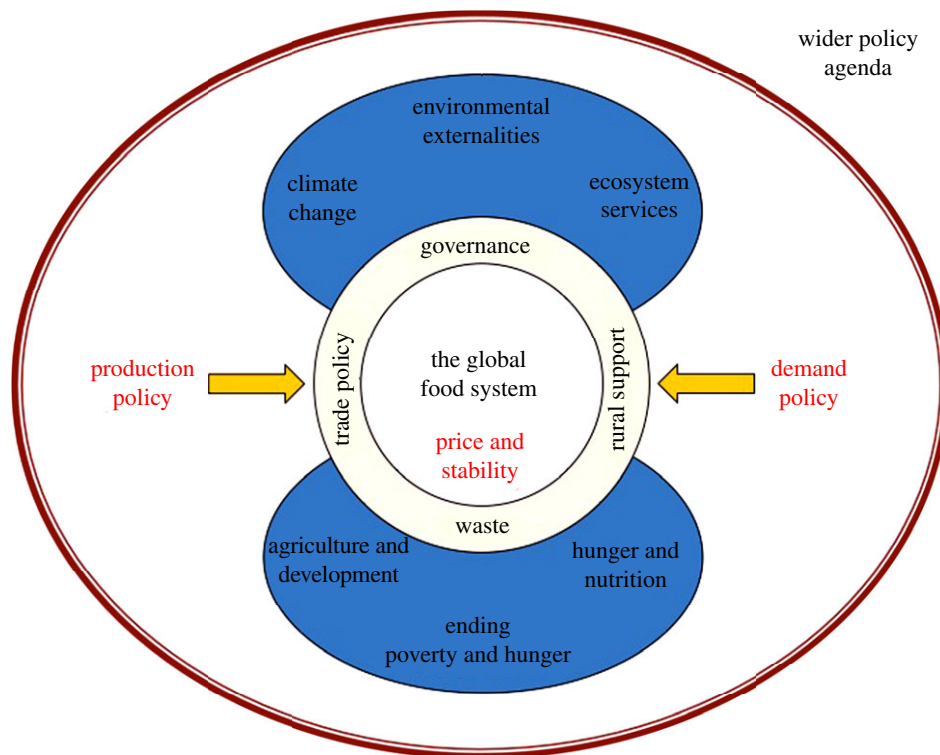


Figure 1. The complexity of global food policy. Policy decisions made about production and demand affect global food prices and their stability, though exactly how depends on numerous national and international policies on rural support mechanisms (such as the Common Agricultural Policy), international trade, the governance of the private sector and efforts to reduce waste. Decisions made about the global food system have profound (and reciprocal) effects on the environment and on efforts to end poverty and hunger. Food policy itself is embedded within the wider policy landscape. Meeting the challenge of global food security requires action on supply, demand, waste and governance with it being critical to consider the effect of any policy action on the environment and the needs of the world’s poorest. (Online version in colour.)

on just one strategy, for example simply increasing food production, or just altering diets.

In this paper, we review one aspect of this food sustainability challenge: the goal of producing more food. This goal is unthinkingly accepted by some and vigorously contested by others. We argue that increased food production is necessary but also emphasize that this alone, as a response to the challenge, is not sufficient. The objective of increasing production needs to be constrained by and linked with other, equally important goals. First, increasing production, and, indeed, maintaining current levels of production must be achieved with less impact on the environment. Hence, we must not ‘intensify’ production but rather ‘sustainably intensify’ production. Second, the goal of increased production must not dominate the food sustainability agenda. Actions to modify population growth and resource intensive consumption patterns, improve systems of governance, and reduce waste are policy goals that must be pursued equally vigorously.

This review is thus about the need for, the place of, and the challenges posed by sustainable intensification (SI). It is structured as follows. In part two, we review in more detail the challenges facing (and caused by) the food system in coming years. Part three describes the rationale underlying calls for SI, and where it sits within the broader suite of necessary responses. Part four takes as its basis the observation that if SI were so easy it would have been done years ago: that while the principles may be sound, its implementation will be difficult and will inevitably give rise to complex trade-offs. These trade-offs are explored in more detail in the context of three specific areas of concern: biodiversity and land use, animal welfare and human nutrition. Part five offers some brief conclusions.

2. Challenges for the food system

The challenges for the food system in the next few decades include: a growing and demographically changing population; average increases in purchasing power and expectations and consequent diet change; resource scarcity; global environmental change (including the climate), and finally the need to mitigate greenhouse gas emissions while simultaneously adapting to its consequences. We consider each of these in turn.

(a) Population growth and demographic change

The next few decades are likely to see between two and three billion more people on this planet, the vast majority of whom will be citizens of least developed countries [5]. Estimates are necessarily uncertain, but, critically, relatively small differences in growth rate over the next 10–20 years will have a major effect on the exact level at which population will peak [12]. Actions such as providing access to reproductive healthcare and improving education, especially for girls, are known to have positive effects on reducing fertility and on improving the wellbeing and livelihoods of poor people, again, particularly women [13,14]. There is also strong evidence that where poor countries can reduce very high rates of population growth, their economies benefit and more people move out of poverty, leading to further reduction in fertility [15].

However, discussion of population issues is often politically delicate or fraught because of the legacy of coercive programmes of fertility reduction as well as religious sensitivities. It is also often argued that the problem lies with excessive *per capita* consumption rather than with population numbers *per se* [16]; and numerous studies highlight the

disparity between the carbon footprints of the average North American as opposed to the average Bangladeshi citizen [17]. However, while we believe action to address consumption is urgently needed, it is simplistic to suppose that this alone will be sufficient in reducing humanity's impacts on the environment, particularly because it is essential that the living standards of today's poor rise—a rise that will inevitably lead to increases in their energy and resource use, and their carbon footprints. Hence, a simple consumption versus population analysis ignores the dynamic interactions between the two 'sides' of the problem (for example that increased prosperity is essential for lower population growth rate), and underplays the very real benefits in managing fertility levels.

In addition to population growth, the next few decades will also see rapid demographic changes. At present, just over half the world's populations live in cities, and by 2050, the figure will be nearer two-thirds [18]. In most developing countries, populations will also, on average, be very young [12]. In developed countries and China (where population growth has nearly plateaued), populations will, by contrast, be ageing [12]. The implications of these demographic changes are not fully understood, with some research suggesting that urban populations tend to demand more resource intensive foods such as meat (discussed below), and others arguing that this reflects higher average incomes rather than something inherent in the process of urbanization *per se* [16,19]. A very important point is that the urban poor in least developed countries are much more exposed to global food market prices than the rural poor. As urbanization increases, so does the likelihood that food price increases and fluctuations lead to political and social instability. *Per capita* food demands in 'young' countries will also be higher than in countries with ageing populations, with implications for average kilocalorie requirements.

(b) Rising average incomes

Notwithstanding huge and in many cases growing inequalities, the global population is becoming, and will continue to become, richer. One consequence of this increase in average wealth is that people's demand for, and ability to pay for, a wider range of foods will increase. In particular, people tend to switch first from staple tubers and grains to more preferred cereals such as wheat and rice, and from there to meat and dairy produce, vegetable oils, fruits, vegetables and processed foods [20,21]. This 'nutritional transition' has environmental consequences, because meat and dairy products in particular are often land and water intensive to produce. It also has impacts on human health; typically as dietary diversity increases people consume a greater range of macro- and micronutrients leading to health benefits. But as diets progressively move through the transition, some of the nutritional costs start to outweigh the benefits. Diets that are dominated by energy-, sugar- and fat-rich foods give rise to problems of obesity and associated chronic disease, the consequences of which are now apparent not just in developed but increasingly in developing countries. Today, chronic diseases already kill more people in low- and middle-income countries than in the developed economies, and the problem is likely to grow rapidly in coming years, even while problems of hunger and malnutrition persist [22,23].

(c) Resource competition and scarcity

A larger and on average wealthier global population will not only demand more food but more of other goods and services too, all of which require land, water, energy and minerals for their production. This increased overall demand for finite resources will lead to increased competition among these sectors, with the negative environmental impacts of one sector also impacting upon others, as in the case of soil and water pollution [2,9].

In the short term, the most pressing issue is competition for water [24]. Agriculture is already the largest consumer of available freshwater and diversion of water from natural habitats has severe effects on biodiversity and ecosystem services. A larger population will also increase the municipal and industrial demand for water which will affect the amount available for agriculture. Competition for water will be exacerbated by the exhaustion of underground aquifers, including several upon which large agricultural regions depend (for example, in eastern Australia, southern Spain, north Africa, the Great Plains of North America, northwestern India and northern China) [24]. A larger and richer population will have greater energy demands which may increase the cost of fuel and fertilizer inputs into agriculture; though projecting future energy prices is complex and uncertain. More people also require more space to live. This may, to an extent, eat into productive agriculture lands. However, the issue here is not so much the impact of urbanization (and other industrial developments) on the *quantity* of land available but on its quality. Urban and industrial pollution, by reducing soil and water quality, can undermine both agricultural productivity and the safety of the food produced.

Concern has been expressed about competition for phosphorus and potash fertilizers, both of which come from mineral deposits [25,26]. In both cases, the most easily exploited sources are finite, and the share prices of companies involved in mining have risen markedly in recent years. It is likely that increased P and K fertilizer prices, though increasing production costs, will stimulate innovation and the mobilization of new reserves, which are probably currently underestimated [27]. They are also likely to spur far greater efforts to recycle nutrients, for example phosphorus from agricultural run-off and sewage. Of course, they may also encourage extraction methods which cause greater environmental damage.

(d) Environmental change

Global and local environmental changes are already affecting food production, mostly in negative ways. There is increasing evidence that particular recent extreme events that have reduced harvests are likely to have been caused by anthropogenic warming.

In the future, climate change will affect food production both by causing gradual changes in temperature, rainfall and so forth, as well as by triggering extreme weather events [28]. Some climate change may benefit food production: for example, secular rises in temperature may mean that land currently unsuitable for agriculture, especially at high latitudes, can now be farmed, whereas CO₂ can promote yields if plants are not limited by other factors. However, integrated assessments that try to combine all the effects of climate change suggest the net result will be reduced yields [29,30]. Indeed, there is concern that these assessments underestimate

the impacts on food production by failing fully to capture the effects of extreme events such as droughts and flooding. Brief periods of very high temperature can have particularly severe effects on plant development, lead to mortality in livestock, and affect productivity by making human conditions difficult and perhaps impossible.

Other environmental factors are also likely to continue to affect food production. It has been estimated that approximately a quarter of all agricultural soils are in some way degraded, undermining their future capacity to produce food [31]. Loss of habitat and pollution from agrochemicals affects pollinators and the natural enemies of pests, reducing the value of important ecosystem services of direct benefit to farmers. Eutrophication owing to nitrogen run-off affects freshwater and inshore fisheries, whereas catches from most fisheries are below optimum owing to poor management [32,33].

(e) The need to reduce greenhouse gas emissions

Action to reduce climate changing emissions is essential if we are to avoid the dangerous consequences of average temperature rises greater, possibly much greater, than 2°C. This means that agriculture, as a major contributor to greenhouse gas emissions, must play its part in addressing the problem. Current estimates suggest that approximately 15% of all greenhouse gas emissions come from food production (with about the same amount coming from land conversion) [17,29]. Any serious attempt to reduce the rise in global temperature must include the agriculture sector, and this may constrain some avenues for increasing production [34–37].

The coincidence of demand- and supply-side pressures impacting the global food system was memorably characterized as the ‘perfect storm’ by the UK’s then Chief Scientific Advisor, John Beddington (<http://www.bis.gov.uk/assets/goscience/docs/p/perfect-storm-paper.pdf>). The exact causes of the recent increases in food prices are still debated, but a case can be made that they are the beginning of a response to the factors discussed above. The food system is at least in part an economic system, and will respond to increased demand by greater production, as well as by innovation to increase resource use efficiency and to use new sources of input. However, evidence shows it will respond imperfectly and sometimes perversely, and with time delays that lead to hunger for many people and irreparable environmental damage in many parts of the world. The environmental ‘externalities’ of food production are not captured in the current market economy. Clearly, action is needed to reorient the food system in a more sustainable direction.

3. Sustainable intensification

Analyses of the drivers that will influence the food system over the next few decades have persuaded many people that we are entering a new period where rapidly rising demand and supply-side stressors threaten to increase food prices to levels that will increase hunger and malnutrition and may cause politico-economic disruption. What is the appropriate supply-side response to these challenges, and what role should research in the natural and social sciences play?

One response to these challenges is often called sustainable intensification (SI). It argues (i) that increased production must play at least some role in meeting the food security challenge of

the next fifty years; (ii) that the vast majority of this increase must come from existing agricultural land; (iii) that increasing the sustainability of food production is of equal importance; and (iv) that we must consider a broad range of tools and production methods to achieve these goals. We examine each of these arguments in turn (see also [38]). Good examples of approaches to SI are described by Conway [39].

(a) The capacity to increase production

Might it be possible to address food security without producing more food? Several groups have argued this position, typically showing that if we take the basic calorific requirements of a human population of 9–10 billion people, then this is less than the calories that can be produced by today’s existing farmland [40,41]. The problem is not our capacity to produce food, but the amount we waste [42], and the fact that we use such a large proportion to feed to livestock to produce meat. If diets were changed and if waste in the food system were eliminated, 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. An increase in the fraction of plants in the human diet would also have significant health benefits.

Those calling for SI completely accept the argument that the response to the challenge of future food security must include diet change, reducing waste and improving the efficiency and governance of the food system [2,11,38,43,44]. They argue that the risks of significant problems in the future are sufficiently high that action is needed on all fronts, and that there are likely to be synergies with other socio-economic objectives, including health and equity. It can, however, be very difficult to alter entrenched behaviours. Policy-makers have to date proved fearful of robust approaches, whereas ‘soft’ social marketing type measures have found limited success. These difficulties are not an argument for not trying to make these changes but counsel against relying solely on a subset of possible measures. Much of the discomfort many people feel with calls for SI is due to the worry that it will distract from actions needed in the non-production sides of the food system. We argue strongly that SI and indeed any supply-side policy should be developed within the broad context of food system policy including issues of diet, waste and governance. Such an approach is needed to address food security but is also important to allay concerns that SI is a part of a purely ‘productionist’ agenda.

Much of agriculture in developed countries is only economically viable with state support. The justification for such market-distorting intervention is society’s wish to maintain rural communities and rural economies in high-wage countries, especially in areas where agriculture is not highly productive, though strong political pressure from influential groups is also very important. The need to address global food security has been used as an argument to increase the support for agriculture in the developed world. It is sometimes phrased in moral terms—that the rich world has a duty to produce food to feed the world. Such arguments, which may invoke SI as the best way to increase production, are problematic to many people. They point out that subsidizing food production in the rich world may have perverse effects on agricultural livelihoods in developing

countries that may set back their food security. They also characterize the arguments as special pleading by the agricultural sector, an attempt to justify a return to the forms of production subsidies that have largely been phased out in developing countries.

In our view, what is required is not necessarily an immediate increase in production but for the farming industry to be prepared to respond efficiently to any increased demand for food and, of equal importance, for that response to take a sustainable path. Of course, were demand to increase, the market economics of the farming system would see a production response. SI policy should seek to identify the market failures that would prevent the appropriate response. This includes investment in pre-competitive research for seeds, breeds and technologies that will increase yields, productivity and input efficiency. It also should encompass investment in human and social capital and, especially in less developed countries, in physical and economic infrastructure. And of critical importance, it should seek to address the externalities of food production, in particular its effects on the environment, and the many situations where markets fail to produce the best outcomes for society.

(b) Intensification and extensification

If the premise that an increase in production must be part of the response to threats to food security is accepted, then, logically, it could be achieved by bringing more land into agriculture—‘extensification’—or through increasing the productivity of the existing agricultural footprint—‘intensification’. The proponents of SI argue that there are major costs to relying on extensification as the chief strategy to increase production. The conversion of new land to agriculture nearly always results in very significant releases of greenhouse gases into the atmosphere. This is particularly true when the land is converted from forest where there are large standing stocks of carbon, but conversion of wetlands and unfarmed grasslands also results in significant emissions. In addition to greenhouse gas emissions, conversion of natural habitats to food production typically results in major biodiversity losses and can also affect other ecosystem services, for example the ability of land to store water and prevent flooding, or to purify water for drinking.

Intensifying food production causes its own environmental problems, but several studies suggest these are fewer than when new land is brought into agriculture. Burney *et al.* [45] computed the extra greenhouse gas emissions resulting from the ‘green revolution’, the revolution in germplasm and production techniques that greatly increased production in the second half of the twentieth century, especially in Asia. Although these were substantial, emphasizing the problems of intensification as currently practiced, they were still much less than would have occurred if yields had remained at pre-Green Revolution levels and production had been raised by land clearance. Looking into the future, Tilman *et al.* [46] project global demand for food and calculate the greenhouse gas emissions if the food is grown on converted land or if yields are raised on existing agricultural lands through the application of fertilizers (whose production leads to the emission of considerable greenhouse gases). Again, land conversion is the poorer option. As Tilman *et al.* stress, such comparisons underestimate the potential advantages of intensification if done sustainably: while little can be done to mitigate emissions from land conversion, a policy of SI offers the prospect of

increasing input efficiency and further reducing emissions. To be clear, these papers are not endorsements of future intensification of the type practiced up to now—they illustrate the dangers of land conversion and define the challenge of a new type of SI.

There is not a sharp distinction between existing agricultural land and uncultivated land. Some agricultural land has become so degraded that it produces little output. Returning such land to agriculture (the restoration of Loess Plateau in China is a good example) can increase food production with few negative or even positive environmental benefits. However, the issue is context specific. Abandoned agricultural land that has reverted to forest (as for example over much of New England) may be as environmentally costly to restore to food production as pristine forest. In general, it is the nature of the current land state rather than its history that is significant.

Calls for SI do not mean that production should be increased uniformly over all farming regions, though it does imply an overall increase in the global supply of food. Improving environmental sustainability may mean that in some areas yields or yield gains must be sacrificed for better environmental outcomes. It may be desirable to take some of the most critical habitats for biodiversity, and some unproductive agroecosystems, completely out of agriculture (rewilding) in order to maximize their value in supporting biodiversity or societal important ecosystem services. We return to some of these issues below.

Finally, in this section, we have used the word ‘intensification’ simply to mean increasing yields (which could be from a single crop or through increasing crop frequency) within the same area of land as opposed to ‘extensification’, obtaining the same result from a greater area of land. The word ‘intensification’, however, is often associated with specific farming practices, and these connotations are responsible for some negative reactions to calls for SI. This issue is particularly acute when discussing livestock production where intensification is virtually synonymous with factory farming. We acknowledge this problem, though for the moment continue to use the widely used term SI in the neutral sense of increasing yields while reducing environmental harm.

(c) Sustainability is a ‘must have’ not a ‘nice to have’

Critical to the notion of SI is the realization that the way we produce food now is literally unsustainable. Many current forms of food production damage the farming environment in ways that undermine future food production, for example through excess water extraction or unsustainable soil management. They also result in damage to the wider environment, for example, because of fertilizer leaching and the release of greenhouse gases. Habitat conversion for agriculture, water extraction from lakes and rivers as well as poor fishing practices on the high seas devastate biodiversity.

SI should not be interpreted as environmental business-as-usual with marginal reductions in negative externalities. It calls for a radical refocusing of food production on the *twin aims* of increasing yields and improving environmental performance. The results of this programme will very much be location specific. For example, in many lesser-developed countries, substantial yield increases are possible, and the research programme underlying SI seeks to determine a development trajectory that will lock in these gains with the fewest negative

environmental side-effects, ideally bypassing many of the errors made in the way today's rich world developed. In richer countries, with high-input high-yield agriculture, the emphasis may be much more on increasing input efficiency. As mentioned above, where current practice is very damaging, yield reductions to improve environmental outcomes may be required.

Critics of SI see the concept as a Trojan horse, sneaking in intensive farming under the camouflage of sustainability [41]. They are not reassured when they see agricultural trade bodies and agrochemical companies espousing SI. Certainly, some bodies will use SI for their own lobbying ends, whereas many others will genuinely engage with its goals. The potential for SI to be hijacked calls for vigilance and monitoring, not, we believe, for the rejection of the underlying idea. Engagement with the private sector, and understanding how to incentivize SI, will be critical in delivering sustainable agricultural improvements to farmers.

(d) Agricultural approaches and systems

The goal of SI is to achieve higher yields at the aggregate level with fewer negative impacts on the environment. This is not an easy goal to attain, and hence there is a need for experimentation to ascertain which production techniques are the most effective and in which contexts. Thus, ideas from biotechnology, conventional farming, agroecology and organic farming may all be used to achieve this goal of sustainable yield increases. SI does not privilege any particular type of agriculture.

This philosophy stands in contrast to more ideologically driven approaches to food production. For example, the organic movement only certifies production methods that are in accordance with its underlying principles. Similarly, the agroecology movement rejects completely certain forms of food production in developing countries, including genetically modified (GM) crops and what it terms 'industrial agriculture'. It is harder to define a movement on the other side of the ideological divide but there are certainly those who see GM as a silver bullet, who dismiss environmentally sensitive approaches to farming (and particularly the imposition of environmental standards or conditions) or who challenge the need to address demand (an issue that, by contrast, is often bound up in discussions about organic or agroecological farming). A minority on the libertarian right would go further and oppose any state intervention including support for rural communities.

By not ruling out any particular production method SI leaves itself open to criticism from everyone who holds an *a priori* ideological stance. To date, the majority of attacks have focused on SI's inclusion of GM as one potential technology that might be used. This excessive emphasis on GM, both by its opponents and supporters, exaggerates its importance as an issue. GM is likely to be one tool in a necessarily diverse and well-stocked toolbox. Other concerns about SI relate to whether it might be used to justify Western models of agriculture which, when introduced to low-income countries, harm smallholders. We return to this issue in the section below.

(e) Concepts related to sustainable intensification

Although SI is currently the term in vogue, it is related to other ideas about how food production needs to transform itself which we briefly note here. For example, Cassman [47, p. 5953] coined the phrase 'ecological intensification' in a

paper on cereal production that anticipates many of the analyses of the last few years: 'at issue, then, is whether further intensification of cereal production systems can be achieved that satisfy the anticipated increase in food demand while meeting acceptable standards of environmental quality. This goal can be described as an ecological intensification of agriculture'. Recently, Conway [39] has suggested that in a developing country context SI might be decomposed into a series of sub-tasks: ecological intensification (e.g. conservation agriculture, agroforestry and integrated pest management), genetic intensification (plant and animal breeding) and market intensification (providing a socio-economic enabling environment).

'Climate-smart agriculture' was defined by the FAO [6] as 'agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances achievement of national food security and development goals'. Although concentrating on one aspect of sustainability alone, it is clearly related. The 1992 Earth Summit in Rio endorsed 'eco-efficiency' which was defined by the World Business Council for Sustainable Development (<http://www.wbcsd.org>) as the production of 'competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life cycle to a level at least in line with the Earth's estimated carrying capacity'. There are debates about the meaningfulness of defining a global carrying capacity, but, again, this concept seeks to meld increased production with reduced environmental impact.

4. Sustainable intensification and other food system goals

The focus of SI—more food with less environmental impact—raises many questions as regards its practical implementation, and how it relates to other goals for the food system. We discuss three of them here. We begin by looking at SI's relationship with biodiversity and other ecosystem services, before turning to the relationship between food provision and the nutritional quality of the food produced. Third, we consider the implications of SI for animal welfare.

(a) Biodiversity, ecosystem services and multifunctional landscapes

The environment in which we live and which we share with the majority of the world's plants and animals is dominated by human food production. Policies that seek to protect and preserve biodiversity and ecosystem services must take into account the need to feed the global population. This is true at both broad and local scales. Meeting the demands of people for food is such a dominating political imperative that where it fails, the protection of nature and the environment will always be relegated. But might this relegation reflect a failure of policy imagination or political courage: the simplistic opposition of 'food' on the one hand against 'the environment' on the other? The type and choice of food can be altered to reduce land pressures, greater efforts can be made to distribute food differently, to reduce losses and waste in the food system. Governments have seldom considered these approaches (other than in times of war), the consequence

being that biodiversity, as well as other environmental goods and services, have suffered.

But, inevitably, there will always be some trade-offs between biodiversity protection and human needs (and demands), and the challenge is how best to navigate them. A key issue to consider is how land can optimally be used to achieve multiple goals such as food production and protection of biodiversity? One approach might be to develop or promote systems of food production which are more favourable to wildlife [48]. However, this approach often, although not always, tends to be less productive when output is measured in terms of kilocalories of food produced per unit time and area (an issue returned to below). Another might be to increase productivity on farmland, even at a cost to on-farm biodiversity, in order to minimize the land area needed to produce a given amount of food, so 'sparing' non-farmland for biodiversity. The optimum approach is likely to depend on various factors, including the pre-existing biodiversity baseline against which the relative impacts of the two approaches are assessed. Phalan *et al.* [49] (and in the current volume) explore whether 'land sharing' or 'land sparing' represents the best approach for sustaining biodiversity of key species. Their study considers the spectrum of land use from natural rainforest to relatively high-input agriculture in Ghana and India. They look at the relationship between yield intensification and the numbers of local species (trees or birds), and then ask for a given yield target whether biodiversity is best maintained within an agricultural landscape (land sharing) or by not farming some areas and maximizing production in other locations (land sparing). For the wet-tropic environments they study, land sparing is clearly superior though this is unlikely to be the result everywhere, especially in savannah regions where herding and wildlife are more reconcilable, and in Old World Mediterranean biomes where biodiversity has evolved with agriculture. In much of Europe, moreover, the major policy question is likely to centre not so much on the merits of land sparing versus sharing *per se*, but as to whether to concentrate environmental investment in those areas likely to produce the greatest benefits for biodiversity and ecosystem services or to spread investment more thinly.

The idea of a multifunctional landscape with different areas producing different services determined by their comparative agricultural or ecological advantage, and where all synergies among different outputs are realized, is hard to disagree with. Implementing it is much more difficult. Market mechanisms alone are unlikely to produce good outcomes, because the ecosystem services provided by landscapes are not valued in monetary terms. The risk is that, whatever the theoretical merits of land sparing or land sharing in any given context, market forces will tend to foster further agricultural land expansion, if doing so leads to greater profits. Hence, while natural and social science analysis can help illuminate trade-offs and suggest optimum land allocations to different functions, progress on achieving a multifunctional landscape is absolutely dependent on political will and working governance mechanisms and institutions. This is clearly a policy priority.

As stressed above, SI does not imply that production should be increased everywhere irrespective of the trade-offs between yields and the other services, in the broadest sense of the term, that land provides. In some areas, maintaining current yields or allowing yields to drop may be the

best policy. Such trade-offs are easiest to analyse where the alternative land use is the production of other marketable products such as fibre, wood or energy although complexities arise when there are substitutes for these alternatives. For example, a major policy debate is the degree to which the use of land for biofuels has contributed to current food price volatility.

Trade-offs between land uses that produce goods not so easily marketable—so called environmental services—are clearly harder to analyse. While environmental economics can ascribe some monetary value to them, without functioning markets this value will always to some extent be approximate, arbitrary and perhaps accorded lower status. Decision-makers and society, in general, inevitably have to make political decisions about competing priorities, often where views may differ within the population, and where issues of stewardship and the rights of future generations need to be taken into account.

(b) Animal welfare

To many in the animal welfare community 'intensification' is synonymous with a particular form of livestock production in which animals are kept in highly artificial environments and provided with high-input diets very different from their natural food [50,51]. Often, the breeds of animals used are strongly selected for narrow yield goals, and this can lead to congenital health problems. For many people, including animal ethicists, intensification implies little consideration for animal welfare.

Leaving aside for a moment the morally contested nature of the word 'intensification', is it possible to increase livestock yields, while not compromising or even improving animal welfare? In order to answer this issue, the 'baseline' level welfare needs to be considered: though there is such a multitude of different livestock-rearing regimes that generalizations require great caution. It is also important to define what is meant by 'good welfare', because there are differing conceptions on what this means [52]. Most of the thinking in this area has been undertaken in the developed world and is thus influenced by its particular set of values. In general, welfare definitions tend to include the requirement not only that animals are in good health, but also that they are somehow experiencing a 'life worth living'. This second element typically implies that they are fulfilling their particular animal selfhood by performing activities and behaviours that are instinctive and that may cause distress if they cannot be performed. It is also argued by some that there is greatest potential for achieving good welfare if animals are reared in an environment similar to what their nearest wild relatives might experience, albeit without predators. Based on these considerations the UK's 'five freedoms' code of practice [53] defines animal welfare as a state where animals are physically fit, free from hunger, pain or fear or undue stress, and are able to carry out behaviours they are motivated to perform in conditions that incorporate elements of what they would experience in their closest natural environment.

But stakeholders place different weight on the relative importance of these criteria. They also differ in the weight they place upon achieving animal welfare when compared with economic considerations, issues of food security or simply food preferences.

What, therefore, is the relationship between SI and welfare, defined in this double sense of 'health' on the one hand, and 'wellbeing' on the other?

Consider less-developed countries first. Many nomadic and semi-nomadic pastoralists rely on livestock for the vast majority of their food intake and have very sophisticated techniques for maintaining yields in often very adverse environments. Cattle and other livestock typically represent most of an individual's wealth and investment in their health and wellbeing is a priority although these are often undermined by the scarcity of forage and by endemic diseases. Thus, welfare, defined in terms of physical health, may be poor, whereas other aspects of welfare—such as freedom to perform natural behaviours in a natural environment—may be good. Some 'intensification' in terms of measures to improve pasture quality and better access to veterinary care is likely simultaneously to improve productivity as well as health, so enhancing welfare overall. The same may often be the case in smallholder mixed-crop livestock systems.

But where meat production begins to move more into the commercial sphere, there is a risk that welfare is compromised. Poor welfare, in many cases, arises owing to a mismatch between the breed and its environment, for example where highly productive breeds are fed on poor-quality feed, or traditional breeds raised on commercially formulated feeds, with negative consequences for health. Poor animal welfare may result from a lack of skills, poor housing, restrictions on natural behaviour, or in some cases on a lack of concern for good welfare. In such circumstances, there is often great scope for improving animal welfare through progress in breed–feed matching and better veterinary care and stockmanship. Such improvements can also raise yields and improve environmental outcomes. Here, the SI and animal welfare agendas are potentially congruent, at least unless the levels of intensification are very high.

In most developed countries, yields are far higher, and the room for improvement more constrained. Recent research shows that significant yield gains are still possible if more attention is paid to animal health and welfare. Advances in our understanding of animal physiology and behaviour, as well as sophisticated real-time means of monitoring behaviour and welfare, can both be mobilized to design husbandry regimes that also improve economic outputs. It is also possible to reconsider animal breeding strategies, selecting not only for yield parameters but to avoid traits that impair health or an animal's quality of existence. Positive selection for traits that improve welfare may also be feasible.

However, in these already intensive systems, there is a risk that further productivity increases may not only be marginal, but lead to a reduction in welfare. In these circumstances, there is a need for society to consider its values and demands carefully, most particularly its demand for animal products. It may not be possible simultaneously to achieve high welfare, good environmental outcomes, and at the same time, enjoy current diets which are high in meat and dairy products: something may have to give.

Although discussions of food security frequently invoke time horizons of 50 or more years ahead, in reality, they will be overtaken by events and will be policy relevant for a much shorter period of time. One 'game-changing' development, with profound consequences for animal welfare, that is already beginning to receive attention is artificial meat. While far from certain, it is likely that within 20 years, we will be

able to produce artificial meat whose taste will be as acceptable to people as meat currently used in processed foods (perhaps more acceptable) and quite conceivable that artificial meat will be indistinguishable from real meat in blind tests. But will consumers accept such meat, irrespective of its taste? Who would gain or lose financially from such a development, both among countries and sectors of societies? What would be the environmental and welfare consequences? And, perhaps most critical to policy today, do the consequences and chances of success justify a marked increase in research investment in these technologies?

(c) Human nutrition

Today, nearly a billion people remain chronically undernourished, subsisting on diets that lack sufficient intakes of calories and protein [54]. An even larger number, while not physically hungry or underweight, nevertheless suffer the health consequences of malnutrition, a situation where diets are lacking in the micronutrients essential to proper bodily functioning.

At the same time—and often within the same country—many people are increasingly shifting to diets dominated by meat and dairy products, oils and refined carbohydrates. As a result, around 1.5 billion people worldwide are obese or overweight. Obesity is no longer only a rich-world problem—most of these people are citizens of low- and middle-income countries, and many of them are poor [18]. These people are at risk of a range of diet-related illnesses, including cardiovascular disease, strokes, diabetes and some cancers. Some of them may, at the same time, suffer from micronutrient deficiencies.

There has been some concern that increased attention to food security and, in particular, to the need to increase food supply has distracted attention from the continuing fight to improve human nutrition. More specifically, there are worries that the successful pursuit of the SI agenda may lead to an increase in food production, but to a poorer, more monotonous and nutritionally inadequate diet. For example, consider the increased adoption of high-yielding and resource-efficient grains in low-income countries. Were these to replace low-yielding and nutritionally unbalanced strains, the outcome would be positive; but, if the drive for more intensive and more profitable agriculture were to displace diverse village gardens or sources of wild foods (without providing any other source of nutritional diversity), then poorer diets may result. Exactly, what types of negative unexpected nutritional consequences may occur is obviously system- and location-specific, but efforts to anticipate and avoid them should be part of any SI strategy.

There is of course scope to apply SI to the breeding of crops that are more 'intensive' in their nutritional profile. Cases in point include orange-fleshed sweet potato, bred by conventional means to provide a rich source of vitamin A, and 'golden rice' which has been developed using GM technology to produce a vitamin A precursor. Other projects are underway to enhance particular key micronutrients of crops, such as cassava, sorghums and millets, that grow in very harsh conditions and are important to the diets of very poor people. Although, not currently part of the SI agenda, there is obvious opportunity to link breeding for increased yield and greater input efficiency and resilience with better nutrition.

However, there is concern that a focus on the genetic improvement of crops, even those bred for greater nutrient content, as supporting one particular approach to improving

human nutrient intakes, oversimplifies the nature of the malnutrition challenge. It is argued that relatively simple nutritional manipulations cannot adequately substitute for a rich and varied diet that can best meet the complexities of human food requirements [55]. Clearly, where the choice is between a very poor diet and a diet containing nutritionally fortified crops the latter is preferable—but the fear is that excessive focus on technological solutions will distract attention and resources away from more multifaceted approaches to addressing malnutrition, approaches that also take into account the socio-economic conditions within which malnutrition arises. Thus, while biofortified crops are likely to play a very important role in improving the nutrition of the world's poorest people, they should be seen as only part of the solution to poor diets and research in this area pursued in tandem with other approaches.

While agronomic history to date shows that research has, indeed, concentrated on a limited number of crops and animals that dominate the human diet, there is potential that the reverse could be true if the SI approach were carefully and explicitly applied to improving nutritional outcomes at multiple spatial scales. At the genetic level, the continuing revolution in plant and animal molecular biology is providing tools that will greatly facilitate the genetic improvements of species that, to date, have largely been ignored by breeders. At the local level, the stress SI places on reducing environmental impacts and increasing resource efficiency could be applied to research on crops and livestock that are particularly suited to local conditions, thereby increasing crop, and thus nutritional, diversity. At the dietary level, the creation of village gardens and approaches that integrate terrestrial and aquatic food production fit into the SI emphasis on using all land resources efficiently. In short, the potential exists to improve nutritional outcomes through the application of SI thinking. However, so far, there has been little recognition of the need to link these two agendas and SI has yet to make a significant difference to the lives of those suffering from malnutrition.

All this underlines the point that the successful application of SI thinking, in diets as for animal welfare or in the case of biodiversity conservation, requires effective governance that brings together all relevant policy and regulatory agencies. This will be true of SI as it is of any other approach aimed at achieving sustainable food security.

5. Conclusion

SI is in many ways a simple logical deduction from a set of premises: (i) it is virtually certain that demand for food will go up dramatically over the coming decades and increased production must be part of the response (but not the only one) to ensure food security; (ii) conversion of new land for

agriculture would cause significant harm to the environment; (iii) reducing the environmental impact of food production is essential for future human wellbeing and prosperity; and (iv) the challenges are such that tools from all forms of agriculture should be considered without prejudice. But accepting these premises simply leads to a description of the aspirational nature of SI, not how it is best achieved. Pursuing SI will entail a major programme of research that involves social sciences as much as the natural sciences. Beyond research the implementation of SI will require trust to be built among the many stakeholders in the food system, all of whom will be required to make compromises of different sorts. And while SI needs to be central to the way we produce food in the future it needs to be integrated within a nexus of strategies aimed at achieving food system sustainability, in the broadest sense of the phrase.

Are there alternatives to SI? At one level, the same approach could be adopted but called by a different name, sustainable yield increases, or ecological intensification, for example. This should not be dismissed as mere semantics—words matter in policy-making and in the public acceptance of policy. The originators of SI were focused primarily on increasing crop yields—but as discussed above 'intensification' has very negative associations for many people as applied to farm animals. On the other hand, some policy documents in the USA now avoid the word 'sustainable' because of its negative connotations for some political groups.

At a second level, one might accept the idea that food security poses a major challenge but argue that it can be met by changing diets, reducing waste or by a radical reorganizing of the politico-economic landscape. For this perspective, increases in food production are not required. As argued above, this seems to us a hugely risky strategy—the challenges are such that movement is required on multiple policy fronts.

Finally, there is the business-as-usual alternative to SI: unsustainable intensification. As demand for food rises, then the economic pressures to produce food will increase, leading to land conversion, and the types of intensification that damage the environment and other food system goals. In the face of a multitude of externalities (costs not captured in the price), market distortions and time lags, it is inconceivable that the market alone will furnish solutions unaided. The consequences of unsustainable intensification will damage the planet and undermine its capacity to support future food production.

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