BLOSSOMING TREASURES OF BIODIVERSITY

46. Golden Rice – a food fight to enhance the unsustainable monarch of mega-crops

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(Received 4 September 2014; final version received 4 September 2014)

Introduction

All major cultivated crops contribute to the ‘ecological footprint’ of human activity that robs biodiversity of habitat. However, only about a dozen of the leading crops (here termed ‘mega-crops’) have provided the food that has permitted the world population to expand to 7 billion. These have become indispensable to the maintenance of the current food supply, but are deleterious to biodiversity in important respects. They are also so nutritionally limited (most produce starch and not much else) that their overconsumption is harmful. Indeed, excessive dependence on the leading carbohydrate crop staples by poor people is the leading cause of world hunger. To address malnutrition, attempts are underway to genetically engineer the principal crops so that they will produce vitamins and essential minerals that they currently cannot supply adequately. Regrettably, this would increase dependency on these staples, whereas promoting the growth and consumption of a wider array of foods would be more beneficial for both humans and biodiversity.

The previous 45 articles of this series emphasised relatively poorly known but promising crops, which at least in some ways are biodiversity-compatible. By contrast, this contribution examines Rice, the world’s most valuable crop, a staple of over half of humanity, supplying a remarkable 21% of human food energy. Rice constitutes the premier example of how we have become over-dependent on a single food source to the detriment of ourselves and the ecology of the world. This contribution examines a dispute over the merits of Golden Rice, a genetically engineered form with improved nutritional properties. Golden Rice is regarded as the most controversial and instructive case of how biotechnological advances in food production need to be evaluated in the broad context of long-term societal and ecological outcomes, not just for narrow, short-term gains. The thesis advanced here is that while Rice is indeed an admirable cereal, too much of this good thing is a bad thing, and sustainable production of other crops should be emphasised.

This presentation sequentially reviews (1) key background considerations for evaluation of the problems associated with continuing to expand human reliance on dominant crops like Rice at the cost of investing in alternative sustainable crops; (2) the contentious difficulties associated with Golden Rice; and (3) strategies to reduce human reliance on mega-crops like Rice. One of these strategies is to reduce consumption of mega-crop-based obesogenic foods while favouring a biodiversity-rich diet. Paradoxically, as will be pointed out, eating a much wider representation of our fellow species can be good for them.

Agriculture: the worst mistake in the history of the human race?

Agriculture was invented independently in different areas of the world at different times dating back at least 12,000 years. Agricultural systems evolved in widely separated regions, notably between 5000 and 11,000 years ago. The prehistoric transition from subsistence on free-living wild species to culturing and domesticating them has been termed the ‘Neolithic Revolution’ or the ‘Origin of Agriculture’. By 2000 years ago, agriculture had become the main source of food in the world. Today, agriculture is the dominant force affecting the welfare of the planet. Astonishingly, the world land area dedicated to agriculture is 38.5%, and the total world water withdrawal used for agriculture is 95% (FAO-1).

While humans are omnivores, about 85% of our food today (on a caloric basis) comes directly from terrestrial plants, and just a dozen cultivated species provide 75% of our sustenance (Small 2009; see Table 1). The grass family (which includes Wheat, Rice, Corn (Maize), Barley, Sorghum, millets, Oat, Rye and Sugar Cane) furnishes 80% of calories consumed by humans. Only three grass family crops – Wheat, Rice and Corn – account for about 60% of the calories and 56% of the protein that humans get directly from plants. The leading cereals and oilseeds

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also are now used to supplement feed for livestock which provide humans with meat, milk and eggs, exacerbating human dependence on the mega-crops. Most of the world’s cropland is used to produce grain, of which humans consume about 50% directly and the other 50% indirectly as livestock products (Brown et al. 1998). Cropland is also employed extensively to cultivate non-food crops, reducing land available for food production. Examples include Cotton for fibre, Jojoba for industrial oil, Tobacco for smoking, Lavender for perfume and Ginseng for medicine. Increasingly, food crops are being used to produce transportation biofuels, particularly ethanol (from crops such as Sugar Cane and Corn) and oilseed-based diesel (from crops such as Soybean and Rapeseed), a development sometimes called ‘petrofarming’ that many view as alarming because it makes food commodities more expensive for the poor.

Agroforestry, the cultivation of trees mostly for timber and pulp, further reduces arable land that could be used to produce food.

Human dependence on domesticated species is now profound; probably only about 1 billion people could survive on Earth by relying just on wild species for food (Small 2013), and we are engaged in a struggle to generate enough food to sustain our increasing numbers. The great irony is that humankind has enslaved selected species as crops and livestock, but in turn we have become inescapably dependent on these domesticated species for survival. The invention of agriculture and consequent departure from a lifestyle dependent on hunting wild animals and gathering wild plants was, according to Diamond (1987), ‘the worst mistake in the history of the human race’. One might with equal logic malign sanitation, medicine and other technologies that have become essential for maintaining modern societies. However, advances in agricultural technology have been extraordinarily harmful to the planet and its life forms, making it advisable to examine possibilities of harm reduction. The relationships among food and the welfare of both humans and biodiversity are complex (Conforti 2011; FAO-2; FAO-3; FAO-4; FAO-5).

In hunter-gatherer times, humans obtained food by hunting, fishing and foraging, and since then our physiological requirements for food components have not likely evolved substantially. Cereals were the primary basis of the agricultural revolution, because they are high-yielding, have very limited toxins and can be stored for years. Unfortunately, cereal grains are mostly composed of carbohydrates, and are therefore poor nutritionally. There is some evidence that the transition from a mixed wild diet to partial dependence on a cultivated cereal-dominated diet was slightly deleterious to human health when it occurred in ancient times (Sands et al. 2009), but today when cereals and tubers provide most of the caloric food energy consumed by mankind, it is tragically clear that inadequacies of a diet dominated by a single crop is the basis of most under-nutrition. Of course, an inadequate supply of food produces poor health and mortality for individuals, but it also results in low worker and national productivity.

Mega-crops: a deal with the devil?

Most plant food on the planet is now obtained from the mega-crops, usually grown as monocultures, i.e. as single crop species on an area excluding all other plant species. Most of the world’s major crops (Table 1) are cultivated as vast monocultures. This is the case for most major cereals, notably Wheat and Corn (Maize), and most major oilseed crops such as Soybean, Rapeseed (Canola) and Oil Palm. Orchard crops such as Apple, Banana and Grape are often raised in relatively small

### Table 1. The world’s most important agricultural crops, ranked by international dollar value. Based on 2012, the latest year for which complete statistics are available.

| Rank (by $ value) | Crop (commodity) | Value (international $1000) | Tonnage (metric tonnes) |
|------------------|------------------|-----------------------------|-------------------------|
| 1                | Rice, paddy      | 185,579,591                 | 719,738,273             |
| 2                | Wheat            | 79,285,036                  | 670,875,110             |
| 3                | Soybean          | 60,692,327                  | 241,841,416             |
| 4                | Tomato           | 59,108,521                  | 161,793,834             |
| 5                | Sugar Cane       | 57,858,551                  | 1,832,541,194           |
| 6                | Maize (Corn)     | 53,604,464                  | 872,066,770             |
| 7                | Potato           | 48,770,419                  | 364,808,768             |
| 8                | Grape            | 38,336,711                  | 67,067,129              |
| 9                | Cotton (fibre)   | 37,095,127                  | 25,955,096              |
| 10               | Apple            | 31,883,555                  | 76,378,738              |
| 11               | Banana           | 28,209,561                  | 101,992,743             |
| 12               | Cassava          | 25,691,234                  | 262,585,741             |

*The 12 crops listed include the world’s leading food staples except for Cotton, which is mostly a source of textile fibre. The ranking of the world’s leading food crops has fluctuated over time. In the recent past, leading food crops have also included Banana (and plantain), Sugar Beet, Sweet Potato, Barley, Oat, Sorghum and others. Source: [http://faostat.fao.org/site/339/default.aspx](http://faostat.fao.org/site/339/default.aspx)*
plantations and because the plants are very large and perennial, they can be grown widely spaced to allow considerably biodiversity to thrive. Vegetable crops such as Cassava (Manioc), Potato and Tomato are frequently grown in small gardens that can be quite compatible with biodiversity. Rice tends to be grown in relatively small monocultures simply because wetland locations tend to be fragmented on the landscape. While large monocultures are blamable for the lion’s share of the world’s environmental and biodiversity crises, all of the mega-crops are associated with environmental problems.

For centuries the legendary pact that Faust made with Mephistopheles has been a popular theme in literature. Faust exchanged his soul for great knowledge and pleasure – essentially sacrificing what is most important for short-term rewards. There is a very disturbing parallelism with how humankind has accepting the bounty produced by mega-crops at the cost of endangered the future of life on the planet. Humanity has become trapped into a vicious cycle: high-caloric but nutrient deficient mega-crops are increasingly produced by factory farming to meet demand to alleviate hunger and poverty, but this simply exacerbates demand, hunger and poverty because: (1) traditional, more nutritional crops are displaced; (2) population growth increases demand for food, obliterating per capita gains; (3) free-market capitalism dictates that despite their disadvantages the greater profitability of mega-crops drives their increasing importance, and indeed their frequent diversion into non-food uses, such as bioenergy; and (4) environmental degradation associated with mega-crops decreases the availability of arable land to produce food.

Why are mega-crops bad for biodiversity? Of course, usurping large amounts of land for agriculture physically excludes most of the species that once occupied the habitats that were there. Moreover, adjacent habitats are affected by agricultural activities. Almost all major crops require considerable ‘agricultural inputs’ – one or more of water (irrigation), biocides (herbicides, pesticides, fungicides, bactericides) and fertiliser. Mechanised tilling of the soil, planting and harvesting additionally require the sacrifice of fossil fuels. These activities result in chemical pollution of soil, water and the atmosphere, and displacement or destruction of native animals, plants and soil organisms (McLaughlin and Mineau 1995). Unfortunately until very recently biodiversity has been neglected by agriculture (Figure 1).

Aside from the detrimental ecological aspects of mega-crops for biodiversity, the overdependence on the small number of leading crops is associated with severe economic problems resulting from periodic surpluses and unwise subsidies. As well, it is ancient wisdom that reliance on one crop is like putting all your eggs in one basket. All crops are subject to disasters because of pests, diseases and variation of climate. Monocultures are especially vulnerable (note Figure 2), and indeed Wheat, the world’s second most important crop, is currently seriously threatened by rust fungus (Chamy 2014). Growing

Figure 1. The uneven balance of agricultural activity and biodiversity. Prepared by B. Brookes.
several crops ensures that at least some will produce a reasonable harvest. Still another consideration is that the efficiency of growing huge monocultures is at the price of decreasing employment and rural diversity. Socially, there are advantages to having more small farms specialising in crops that require great skill and knowledge.

The extraordinary efficiency of monocultural production has enabled the planet to accommodate its huge population exceeding 7 billion people. Indeed, failure of several of the world’s most important mega-crops would inevitably produce widespread famine and death. Unfortunately, like some of our pampered ‘ companion animals,’ mega-crop species are so genetically weakened compared to their wild ancestors that they cannot exist without very extensive human care. Today, our most important food species demand high inputs of chemicals, water and energy, which result in environmental problems. Given modern agricultural technologies, a high-output of food sufficient to feed the world is apparently only feasible by maintaining the leading mega-crops. It is possible to alleviate the associated environmental damage by utilising a variety of farming practices (see, for example, Altieri undated; Shiva 1993; Standage 2009), but vast expanses of homogenous cultivated crops inevitably contribute to erosion of biodiversity.

The human monoculture

Most people now live in cities, uncharitably called ‘urban jungles,’ in which humans are so predominant that they virtually constitute monocultures. The phrase ‘human monoculture’ is usually encountered in sociological or philosophical analyses of how human culture is being progressively homogenised (for example, with respect to how fast food chains are being established throughout the world, or how English has become the predominant language). However, populating very large areas more or less exclusively by our species produces ecological hazards that in some respects are reminiscent of those associated with mega-crop monocultures. These problems include the usurping of large areas of land, the necessity of providing huge inputs of fossil fuels and water, and the inevitable outflow of toxic materials that affect surrounding ecosystems. Moreover, concentrating any species in one area is an open invitation to attack by harmful organisms; just as mega-crops require extensive protection from parasites, herbivores, bacteria, fungi and viruses, so people living in cities need extensive health care and sanitary measures against vermin, disease-causing organisms and the accumulation of their own wastes. Agriculture is the chief technology that has allowed the human mega-monoculture to develop so spectacularly in recent times (Figure 3), to the point that the welfare of all other creatures in the world is now threatened.

Human population issues

At the heart of most of the world’s problems, and certainly of the current environmental and biodiversity crises, is human expansionism, popularly expressed in the phrases ‘population explosion’ and ‘population bomb’. The populations of all species expand over time to exploit available resources, the ultimate numbers limited principally by (1) the biological adaptations of the species that enable it to capture resources; and (2) competition with other species, especially disease-causing microorganisms. Humans are unique in that science and
technology progressively (1) expand our abilities to exploit the world’s resources and (2) eliminate or at least control our competitors.

‘Carrying capacity’ for a species in a given environment is the maximum population size that can be maintained indefinitely, as limited by available necessities such as food, water and habitat. The Earth’s carrying capacity for the human species has been debated for many years. In 1679, Dutch scientist Antonie van Leeuwenhoek, famous for inventing the microscope, calculated that the world could support a maximum of 13.4 billion people, a figure that is surprisingly consistent with recent estimates. However, demographers today are generally hesitant to assess the ultimate number of people possible on Earth, particularly because it depends on future technological innovations (i.e. carrying capacity may be larger in the future). Examination of the history of population growth of the human population certainly shows alarmingly explosive growth in recent years (Figure 3). However, the rate of increase has been leveling off, suggesting that growth may cease. On the other hand, demand for resources by humans is increasing, and coupled with the huge human population, the world is facing dire problems related to carrying capacity.

‘Sustainability’ is the key term that has been adopted towards the goal of working towards an equilibrium whereby humans coexist with both biological and inorganic resources in the world so that they continue to be available indefinitely in required amounts. Unfortunately most species, many habitats and some ecosystems do not supply significant resources, and so are of limited relevance to those whose interests are primarily economic. Accordingly, ‘sustainability’ is now widely misconstrued to refer narrowly to the welfare of a particular resource (such as a food fish, hydroelectric energy or water) even at the cost of associated destruction of other inanimate and biotic components of the planet.

Clearly, the very large number of humans is a concern because the demand for resources has degraded the world’s ecosystems, habitats and biodiversity (Figure 4), threatening not just the millions of wild species on the planet, but also the welfare of people. However, it is now recognised that less destructive technologies as well as environmental rehabilitation are necessary, although the requisite international cooperation has been painfully slow to develop. It has been noted that consumption of more resources is much higher in rich nations with relatively limited human populations than in poor countries with relatively large populations, and accordingly the rich have a greater responsibility to address environmental issues. One of the simplest ways of reducing the stress on biodiversity caused by the need to produce more food is simply to decrease food wastage, since about a third of all food produced globally for human consumption is wasted (Miller and Welch 2013), mostly in rich nations.

Figure 4. The uneven balance of humans and biodiversity. Prepared by B. Brookes.
Livestock mega-cultures are also detrimental to biodiversity

The most important livestock are bovines (cows and cattle), swine and chickens (Table 2). Cattle, sheep and goats are often raised for all or part of their lives in a ranch setting, on grazing lands where they do in fact, like monocultured plants, dominate large tracts of land, albeit not as completely or uniformly as do crops. Sometimes animal aquaculture is also conducted in natural bodies of water. Swine, chickens, and several other domesticated animals are more often raised in narrowly confined quarters. The culture of the leading livestock species poses significant problems for biodiversity, in parallel to the cultivation of mega-crops. Much of the world’s natural grasslands has largely been converted to grazing pastures for livestock, or for producing megacrop cereals for animal feed. Livestock systems occupy 30% of the world’s terrestrial surface area (excluding ice-covered regions). Agricultural production of animals is associated with deforestation, pollution of soil, water and the atmosphere, degradation of ecosystems and shrinking availability of fresh water. Growing affluence in developing countries, notably China and India, is associated with growing demand for a diet with more meat, and this is severely straining the world’s food production capacity (Rask and Rask 2011). It is well known that meat is an ecological luxury, since much more of the Earth’s resources need to be sacrificed than to produce an equal nutritive equivalent of plant tissue (Lappé 1975). It has been pointed out by defenders of animal production that marginal lands unsuitable for crops can be used to produce livestock. Unfortunately, it is in marginal lands that biodiversity is most at risk.

Biodiversity significance of geographical disparities in poverty, population and hunger

Getting enough nutritional food is a problem associated with poverty, which is most common in Developing, highly populated, less affluent countries of the Southern Hemisphere. Close to 1 billion people suffer from hunger due to inadequate intake of calories and protein and another 2 billion suffer from so-called ‘hidden hunger’ – deficiencies of vitamins and minerals (FAO-6). Food insecurity, starvation and nutritional deficiency diseases are key issues in less developed nations. By contrast, in much of the affluent, relatively less populated Western World (especially Europe and North America), nutritional deficiency is rare while ‘over-nutrition’ (overeating and obesity) is a key issue (Lindeberg 2010). Birth rates and population increase are usually lowest in rich countries, where food is so abundant that wastage is common, and are highest in poor countries where food is scarce (Figure 5). Biodiversity is much higher in most ‘Southern,’ poor, Developing, or Third-World Countries, where the expanding, already high human populations are degrading habitats and endangering biodiversity, and funds are very limited for conservation and remediation (Sanderson 2005; Fisher and Christopher 2007). By contrast, in most ‘Northern,’ affluent countries population growth is less of a driver of habitat and biodiversity destruction, there are fewer endangered species, and funds are much more available for biodiversity protection. This is not at all to diminish the importance of conservation of habitats and biodiversity in affluent temperate regions, but simply to identify where biodiversity issues are most acute, and how this is driven by the need for food.

A long growing season and high insolation (especially when the sun is directly overhead) are reasons why the productivity of plants is much higher in tropical and semi-tropical regions than in temperate locations. Since poor developing countries are in tropical and semi-tropical regions, it would seem that these factors should make agriculture more productive than in the more affluent regions, and to a degree this is true (soil conditions and climate are also important factors). However, agricultural science and technology are far more advanced in the affluent regions of the world. Moreover, in Developing Countries the need to generate scarce income means that agricultural crops are often grown for export to the North. These considerations exacerbate the harm to habitats by agriculture in Developing Countries. Of all mega-crops grown in the Third World, Oil Palm (Figure 6) has acquired the reputation as being the most harmful to biodiversity.

Food is one of the principal bases of wealth, security and political influence, with respect to personal, business

Table 2. The world’s most important livestock products, ranked by international dollar value. Based on 2012, the latest year for which complete statistics are available.

| Rank (by Svalue) | Product       | Value (international $1000) | Tonnage (metric tonnes) |
|------------------|---------------|-----------------------------|-------------------------|
| 1                | Cow milk      | 187,277,186                 | 625,753,801             |
| 2                | Cattle meat   | 169,476,916                 | 62,737,255              |
| 3                | Pig meat      | 166,801,086                 | 108,506,790             |
| 4                | Chicken meat  | 132,085,858                 | 92,730,419              |
| 5                | Chicken eggs  | 54,987,685                  | 66,372,549              |

Source: http://faostat.fao.org/site/339/default.aspx
and national levels, and so food production and distribution are competitive, controlled, indeed often exploitative enterprises, both in local and geopolitical arenas. It is commonly asserted that there is more than enough food to feed the world, and what is needed is simply to distribute it to those with insufficient supplies. Indeed, admirable food aid programmes are heroically attempting not just to provide short-term food assistance but to generate ‘food sovereignty’ (production sufficiency) in areas of need, particularly in southern Asia, Africa and South America. Unfortunately food sufficiency is intimately related to the issues of population growth and ecosystem degradation, which are not being adequately controlled. ‘The linkages between biodiversity, food and nutrition should be more widely studied, researched and publicised, and more efforts should be made to mainstream the concept into food, agriculture, health, trade and nutrition sector policies and programmes’ (FAO-7).

**Are the champions of increased food production heroes or villains?**

Famine and starvation have been preoccupations throughout history, and so those who have spearheaded agricultural technologies which increase food availability have been recognised as extraordinary humanitarians. Two millennia ago, when the population of Earth had reached perhaps 250 million, eking out a living was difficult and the much celebrated story of Jesus miraculously multiplying food to feed the starving masses (Figure 7(a)) was received as completely praiseworthy. As late as the first half of the twentieth century the view that magnifying food production is unquestionably good was still widely held. The Russian geneticist and agronomist N.I. Vavilov (1887–1943, Figure 7(b)) made monumental contributions to the preservation of wild crop relatives in gene banks that have been responsible for huge increases in food production, and the value of his work has been universally accepted. But in the second half of the twentieth century, critics became concerned with two alarming results of agricultural technologies.
associated with increased food production: (1) a ‘catch-22’ (no-win) situation is created, whereby more food produces more people demanding more food, and this cycle continues, merely postponing an ultimate starvation catastrophe; (2) with increasing demand for food production, the ecology of the planet, along with biodiversity, becomes degraded. The concerns with the negative aspects of increased food production were enunciated vigorously with respect to the ‘Green Revolution’ which occurred between the 1940s and the late 1960s. This involved greatly increased agricultural production, particularly in the Developing World, substantially because of new cereal varieties (particularly of Rice, Wheat and Corn) with greatly increased yield due to their capacities to utilise synthetic fertilisers (increased irrigation and pesticides also contributed to greater yield). Between 1950 and 1984, world grain production increased 250%. Norman Borlaug (1914–2009, Figure 7(c)), the ‘Father of the Green Revolution,’ has been credited with saving over a billion people from starvation, and he consequently received the Nobel Peace Prize in 1970 for his work. He has also been accused of contributing to the world’s ecological and social maladies that have accompanied the addition of a billion people to the planet. His defenders, in turn, accused his critics of elitism and of ignoring the immorality of allowing a billion people to starve to death (see, for example, The Guardian 2014).

Ethically, the Green Revolution presents a morally ambiguous conundrum, since both substantial harm and benefits have resulted. Whether it will be possible to forge another Green Revolution to meet the anticipated growth of the human population during the current century is uncertain (Heywood 2011).

The relationships between agricultural progress and environmental regress tend to be oversimplified. Technological innovations, including advances in agriculture, are not necessarily associated with increase in human population, human demands for resources, or consequent damage to the environment and biodiversity. Although this has been the general pattern, we humans have the choice of if, when, where and how to apply particular technologies in order to minimise risk and harm.
The associated ‘blame game’ that has been widely practiced with respect to the environmental and biodiversity crises also tends to be oversimplified with respect to agricultural technology. Blaming corporations, politicians, particular technologies (such as genetic engineering) and even particular crops (such as Rice, the principal subject of this essay) detracts from recognising the most intractable issue: we humans need to comprehend more clearly how we have become ensnared in an exploitative relationship with the planet that must be ameliorated for the welfare of ourselves, if not indeed also for our fellow species.

Bias, values and priorities in relation to inconvenient biodiversity truths

The literature dealing with poverty alleviation in relation to agricultural technologies, particularly genetic engineering, frequently is biased towards the scientific validity and benefits on the one hand, or the scientific fallacies and risks on the other. Scientific fact is determined by scientists, but many scientists today are employed by industry and government, their research tends to support short-term economic priorities, and alleviation of long-term environmental and biodiversity problems tends to be overlooked. Conversely, those who are deeply concerned with environmental issues are sometimes hypocritical of biotechnology. Not only scientists and the general public, but ethicists and clerics have also been polarised by the subject. The divide between supporters and detractors of particular biotechnologies is deeper than simply analysis of pros and cons; the key issue is one of comparative values of benefits (albeit short-term) that accrue primarily or exclusively to humans versus risks to habitats and biodiversity. Most reasonable people understand that some compromise is necessary, but differ in viewpoints about the extent that we need to limit human desires on behalf of the survival of other life forms and the health of planetary ecosystems. Depending on one’s personal perspective on this issue, readers are likely to support or reject the analysis presented in this paper.

The agricultural technology trap

Food is the most basic need of all animals, including humans. Most animals perish because of starvation, and populations eventually stop growing in numbers or expanding in physical space occupied because the supply of food becomes limiting. In hunter-gatherer times, this was surely true for most people, but progressively some societies developed superior ways of generating food, and in recent times scientific advances have resulted in huge gains in crop production, not just for food, but also for utilisation of plant materials for fibre, fuel, medicines and a very wide range of industrial materials. In retrospect, it is clear that we are in a trap of our own making. We are biologically programmed to want more resources (greed is natural) and to produce more humans (sex is natural), and our addiction to improving technologies allow us to exploit more and more of the world (you can’t stop progress). Of course, we now appreciate that big as it is, our planet cannot continue forever to meet growing demands for resources. But we do seem to be stuck on a culinary treadmill; if we get off too abruptly, people will literally starve, but if we stay on, the planet will become progressively denuded of natural flora and fauna, and the life-sustaining systems of Earth could become catastrophically degraded. The key issue to be resolved is ‘Can we survive and live decently on this planet without driving our non-human contemporaries to extinction and depriving us of our genetic treasure?’ (UNEP 2014).

Why feature Rice as a whipping boy to criticise the ecological damage associated with mega-crops?

English princes of the fifteenth and sixteenth centuries were assigned ‘whipping boys’ to receive the punishment that properly should have been given to their royal backsides when they misbehaved. Whipping boys were usually honoured companions of the princes, and obviously they did not merit discipline. Similarly, of the millions of species on Earth, Rice has been the most highly valued companion of humans, and really should not be blamed for the ecological misbehaviour of humans. The problem is that mega-crops are bad for the planet, and Rice is the leading mega-crop. Of course, because crops like Rice are so important, their improvement is important, but as emphasised in this review, reducing their importance would improve the world in significant respects. Realistically, financial, political and research interests allied with the mega-crops will ensure their continued domination of the world; this paper is a plea to divert at least some of the resources currently monopolised by the mega-crops to alternatives that are more beneficial for both humanity and biodiversity.

A brief portrait of Rice – the world’s most important crop

Asian rice (Oryza sativa) is a native grass of the tropics and subtropics of Southeast Asia, and grows best in a hot, moist climate. It is normally grown as an annual but can survive as a perennial in tropical areas. Traditionally seedlings are established in protected beds, then transplanted into floodmed fields (Figure 8). The plants are typically 60–180 cm (2–6 feet) tall. Domestication of Rice occurred perhaps as far back as 10,000 years, in the river valleys of South and Southeast Asia and China. Rice is
now commercially cultivated in over 100 countries, representing all continents of the world except Antarctica. World Rice acreage from 2004 to 2013 averaged 159 million ha (FAO-1). Rice occupies a greater area of the world than any other cereal, and produces a greater food value per unit area than the other leading cereals (Juliano 1993).

There are more than 15,000 different varieties, organised into three basic groupings: (1) Indica – usually tropical and long-grain, the most widely consumed type; (2) Japonica – also known as Sinica, usually temperate-climate and shorter-grained, the type used to make sweet rice pudding along with milk, eggs and sugar, because it cooks quickly and amalgamates more easily than the long-grained variety; and (3) Javanica – also known as bulu, tropical to sub-tropical, medium- to long-grain. Indica Rice is cultivated in Indochina, Thailand, India (hence the name Indica), Pakistan, Brazil and the southern United States. Japonica is mostly grown in colder-climate countries, including Japan (hence the name Japonica), Korea, northern China and California. Javanica is grown particularly in Indonesia (the name Javanica is based on the Indonesian island of Java). With the creation of more and more varieties, the distinction of these three types of Rice has become increasingly blurred.

‘Upland Rice’ is grown without submersion, usually on terraced hillsides; ‘lowland Rice’ (paddy Rice), the predominant category, is grown in beds that are flooded during much of the growing season (with a water level of 10–15 cm or 4–6 inches), with the water drained off as the plants approach maturity. In Asia, the monsoon (a season of torrential rains followed by a dry spell) naturally provides the necessary cycle of wetness and dryness.

About 95% of the world’s rice is produced in Developing Countries and more than 90% in Asia (Table 3; Juliano 1993). China, India and Indonesia are the largest producers. While rice is responsible for 80 to 90% of the dietary intake of Asians, at the latitude north of Beijing, called the ‘Rice Line,’ wheat replaces rice as the staple food. India tends to be divided into two food areas: wheat and meat in the north, rice and vegetables in the tropical south. Rice is the primary staple of more than two billion people in Asia and hundreds of millions of people in Africa and Latin America. Throughout history failures of the Rice crop have caused widespread famine and death; conversely, in human history there is a close relationship between expansion of Rice cultivation and rapid rises in population growth. It has been stated that ‘to meet the increasing demand for food from the rising

Figure 8. Rice farmer in Vietnam. Public domain photo by Philippe Berry.

Table 3. Leading rice producing countries in 2012. Data from FAO-8.

| Country     | Million metric tons |
|-------------|---------------------|
| China       | 204.3               |
| India       | 152.6               |
| Indonesia   | 69.0                |
| Vietnam     | 43.7                |
| Thailand    | 37.8                |
| Bangladesh  | 33.9                |
| Burma       | 33.0                |
| Philippines | 18.0                |
| Brazil      | 11.5                |
| Japan       | 10.7                |
population of Asia... a 50% increase in Asian Rice yields is required by 2050’ (Sheehy, Mitchell, and Hardy 2000).

Red or African Rice (O. glaberrima) is thought to have been domesticated as early as 3500 years ago in the delta of Niger, from which it was introduced into other parts of West Africa, where diverse cultivars were selected. The reddish colour of the grain has been said to be one of the reasons why this rice is much less popular than Asian Rice, the white colour of the latter being generally preferred. Asian Rice is more easily produced, harvested and milled. African Rice continues to be produced mostly by small-scale farmers, mainly for local consumption, often in remote areas of Africa. It is cultivated principally in Nigeria, Mali, Niger’s inland delta, and to a lesser extent on the hills near the Ghana–Togo border and in Sierra Leone. African Rice is important in a number of West African rituals.

Amylose is a kind of starch that is present in the rice grain. ‘Non-waxy’ rice is rich in amylose; ‘waxy rice’ is low in this material. Waxy rice absorbs less water while cooking, and is sticky or ‘glutinous’ after cooking (the stickiness has nothing to do with gluten which is not present in rice). Examples of non-waxy rice are basmati, Carolina Gold and Texmati. Examples of waxy rice with low amounts of amylose include Thai jasmine, Italian, Spanish and some Japanese rice. Examples of waxy rice with very low amylose content include Thai and Chinese sticky rice (known also as sweet rice). As noted above, rice varieties have traditionally been classified as indica, japonica, and javanica. High- and intermediate-amylose rices (i.e. non-waxy types) are usually indicas (i.e. long-grain). Low-amylose rices (i.e. waxy types) tend to be javonicas (Thai jasmine is an exception). Javanica tends to be intermediate in amylose content.

Because rice flour is nearly pure starch and free from allergens, it is the main component of infant formulas and face powders. Because of the low fibre content, rice powder is useful for polishing camera lenses and expensive jewelry.

Rice is most frequently consumed as cooked, entire grains, in contrast to most other cereals, which are milled into flour or meal to make bread, pasta porridges and other foods. Rice with the inedible hulls removed but the bran left on is brown rice, whereas rice that is further milled to remove the bran is white (‘polished’) rice, which may be further milled to produce ‘pearled’ rice. ‘Black rices,’ of which there are many varieties, have a black-coloured bran layer (the grain is white underneath). Some rices even have red-coloured bran. Brown rice has a nutty flavour that is stronger than that of white rice. Most people (including those in Asia, where rice consumption is centred) prefer white rice to brown, although the latter is more nutritious (often white rice is enriched with iron, niacin and thiamin in order to restore some of the nutritional value). Brown rice is difficult to digest because of the high fibre content, and tends to become rancid if stored for a long period (the oil-rich germ is the part that goes rancid). Since brown rice contains bran and germ, it is rich in vitamin B1 (thiamin). A disease called beriberi, characterised by inflammation of the peripheral nervous system and a loss of muscle tone in the arms and legs, is caused by a dietary deficiency of vitamin B1. This disease reaches epidemic proportions in Asia and Africa among people who subsist on a diet of white rice.

‘Poor-quality rice is featureless and tasteless. There is a lot of poor-quality rice in the world, especially nowadays. Many of the new genetically manipulated rices... that were developed to provide more food for more people, do have increased yields, but at the same time they’ve suffered from a loss of flavour... Rice, like bread, should have good flavour, smell and texture.’ (Alford and Duguid 1998)

Rice accounts for 21, 14 and 2 per cent of global human food consumption with respect to content of energy, protein and fat, respectively (FAO-9). Rice production is particularly concentrated in areas of Asia and Africa (Figure 9(a)) where hunger is most prevalent (Figure 9(b)), and this over-dependence on one crop is therefore of most concern in these areas.

Environmental costs of rice production

‘Environmental problems related to rice production include global climate changes: increases in atmospheric carbon dioxide, methane and nitrous oxide and a decrease in stratospheric ozone with a resultant increase in the ultraviolet-B radiation reaching the Earth’s surface, retention of solar radiation (the greenhouse effect) and global warming. Rice fields have been cited as the major generators of methane and nitrous oxide’ (Juliano 1993). Rice is one of the largest water-consuming crops in the world, using almost one-third of available fresh water (Anonymous 2014), but in the major rice producing locations the crop is grown during the wet (monsoon) season, using natural rainwater, so in a sense the natural ecosystems are being respected. However, in regions of the world where groundwater sources are required for irrigation, Rice is an ecologically expensive crop. More seriously, the very widespread use of nitrogen fertilisers in Rice production results in extensive aquatic pollution (Chapagain and Hoekstra 2010).

However, as with most crops, appropriate environment-friendly cultural techniques can be used to reduce the ecological damage associated with Rice. A particularly
promising way of compensating for the nutritional deficiencies of Rice is to utilise the shallow waters in which it is grown to raise edible aquatic animals (Halwart 2006). Another way of associating Rice production with the generation of edible animals is to employ tiny floating plants such as Azolla species, which can reduce the need for nitrogen fertilisers (Azolla is symbiotically accompanied by nitrogen-fixing organisms) and to feed livestock (Small and Darbyshire 2011). These are examples of ‘polyculture’ (agriculture using multiple crops in the same space), considered to be more environmentally friendly than monoculture.

Less than 5% of rice enters international trade, and most is consumed within a short distance of where it is produced. Such ‘locavore’ consumption is considered a way of promoting sustainability.

Possible environmental benefits from profound genetic modification of Rice

‘Green biotechnology’ is a phrase that has been used to suggest that some innovations are benign or even beneficial ecologically. While some regard the expression as oxymoronic, and another example of ‘greenwashing,’ one should keep an open mind towards the possibility that claims of eco-friendliness may be valid in some cases. Because it is the world’s most important crop, Rice is the subject of intensive agricultural research, particularly involving management techniques and genetic selection in order to increase yield and quality. Very ambitious genetic engineering projects have been undertaken to modify the fundamental nature of the Rice plant. These include attempts to transfer the highly efficient C4 photosynthetic pathway to Rice and so make

Figure 9. Coincidental occurrence of Rice production and malnutrition. (a) Geography of Rice yield. Figure by Andrew MT (CC BY 3.0). (b) Areas of world where more than 5% of the population is undernourished. Figure by Lobizón (CC BY 3.0).
the plant more productive (Sheehy, Mitchell, and Hardy 2000), and attempts to enhance the ability of Rice to associate with nitrogen-fixing bacteria and so reduce or even eliminate the need to provide nitrogen fertilisers (Santi, Bogusz, and Franche 2013). The economic benefits from such ambitious undertakings are clear. In principal, there also seem to be potential benefits for biodiversity: increasing yield is a way of decreasing the need to use wildlands for food production, and decreasing the need to apply fertilisers is a way of decreasing environmental pollution. However, as argued in this paper, the long-term social and environmental costs of biotechnological innovations need to be carefully evaluated. The intense debates over the costs/benefits of engineering herbicide resistance into crops exemplify the ambiguities associated with revolutionary biotechnologies. The following extremely controversial attempt to increase the nutritional importance of Rice by genetic engineering is a particularly instructive example of the need for caution when tampering with Mother Nature.

Golden Rice

Rice is a staple for more than half of the human race (FAO-10). However, it does not provide an adequate balance of nutrients, and overdependence on it by poor people in Asia has resulted in malnutrition, particularly for protein, some minerals (iron; and iodine in regions where the soils are naturally low in this element), and some vitamins (notably thiamine (vitamin B₁), riboflavin (vitamin B₂) and vitamin A (discussed in detail in the following).

‘Vitamin A,’ a group of organic compounds (carotenoid derivatives), occurs in animal foods, such as meat, fish, poultry and dairy products. The phrase ‘vitamin A,’ more correctly ‘provitamin A,’ is also used for several compounds in plant-based foods, particularly beta-carotene, which many animals including humans employ as precursors to synthesise vitamin A. Most people in the Developed World have diets providing adequate vitamin A, but many in the Developing World subsist largely on starchy, high-calorie staples with excellent storage properties (notably rice, corn, sorghum, wheat, cassava and potato) but with insufficient provitamin A. In poor countries, meat (which provides sufficient micronutrients) is often too expensive, and fruits and vegetables (such as tomatoes and carrots) that can provide pro-vitamin A are generally seasonal and perishable. Vitamin A plays essential roles in vision, immune response, skin and bone growth, reproduction and embryonic development. Vitamin A deficiency particularly weakens the immune system, and deteriorates the light-sensitive rod cells necessary for low-light vision. Extreme deficiency results in xerophthalmia, an irreversible form of blindness. Over 4 million children worldwide are affected by vitamin A deficiency, and as many as half a million become partially or totally blind. Pregnancy accentuates the need for vitamin A, and over half a million pregnant women die due to vitamin A deficiency. (See Bai et al. (2011) for a general review.)

An obvious cure for nutritional deficiency is supplementation, as is standard practice in rich nations, either by simply providing vitamin pills or by adding required nutrients to commercially available foods on an industrial scale. Food aid programmes using these techniques have been very successful in some cases, much less so in others, often because of cost and delivery limitations (Thompson and Amoroso 2011). However, modifying plants by selection or genetic engineering to increase deficient vitamins or minerals (‘micronutrient biofortification’) is also a recognised alternative (e.g. Bashir et al. 2013).

In the early 1990s, the Rockefeller Foundation sponsored research to genetically engineer increased provitamin A (beta-carotene) production into Rice. The pathway for such biosynthesis is present in green parts of Rice, but not in the endosperm (the starchy part of the grain). Genes (‘transgenes,’ notably one from Daffodil) were introduced into Rice which resulted in a form with relatively high beta-carotene. High-provitamin A Rice became known as ‘Golden Rice’ because of the yellowish colour (Figure 10) visible after milling and polishing, due to the presence of beta-carotene in the endosperm (Schaub et al. 2005). In 2001, Golden Rice had been improved to the point that a lead article and a bold headline on the cover of Time magazine proclaimed that ‘this rice could save a million kids a year’. Since then, there has been appreciable additional improvement of the provitamin A content of several Golden Rice cultivars, but very limited progress in implementing programmes of growing, using and testing Golden Rice.

Figure 10. Golden Rice grains (upper right) compared to white Rice grains (lower left). Photo by International Rice Research Institute (CC BY 2.0).
It should be appreciated that traditional plant breeding can usually produce cultivars with improved provitamin A content, although genetic engineering appears capable of achieving this much more quickly. In some cases genetic variation for a characteristic is simply not present in a particular crop, so introducing transgenes is the only option for improvement. A common criticism levelled against modern food cultivars is that they are less nutritional than older varieties, and indeed sometimes even their wild ancestors. Accordingly, creating cultivars with greater nutritional value seems very attractive, and indeed genetic engineering is under consideration for achieving this in other major crops, especially those that are employed as staples in poor countries. Corn and Banana are principal candidates for being engineered to produce high provitamin A, because, like Rice, they are associated with deficiencies of vitamin A. Aside from the much-argued risks and benefits of genetic engineering per se, at least the goal of increasing the nutritional value of foods seems justified. Regardless of nutritional merits, several socioeconomic issues have militated against the adoption of cultivars with genetically enhanced levels of provitamin A, not just in Golden Rice but in other crops. The widespread opposition to ‘frankenfoods’ has effectively prevented the dissemination of Golden Rice in rich countries (where it is doubtfully advantageous), and has greatly retarded experimentation in poor countries. In poor regions the unfamiliar yellow or orange colour could be a deterrent, but this kind of problem often can be overcome by education.

Golden Rice has become a poster child for both the opponents and proponents of genetic engineering. The debate has often been emotional, supporters sometimes alleging that the opposition is preventing children and pregnant women from being saved from blindness and death by fear-mongering with respect to health and environmental issues. The hyperbolic claim has even been made that such opposition amounts to ‘a crime against humanity’. Detractors have in turn sometimes challenged the motives of the supporters of Golden Rice, and interpreted it as a Trojan horse intended to make genetically modified organisms seem attractive. Brooks (2010, 2013) provides particularly insightful analyses of the conflicting forces that have stalled the Golden Rice initiative.

Claims and counterclaims have been debated in the scientific and popular literature regarding whether, for combatting vitamin A deficiency in malnourished populations, Golden Rice is ‘biologically effective’ (actually works in the real world). There are dozens of recent papers applauding Golden Rice (e.g. Enserink 2008; Potrykus 2012; Alberts et al. 2013; Finkel 2014). However, as will be evident in the following analysis, this paper is not concerned with the particular therapeutic merits of Golden Rice, but rather with how it epitomises a short-term strategy that increases the world’s dependence on mega-crops at the long-term expense of the health of both humans, habitats and biodiversity.

The chief problem with Golden Rice and indeed similar ‘biofortificants’ modified to enhance dietary deficiencies is that it contributes to increasing over-dependency on a very restricted set of carbohydrate staple crops. ‘Ready-to-use therapeutic foods, supplements or fortificants, including biofortificants… have contributed to the neglect of the consumption of diverse foods within local culture. The more sustainable and efficient way to improve nutrient contents of diets is to improve diet diversity, i.e. consuming a variety of foods that are naturally high in micronutrients and locally available, such as fruits and vegetables… a food-based approach which promotes dietary diversity is a more sustainable solution to reduce hunger and malnutrition’ (FAO-7). While biofortification may not be a ‘magic bullet’ for addressing world nutrient deficiency, there is support for considering it to be a useful adjunct approach (e.g. Johns and Eyzaguirre 2007; Bhullar and Gruissem 2013; Miller and Welch 2013).

‘Globalisation, industrialised agriculture, population growth and urbanisation have changed the patterns of food production and consumption that has profoundly affected the ecosystems and human diets. Drastic changes in food habits happened in many countries around the world, where locally available nutritionally-rich foods have been gradually replaced by a few foods that originated abroad, which are energy-dense and nutritionally-poor. Such dietary simplification neglects traditional nutritious foods and is also associated with micronutrient deficiencies and diet-related chronic diseases…. Biofortification (e.g. Golden Rice) has been considered as a strategy to combat micronutrient deficiencies; however, micronutrient deficiencies generally involve more than one micronutrient. Furthermore, biofortification as a strategy that focuses on increasing a subset of nutrients in a few staple foods risks further simplification of diets…. Biodiversity, agriculture, food and nutrition are all interrelated and all contribute to promote health.’ (FAO-7)

The natural healthy human diet and why it promotes biodiversity

For babies and infants, the most perfect food is mother’s milk, and so during the early years humans are ‘monophagous,’ specialised to live on just one source of nutrition. After weaning, however, we are decidedly polyphagous.
Humans are naturally omnivorous, adapted to consuming plants, animals, fungi and indeed most groups of living things currently recognised. We are also generalist feeders, suited to a very varied diet; indeed, by a considerable margin, Homo sapiens consumes more species than any other organism that exists or has ever existed. Flowering plants (angiosperms) constitute 50–90% of the volume of food of most humans, with up to 75,000 species being edible (if not necessarily palatable) and about 7000 commonly eaten somewhere (Procheș et al. 2008). Anthropological observations of food habits of pre-civilised societies have indicated that often hundreds of wild plants are consumed. Most of the remaining human diet is furnished by vertebrate animals, with minor contributions from algae, fungi and other groups of animals and plants (Procheș et al. 2008). Today, the average world diet is comprised of about 14% meat (including fish, poultry, and products such as eggs and milk, but excluding animal fats such as lard), while plant-based food constituting virtually all of the remainder (Small 2009).

It has been estimated that humans require about 50 food constituents for good health. Notable classes of indispensable dietary nutrients include fats (linoleic acid and linolenic fatty acids must be ingested), proteins (at least nine amino acids are necessary), vitamins (by definition, all vitamins are required), and minerals (at least 11 ‘microminerals’) and of course water. In addition, dietary fibre and many ‘phytochemicals’ in plants that are not essential to humans are nevertheless known to promote health. A diet based predominantly on plant tissues is now known to contribute to health; conversely, dietary diseases are associated with avoidance of plant foods. Essentially every food consumed by humans is deficient in some nutrients, but sufficient nutrients are obtained by eating an appropriate balance of different foods. Clearly, we should eat a wide variety of foods, especially plant foods, and this means that a wide variety of crops, not just a few excessively caloric mega-crops, should be cultivated. It follows that re-establishing the traditional human eating pattern of consuming many more vegetables, fruits and grains is a pathway to reducing reliance on mega-crops, and increasing the compatibility of agriculture and biodiversity.

A crime against nature: dietary monotony

The food and pharmaceutical industries are currently marketing nutritionally-balanced ‘meal in a milkshake’ preparations that can be hurriedly gulped down to save time for the demands of a stressful day. The penal industry offers ‘nutraloaf’ and ‘mystery meat,’ nutrient-rich but bland materials fed monotonously for long periods to misbehaving inmates as punishment. Of course, for medical reasons it may be necessary to adhere to a restricted diet, but our natural adaptations and instincts are best directed to the consumption of many of our fellow species. While it may seem contradictory, as explained in the following, eating a very wide representation of the world’s species may actually be doing them a favour.

Why today’s unhealthy diet of prepared foods is bad for biodiversity

The affluent world now lives in an era of ‘prepared,’ ‘fast,’ and ‘convenient’ food, or less charitably ‘junk,’ ‘counterfeit,’ ‘artificial,’ ‘fake’ or ‘synthetic’ foods. The traditional bases upon which foods have been selected – aroma and nutritional qualities – are no longer essential criteria, since taste, and scent can simply be added. Even the problem of ‘empty calories’ has been addressed (albeit inadequately) by adding nutritional molecules. The use of preservatives means that freshness is also no longer apparently important (in fact, a range of unhealthy but highly addictive constituents (sugar, salt and saturated fats) that have become key features of modern prepared foods. Ingenious texturising and colourants are often employed to make fast foods resemble real foods (a milk shake today may be devoid of dairy products). Unfortunately, food is being marketed primarily for sensory gratification, not for sustenance, and is being relentlessly and deviously advertised (most perniciously, to children). The result has been health problems, suffering and a fat epidemic; worldwide, 1.2 billion are overweight and 475 million are obese (FAO-11); in the Western world, half of people are overweight, one in six is obese. Many major chronic illnesses characterise modern industrialised societies, notably heart disease, hypertension, obesity, adult-onset diabetes, some kinds of cancer and dental caries, and most foods currently marketed are substantially responsible.

What does this have to do with biodiversity? The staple constituents that are used to manufacture prepared foods mostly come from mega-crops, because they are cheap and available in very large quantities. These particularly include sugar (from Sugar Cane and Sugar Beet), fructose (from Corn), starch (especially from Potato), fats and oils (from the leading oilseeds), and cereals (from the...
major cereals). The commercial prepared food industry now dominates food consumption, and in turn the mega-crops dominate these foods, reducing crop diversity and thus further endangering all biodiversity.

In the past, people had to work, forage or hunt to obtain food, and indeed the exercise contributed substantially to keeping people healthy. Now, for most people food is obtainable with very little effort (Figure 11). In the past, people usually died in middle adulthood, often from injuries and infection. Medical science now prolongs life. So not only are there more people on Earth, but we are living longer and many are eating like gluttons and indeed wasting food, all of which increases the need for food production which in turn adds to stress on the environment and biodiversity.

Alternatives to Rice and other mega-crops

While industrial/agribusiness monocultures are currently indispensable, there are sound reasons to support alternative sources of food. Wild nature (particularly the oceans) still provides sustenance for many people, and every effort should be made to preserve diminishing natural food supplies. Home (‘kitchen’) gardens, merely by their small size, are highly compatible with wildlife. The most important alternative to the mega-crops is small-scale farms, especially those growing minor crops. Small, rural farms tend to use less, if any, biocides, and make more use of natural fertilisers (especially manure), and in these respects are environmentally beneficial. ‘Agrarianism’ is a movement advocating a rural and semi-rural way of life, both as a means of achieving personal satisfaction and coexisting in a sustainable fashion with the environment. Small, mixed farms are almost always a relatively friendly environment for both wild plants and animals, providing different habitats among the different crops that support wild species. The continuing demise of the small family farm and the growth of huge corporate farms is therefore a growing concern for the environment. In much of the Third World, small subsistence farms are still the norm, and support as many as a billion people (Heywood 2011). While subsistence agriculture is very much less efficient than factory farming, it is much more compatible with the environment. In tropical and subtropical countries, which have many more species than found in temperate regions, subsistence and small-scale farms assist in the survival of vanishing biodiversity. A related matter is the supply of ‘land races’ (localised breeding selections) of many useful plants that are maintained on small farms, many of which would disappear with the elimination of the farms. While many of these advantages are not measurable in monetary terms, they are of great value to the health of the planet and its wild species. Although small farms individually lack the productive potential of factory farms, their output can be substantially increased by programmes of ‘sustainable intensification’ (Collette et al. 2011).

A very promising but much neglected alternative to mega-crops is the development of ‘underutilised crops,’ also known as ‘minor,’ ‘neglected,’ ‘underexploited’ and ‘orphan’ species. ‘There are thousands of plant species that provide edible fruits, grains, leaves, nuts, oils, roots and tubers, and that provide medicines, spices, stimulants and other products, which currently contribute significantly to the livelihoods, health and environments of hundreds of millions of people worldwide, especially in the tropics and subtropics… they have the potential to make a much stronger contribution to the development of poor communities, especially in the context of current and emerging global challenges for agriculture caused by climate change, population growth and other factors’ (Dawson et al. 2009). ‘Heirloom’ cultivars of edible plants and rare breeds of edible livestock are in constant danger of extinction, since they demand for them is very low. Encouraging increased consumption of these is a

![Figure 11. Comparison of life styles and diet in past times and today. (a) In the past, hunting for game and foraging for plant foods demanded considerable physical effort, promoting fitness. Because food was scarce, an abundance of different plants was consumed, ensuring balanced nutrition. (b) Today, overabundance and overconsumption of processed, refined, nutritionally deficient prepared foods have led to an epidemic of obesity and associated health issues, worsened by sedentary, stressful lifestyles. (Prepared by B. Brookes.)](image-url)
way of promoting the preservation of such agricultural biodiversity.

Can revolutionary food production technology reverse the need to usurp more habitats?

Technology, or more precisely biotechnology, is the means that humans are using to degrade habitats and biodiversity, but at least in theory some new biotechnology could represent salvation for biodiversity. Many environmentalists have become hostile to biotechnology because innovations desirable in some respects are often associated with undesirable and unintended harm to biodiversity. Unfortunately, biotechnology of crops has been concerned almost exclusively with increasing productivity, with virtually no regard for environmental/biodiversity consequences. It is necessary, however, to keep an open mind on the subject, because it may be possible to manufacture food in the future without the substantial destructive effects on the world that result from current agricultural technologies. Aquatic cultivation of some algae and miniature floating plants can be much more productive than conventional terrestrial agriculture (Small 2011; Small and Darbyshire 2011), and may be a way of avoiding future use of wildlands. Meat tissues might be cultured in vitro (‘test tube’ culture), reducing or eliminating the need to cultivate or harvest animals for food (Chamary 2012). At the moment, however, it seems very unlikely that we can escape the need to generate food in the same ways that we have for thousands of years. Moreover, it should be borne in mind that food ultimately is simply captured sunlight, and the inherent limitations of photosynthesis constrain how much can be produced. ‘Accelerating the progress towards hunger reduction and nutrition improvement is less about the development of innovations and technologies, but more about focusing on what is already known and in practice, with enduring efforts to conserve and use biodiversity’ (FAO-12).

Ignorance of biodiversity is contributing to malnutrition

As noted earlier, the leading staple crops are grains (fruits or seeds), roots and tubers. In all of these, humans are eating storage chemicals that nature intended to nourish plants, not humans, so not surprisingly they are deficient in micronutrients required for people. By contrast, the foliage of most plants, although incapable of furnishing much caloric energy to humans (we can’t digest cellulose), is remarkably rich in nutritional compounds (Beyer 2010). Also, the plant kingdom is extremely diverse, and in any area of the world there are at least some plants available with desirable micronutrients. Nature puts toxins in plants to protect them from being eaten, but in early times people were extremely knowledgeable about which ones in their neighborhood were edible, and often consumed nutrient-rich wild plants growing nearby. Today, especially in Developing Countries, a common bias has developed that local wild food plants are inferior, and their use is indicative of low-class behaviour. It is highly ironic, tragic and preposterous that wild plants are extensively available throughout the world whose leaves or other organs could be used to alleviate nutritional deficiencies, but are being ignored. Similarly, during the European age of colonisation, explorers and settlers commonly developed scurvy while ignoring the vitamin-C-rich nearby plants that could have cured them. In nineteenth century Ireland, when most people had only potatoes to eat, wild plants were commonly added to the meal, a practice that surely compensated for the starchy diet. To address world hunger, billions of dollars are being invested to develop new biotechnologies. A small fraction of this, diverted to educate disenfranchised people about the food value of their local flora, could be extremely beneficial. Wild plants can no longer be staple caloric food sources for large numbers of people in poor regions, but they can be used effectively as significant micronutrient and vitamin sources.

A particularly instructive case was documented by Engelberger (2012), who addressed the widespread vitamin A deficiency in Micronesia. Until Western dietary practices were introduced, indigenous people historically avoided vitamin A deficiency by consuming local green leafy vegetables. Engelberger carried out a search for abandoned native provitamin-A-rich plants. These were identified, and proved to provide a much more reasonable solution than the ‘vitamin A fiasco’ (Latham 2010) supplementation programme previously implemented. Bruinsma (2003) noted that ‘Golden Rice could have counterproductive impacts on nutritional problems by curtailing the progress made in educating people to diversify their diet and increase the diversification of agriculture production’. Indeed, there is a disconcertingly imperialistic aspect about the efforts of affluent interests to thrust ‘biotechnology for the poor’ on the Global South (Jansen and Gupta 2009).

Respecting nature and natural food

The problems explored in this paper are concerned with the extent to which we humans are willing to employ technology to distort nature and our relationship with the natural world. We have manipulated much of the world’s habitats and creatures to meet our immediate needs, particularly for food. But the results are clearly less than satisfactory for both the planet and us. The relentless exploitation of resources has sickened the planet, while the pervasive substitution of artificially constructed,
addictive foods for natural ones has had similarly disastrous consequences for our health. Much of the difficulties to date result from (as so often is the case) implementation of technological innovations before the science has been adequately established, and before social, environmental and consumer concerns have been adequately considered. It is also unhelpful that powerful business interests seem hell-bent on short-term profit, and governments often seem unconcerned with adequate regulation and education. But in the final analysis, the human species collectively and individually is responsible for reversing the harm that we are doing to ourselves and Mother Nature. As discussed in this review, our dietary habits can contribute substantially to improving the world. Food is not simply a means to sustain life, and the human dependence on mega-crops needs to be reduced. Eating the wide range of culinary delights that Nature has provided (Figure 12) rather than from the processed food industry is a way of respecting, promoting and celebrating biodiversity.

Believe it or not

- Ice cream was invented in China around 2000 BC when a milk-and-rice mixture was packed in snow.
- The tradition of throwing rice at newlyweds traces to the ancient use of rice in Asia as a symbol of fertility in religious ceremonies. Rice was also considered to be a symbol of health and prosperity, and a means of appeasing evil spirits so they would not bother the wedding couple.
- Women of Honshu Japan, while harvesting rice, wore stylised masks centuries ago to make them unattractive to male supervisors. Such masks are still sometimes worn today by rice harvesters, but as protection against insects and sunburn.
- Rice was very important in Britain’s Carolina colonies (although the crop is no longer commercially significant). At the conclusion of the American Revolution, the British removed all the rice, including seed rice, to prevent the new American nation from growing the crop. Thomas Jefferson (1743–1826, third American president) smuggled rice that would grow in dry fields out of Italy, and introduced it to the Carolinas in 1787, restarting the American rice industry. Jefferson’s action was risky, as exporting the rice at the time carried the death penalty.
- Rice is so important in China, where people consume about 0.45 kg (1 pound) every day, that the word for ‘agriculture’ is the same word as for ‘rice’. A common greeting equivalent to ‘How do you do?’ is ‘Have you had your rice yet?’
- Exposure to the taste of foods in childhood tends to result in life-long preferences, and this probably explains why rice is esteemed in Asia, but not so much in Western culture. In a 1951 survey of food choices in the US Armed Services, rice pudding (Figure 13(a)) was the least favoured dessert. Rice cakes (Figure 13(b)) were a trendy dessert for some time in North America, desired for their limited content of calories, although they are sometimes said to taste like cardboard.

Figure 12. Healthy, natural food. (a) Plant foods (public domain photo, United States Department of Agriculture). (b) ‘Freedom from Want,’ by American artist Norman Rockwell (public domain photo from US National Archives and Records Administration).
RICE is a mnemonic for Rest, Ice, Compression and Elevation, procedures for treating soft tissue injuries.

‘Snap! Crackle! Pop!’ is a registered trade mark of Rice Krispies, known for the curious sounds produced when milk is added. The puffed rice is filled with tiny air bubbles of different sizes, and when liquid is added it is unevenly absorbed. This results in uneven swelling of the kernel’s starch structure, producing a breaking action which is accompanied by the well-known noises.

Acknowledgements
Brenda Brookes skillfully assembled and enhanced the illustrations for publication. Creative Commons Licenses employed in this article: CC BY 2.0 (Attribution 2.0 Generic): http://creativecommons.org/licenses/by/2.0/; CC BY 3.0 (Attribution 3.0 Unported): http://creativecommons.org/licenses/by/3.0/. CC BY SA 3.0 (Attribution-ShareAlike 3.0 Unported): (http://creativecommons.org/licenses/by-sa/3.0/).

Key information sources
Alberts, B., R. Beachy, D. Baulcombe, G. Blobel, S. Datta, N. Fedoroff, D. Kennedy, et al. 2013. “Standing up for GMOs.” Science 341 (6152): 1320. http://sciencemag.org/content/341/6152/1320.full.
Alford, J., and N. Duguid. 1998. Seductions of Rice: A Cookbook. Toronto, ON: Random House Canada.
Altieri, M. A. undated. “Agroecology in Action. Modern Agriculture: Ecological Impacts and the Possibilities for Truly Sustainable Farming.” Accessed August 2014. http://nature.berkeley.edu/~miguel-alt/modern_agriculture.html
Anonymous. 2014. “How Better Rice Could Save Lives. A Second Green Revolution.” Accessed August 2014. http://www.economist.com/news/leaders/21601850-technological-breakthroughs-rice-will-boost-harvests-and-cut-poverty-they-deserve-support
Bai, C., R. M. Twyman, G. Farré, G. Sanahuja, P. Christou, T. Capell, and C. Zhu. 2011. “A Golden Era – Pro-Vitamin A Enhancement in Diverse Crops.” In Vitro Cellular & Developmental Biology – Plant 47: 205–221.
Bashir, K., R. Takahashi, H. Nakanishi, and N. K. Nishizawa. 2013. “The Road to Micronutrient Biofortification of Rice: Progress in Prospects.” Frontiers in Plant Science 4: 1–7.
Beyer, P. 2010. “Golden Rice and ‘Golden’ Crops for Human Nutrition.” New Biotechnology 27: 478–481.
Bhullar, N. K., and W. Gruissem. 2013. “Nutritional enhancement of rice for human health: the contribution of biotechnology.” Biotechnology Advances 31: 50–57.
Brooks, S. 2010. Rice Biofortification: Lessons for Global Science and Development. London: Earthscan.
Brooks, S. 2013. “Biofortification: Lessons from the Golden Rice Project.” Food Chain 3: 77–88.
Brown, L. R., C. Flavin, H. French, J. Abramovitz, C. Bright, F. Dunn, G. Gardner, et al. 1998. State of The World, 1998, Worldwatch Institute Report on Progress Toward a Sustainable Society. 15th ed. New York: W.W. Norton & Co.
Bruinsma, J., ed. 2003. “World Agriculture: Towards 2015/2030. An FAO Perspective.” Accessed August 2014. http://www.fao.org/docrep/014/i2280e/i2280e00.htm
Chamary, J. V. 2012. “The Future of Food.” http://sciencefocus.com/feature/health/future-food.
Chamy, C. 2014. “Wheat Rust: The Fungal Disease That Threatens to Destroy the World Crop.” Accessed August 2014. http://www.independent.co.uk/news/uk/home-news/wheat-rust-the-fungal-disease-that-threatens-to-destroy-the-world-crop-9271485.html
Chapagain, A. K., and A. Y. Hoekstra. 2010. The Green, Blue and Grey Water Footprint of Rice from both a Production and Consumption Perspective. Delft, the Netherlands: UNESCO-IHE Institute for Water Education.
Collette, L., T. Hodgkin, A. Kassam, P. Kenmore, L. Lipper, C. Nolte, K. Stamoulis, and P. Steduto. 2011. Save and Grow: A Policymaker’s Guide to the Sustainable Intensification of Smallholder Crop Production. Rome, Italy: Food and Agriculture Organization of the United Nations.
Conforti, P., ed. 2011. Looking Ahead in World Food and Agriculture. Perspectives to 2050. Rome, Italy: Food and Agriculture Organization of the United Nations. Accessed August 2014. http://www.fao.org/docrep/014/i2280e/i2280e00.htm

Figure 13. Familiar rice-based confections. (a) Rice pudding. Photo by Rudi Riet (CC BY 2.0). (b) Rice cakes. Photo by Evan-Amos (CC BY SA 3.0).
Schaub, S., S. Al-Babili, R. Drake, and P. Beyer. 2005. “Why is Golden Rice Golden (Yellow) Instead of Red?” Plant Physiology 138: 441–450.
Sheehy, J. E., P. L. Mitchell, and B. Hardy, eds. 2000. Redesigning Rice Photosynthesis to Increase Yield. New York: Elsevier.
Shiva, V. 1993. Monocultures of the Mind. Perspectives on Biodiversity and Biotechnology. London: Zed Books.
Small, E. 2009. Top 100 Food Plants: The World’s Most Important Culinary Crops. Ottawa, ON: NRC Press.
Small, E. 2011. “Blossoming Treasures of Biodiversity. 37. Spirulina – Food for the Universe.” Biodiversity 12 (4): 255–265.
Small, E. 2013. North American Cornucopia: Top 100 Indigenous Food Plants. Boca Raton, FL: Taylor & Francis/CRC Press.
Small, E., and S. J. Darbyshire. 2011. “Blossoming Treasures of Biodiversity. 35. Mosquito Ferns (Azolla Species) – Tiny ‘Super Plants’.” Biodiversity 12: 119–128.
Standage, T. 2009. An Edible History of Humanity. New York: Walker & Company.
The Guardian. 2014. “Norman Borlaug: Humanitarian Hero or Menace to Society?” Accessed August 2014. http://www.theguardian.com/global-development/poverty-matters/2014/apr/01/norman-borlaug-humanitarian-hero-menace-society.
Thompson, B., and L. Amoroso, eds. 2011. Combating Micronutrient Deficiencies: Food-Based Approaches. Wallingford: CABI International.
UNEP. 2014. Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Panel. New York: United Nations Environment Panel. Accessed August 2014. http://www.unep.org/resourcepanel/Publications/AreasofAssessment/AssessingGlobalLandUseBalancingConsumption/tabid/132063/Default.aspx
United Nations. 2013. World Population Prospects, the 2012 Revision. New York: United Nations.