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The effect of environmental change on food production, human nutrition and health

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Worldwide degradation of arable land, freshwater depletion and the loss of biodiversity are three of several ongoing 'global environmental changes' that endanger the biosphere's human utility – including food supplies, an essential, 'utility'. The degradation of local and regional food-producing environmental assets is a familiar story historically. Today, however, pressures and stresses on food production are becoming global in scale, reflecting (in addition to the above three) a range of large-scale human-induced environmental changes, such as global climate change and environmental nitrification. Human-induced biodiversity loss reflects land-use changes, other aspects of the over-exploitation of productive terrestrial and marine ecosystems, climate change, and the trans-boundary migration of pollutants and exotic species. Indeed, biodiversity loss has, for long, been an inevitable trade-off against the increased capacity to produce food for larger human populations – as occurs in agrarian societies when forests are replaced by crops. More recently, trade, technology, knowledge dissemination, and the worldwide transformation of ecosystems have further boosted food supplies for the increasing human population. (That this abundance often fails to improve health, for example by fuelling obesity, is another story.) Recent time-series data show an unusual, continuing, decline in per capita yields of grain, globally, since 1996. Detrimental environmental changes may be a contributory explanation, but causal attribution is complex. The links between environmental changes, food production, nutrient status and human health are similarly complex, and difficult to demonstrate epidemiologically. These environmental (particularly ecosystem) changes mostly affect the health of populations via complex, indirect pathways, and these impacts are modulated by local social-economic conditions.

Key words: Environmental change, population, climate change, food production, health

Introduction

Debate over land, food, water and energy supplies in relation to human needs is longstanding. Thomas Malthus is often considered as first noting a mismatch between geometric population growth and arithmetic food production growth. In fact, the debate is much older.[1] Historically, food availability has always been the most fundamental constraint on human population size. Over time, humans have found many ways to expand food supplies and hence the local environmental carrying capacity. Having gradually replaced foraging and hunting over the past 10,000 years, farming has become both more extensive and intensive. Indeed, there are many historical examples of over-exploitation of agro-ecosystems, entailing non-sustainable production practices.[2] These include the eventual decline of agriculture in the ancient Mesopotamian and Harappan civilizations. The fratricide in Rwanda in 1994 is deemed by some commentators to have reflected the land pressures and food shortages bearing on a rapidly growing population of eight million living in a tiny country with an estimated environmental carrying capacity of only six to seven million.[3]

In his apocalyptic vision, 1900 years ago, St. John the Divine saw a world continuously ravaged by the Four Horseman: conquest, warfare, famine and pestilence. Today, though, we cannot ignore the macro-Malthusian possibility (albeit not yet a probability) of world population size exceeding food supplies at global scale. World population appears set to complete a six-fold increase from 1.5 billion in 1900 to around 8-9 billion in 2050, after which it may plateau or decline. Can we produce sufficient food (and achieve a fairer distribution of it)? The modern agricultural revolution, dating from the eighteenth century has intensified and spread; the recent Green Revolution has boosted grain yields; and we may develop genetic biotechnologies and precision-farming techniques to expand world food production further.[4] However, uncertainties remain about the sustainability of these production-enhanced methods.

Meanwhile, malnutrition remains a serious international problem. Although the estimated proportion of persons that are protein or calorie undernourished has declined gradually gradually over recent decades, the absolute numbers are

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not yet obviously falling.[5] The estimated total number, in the year 2000, was 840 million, of which 799 million were within the less developed countries. In the Global Burden of Disease assessment made by the World Health Organization for the year 2000[6] protein and/or calorie under-nutrition accounts for an estimated 10% of the world's total burden of disabling illness and premature death. Among the poorest countries, about a quarter of the burden of disease is attributable to childhood and maternal under-nutrition. Meanwhile, among the rich countries, diet-related risks (mainly over-nutrition) in combination with physical inactivity accounted for a third of the burden of disease.[7]

The distribution of global dietary energy supply became more bimodal in the 1990s, reversing an improvement seen in the 1980s.[8] The number of hungry people increased in several developing countries, particularly in India.[5] As well, a new phenomenon of under-weight children associated with overweight parents emerged, particularly in Latin America.[9]

Environmental stresses and food production

Some scientists argue that, worldwide, agricultural activity is likely to cause more global environmental damage than are better-known changes such as global climate change.[10] Land degradation has already occurred widely. Approximately one-third of the world's fertile soil is estimated to have been moderately or severely damaged via erosion, salination, water-logging, chemicalisation, loss of organic material and physical compaction.[11,12]

The spread of irrigation has caused salination and water-logging in many locations. Ground-water supplies have been widely depleted as aquifers have been over-exploited. This is now a critical problem in northern China, the American midwest and northwest India. The chemicalisation of soil and waterways will increase as the use of nitrogenous fertiliser increases. Already the past half-century's combination of huge increases in nitrogenous fertiliser use, in livestock production, and in fossil fuel combustion has added greatly to the level of biologically active ("fixed") nitrogen within the biosphere. This has contributed to soil acidification and has caused increasingly high nitrate levels in ground, surface and coastal water.[13,14]

Against this background, questions arise about how, in future, other great changes in global environmental systems and processes might affect food production. Global climate change is an acknowledged major source of likely future stress on both terrestrial and marine food production, and is attracting much of the scientific and policy debate. However, there are other incipient large-scale environmental changes that will affect food production, including the accelerating loss of biodiversity (with knock-on effects on crop and livestock pest species), and the perturbation of several of the great elemental cycles (nitrogen, sulphur and phosphorus), and, less certainly, increased ultraviolet radiation exposure due to stratospheric ozone depletion.

Further, the impacts will not be simply additive; many of these processes will interact with one another. For example, the probability of crop infestations by pests may be influenced multiplicatively by changes in climatic conditions, the weakening of photosynthesis and plant biology by both increased ultraviolet irradiance and micronutrient deficiencies, the depletion of predator species, and water shortages. In the other direction, the need to increase global food production is likely to reduce biodiversity (especially via clearance of forest and woodland) and simplify many ecosystems, thereby continuing a longstanding trend.[10,15]

Food production and health

The health of human populations is fundamentally dependent upon the services of productive ecosystems for food. This is most obvious in poor countries – especially in rural areas – where food is derived almost exclusively from local sources. Human dependence on ecosystems for nourishment is less apparent, but ultimately no less fundamental, in richer urban communities. Historically, loss of productive ecosystem services has led to the collapse of whole civilizations. For example, the Mayan empire was lost around one thousand years ago as a result of soil erosion, silting of rivers and drought, leading to agro-ecosystem failure.[16,17]

Aggregate food production is currently sufficient to meet the needs of all, yet of the present world population of just over 6 billion, about 800 million are underfed, while hundreds of millions are overfed. Further, at least another billion experience significant micronutrient deficiency, for substances such as iron, iodine, zinc and some vitamins. This imbalance has been driven primarily by social factors, though ecological factors may play an increasingly important role in the future.

In poor countries, the number of people per hectare of arable land increased from three in 1961-63, to five in 1997-99.[18] Poverty and hunger have tended to force people onto marginal, drought-prone lands, with poor soil fertility. Worldwide, agricultural production has tripled in the last four decades. This has occurred mainly through growth in yield (including the Green Revolution technologies), whereas the annual rate of expansion of cropland has declined around seven-fold over that period. Total calorie production has, so far, kept pace with population, particularly through the expansion of calorie-dense oil crops. However, as indicated in Figure 1, the production of grain is now falling behind population increase at the global level. Improvements in yield, especially for grain, have slowed.[16,18] Cereal grains comprise an important index since they account for 50-60% of total world food energy – most grain being consumed directly, while about one third is consumed via its conversion into chicken, pork and beef.

The recent downturn is presumably multi-causal. Likely contributors include the switch from grain to non-grain cropsin some regions, the government-subsidised idling of grain-farming land in USA, the downturn in agriculture in Russia and the former USSR countries, the widespread decline in soil fertility and productive land area, and, perhaps, the early impacts of global climate change (see also below). Will world production of cereal grains catch up and then keep pace with future population growth and in-creased consumer demand (increasingly

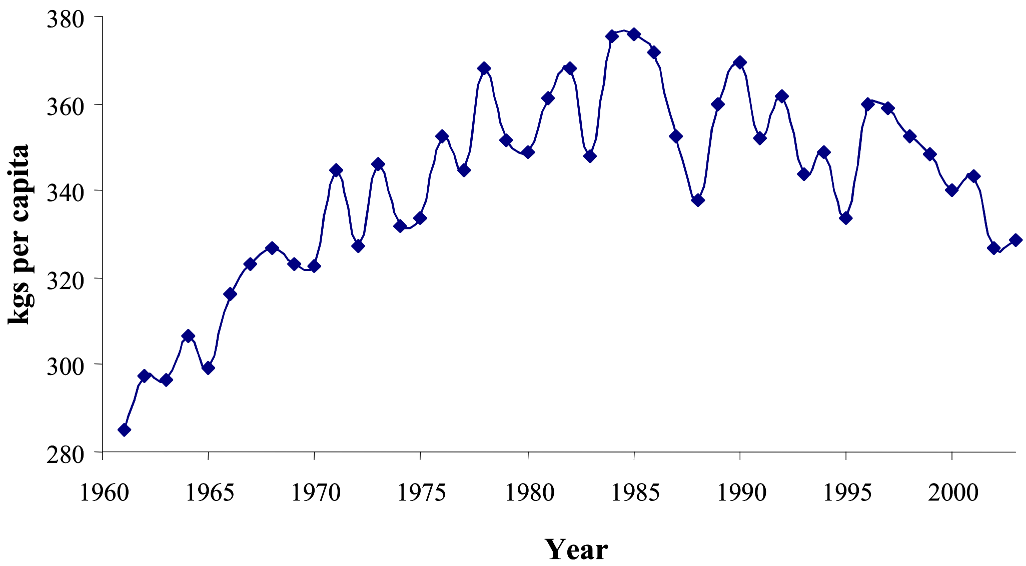

Figure 1. Global grain production (kgs per capita). Raw data from Food and Agricultural Organization[19] and UN Population Division[20]

indirect, as more grain is diverted into livestock production)? The answer will depend on the balance achieved between the positive and negative influences. Global environmental changes, summarised in the previous section, loom as a major source of potentially negative influences. Forecasts by most international agencies remain optimistic: they fore-see future grain production matching the combination of increased population size and rising consumer demand, at the global level, over the next 2-3 decades. At the regional level, however, the prospect is for worsening food security in sub-Saharan Africa and perhaps for the poor in South Asia. Whatever else, it seems clear that cereal grain exports from North America, Europe, Australia and Latin America must rise to meet the increased demand in many developing countries as populations continue to grow.[21]

It has been estimated that, today, nearly a quarter of useable land has undergone reduced productivity, and about a billion people are affected by land degradation either through soil erosion, water logging or salinity of irrigated land. Providing sufficient food for an expected human population of 8-9 billion people will require a profound redistribution of resources if it is to be achieved sustainably.

In many countries, agricultural production is increasingly dependent on irrigation, and this is likely to lead to conflict where there are existing tensions over access to freshwater supplies.[22] Many river systems (and thus scarce water resources) are shared uneasily between neighbours in unstable regions: the Nile, the Ganges, the Mekong, the Jordan and the Tigris and Euphrates rivers.[22,23] "Water wars" have therefore been postulated as increasingly likely in future, as population pressures and demands increase, including in the Middle East, Central Asia, and between Ethiopia and Egypt, Lesotho and South Africa, and India and Bangladesh. The potential consequences of environmental changes (particularly global climate change) and ecosystem disruption on food production and human health are discussed in the following sections.

Fresh water

Freshwater is a key resource for human health; it is used for growing food, drinking, washing, cooking and for the recycling of wastes. Of all available water globally, only 2.5% is fresh, and less than 1% is readily available in lakes, rivers and underground. The rapid recent growth in human demand for freshwater, especially for irrigated agriculture, has depleted many of the world's great aquifers ("fossil water"), including in northern China, the American Midwest and northwest India.

Worldwide, almost 4% of the global burden of disease is currently attributable to unsafe water, sanitation and hygiene. In the next century, water resources will be strongly affected by trends in population, land use and the management of fresh water ecosystems. Increasing demand for food, in particular, will worsen water scarcity. By 2025, it is estimated that nearly half the world population will live in river basins where water is scarce and 70% of readily available water supplies will be used.[18] Water scarcity can lead to use of poorer quality sources of freshwater, which are more likely to be contaminated, tending to cause increases in water-related diseases.

At present, 1.1 billion people lack access to safe water supplies, while 2.4 billion people lack adequate sanitation.[24] Lack of improved water and sanitation is strongly associated with poverty, although this relationship varies between regions.[25] Along with sanitation, water availability and quality are well-recognised as important risk factors for infectious diarrhoea and other major diseases.[26-28] The associated effects on human health are severe. Poor countries, with inadequate provision of water and sanitation, will be most vulnerable to these effects which impact most severely on children.

Climate change

Global climate change is one of the best known of the various large-scale environmental changes occurring in today's world. The modern profile of economic activities, globally, has been increasing the atmospheric concentration of so-called greenhouse gases. These energytrapping gases amplify the natural "greenhouse effect" that keeps the Earth comfortably above freezing-point. The greenhouse gases (GHG) comprise, principally, carbon dioxide (mostly from fossil fuel combustion and forest burning), plus various other heat-trapping gases such as methane (from irrigated agriculture, animal husbandry and oil extraction), nitrous oxide, water vapour and various human-made halocarbons. In its Third Assessment Report, the UN's Intergovernmental Panel on Climate Change (IPCC)[29] stated: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." During the twentieth century, world average surface temperature increased by approximately 0.6°C, and around two-thirds of that warming has occurred since 1975. Concurrently, there is evidence that climate variability has increased in various regions of the world.

Over the coming century, as shown in Figure 2, world average temperature is predicted to increase within the range 1.4-5.8 °C.[29] This anticipated increase will be greater at higher latitudes, and will be greater in winter than in summer. Meanwhile, overall, rainfall will increase. However, many parts of the terrestrial globe will become drier, and in other areas it is expected that precipitation events will be come more severe (thus increasing the risk of flooding).[30]

In recent decades, many non-human physical and biological systems have undergone changes that are reasonably attributable to the recent global warming. This includes the retreat of glaciers, the diminution of sea-ice, and the earlier occurrence of bird-nesting, flowering and insect migrations.[29] The Intergovernmental Panel on Climate Change (IPCC) has assessed that this overall pattern indicates the incipient impact of warming around the world. So, given these changes in non-human systems, what impacts might we expect on human settlements, food production, environmental security, and, more generally, wellbeing and health?

The human impacts of climate change and consequent environmental changes will differ between locations and geographical settings. The Third Assessment Report of the IPCC[29] stated (Volume II, pp 4-5) that: "There is emerging evidence that some social and economic systems have been affected by the recent increasing frequency of floods and droughts in some areas. However, such systems are also affected by changes in socio-economic factors such as demographic shifts and land-use changes. The relative impact of climatic and socio-economic factors are generally difficult to quantify. Human systems that are sensitive to climate change include water resources; agriculture (especially food security) and forestry; coastal zones and marine systems (fisheries); human settlements, energy and industry; insurance and other financial services; and human health. The vulnerability of these systems varies with geographic location, time and social, economic and environmental conditions."

Global climate change and food production

Long human experience makes clear that climatic fluctuations can disrupt food production, causing famine, deaths and social unrest. In Europe and North America the climate is less irregular than in most other regions of the world, particularly tropical and subtropical regions. Floods and famines in China and famines in India have been notorious killers over the centuries.[31,32] In China, where vegetables and grain have long accounted for nearly all of the caloric intake of the rural peasantry, famines have been recorded in one or more provinces in over 90% of all years between 108 BC and 1910 AD. Great famines have occurred once or twice every century in India over the past thousand years, each causing hundreds of thousands, sometimes millions of deaths.

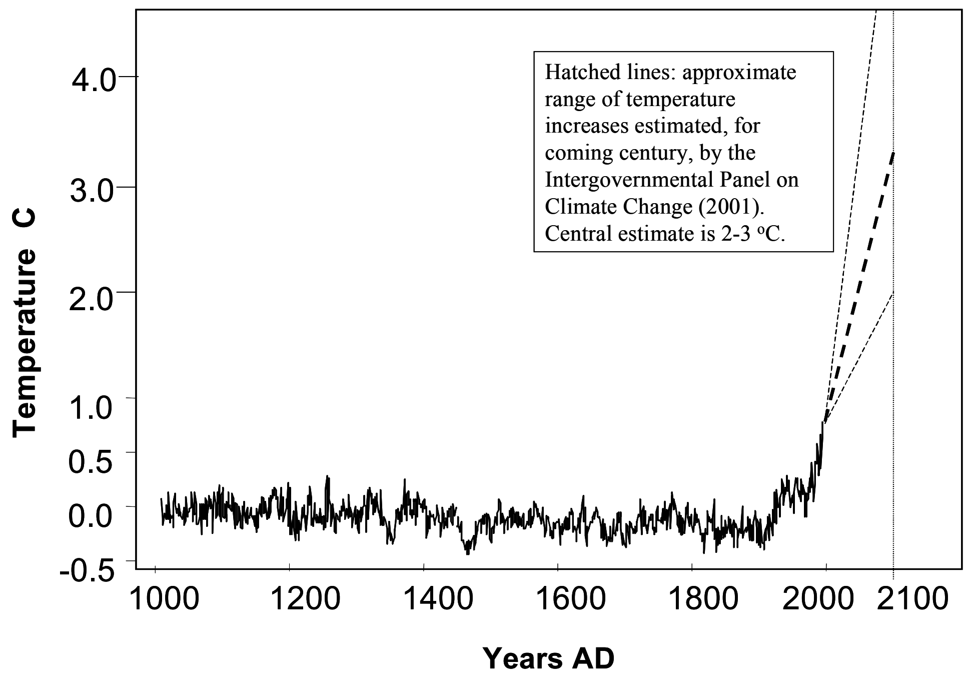

Figure 2. Reported variations in Earth's average global surface temperature since 1000 AD, supplemented by estimated range of increases over the coming century in response to recent and

hundreds of thousands, sometimes millions, of deaths. Smaller famines have occurred more often, usually in association with the weakening of the monsoon system induced by El Niño events. The last great peace-time famine in India, occurring in 1899 at the end of a moderately severe famine during 1896-98, probably caused over four million deaths.[32]

Food yields, especially of agricultural crops, are likely to be affected by shifts in climatic mean conditions. Those shifts would entail warmer temperatures, changes in growing seasons, altered patterns of precipitation, and (in many rain-dependent regions) reduced soil moisture. There are concerns that warmer temperatures, especially at night, may reducing yields in tropical regions.[33,34] One of these studies, at the International Rice Research Institute (IRRI) found that the yield of rice fell by 10% for every 1^{o}C increase in the mean night-time minimum temperature during the dry season.[34] There are also concerns that excessive heat will harm the flowering process of rice.

The impacts of a change in mean climatic conditions are unlikely to all be adverse. Regions with a temperate or cold climate are predicted to experience increased yields in response to higher temperatures. Frosts are likely to decrease, thus lengthening growing seasons. However, many mid-continental and semi-arid regions would be vulnerable to crop failures caused by small increases in warming and soil drying. Irrigation-dependent agriculture would be vulnerable to reduced rainfall, exacerbated by heightened evaporative losses. Less predictably, climatic changes would influence the ecology of plant pests and pathogens. Further, a less quantifiable risk arises from the likely increase in extreme weather events under a climate change regime. Floods, droughts, storms and fires all pose episodic, sometimes severe, risks to regional food production.[35]

Scientists have used dynamic crop growth models to simulate the effects of climate change, in conjunction with increased atmospheric carbon dioxide on cereal crop yields. These models represent the important physiological processes responsible for plant growth and development. They also include other major factors that affect yields: climatic conditions, soil characteristics, management practices and genotypic features. The models can be used to predict both rain-fed and irrigated crop yields. Note, however, that none of the models yet in use include consideration of the climatic modulation of pest or pathogen activity.

Cereal grain yields are of particular interest. As discussed above, the global cereal harvest became a little less stable during the 1990s, and there has been a decline in annual per-person production during the period 1996-2003 (Fig.1).[36] Could this be partly due to changing climatic conditions? There are, of course, many influences – ecological, commercial, consumer-driven and political – upon food production patterns. However, temperature, rainfall and soil moisture are fundamentally important to agriculture and horticulture. These act not only via the central processes of photosynthesis and the resultant growth of grains, but via weather disasters, influences on crop pests and diseases, and loss and spoilage.

The impact of standard scenarios of climate change, over three future time-slices during this current century, has been modelled recently by several groups of scientists, working particularly with climate change scenarios from the Hadley Research Centre, UK Meteorology Office and the European Commission Hamburg Centre.[37-39] These studies incorporate estimates of future trends in population growth, economic development, governmental policies on pricing, world food trading and agricultural technological developments. Overall, these modelling studies indicate that the imposition of climate change is likely to cause a "modest" net decline in total global yield.

This research also highlights that there will be marked differences in the impact of climate change on local cereal production in regions around the world. In short, the models indicate a world of "winners and losers" – the winners generally being in temperate zones, including the developed countries of Europe and North America, along with northern China and much of South America, while the losers tend to be in low-latitude countries where food insecurity is already widespread (including South Asia, parts of the Middle East, North Africa, much of Sub-Saharan Africa, and Central America). The resultant additional hunger and malnutrition would increase the risk of infant and child mortality and cause physical and intellectual stunting.[40] In adults, energy levels, work capacity, income and health status would be compromised.

Water is an essential input to agriculture and animal husbandry. For example, currently four-fifths of water usage in India is for agriculture. In many regions water supplies may be adversely affected by climate change. Reductions in rainfall are most likely in South Asia, the Middle East, North Africa and Central America. Tensions over freshwater shortages would be exacerbated by climate-related changes in rainfall where adjoining countries share river basins, particularly in North Africa, the Middle East, South Asia and Southeast Asia. Conflict and public health crisis might then result.

Sea-level rise is another environmental consequence of global warming. A half-metre rise (at today's population), which could occur by 2100 because of climate change, would approximately double the number who experience flooding annually from around 50 million to 100 million. Some of the world's coastal arable land and fish-nurturing mangroves would be damaged by sea-level rise. Rising seas would also cause salination of coastal freshwater aquifers, particularly those beneath small islands.

Food, environments and health: historical and current perspectives

On average, a natural wilderness environment supports approximately one hunter-gatherer per 10 square kilometers (i.e. 1000 hectares), and provides a seasonally varying mix of plant and animal foods. With modern intensified farming methods, many more people can be supported, at least temporarily. The global average is now 4 persons per hectare of arable land. That is, the world's approximately 1.6 billion hectares of arable land, which currently yield about 2.2 billion tonnes of cereal grains, support 6.4 billion people. Livestock graze upon a further 3 billion hectares of pastoral land.

Ever since human societies began replacing the low-impact hunter-gatherer life with that of farming and pastoralism there has been a need to find and clear fertile land. The expansion of populations and the rise of ancient civilisations depended crucially on the extension of labour-intensive agriculture, capable of yielding a food surplus to feed the urban elites and workers. The thousand-fold increase in human numbers since the advent of early agriculture has necessitated the clearing of forest and woodland on all continents. Between the tenth and fifteenth centuries in Europe, approximately three-quarters of natural lowland forest was cleared. The process continues today in many parts of the world, most spectacularly in the Amazon basin, central and west Africa, Southeast Asia and parts of Siberia.

From the world's arable land, approximately one-sixth of which is now artificially irrigated, comes the plant food that makes up the majority of the human diet. Over half of our dietary energy comes from cereal grains, predominantly wheat, rice and maize (corn). Recent global grain production trends have been discussed above. Around one-quarter of total animal protein consumed by humans comes from the sea. Indeed, in many countries, such as the Philippines, Bangladesh and the Pacific islands, fish is the main source of animal protein. The annual global catch of seafood, which rose rapidly during the 1960s to 1980s to around 100 million tonnes, has increased little over the past decade. Most of the world's great ocean fisheries are being exploited at or beyond their limit. Several (including the northeast Atlantic "Grand Banks" and North Sea cod fisheries) have experienced very serious declines.

During the 1980s and 1990s, the combination of erosion, desiccation and nutrient exhaustion, plus irrigation-induced water-logging and salination, rendered about one-fifteenth of the world's readily arable farmland unproductive. Much more land was seriously damaged. In Australia, the spreading salination of denuded farmland is becoming a serious national problem. As population size increases, as regional climates alter in response to global climatic changes, and as biodiversity loss increases the probability that pests and diseases will afflict food crops and livestock, there will be further stresses on the world's food-producing systems.

The successes of the 'Green Revolution' of the 1960s to the mid-1980s depended on laboratory-bred high-yield cereal grains, fertilisers, groundwater and arable soils. In retrospect, it appears that those productivity gains depended substantially upon the expenditure of ecological 'capital', especially via damage to topsoil and depletion of groundwater. In India, for example, an estimated 6% of cropland was subsequently taken out of production because of water-logging, salinity and alkalinity that occurred during the 1970s and 1980s. The Green Revo-lution is also claimed by some to have exacerbated various micronutrient deficiencies – e.g maternal anaemia and childhood deficiencies in iron, zinc and beta-carotene – because the higher-yielding strains of wheat and rice, while replete with more energy-rich macronutrients, tend to have reduced concentrations of micronutrients. Other causes for this include a more monotonous diet, with fewer pulses, and that some of the fertilizers used by the Green Revolution are deficient in trace elements, especially zinc.[41]

Although world food production outpaced population growth over most of the past half-century, those successes were achieved partly by depleting natural environmental resources; that is, by borrowing against the future. So, what types of diet will be ecologically sustainable in future? What is the balance of gains and losses due to intensive agriculture and livestock production, both to the environment and human health? And what types of diet will be acceptable in a world in which consumer expectations in urbanising lower-income countries are rapidly changing towards the meat-enriched, highly processed, freight-intensive diets that have been typical of high-income countries? There is an irony here. As lower-income countries aspire to diets richer in animal foods and less dependent on plant staples, diets in high-income countries are evolving towards those of the Mediterranean and non-Western cultures – with more fruit and vegetables, more whole-grain foods and less animal fats.

There are other environmental dilemmas here. For example, transport is energy-intensive; and fruits and vegetables have high water content and are therefore much heavier to transport, per unit nutrient, than are cereal grains and lentils. Yet, increasingly, epidemio-logical evidence shows that diets high in fresh fruit and vegetables lower the risks of many major types of cancers, heart disease, diabetes and other diseases. The solution will lie in developing transport that is powered by renewable energy sources, in encouraging the consumption of locally grown plant foods, local technological developments (such as 'smart' greenhouses) and, where appropriate, genetically adapting non-local species of fruits and vegetables to facilitate their local production.

In considering future options for feeding the world we must keep the criterion of population health to the fore. We should therefore note that: (i) the types of diet eaten by our agrarian and, particularly, our hunter-gatherer predecessors provide a template for thinking in evolutionary terms about human biology and its dietary needs; (ii) the health gains occurring in Western societies over the past 150 years have in part reflected improvements in food transport, refrigeration and distribution systems, and the associated increase in seasonal importation of fresh fruits and vegetables; and (iii) the diets in some high-income countries today, such as those of the Mediterranean region and Japan, appear to confer wide-spread health benefits.

Future prospects: security and sustainability?

Experts are divided on the outlook for feeding the world in the coming decades. A neo-Malthusian situation lurks in the background, entailing a race between the pressures of population growth and increasing consumer affluence, on the one hand, and the technological capacity to increase yields sustainably – including via more efficient irrigation, ecologically-sound genetic modification of crops (to suit them better to available environments, both natural and degraded), and the farming of sea-foods. In recent decades, most emphasis has been on increasing the supply side of this equation – increasing food. This emphasis needs balance with efforts to reduce the demand side – an acceleration of the global demographic transition through means such as education and a more equal distribution of human rights.[42]

Fish farming, which has grown at over 10% annually recently, holds considerable potential. Indeed, we may foreshadow a basic shift in the human diet: fish ponds offer great advantage over cattle feedlots in a protein-hungry world of land and water scarcity. China, with 3,000 years experience, leads the way with aquaculture: its ponds, lakes and rice paddies currently account for two-thirds of the world's annual aquacultural yield of approximately 35 million tonnes.

Aquaculture, however, is prone to problems of infection, pollution and various ecological difficulties. Salmon and shrimp are especially problematic. Salmon are carnivorous and their production therefore intensifies environmental pressures — they require 5 tonnes of fish-meal per tonne of salmon produced. Salmon stocks, selectively bred for fast growth, are prone to lice and viral infections, despite heavy chemical treatment of their water. Shrimp farming, especially around Asian coast-lines, has widely destroyed mangrove forests and polluted coastal waters. Further, most farmed shrimp is for export to higher-income populations, and so its production does not directly alleviate local food shortages.

At the regional level, meanwhile, food shortages persist. The prospect over the coming decades is for worsening food security in sub-Saharan Africa and perhaps for the poor in South Asia. On current trends, by 2025 Africa will be able to feed only around 40% of its population, likely by then to total about 1 billion. In many parts of Africa the soils are relatively thin and infertile, and poverty, rapid population growth, poor governance and limited infrastructure have precluded both restoration of those soils with fertilisers and organic matter and any respite from production pressures.[43]

The impacts of climate change have been discussed above. Food yields, especially of agricultural crops, are also likely to be affected by human-induced global warming, entailing warmer temperatures, changes in growing seasons, altered patterns of precipitation, and (in many rain-dependent regions) reduced soil moisture. Irrigation-dependent agriculture would be vulnerable to reduced rainfall, exacerbated by heightened evaporative losses. However, the impacts of climatic change may not all be adverse. Regions currently with a temperate or cold climate might undergo increased yields in response to increased temperature - whereas many mid-continental and semi-arid regions would be vulnerable to crop declines caused by increases in warming and soil drying.

In light of lessons learnt from the Green Revolution, we must seek to improve yields by ways that leave the natural resource base intact. Major possibilities include biological methods of pest and weed control, adequate crop rotation, and mixing of crops with forestry and livestock. Innovative forms of soil enrichment, using nitrogenous trees, offer cost-effective ways to reduce fertilizer use in parts of Africa, although this may increase nitrogen runoff.[44] A "doubly green revolution" combining crop varieties designed to perform well under low-input and stress conditions, the judicious use of inorganic inputs, and the engagement of farmers in analyzing their needs and adapting new varieties and agronomic practices to their own conditions may be emerging.[45] The pre-Columbian inhabitants of Brazil used a form of soil enrichment called "terra preta" which offers hope of a more sustainable form of tropical agriculture, including by using sylviculture.[46] Multiple forms of rice, grown together, appear to result in a synergism that enhances disease resistance and reduces pesticide use, without genetic engineering.[47] A new breed of rice, developed in West Africa has been claimed to increase yields, even without fertilizer.[48] On the other hand, the benefits of another method of increasing rice yields, developed in Madagascar and known as the system of rice intensification, have been questioned.[49]

We must also find ways to make food more accessible and affordable for all people. This proposition highlights a fundamental tension: most of the emergent new yield-increasing techniques, grounded in genetic engineering, are best suited to the world's flat lands with good soils, plenty of water, and effective commercial and governmental infrastructures. In other words, these techniques are better suited to temperate First World regions than to the often food-insecure, agriculturally marginal regions in developing countries. If new technical developments in crop production are not tailored more to those populations, via dialogue between scientists, extension workers and local farmers, the rich-poor gap will continue to widen and widespread malnutrition will persist. In sub-Saharan Africa, this gap is likely to be exacerbated by the social and other costs of HIV/AIDS, including loss of labor and knowledge.[50]

The conventional options for boosting plant-food production would include pressing more land into service, extending irrigation, and greatly increasing fertiliser use. However, limits are being reached on various environmental and biological fronts. Therefore, higher priority must be given to developing sustainable methods. Livestock production should optimise the use of plant-food energy. Plant and animal production do not necessarily compete with each other: ruminants such as cows and sheep *can* graze on land that otherwise would not be suitable/useful for growing crops. However, grazing animals often cause soil erosion, competition with indigenous animal species, and the eutrophication and microbiological contamination of waterways. The routine use of antibiotics in animal feed (as growth promoters) presents a worldwide risk of antibiotic-resistant bacteria arising within livestock and passing to meat-eating humans.

There is much potential in the genetic modification of food species, particularly in adapting them to the available environment. However, worries remain about potential adverse ecological and health consequences. Further, we face a major challenge in directing this ingenious biotechnology to socially beneficial ends, rather than profit-maximising ends.

Conclusions

Environmental influences on the production of food - crops and livestock on land, wild and cultivated fisheries -

are diverse, complex and interactive. There is extensive evidence that over-use and mis-use of arable land, around much of the world in recent decades, has resulted in substantial degradation and loss of productive land.

We still have much to learn about how the various biotic food-producing systems respond to changes in environmental and ecological circumstances. Nevertheless, pressed by new questions about the impacts of large-scale environmental changes on food production, much new research-based insight is being generated. An important example is the complex question about how global climate change is likely to affect food production. On balance, climate change - at least in the medium-to-longer term if not over the next several decades - is likely to adversely affect food production, especially in regions that are already food-insecure. The prospect of increased climatic variability further increases this risk.

Given that global environmental changes could adversely affect world food production, we should apply the Precautionary Principle. There are finite, and increasingly evident, limits to agro-ecosystems and to wild fisheries. Our capacity to maintain food supplies for an increasingly large and expectant world population will depend on maximising the efficiency and sustainability of production methods, incorporating socially beneficial genetic biotechnologies, and taking preemptive action to minimise future detrimental, ecologically damaging, environmental changes.

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