The next green revolution: Its environmental underpinnings*

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In order to keep pace with population growth and the imperative of upgrading nutrition, the world faces the challenge of doubling food production within the next three decades. This will be all the more difficult in that the natural resource base underpinning agriculture is being degraded and depleted at unprecedented rates. This places a premium on an Evergreen Revolution, wherein future agriculture will depend heavily on scientific inputs, policy initiatives and funding support.

The challenge ahead

THREE decades from now we shall need to be feeding another 2.5 billion people, two-fifths more than today. We should aim to provide them with at least 50–60% more food in order to ensure that they are all adequately nourished and to cater to increased affluence. This challenge compares with that of the first Green Revolution, when the world's farmers expanded grain production by 164% in just three decades – a period when global population almost doubled. Can farmers do it again?

Today's challenge is at least as big in salient respects, and it is made tougher by decline in the environmental resource base: soil erosion, water shortages, desertification, acid rain, increased UV-B radiation and global warming. The challenge is feasible, provided that it is a science-based effort (much more research) instead of a resource-based affair (soils, water, fertilizers, etc.). Yet precisely when there is a premium on agricultural science like never before, governments are slashing their research budgets.

Soil erosion

During the past 20 years some 500 billion tonnes of topsoil have been eroded away (roughly equivalent to all the topsoil in India's croplands)[1], followed by another 25 billion tonnes each year[2] (see also Pimentel *et al.*[3], who estimate the current rate of loss could be as much as 75 billion tonnes per year). During the past 40 years, at least 4.3 million square km of croplands have been abandoned because of soil loss, an expanse equivalent to 30% of today's croplands[4,5]. Without better soil-conservation practices, between 1.4 million and 2.0 million square km (the smaller expanse is half as big again as Pakistan) will lose most of their good-quality soil over the next two decades[3,6].

Soil erosion is all the more serious today in light of the declining use of fertilizers, which have long served to offset loss of soil nutrients through erosion. If erosion is allowed to continue virtually unchecked, it could well cause a decline of 19–29% in food production from rainfed croplands during the 25 years 1985–2010 (ref. 7). In countries as disparate as Mexico, Costa Rica, Mali and Malawi, soil loss causes annual decline in farm output worth 0.5 to 1.5% of GNP[8], and a much higher proportion of the household income of the poorest people – precisely the ones who need to buy food to offset shortfalls from their eroded farmlands. Yet upwards of half a billion impoverished people in developing countries find themselves obliged to farm hillsides where they cause exceptional erosion[9].

Desertification

Desertification – whether deriving from natural climatic change or human activities or both – threatens 45 million square km, nearly one third of earth's land surface. It undermines the livelihoods of at least 900 million people in 100 countries, of whom 135 million are experiencing the rigours of severe desertification[10,11]. Already it eliminates 60,000 square km of agricultural land each year, and reduces another 200,000 square km to a state of grossly depleted productivity. The cost of agricultural output lost is around $42 billion per year[11,12].

Salinization and water logging of irrigated lands

Irrigated lands produce almost 40% of our food from only one-sixth of our croplands. Equally important, they contributed more than half of the increase in food pro-

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duction during the Green Revolution's heyday from the mid-1960s to the mid-1980s (ref. 4). Given the expected demand for additional food during the foreseeable future, plus the lack of further good-quality land to open up for agriculture, we shall need to turn to existing croplands for ever-greater harvests – and especially to irrigated lands as the most productive of all croplands. These irrigated lands, now covering some 2.6 million square km (out of 14.4 million square km of all croplands) or an aggregate expanse equivalent to almost the whole of India, may have to produce half or even two-thirds of our additional food in the future[13,14].

The irrigated expanse increased by an average of 2.8% per year during 1950–80, but only 1.2% since then. Future expansion is likely to be no more than 0.3% per year, and possibly none at all[15]. In per-capita terms, irrigated lands have shrunk by 6% during 1978–90, and are expected to contract by a further 12% during 1991–2010 (ref. 16). As much as 250,000 km^2 of irrigated lands, or almost one-tenth of the total, have been salinized enough to reduce crop yields, and another 15,000–25,000 square km are so severely affected every year that many of them have to be abandoned[4,14]. Because of salinization together with water logging, 450,000 km^2 of irrigated land in developing countries need immediate and costly reclamation if they are not to be lost to agriculture[17,18].

Water deficits and droughts

Already 550 million people experience shortage of renewable water. In 88 developing countries with 40% of the world's population, the problem has become a serious constraint on development in general and agriculture in particular. The total number of people to experience water shortage is projected to reach three billion by 2025 (range, 2.8 billion to 3.3 billion), largely because of population growth, and it could even grow to the order of 4.4 billion by 2050. The prospect in many regions could be made markedly worse by the climatic vagaries of global warming.

It is unlikely that this demand will be met only because of practical upper limits of useable renewable freshwater stocks. The principal areas at risk include (though not confined to) parts of India and Pakistan, the Middle East, and much of Africa. More than one billion people affected in 2025 are expected to be in Africa, comprising two-thirds of the continent's projected population[19,20]. All these regions except for the Middle East suffer some of the most severe food shortages already.

Tropical deforestation

Water shortages are aggravated if not primarily caused in many parts of the humid tropics by deforestation. Tropical forests are being destroyed at rates (usually 1–2% per year) that presage the elimination of large expanses early next century. As the forests disappear, especially in upland catchments, so do many of their watershed services and hydrological functions, causing year-round water flows in downstream areas to give way to flood-and-drought regimes. 40% of the farmers from the developing world depend upon regular flows of rivers and streams from healthy watersheds to irrigate their croplands[21]. In the Ganges Valley with its 500 million smallscale farmers in India and Bangladesh, the annual watershed costs of Himalayan deforestation were estimated as far back as the early 1980s at more than US $1 billion in India alone[22]. A similar decline of watershed services is becoming apparent in the densely populated valleylands of the Irrawaddy, Salween, Chao Phraya and Mekong Rivers in Southeast Asia – a region where the biggest constraint on rice production is not lack of arable land or agronomic inputs but shortages of cropland water[23].

In addition, there is evidence that deforestation sometimes results in reduced rainfall[24]. In north-western Peninsular Malaysia, the Penang and Kedah States have experienced disruption of rainfall regimes to the extent that 20,000 hectares of paddy ricefields have been abandoned and another 72,000 hectares have registered a marked production drop-off in this rice bowl of the Peninsula[25]. Similar deforestation-associated changes in rainfall have been documented in parts of Philippines, south-western India, montane Tanzania, south-western Ivory Coast, north-western Costa Rica and the Panama Canal Zone[26].

Table 1. World grain production, 1950–96

Year	Grain total (million tonnes)	Per capita (kg)
1950	631	247
1960	847	279
1970	1096	296
1980	1447	325
1981	1499	331
1982	1550	336
1983	1486	317
1984	1649	346
1985	1664	343
1986	1683	341
1987	1612	321
1988	1564	306
1989	1685	324
1990	1780	336
1991	1696	315
1992	1776	316
1993	1703	307
1994	1745	309
1995	1694	295
1996	1820	315

Source: Brown *et al.*[43].

Table 2. Per-capita cropland availability in 1990, and projected to 2025 (hectares)

Country	1990	2025
Mexico	0.29	0.18
Colombia	0.17	0.11
Ecuador	0.27	0.15
Peru	0.17	0.10
Egypt	0.05	0.03
Nigeria	0.34	0.14
Ethiopia	0.29	0.11
Kenya	0.10	0.04
Tanzania	0.13	0.05
Pakistan	0.17	0.07
India	0.20	0.12
Bangladesh	0.09	0.05
Indonesia	0.12	0.08
Vietnam	0.10	0.05
China	0.08	0.06
Philippines	0.13	0.08

Source: *Engelman and LeRoy*[34].

The minimum amount of arable land required to sustainably support one person is 0.07 of a hectare. This assumes a largely vegetarian diet, no farmland degradation or water shortages, virtually no post-harvest waste, and farmers who know precisely when and how to plant, fertilize, irrigate, etc.

The collective population of the above countries today is 3.2 billion (56% of the world's population), and it is projected to grow by 2025 to 4.6 billion (56%).

For further elucidation, see text.

Decline of biodiversity

In contrast with the environmental constraints listed above, biodiversity decline exerts a mostly indirect and long-term impact. A good number of species and their populations supply genetic resources for new foods and improved forms of existing foods[27,28]. We shall need all the genetic variability we can find to cope with both present pests and diseases and future problems such as the vagaries of climatic change. That is, there is an unprecedented premium on crop types with resistance to too little or too much rainfall, increased UV-B radiation, and new pathogens. Yet we are losing in the region of 50,000 species a year from a planetary complement of 10 million species (minimum reckoning), and probably a much higher proportion of species' populations. This extinction rate is accelerating rapidly: we may well witness the demise of half of all species and most populations of surviving species by the middle of the next century[29–31].

Still more important, our agricultural crops are sustained through constant infusion of fresh germplasm with its hereditary characteristics. Certain infusions come from wild relatives of modern crops, others from land races and so-called primitive cultivars. Thanks to this regular 'topping up' of the genetic or hereditary constitution of the United States' main crops, the Department of Agriculture estimates that germplasm contributions lead to increases in productivity that average around 1% annually, with a farm-gate value that now tops $1 billion[32].

Regrettably, wild gene pools are being rapidly depleted. Wheat, for instance, flourished across an expanse of more than 230 million hectares in 1995, featuring a rough average of two million stalks per hectare. This means that the total number of individuals exceeded 460 trillion, probably a record[33]. As a species, then, wheat is the opposite of endangered. But because of a protracted breeding trend toward genetic uniformity, the crop has lost the great bulk of its populations and most of its genetic variability. In extensive sectors the original range of wheat where wild strains have all but disappeared, there is virtual 'wipeout' of endemic genetic diversity. 95% of Greece's native wheat, have become extinct; and in Turkey and extensive sectors of the Middle East, wild progenitors find sanctuary from grazing animals only in graveyards and castle ruins. As for wheat germplasm collections, they were described more than one dozen years ago as 'completely inadequate' – and that was without considering future broad-scale problems such as acid rain, enhanced UV-B radiation and global warming[34].

We can tell a related story with respect to rice. In the early 1970s Asia's rice fields were hit by a 'grassy stunt' virus that threatened to devastate rice production across more than 30 million hectares from India to Indonesia. Fortunately a single gene from a wild rice offered resistance against the virus. Then in 1976 another virus, known as 'ragged stunt', emerged; and again, the most potent source of resistance proved to be a wild rice. The economic returns from these wild rices would be more than enough to pay for all the expenses of preserving the collection of rice germplasm at the International Rice Research Institute in the Philippines. Several other diseases could impose widespread losses on Asia's rice crop, but at least a 100 wild rice appear to harbour resistance[25].

Landlessness

Landlessness – or, to be realistic, functional landlessness – can plainly reflect population pressures. Often, it derives from environmental factors when land degradation has virtually eliminated the productive value of erstwhile farmlands, whereupon there is less worthwhile land to go around in communities that may already find population pressures make individual holdings unduly small. Landlessness usually stems too from a number of political, economic, social and legal problems; and it can often be deemed a poverty problem. It is unusually acute in Mexico, Colombia, Ecuador, Peru, Egypt, Nigeria, Ethiopia, Kenya, Tanzania, Pakistan, India, Bangladesh, Vietnam, Indonesia, China and Philippines. Their aggregate populations today total 3.2 billion (56% of humankind), projected to reach 4.6 billion (56%) by 2025 (ref. 13).

The minimum amount of agricultural land necessary for sustainable food security, with a diversified diet similar to those of North America and Western Europe (hence including meat), is 0.5 of a hectare per person. This does not allow for any land degradation such as soil erosion, and it assumes adequate water supplies. Very few populous countries have more than an average of 0.25 of a hectare. It is realistic to suppose that the absolute minimum of arable land to support one person is a mere 0.07 of a hectare–and this assumes a largely vegetarian diet, no land degradation or water shortages, virtually no post-harvest waste, and farmers who know precisely when and how to plant, fertilize, irrigate, etc.[17]. In India, the amount of arable land is already down to 0.2 of a hectare; in Philippines, 0.13; in Vietnam, 0.10; in Bangladesh, 0.09; in China, 0.08; and in Egypt, 0.05. By 2025 the amount is expected to fall to: India, 0.12 of a hectare; Philippines, 0.08; China, 0.06; Vietnam, 0.05; Bangladesh, 0.05; and Egypt, 0.03 (refs 35–37).

By 2025 or shortly thereafter, some of these countries, notably India, Bangladesh, Pakistan, Indonesia, Egypt, Ethiopia, Nigeria and Mexico, may need to triple their grain imports[38]. Of course, they could rely on foreign food provided it is available at the right price. Japan is one of the most land-short countries of all, with only 0.06 of a hectare of arable land per person today, projected to fall to 0.04 in 2025. But Japan can afford to buy all the food it wants, and presumably will continue to do so.

A related problem contributing to landlessness is 'the jobs famine'. The developing countries' workforce is around two billion people. Of these, at least 750 million are unemployed or grossly underemployed; their total exceeds the entire workforce of the developed countries (unemployment in OECD countries amounts to around 30 million). By the year 2025 and because of past population growth, the developing countries' workforce is projected to expand to more than three billion[39]. Note that this latter figure is hardly a projection, subject to possible reduction through policy interventions; most of the future workers have already been born.

To provide employment for the new workers, let alone those without work today, developing countries will need to create an average of 40 million new jobs per year for the next three decades. The United States, with an economy half as large again as the entire developing world's, often has difficulty in generating an additional two million jobs each year. Many unemployed people in developing countries find they can gain a livelihood only by cultivating marginal lands such as forests, dry savannahs and hilly terrain, thus aggravating problems of deforestation, desertification and soil erosion[40,41]. Equally important, unemployed people are generally impoverished, meaning they have little means to buy food even when it is available.

Agricultural stress

The seven problems summarized above can be considered together as 'agricultural stress'. Overall at least 2.9 million square km of farmlands, an area almost the size of India, have lost virtually all their productive capacity[6]. In addition, 70,000 to 100,000 square km of farmlands are abandoned each year as a result of degradation, while another 200,000 square km become essentially infertile[9,42]. In addition, there are problems of inadequate agrotechnologies and extension services, plus lack of rural infrastructure such as road networks, marketing systems and credit facilities. All these problems work in compounding accord with population pressures and associated poverty. The worst degradation tends to be in countries with high population densities, notably India, China, Philippines, Indonesia (Java), Vietnam, Thailand, Bangladesh, Pakistan, Ethiopia, Nigeria, and sectors of Andean South America. These countries and areas have an aggregate population today of 3.1 billion, projected to reach 4.3 billion by 2025. While some are advancing economically, several others are still trying to relieve widespread poverty.

As noted, we shall need to feed an extra 2.5 billion people by 2025. Yet during the two decades 1994–2013, at least 1.4 million square km and possibly as much as 2.0 million square km of fertile land are expected to lose much of their agricultural value. If land degradation is not halted, it will more than negate all gains from the opening up of new agricultural lands during the next two decades (at most, 50,000 square km per year)[4]. Indeed there are few areas at all to be opened up for agriculture. Cropland expanded at an average annual rate of 0.8% per year throughout the period 1950–80, but since then the expanse has been contracting at an average annual rate of 0.5%; and primarily because of population growth together with urbanization and industrial spread into farming areas, plus the sheer lack of new lands for agriculture, the amount of per-capita arable land has declined since 1984 by an average of 1.9% per year[4,35].

At the same time, there is the agreed imperative of expanding grain production by 2.0% per year throughout the next three decades. While grain production increased by an average of 4.7% per year from 1950 to 1985, the growth rate dropped to an average of 0.3% per year during 1986–95 (refs 43, 44). It will be difficult indeed to push it back up to 2.0% because of three factors: the shortage of good-quality croplands waiting to be opened up, the progressive loss of existing croplands to urbanization and industrialization, and a suite of intensifying environmental problems. True, the bulk of the grain harvest growth in recent decades has come not from cropland expansion but from yield increases, yield being output per unit of land (including the impact of both biological growth and cropping intensification). In turn, half of the yield increase from the mid-1950s to the mid-1980s came from irrigated lands[45], and as we have seen, the expansion of irrigation has slowed because of lack of suitable additional lands, deterioration of existing lands, and competition for water supplies[46,47]. (By contrast, certain observers, e.g. Alexandratos[13], expect that between half and two-thirds of increase in crop production between 1996 and 2010 will come from irrigated lands.) In addition, there are many other environmental problems overtaking croplands, whether irrigated or not.

On top of these above-mentioned environmental constraints of the present time, two others are waiting in the wings. Like the rest, they are likely to exert progressively increasing impact, and to be mostly irreversible within time horizons of interest to most people alive today.

Ozone-layer depletion and increased UV-B

Depletion of the ozone layer allows additional UV-B radiation to reach the earth's surface, with adverse impact on crop plants on land and phytoplankton-based food chains in the seas. Experiments show that enhanced UV-B cuts crop yields by anywhere from 5% for wheat to 90% for squash, with other sensitive crops in between. Soybean, for instance, a prime source of protein and second in value to corn in the United States, could lose one quarter of its productivity. Others unduly vulnerable include barley, peas and cauliflower[48,49].

As for phytoplankton, being the most abundant type of ocean life in both weight and sheer numbers (one litre of seawater can contain millions of phytoplankton plantlets), no other life form appears to be so susceptible to UV-B radiation. As the phytoplankton disappear, so will zooplankton (microscopic animals that feed on them), then fish, fish-eaters, and so on to the end of the famished line[50]. This does not bode well for marine fisheries, which supply more animal protein than any other source for over one billion people from the developing world.

Extreme weather events and global warming

In recent years there has been a series of weather anomalies. The United States witnessed an east coast 'storm of the century' in March 1993, followed a few months later by record flooding in the Midwest; and at the end of the year, Alaskans within 25 km of the Arctic circle enjoyed 6°C, a heatwave by contrast with the usual –46°C, yet Michigan endured its lowest temperatures in 100 years and Melbourne experienced its coldest Christmas for more than 100 years. In mid-1994 northern India had its highest temperatures in half a century, while several southern parts of the United States experienced a heat wave of 49°C and south-eastern states recorded unprecedented rainfall. In January 1995, parts of California received as much rainfall in a single day as they generally receive in a whole year. Since early 1995 there has been a further list of such freak phenomena.

Indeed the whole of the 1980s and the first half of the 1990s have been characterized by what a leading British climatologist, John Houghton[51], terms 'the frequency and intensity of extremes of weather and climate'. As experience shows already, these sharp weather shifts have a capacity to exert strong adverse impact on agriculture. Apart from the obvious impacts of flooding or drought, the prolonged heat in the late summer of 1995 in the United States' grain belt, also in other grain-basket regions of the European Union, the Ukraine and Russia, lead to withering of the crops, causing a 2% decline in the grain harvest worth 35 million tonnes[37]. This loss would have been enough to make up the diet of nearly 900 million malnourished people.

The recent extreme weather events suggest 'something wrong in the climate works' – and possibly a portent of global warming, which may not approach gradually but in jerks. Global warming models predict more violent weather in many parts of the world as the atmosphere slowly but steadily warms up[52,53]. To cite the Chairman of the Intergovernmental Panel on Climate Change, Bert Bolin[54], 'Most of the damage due to climate change is going to be associated with extreme events, not by the smooth global increase of temperature that we call global warming'. In the long run, global warming offers much scope for climatic vicissitudes: an event with a return period of ten years today could well become a three-year event[55].

Also significant is the prospect of global-warming effects such as shifts in monsoon systems and the arrival of deep and persistent droughts, with all that both would entail for agriculture. Monsoon patterns could be profoundly affected by a temperature rise of only 1°C, in fact to an extent that would dwarf the direct drought effects of such a temperature rise[56] (see ref. 18 also). The area most vulnerable to monsoon dislocations is the Indian sub-continent, projected to feature 1.9 billion people by the year 2025 (49% more than today). India relies upon the monsoon for 70% of its rainfall[57], hence its agriculture is critically dependent upon the stable functioning of the monsoon system. In broader terms, the entire Asia–Pacific region is markedly vulnerable to monsoonal changes if only because it contains well over half the world's population, projected to become a still larger proportion by 2025 (ref. 58).

As for drought and its repercussions, this is more of an 'iffy' issue since the climatic quirks are less well predicted through global-climate models at a regional level than is the case with monsoon patterns. So far as we can discern, droughts with only a 5% frequency today may increase to 50% by 2050 (ref. 59). Areas susceptible to drought include much of northern Mexico, northeastern Brazil, the Mediterranean basin, the Sahel, the southern quarter of Africa, and sectors of middle and tropical latitudes of Asia[60,61]. In the Sahel, for instance, rainfall may decrease even more than in the past three decades[62]. In China, more rain may fall in the north of the country and less in the fertile south where most of the population lives[63,64]. Also likely to be affected by drought are parts of the United States, southern Canada, southern Europe and Australia[65], these being areas important in this context since they produce much of the surplus food that sustains more than 80 developing countries today.

According to some innovative analysis[66], involving drought among a host of other agricultural problems, a plausible global-warming scenario for early next century indicates that there could be a 10% reduction in the world grain harvest on average three times a decade. The 1988 droughts in the United States, Canada and China alone resulted in almost a 5% decline; and a mere 0.5°C increase in temperature could reduce India's wheat crop by 10% (it is likely that there will soon be a rise in temperature of 0.25°C per decade). Given the way the world's grain reserves dwindled almost to nothing as a result of the late 1980s droughts[2,67], it is not unrealistic to suppose that each such grain-harvest shortfall could result in huge numbers of starvation deaths – anywhere, according to the computer-model calculations, from 50 million to 400 million people[66].

Mega-scale famines are held at bay today in part through food shipments from the great grain belt of North America among other food-exporting regions. In a globally-warmed world, this grain belt could become unbuckled to an extent that there would be fewer such shipments as Americans find it harder to feed themselves, let alone other countries. The Great Plains, being a region 2100 km long (north/south) and 800 km wide, already feature weather extremes in the form of severe droughts, heatwaves, cold, winds, storms, floods and tornados. The western portion between the 100th meridian and the Rocky Mountains verges on semi-desert, with a drought already every 20 years or so. These phenomena could well increase markedly through global warming.

Overall assessment of environmental constraints

The environmental constraints listed are certainly constraining. They limit the outlook for agriculture like never before – precisely at a time when we need agriculture to become productive like never before in order to cater to population growth and its demographic dynamics. Certain of the constraints can be somewhat contained provided we recognize them in their full scope. Yet they are largely dismissed at one of the places where they should be most heeded, the Food and Agriculture Organization (FAO), which merely calls for 'continued efforts to maintain and upgrade the world's food production capacity, e.g. investment in agricultural research, extension services, increased efficiency in water use, etc'.[68]. Each of these three issues is headed in the wrong direction, as are problems omitted altogether from the publication cited, notably soil erosion, desertification and deforestation among other forms of land degradation, plus water shortages and emergent superproblems such as global warming. The FAO rationale is that our only guide to the future is the past – even though there is abundant evidence that the future will no longer be a simple extension of the past, and that we must expect a host of basic departures from former patterns and trends.

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