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FEEDING A WORLD OF 10 BILLION PEOPLE: THE MIRACLE AHEAD*

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Introduction

I would like to express my appreciation to Professor Malcolm Elliott, founding Director of the De Montfort University Norman Borlaug Institute for Plant Science Research, Pro-Chancellor Dr John White, Vice-Chancellor Professor Kenneth Barker, and to the University's Board of Governors and faculty for the twin distinctions of naming a research institute in my honor and for awarding an Honorary DSc degree to me.

Professor Elliott has asked me to explore with you the complexities and challenges of feeding a world of 10 billion people, an event that will almost certainly occur during the lifetime of most students present here tonight. To give you some idea of the rate of population explosion we are now experiencing, in 1914, when I was born, there were only about 1.6 billion mouths to feed; today, we number some 5.8 billion.

The invention of agriculture - some 10 000 to 12 000 years ago - heralded the dawn of civilization. It began with rainfed, hand-hoe agriculture, which evolved into animal-powered, scratch-tooled agriculture, and finally into an irrigated agriculture along the Euphrates and Tigris rivers that for the first time allowed humankind to produce food surpluses. This permitted the establishment of permanent settlements and urban societies which, in turn, engendered culture, science and technology. The rise and fall of ancient civilizations in the Middle East and Meso-America were directly tied to agricultural successes and failures, and it behoves us to remember that this axiom still remains valid today.

I am now in my 53rd year of continuous involvement in food production programmes in developing nations. During this period, I have seen much progress in increasing the yields and production of various crops, especially the cereals, in many food-deficit countries. Clearly, the research that backstopped this progress has produced huge returns. Yet, despite more than tripling the world food supply during the past three decades, the so-called "Green Revolution" in cereal production has not solved the problem of chronic undernutrition for hundreds of millions of poverty-stricken people around the world. They are unable, due to unemployment or underemployment, to purchase the food they need, despite its abundance in world markets.

I must also acknowledge that in many of the more productive areas - especially the irrigated areas located in warm climates - there are problems of soil erosion and declining water quality which, if left unchecked, can lead to the permanent loss of prime agricultural land. In most cases, as I will argue later in this presentation, the root cause of this environmental degradation has been mistaken economic policy - not modern, science-based technology.

Poets - and city folk - love to romanticize agriculture, portraying it as some sort of idyllic state of harmony between humankind and nature. How far this is from the truth!

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Since Neolithic man - or most probably woman - domesticated the major crop and animal species some 10 to 12 millennia ago, agriculture has been a struggle between the forces of natural biodiversity and the need to produce food under increasingly intensive production systems. Thanks to advances in science during this century - which is when the population bomb really went off - food production has kept ahead of population growth and, in general, has become more reliable. But with the global population currently increasing by one billion each decade, meeting future food demand is becoming ever-more challenging and worrisome.

Our World Food Supply

In 1994 global food production of all types stood at 4.74 billion metric tons of gross tonnage and 2.45 billion tons of edible dry matter (**Table 1**). Of this total, 99 % was produced on the land - only about 1 % came from the oceans and inland waters, even though 70 percent of the earth's surface is covered with water. Plant products constituted 93 % of the human diet, with about 30 crop species providing most of the world's calories and protein, including eight species of cereals, which collectively accounted for 66 % of the world food supply. Animal products, constituting 7 % of the world's diet, also come indirectly from plants.

Had the world's food supply been distributed evenly, it would have provided an adequate diet (2,350 calories, principally from grain) in 1994 for 6.4 billion people - about 800 million more than the actual population. However, had people in Third World countries attempted to obtain 30 % of their calories from animal products - as in the USA, Canada, or EEC countries - a world population of only 2.6 billion people could have been sustained - less than half of the present world population.

TABLE 1

World Food Production, 1994

	Production (millions of metric tons)			
Commodity	Gross Tonnage	Edible Matter[1]	Dry Protein[1]	Increase, % 1980-90[2]
Cereals	1 950	1 623	162	22
Maize	570	501	52	19
Wheat	528	465	55	22
Rice	535	363	31	35
Barley	161	141	14	7
Sorghum/millet	87	78	7	-7
Roots & Tubers	583	156	10	9
Potato	265	58	6	3
Sweet potato	124	37	2	-7
Cassava	152	56	1	24
Legumes, oil-seeds, oil nuts	387	263	88	48
Sugarcane & sugarbeet[3]	133	133	0	21
Vegetables & melons	486	57	5	32
Fruits	388	53	2	28
Animal products	858	170	75	25
Milk, meat, eggs	760	143	57	21
Fish	98	25	18	29
All Food	4 743	2 456	343	24

[1] At zero moisture content, excluding inedible hulls and shells.

[2] 1979-81 and 1989-91 averages used to calculate changes.

[3] Sugar content only.

Source: 1994 FAO Production Yearbook

These statistics point out two key problems of feeding the world's people. The first is the complex task of producing sufficient quantities of the desired foods to satisfy needs, and to accomplish this Herculean feat in environmentally and economically sustainable ways. The second task, equally or even more daunting, is to distribute food equitably. Poverty is the main impediment to equitable food distribution, which, in turn, is made more severe by rapid population growth.

Projected World Food Demand

During the 1990s, world population will grow by nearly one billion people and then again by another one billion people during the first decade of the 21st Century. A medium projection is for world population to reach 6.2 billion by the year 2000 and about 8.3 billion by 2025, before hopefully stabilizing at about 11 billion toward the end of the 21st Century.

At least in the foreseeable future I believe we will continue to rely on plants -and especially the cereals - to supply virtually all of our increased food demand. Even if current per capita food consumption stays constant, population growth would require that world food production increases by 2.6 billion gross tons - or 57 % - between 1990 and 2025. However, if diets improve among the destitute who live in hunger, estimated to be 1 billion people living mainly in Asia and Africa, world food demand could increase by 100 percent - to above 9 billion gross tons - over this 35-year period.

Using the population growth rates shown above, and expected changes in per capita cereal demand, I have come up with the following cereal production projections through the year 2025 (**Table 2**), and the requisite yield increases needed if we assume that virtually all of the increased production will come from existing farmlands.

Raising Yield Levels on Existing Agricultural Lands

While somewhat of an oversimplifying assumption, since there are still some vast areas to bring into production in South America and Africa, much of the projected increases in food supply will have to come from land

TABLE 2

Current and Projected World Cereal Production and Demand (millions of tons) and Yield Requirements

	Actual	Projected		Yield (t/ha)		
	Production	Demand		Actual	Required	
	1990	2000	2025	1990	2000	2025
Wheat	600	740	1 200	2.1	2.8	4.4
Rice	520	640	1 030	2.4	3.1	5.3
Maize	480	620	1 070	3.7	4.1	5.8
Barley	180	220	350	2.3	2.7	4.1
Sorghum/millet	85	110	180	1.5	1.8	2.6
All Cereals	1 970	2 450	3 970	2.5	2.9	4.5

Source: FAO Production Yearbook and author's estimates

currently in production. To meet the projected food demands, therefore, the average yield of all cereals must be increased by 80 % between 1990 and the year 2025. Fortunately, there are many improved agricultural technologies - already available or well-advanced in the research pipeline - that can be employed in future years to raise crop yields, especially in the low-income food deficit countries where most of the hunger and poverty exist.

Yields can still be increased by 50-100 % in much of the Indian sub-Continent, Latin America, the former USSR and Eastern Europe, and by 100-200 % in much of sub-Saharan Africa, providing political stability is maintained, bureaucracies that destroys entrepreneurial initiative are reigned in, and their researchers and extension workers devote more energy to putting science and technology to work at the farm level.

Yield gains in China and industrialized North America and Western Europe will be much harder to achieve, since they are already at very high levels. Still, I am hopeful that scientific breakthroughs - particularly from genetic engineering, will permit another 50 % increase in yields over the next 35 years.

The most frightening prospect of food insecurity is found in sub-Saharan Africa, where the number of chronically undernourished could rise to several hundred million people if current trends of declining *per capita* production are not reversed. Sub-Saharan Africa's increasing population pressures and extreme poverty: the presence of many human diseases, e.g., malaria, tuberculosis, river blindness, trypanosomiasis, guinea worm, AIDS, etc.; poor soils and uncertain rainfall; changing ownership patterns for land and cattle, inadequacies of education and public health systems, poorly developed physical infrastructure, weaknesses in research and technology delivery systems will all make the task of agricultural development very difficult.

Despite these formidable challenges, many of the elements that worked in Asia and Latin America during the 1960s and 1970s will also work to bring a Green Revolution to sub-Saharan Africa. An effective system to deliver modern inputs - seeds, fertilizers, crop protection chemicals - and to market output must be established. If this is done, Africa can make great strides toward improving the nutritional and economic well-being of the downtrodden African farmers, who constitute more than 70 percent of the population in most countries.

Since 1986, I have been involved in food crop production technology transfer projects in sub-Saharan Africa, spearheaded by the Nippon Foundation and its former Chairman, the late Mr. Ryoichi Sasakawa, and enthusiastically supported by former U.S. President Jimmy Carter. Our joint programme is known as Sasakawa-Global 2000, and currently operates in 12 African countries: Ghana, Benin, Togo, Nigeria, Tanzania, Ethiopia, and most recently, in Mozambique, Guinea, Burkina Faso, Mali, Uganda, and Eritrea. Previously, we also operated similar projects in Sudan and Zambia.

The heart of these projects are dynamic field testing and demonstration programmes for major food crops. Although improved technology - developed by national and international research organizations - had been available for more than a decade, for various reasons it was not being adequately disseminated among farmers. Working in concert with national extension services during the past 10 years, more than 600 000 demonstration plots (usually from 0.25 to 0.5 ha) have been grown by small-scale farmers. Most of these plots have been concerned with demonstrating improved basic food crops production technology for maize, sorghum, wheat, cassava, and grain legumes. The packages of recommended production technology include: (1) the use of the best available commercial varieties or hybrids, (2) proper land preparation and seeding dates and rates to achieve good stand establishment, (3) proper application of the appropriate fertilizers, including green manure and animal dung, when available, (4) timely weed control and, when needed, crop protection chemicals, (5) moisture conservation and/or better water use, if under irrigation.

Virtually without exception, the yields obtained by participating farmers on these demonstration plots are two to three times higher - and occasionally four times higher - than the control plots employing traditional methods. Only rarely have plot yields failed to double those of the controls. Hundreds of field days attended by tens of thousands of farmers have been organized to demonstrate and explain the components of the production package. In project areas, farmers' enthusiasm is high and political leaders are now taking much interest in the programme. From our experiences over the past decade, I am convinced that if there is political stability and if effective input supply and output marketing systems are developed (including a viable agricultural credit system) the nations of sub-Saharan Africa can make great strides in improving the nutritional and economic well-being of their desperately poor populations.

Bringing New Lands into Production: the Remaining Frontiers

Most of the opportunities for opening new agricultural land to cultivation have already been exploited (**Table 3**). This is certainly true for densely populated Asia and Europe. Only in sub-Saharan Africa and South America do large unexploited tracts exist, and only some of this land should eventually

TABLE 3

Potential Cropland in the Less Developed Countries

Million ha	Africa	West Asia	S/SE Asia	East Asia	South America	Central America	Total
Potentially Cultivated	789	48	297	127	819	75	2 155
Presently Cultivated	168	69	274	113	124	36	784
Uncultivated	621	0	23	14	695	39	1 392
% of region	79	0	8	11	85	52	N.A
% all regions	29	0	1	0.5	32	2	65

Source: Calculated from Buringh and Dudal (1987) Table 2.6, p. 22, World Bank

come into agricultural production. But in populous Asia, home to half of the world's people, there is very little uncultivated land left to bring under the plough. Apparently in West Asia there are already some 21 million ha being cultivated that should not be. Most likely, such lands are either so arid or, because of topography, so vulnerable to erosion that they should be removed from cultivation.

The vast acid-soils areas found in the Brazilian ***cerrado*** and ***llanos*** of Colombia and Venezuela, central and southern Africa, and in Indonesia are among the last major land frontiers. Historically, bringing these unexploited potentially arable lands into agricultural production posed what were thought to be insurmountable challenges. But thanks to the determination of interdisciplinary teams in Brazil and international research centres, the prospect of making many acid soil savanna areas into productive agricultural areas has become a viable reality.

Let's look briefly at the Brazilian ***cerrado***. The central block, with 175 million ha in one contiguous area, forms the bulk of the savanna lands. Approximately 112 million ha of this block is considered potentially arable. Most of the remainder has potential value for forest plantations and improved pastures for animal production. The soils of this area are mostly various types of deep loam to clay-loam latosols (oxisols, ultisols), with good physical properties, but highly leached of nutrients by Mother Nature in geologic time, long before humankind appeared on the planet. These soils are strongly acidic, have toxic levels of soluble aluminum, with most of the phosphate fixed and unavailable.

In pre-colonial times, the area was sparsely inhabited by a number of Amerindian tribes dependent on a culture based on hunting and gathering of wild plants. During the colonial period, and continuing from Independence up until about 35 years ago, the ***cerrado*** was considered to be essentially worthless for agriculture (except for the strips of alluvial soils along the margins of streams, which were less acidic and where there had been an accumulation of nutrients). The natural savanna/brush flora of poor digestibility and nutritive quality - resulting in low carrying capacity - was utilized for extensive cattle production.

Through a slow painful process over the past 50 years, involving some outstanding scientists, bits and pieces of research information and new types of crop varieties have been assembled; only during the past 20 years have these "pieces" been put together into viable technologies which are now being applied by pioneering farmers. By the end of the 1980s, Brazil's national research corporation, EMBRAPA, and several international agricultural research centres (especially CIMMYT and CIAT), had developed a third generation of crop varieties combining tolerance to aluminum toxicity with high yield, better resistance to major diseases, and better agronomic type. These included rice, maize, soybeans, wheat and several species of pasture grasses, including the panicums, pangola, and brachiaria. Triticale is an interesting man-made cereal that has a very high level of aluminum tolerance, although it has not been utilized much yet, either for forage or for grain production.

Improved crop management systems were also developed, built around liming, fertilizing to restore nutrients, crop rotations and minimum-tillage that leave crop residues on the surface to facilitate moisture penetration and reduce run off and erosion. However, with conservation tillage coming into widespread use, it will be absolutely necessary to work out better crop rotations to minimize the foliar disease infections that result from innocula in the plant crop residues left on the surface from previous seasons.

In 1990, roughly 10 million hectares of rainfed crops were grown in the *cerrado*, with an average yield of 2 t/ha and a total production of 20 million tons (**Table 4**). The irrigated area is still relatively small with an average yield of 3 t/ha and a total production of 900 000 tons. There are also 35 million hectares of improved pasture supporting an annual meat production of 1.7 million tons.

TABLE 4

Production of Cereals and Meat in the Cerrado in 1990

Land Use	Area (10^6 ha)	Productivity (t/ha/year)	Production (10^6 T)
Crops (rainfed)	10.0	2.0	20.0
Crops (irrigated)	0.3	3.0	0.9
Meat (pasture)	35.0	0.05	1.7
Total	45.3		22.6

Source: Prospects for the Rational Use of the Brazilian Cerrado for Food Production by Dr. Jamil Macedo, CPAC, EMBRAPA 1995

The *cerrado* area using improved technology has expanded greatly over the past five years. If it continues to spread, farmers could attain 3.2 t/ha in rainfed crops and 64 million tons of production. If the irrigation potential is developed, which can add another 30 million tons of food production, it is likely that by 2010 food production in the *cerrado* will have increased to 98 million tons- or a four-fold increase over 1990 (**Table 5**).

TABLE 5

Potential Food Production If Available Technology Is Adopted on *Cerrado* Area Already in Production

Land Use	Area (10^6 ha)	Productivity (t/ha year)	Production (10^6 T)
Crops (rainfed)	10.0	2.0	20.0
Crops (irrigated)	0.3	3.0	0.9
Meat (pasture)	35.0	0.05	1.7
Total	45.3		22.6

Source: Prospects for the Rational Use of the Brazilian *Cerrado* for Food Production by Dr. Jamil Macedo, CPAC, EMBRAPA, 1995.

What Can We Expect from Biotechnology?

Over the past seven decades, conventional breeding has produced a vast number of varieties and hybrids that have contributed immensely to higher grain yield, stability of harvests, and farm income. Surprisingly, there has been no major increase in the maximum genetic yield potential of the high-yielding semi-dwarf wheat and rice varieties being grown commercially, since those that served to launch the so-called Green Revolution of the 1960s and 1970s. There have been, however, important improvements in resistance to diseases and insects, and in tolerance to a range of abiotic stresses, especially soil toxicities. But we must also find new and appropriate technology to raise genetic yield levels to higher levels, if we are to cope with the food production challenges before us. One possible breakthrough may be the New Plant Type rice developed by the International Rice Research Institute and now being improved for grain filling, with research support, using genetic engineering techniques, from the Borlaug Institute at De Montfort University.

I am now convinced that what began as a biotechnology bandwagon some 15 years ago has developed some invaluable new scientific methodologies and products which need active financial and organizational support to bring them to fruition in food and fibre production systems. So far, biotechnology has had the greatest impact in medicine and public health. However, there are a number of fascinating developments that are approaching commercial applications in agriculture. In animal biotechnology, we have Bovine somatatropin (BST) now widely used to increase milk production, and Porcine somatatropin (PST) waiting in the wings for approval.

Transgenic varieties and hybrids of cotton, maize and potatoes, containing genes from ***Bacillus thuringiensis***, which effectively control a number of serious insect pests, are now being successfully introduced commercially in the United States. The use of such varieties will greatly reduce the need for insecticide sprays and dusts. Considerable progress also has been made in the development of transgenic plants of cotton, maize, oilseed rape, soybeans, sugar beet, and wheat, with tolerance to a number of herbicides. This can lead to a reduction in herbicide use by much more specific dosages and interventions.

The development of transgenic plants for the potential control of viral and fungal diseases is not nearly as far developed. Nevertheless, there are some very promising examples of specific virus coat protein genes in transgenic varieties of potatoes and rice that confer considerable protection. Different promising disease resistant genes are being incorporated into other transgenic crop species.

Until recently, it has been generally assumed that increases in genetic yield potential in plants (and animals) are controlled by a large number of genes, each with small additive effects. However, the work of recent years shows that there may also be a few genes that are sorts of "master genes" that affect the interaction, either directly or indirectly, of several physiological processes that influence yield. For example, BST and PST are apparently such "master genes." They not only affect the total production of milk or meat, but also the efficiency of production per unit of feed intake. It now appears that the dwarfing genes, *Rht1* and *Rht2*, used to develop the high-yielding Mexican wheats that launched the Green Revolution, also acted as "master genes," for at the same time that they reduced plant height and improved standability, they also increased tillering and the number of fertile florets and the number of grains per spike (harvest index). Biotechnology may be a new window through which to search for new "master genes" for high yield potential by eliminating the confounding effects of other genes.

Can Agricultural Science Stay Ahead of World Population?

So far, agricultural research and production advances - and the efforts of the world's farmers - have kept food production ahead of aggregate world population changes. However, there can be no lasting solution to the world food/hunger/poverty problem until a more reasonable balance is struck between food production/distribution and human population growth. The efforts of those on the food-production front are, at best, a holding operation which can permit others on the educational, medical, family planning, and political fronts to launch an effective, sustainable, and humane attack to tame the population monster.

There is a crying need today for creative pragmatism in research and extension organizations in many parts of the developing world. In particular, we need more venturesome young scientists who are willing to dedicate their lives to helping to solve the production problems facing several billion small-scale farmers. In seeking to push forward the frontiers of scientific knowledge, some researchers often lose sight of the most pressing concerns of farmers and cease to develop products that extension workers can promote successfully. For the Third World, impact on farmers' fields should be the primary measure by which to judge the value of this research work, rather than by a flood of publications that often serve to enhance the position of the scientist but do little to alleviate hunger.

A growing number of agricultural scientists, including Professor Elliott of this university, anticipate great benefits from biotechnology in meeting our future food and fibre needs. Since most of this research is being done by the private sector, which patents its inventions, those of us concerned with agricultural policy must face up to a potentially serious conundrum. Most of those being born into this world are among the abject poor, most of whom live in rural areas of the developing world and depend on low-yielding agricultural production systems to eke out a meager existence. How will these resource-poor farmers be able to afford the products of biotechnology research? What will be the position of these trans-national agribusinesses towards this enormous section of humanity that still lives largely outside the commercial market economy? This issue goes far beyond economics; it is also a matter for deep ethical consideration. Fundamentally, the issue is whether small-scale farmers of the developing world also have a right to share in the benefits of biotechnology. If the answer is yes, then what is the role of international and national governments to ensure that this right is met? I believe we must give this matter serious thought.

Standing up to the Anti-Science Crowd

Science and technology are under growing attack in the affluent nations where misinformed environmentalists claim that the consumer is being poisoned out of existence by the current high-yielding systems of agricultural production. While I contend this isn't so, I ask myself how it is that so many people believe the contrary? First, there seems to be a growing fear of science, *per se*, as the pace of technological change increases. The late British physicist and philosopher-writer, C P Snow first wrote about the split between scientists and humanists in his little book, **The Two Cultures**, which was published in 1962.. It wasn't that the two groups necessarily disliked each other, rather that they just didn't know how to talk to each other. The rift has continued to grow since then. The breaking of the atom and the prospect of a nuclear holocaust added to people's fear, and drove a bigger wedge between the scientist and the layman. The world was becoming increasingly unnatural, and science, technology and industry were seen as the culprits. Rachel Carson's ***Silent Spring*** - which reported that poisons were everywhere, killing the birds first and then us - struck a very sensitive nerve.

Of course, this perception was not totally unfounded As Bittman's little book (**The Good Old Days: They Were Terrible**) about environmental quality in America (and in the United Kingdom and other industrialized nations) in the late 19^{th} and early 20^{th} century, graphically pointed out, we were poisoning ourselves. By the mid 20^{th} century air and water quality had been seriously damaged through wasteful industrial production systems that pushed effluents often literally into "our own backyards." Over the past 30 years, we all owe a debt of gratitude to the environmental movement in the industrialized nations, which has led to legislation to improve air and water quality, protect wildlife, control the disposal of toxic wastes, protect the soils, and reduce the loss of biodiversity In almost every environmental category far more progress is being made than most commentators in the media are willing to admit. Why? I believe that it's because "apocalypse sells." Sadly, all too many scientists, many of whom should (and do) know better, have jumped on the environmental bandwagon in search of research funds. When scientists align themselves with anti-science political movements, like Rifkin's anti-biotechnology crowd, what are we to think? When scientists lend their names and credibility to unscientific propositions, what are we to think? Is it any wonder that science is losing its constituency? We must be on guard against politically opportunistic, charlatan scientists like T.D. Lysenko, whose pseudo-science in agriculture and vicious persecution of anyone who disagreed with him, contributed greatly to the collapse of the former USSR.

Recently a science writer named Gregg Easterbrook wrote an article about me in the U.S magazine, ***Atlantic Monthly***. While I have never met him, I was intrigued by the brief biographical sketch provided about him, which labeled him an "eco-realist." I was prompted to buy his new book, ***A Moment on the Earth***, published by Penguin in 1996, which I am now reading. It's a fascinating and provocative book, based upon a massive amount of research. Following are some of his conclusions, and I quote:

1) If the worthy inclinations of environmentalism are to be transformed from an ephemeral late-twentieth-century political fashion to a lasting component of human thought, the ecological impulse must become grounded in rationality. Logic, not sentiment, best serves the interests of nature.
2) In the Western world the Age of Pollution is nearly over. Almost all of the pollution issues will be solved within the lifetimes of [this audience]. Aside from weapons, technology is not growing more dangerous and wasteful but cleaner and more resource-efficient. Clean technology will be the successor to high technology.
3) As positive as trends are in the First World, they are negative in the Third One reason why the West must shake off its instant-doomsday thinking about the United States and Western Europe is so that resources can be diverted to ecological protection in the developing world.
4) People may not sit above animals and plants in any metaphysical sense, but clearly are superior in their place in the natural order. Either humanity was created by a higher power, or humanity rose to its position through purely natural processes: in [either] case it is absurd for environmental dogma to consider the human role in nature to be bad.
5) In principle, the human population is no enemy of nature. Someday human population may be many times larger than at present, without ecological harm. But the world of the present has more people than current social institutions and technological knowledge can support at an adequate material standard. Thus short-term global population stabilization is desperately required.
6) Nature is not ending, nor is human damage to the environment "unprecedented." Nature has repelled forces of a magnitude many times greater than the worst human malfeasance. Nature still rules much more of the Earth than does genus ***Homo***. To people the distinction between artificial and natural means a great deal. To nature, it means almost nothing at all.
7) The fundamental force of nature is not amoral struggle between hunter and hunted. Most living things center their existence on cooperation and coexistence, the sort of behavior women and men should emulate.
8) Nature, limited by spontaneous interactions among elements randomly disturbed, may have an upper-bound limit on its potential to foster life and evolve. Yet nature appears to enjoy fostering life and evolving. So perhaps nature hopes to acquire new sets of abilities, such as action by design. Therefore maybe nature needs us.

Certainly, we must be environmentally responsible in our efforts to produce ever-greater quantities of food to feed our unrelenting population. But we must also face up to the fact that we cannot turn back the clock and use technologies that were adequate for a much smaller world population.

In sharp contrast to the rich countries, where most environmental problems have been urban, industrial, and a consequence of high incomes, the critical environmental problems in most of the low-income developing countries remain rural, agricultural, and poverty-based. More than half of the world's very poor live on lands that are environmentally fragile, and rely on natural resources over which they have little legal control. Land-hungry farmers resort to cultivating unsuitable areas, such as erosion-prone hillsides, semiarid areas where soil degradation is rapid, and tropical forests, where crop yields on cleared fields drop sharply after just a few years.

I often ask the critics of modern agricultural technology what the world would have been like without the technological advances that have occurred. For those whose main concern is protecting the "environment," let's look at the positive impact of science-based technology on the land. Had 1961 yields still prevailed today, three times more land in China and the USA and two times more land in India would be needed to equal 1992 cereal production (Figures 1 and 2). Obviously, such a surplus of land of the same quality is not available, and especially not in populous China and India.

I have calculated that if the United States attempted to produce the 1990 harvest of the 17 most important crops with the technology and yields that prevailed in 1940 it would have required an additional 188 million hectares of land of similar quantity. This theoretically could have been achieved either by plowing up 73 % of the nation's permanent pastures and rangelands, or by converting 61 % of the forest and woodland area to cropland. In actuality, since many of these lands are of much lower productive potential than the land now under crops, it really would have been necessary to convert an even larger portion of the rangelands or forests and woodlands to crop production. Had this been done, imagine the additional havoc from wind and water erosion, the obliteration of forests, and extinction of wildlife habitats, and the enormous reduction of outdoor recreational opportunities.

In his writings, Professor Robert Paarlberg, who teaches at Wellesley College and Harvard University in the United States, has sounded the alarm about the consequences of the debilitating debate between agriculturalists and environmentalists about what constitutes so-called "sustainable agriculture" in the Third World. This debate has confused - if not paralyzed - policy makers in the international donor community who, afraid of antagonizing powerful environmental lobbying groups, have turned away from supporting science-based agricultural modernization projects which are so urgently needed in sub-Saharan Africa and parts of Latin America and Asia. The result has been increasing misery in smallholder agriculture and accelerating environmental degradation.

This policy deadlock must be broken. In doing so, we cannot lose sight of the enormous job before us to feed 10 billion people, most of whom will be born into abject poverty in low-income, food-deficit nations. And we must also recognize the vastly different circumstances faced by farmers in different parts of the Third World, and assume different policy postures. For example, in Europe or the US Corn Belt, the application of 300-400 kg of fertilizer nutrients per hectare of arable land can cause some environmental problems. But surely, increasing fertilizer use on food crops in sub-Saharan Africa from around 5 kg of nutrients per hectare of arable land to 30 to 40 kg is not an environmental problem but rather a central component of Africa's environmental solution.

Closing Comments

Twenty-seven years ago, in my acceptance speech for the Nobel Peace Prize, I said that the Green Revolution had won a temporary success in man's war against hunger, which if fully implemented, could provide sufficient food for humankind through to the end of the 20th century. But I warned that unless the frightening power of human reproduction was curbed, the success of the Green Revolution would only be ephemeral.

I now say that the world has the technology - either available or well-advanced in the research pipeline - to feed a population of 10 billion people. The more pertinent question today is whether farmers and ranchers will be permitted to use this new technology. Extremists in the environmental movement from the rich nations seem to be doing everything they can to stop scientific progress in its tracks. Small, but vociferous and highly effective and well-funded, anti-science and technology groups are slowing the application of new technology, whether it be developed from biotechnology or more conventional methods of agricultural science. I am particularly alarmed by those who seek to deny small-scale farmers of the Third World -and especially those in sub-Saharan Africa - access to the improved seeds, fertilizers, and crop protection chemicals that have allowed the affluent nations the luxury of plentiful and inexpensive foodstuffs which, in turn, has accelerated their economic development. While the affluent nations can certainly afford to pay more for food produced by the so-called "organic" methods, the one billion chronically undernourished people of the low-income, food-deficit nations cannot. As Richard Leakey likes to remind his environmental supporters, "you have to have at least one square meal a day to be a conservationist or an environmentalist."

At the closure of the Earth Summit in 1992 at Rio de Janeiro, 425 members of the scientific and intellectual community presented to the Heads of State and Government what is now being called the Heidelberg Appeal. Since then, some 3 000 scientists have signed this document, including myself. Permit me to quote the last paragraph of the Appeal:

"The greatest evils which stalk our Earth are ignorance and oppression, and not science, technology, and industry, whose instruments, when adequately managed, are indispensable tools of a future shaped by Humanity, by itself and for itself, in overcoming major problems like overpopulation, starvation, and worldwide diseases."

Agricultural scientists and policy makers have a moral obligation to warn the political, educational, and religious leaders about the magnitude and seriousness of the arable land, food and population problems that lie ahead. If we fail to do so in a forthright manner, we will be negligent in our duty and inadvertently will be contributing to the pending chaos of incalculable millions of deaths by starvation. The problem will not vanish by itself; to continue to ignore it will make a future solution more difficult to achieve.