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2011-05

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Biotechnology in Forestry and Agriculture: Economic Perspectives

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ABSTRACT

Economists are rarely brought into the interdisciplinary research until the biophysical scientists have developed their models, made their measurements or completed their research task. The research economist is then brought in to do what amounts to a consulting task – provide some numbers that indicate impacts on the economy and employment. In this paper, I begin by illustrating cases from forestry where this leads to erroneous and costly policy outcomes. However, the main objective of this paper is to examine the role of genetic engineering in forestry and agriculture. In forestry, planting of genetically-modified (GM) tree species is nearly non-existent, with the exception of hybrid poplar that is used to produce pulp or fuel. However, as explored here, there is a role for GM tree varieties, particularly ones that are resistant to such things as the mountain pine beetle which has adversely impacted forests in British Columbia.

I also examine the role of GM crops in addressing concerns about future food scarcity. As discussed here, there are various factors that suggest the world might encounter future scarcity. These include on the demand side a growing and wealthier global population, and greater demand for energy crops. On the supply side, there are fewer opportunities to expand farmland at the extensive margin, a decline in the rate of increase in productivity, limits to the amounts of inputs that can be applied at the intensive margin, and the closing of the gap between actual and potential crop yield. GM crops are one way to circumvent the potential shortages. However, there are many obstacles that need to be overcome before farmers globally can take advantage of transgenic research, including most importantly barriers put up by the European Union and various environmental NGOs on the grounds of the precautionary principle. These are discussed in some detail.

Key Words: precautionary principle; economics of genetically-modified organisms; agriculture and forestry; mountain pine beetle

JEL Categories: O13, O32, Q11, Q18, Q23

Biotechnology in Forestry and Agriculture: Economic Perspectives

Remarks Prepared for the British Columbia Genomics, Society & Ethics Advisory Committee (GSEAC) Retreat, Vancouver, June 9, 2011

INTRODUCTION

I must admit to some trepidation in giving a talk to a group of people who know much more about genomic research, and possibly even the economic aspects of such research, than I might ever know. For most of my career, I have worked on applied economics and management research in the fields of agriculture, forestry, wildlife and, most recently, renewable energy. I would characterize much of my work as falling in the broad area of bioeconomics. By this I mean that I build models that optimize some economic objective – such as minimize costs, maximize net returns or, more generally, maximize economic wellbeing (where non-market values of ecosystems, wildlife, etc. are included in wellbeing) – subject to political, economic and, especially, biological and technical constraints. It is probably with regards to the biological and technical constraints that one might see a fit between economics and genomic research. At least, this is how I practice economics, although, I must admit, there are times I do not consider myself as an economist but more as an eclectic researcher 'solving' or, more appropriately, 'developing insights into' real world problems.

It is with some frustration, therefore, that I often find my services called upon ex post – after the physical and biological scientists have done their thing. On this score, other economists will agree. What scientists forget is that economic incentives abound – they are ubiquitous. Thus, unless the research question is a very narrow one, economists often need to be brought on board early in the research process. Our task is not one of calculating the employment, regional income and/or government revenue impacts of some discovery after the other scientists have discovered that it is environmentally better to replace process A with process B. Now, there are some economists that do those things, but they are increasingly known as consultants.

Let me begin in the next section by giving you some illustrations from forestry. In doing so, I focus on issues of importance to British Columbia because, in some ways, BC is unique in global terms. Not only is the province a major player in global wood product markets, but it relies to a greater extent than most other jurisdictions on harvests of timber that are classified as old growth, not all of which is original. That is, while BC's wood products sector is modern, its forest management sector remains 'backwoods' in terms of tenure arrangements and investment. I then want to turn to agriculture, the challenge of feeding a growing global population, and implications for genome research. In that discussion, forests will again show up, but as a competitor to crop production. Finally, I want to consider some economic incentives related to property rights, genome research and the role of government.

GENOMICS: AN APPLICATION TO BRITISH COLUMBIA FORESTRY

Let me begin with a couple of examples. First, British Columbia's Forest and Range Practices Act (2004), which replaced the Forest Practices Code (1994), requires forest companies to plant trees after harvesting a site and not allowing them to log adjacent sites until trees are 'free-to-grow' – perhaps some 8 meters tall. The incentive for companies is to plant trees that grow very quickly early on – that reach the free to grow stage as quickly as possible. Species or varieties that might take a little longer to reach the free-to-grow state are eschewed even where such species are healthier, more productive and capable of being harvested at an earlier age than the species/varieties actually planted. Even private companies' research into genetic modification and/or breeding of trees is skewed as a result of a simple rule designed originally to implement reforestation and adjacency constraints to protect forest ecosystems. Thus, rules to protect forest ecosystems could potentially end up harming the environment (although I am not saying they will).

This is known in economics as the principal-agent problem. One of my PhD students is currently examining a variant of this problem in the context of the mountain pine beetle. The provincial government as the forest owner is the principal; the forest companies are the agents because they carry out the 'commands' of the principal. The government wants companies to harvest MPB killed and damaged trees and ones most susceptible to MPB in the near future. The government does not want the companies to harvest spruce, although this is unavoidable because sites are clearcut.[1] The government simply desires that the companies avoid sites consisting principally of spruce, sites that consist of healthy young pine (perhaps mixed with spruce), and/or harvest only the dead, damaged or susceptible pine trees on mixed stands.

[1] Although controversial at times, clear felling of sites is still a preferred management technique and is justified on the basis of costs, human safety, and even biological and ecosystem values.

What happened? The government changed the system of stumpage rates to encourage firms to harvest affected pine while leaving spruce and younger pine for the future. What they found was that the proportion of spruce in the harvest mix actually increased! The system was incentive incompatible. It encouraged firms to take more spruce to cover their costs in harvesting affected pine. The government failed to monitor the way the incentives were working on the ground because they failed to understand how things worked on the ground. The agent had information that was unavailable to the principal.

My second example also relates to the mountain pine beetle. In this case, basic economic thinking is tossed out in favor of technological solutions. The provincial government has a double problem – an increasing area of beetle killed forest and a need to increase generation of electricity without using fossil fuels (a legislated problem). Almost everyone would concur that the simple solution is to burn the beetle-killed biomass to generate electricity. After all, the wood is free and will decay (or burn) and release CO_2 if left unharvested. Where is the error in this thinking? The wood is free!

Engineers at the University of Alberta argue that it was economically feasible to use beetle-damaged wood to generate electricity (Kumar 2009; Kumar et al. 2008). They point out that, along with beetle-killed commercial timber, harvest residuals left at roadside to decay plus sawmill residues could profitably be used to support a power plant. Partly as a result of this research, BC Hydro proceeded to issue a call for industry to build the required power plant, guaranteeing prices of electricity for the life of the power plant. There were no takers. BC Hydro and the government looked for a simple technological fix, but failed to account for economic incentives.

The engineering analysis of free beetle-killed wood for energy assumed that the observed costs of supplying wood to a sawmill at the same location as a yet-to-be constructed power plant was representative of the supply situation that the power plant would face. But the engineers made two critical errors (Stennes and MacBeath 2006; Stennes et al. 2010; Niquidet et al. 2011). First, their costs of harvesting trees, bringing the fiber to roadside and then hauling the wood to the power plant represented average costs based on observations for sawmills in the Quesnel and Williams Lake timber supply areas (TSAs). The timber that had supplied those sawmills came from nearby sites. A power plant would need to obtain fiber from much more distant sites, sites which had been impacted to a much greater degree than those located much closer to Quesnel and Williams Lake. (The nearby sites were stocked with younger timber that is less susceptible to MPB.) A new power plant faces rising marginal costs as fiber needs to be hauled from increasingly more distant and less accessible sites. The power plant could function for a couple of years on nearby fiber, but after that the expense of hauling wood worked against the production of electricity from beetle killed timber (Niquidet et al. 2011). The subsidies offered by BC Hydro were too small. Further, carbon dioxide emissions associated with the project were too great to make it a worthwhile substitute for other investments that reduce CO_2 emissions and/or generate electricity.

Second, the engineers forget that wood fiber, even fiber from beetle-damaged timber, is not a free good. People who advocate the use of fuel wood from BC forests forget one important fact: there is competition for wood fiber, particularly sawmill residues. There already exists a 60 MW wood-burning power plant at Williams Lake, and many sawmills and pulp mills generate electricity from mill wastes (sawmill residues, black liquor). Wood pellet capacity has increased in the BC interior, mainly in response to the rising demand for renewable energy by electricity producers in Scandinavia, Ontario and elsewhere as a result of climate policies. Wood pellets can be used almost without processing in coal-fired power plants. Any investment that increases the demand for wood fiber, a power plant, pellet facility, pulp mill or OSB facility, will increase the price of fiber. As the price of fiber increases, the marginal user will drop out of the market, and that is most likely the energy producers (Stennes et al. 2010).

Interestingly, the price of residual fiber falls with increases in sawmilling capacity. In British Columbia, without sawmills, pulp producers, OSB manufacturers and others will not exist. Indeed, the only wood-burning thermal power plants that can survive are located near a source of fast-growing trees that can feed a plant for 40 or more years. Only hybrid, genetically-modified poplar trees fit the bill. Even then, it is questionable whether power production from wood reduces overall greenhouse gas emissions, because large amounts of fertilizer are required and timber must still be harvested over a large area. Yet, wood burning would not even be considered without GM tree species.

There is another role for GM tree stock. The Forest and Range Practices Act requires forest companies to plant the best-available tree stock after harvesting – currently this implies higher-quality varieties that are the outcome of traditional plant breeding programs. Because it is required in legislation, re-planting of harvested sites with improved stock that results in higher rates of carbon uptake is not an activity eligible for carbon credits under the Kyoto Process of the United Nations' Framework Convention on Climate Change (UN FCCC). However, there is a new program aimed at developing countries but probably applicable to the BC situation that could save the day. Increasingly, international negotiations allow activities that Reduce Emissions from Deforestation and forest Degradation (REDD) to earn certified emission reduction (CER) credits. Indeed, as a result of negotiations at Cancun in December 2010, the narrow role of REDD has been expanded to include sustainable management of forests, forest conservation and the enhancement of forest carbon stocks, collectively known as REDD+. Increasingly climate negotiators appear willing to accept REDD+ activities as potential emissions offset credits.

Under REDD+, it may be possible for BC to earn CERs by enhanced silviculture related to natural disturbance. Some 14.8 percent of the province's land base is officially protected, while 42 percent of forestland (22.6 million ha) has trees that are 140 years or older (BC Ministry of Forests, Mines and Lands 2010). Thus, there are vast areas of forestland that are protected or inaccessible, unaffected by commercial timber operations. Yet, these forestlands have been impacted by wind throw (mainly on the Coast) and by wildfire and the mountain pine beetle (mainly in the Interior). As a result, large areas of forestland are left to regenerate naturally and often end up in a not sufficiently restocked (NSR) state. These areas are not the responsibility of private forest companies and, since the benefits of restocking such areas are small, the government has no incentive to reforest or infill sites affected by natural disturbance. This is because these sites are unlikely to be harvested in the foreseeable future. Economic analyses of naturally disturbed sites in protected, more remote or inaccessible regions confirms that silvicultural activities to address the situation are not worth undertaking.[2]

The economic analyses of restoring naturally disturbed sites neglected the benefits of carbon sequestration. If naturally disturbed sites are replanted to improved tree stock as opposed to being allowed to regenerate on their own with natural stock, there could be a potentially large increase in the amount of carbon sequestered. Not only will artificial regeneration lead to an earlier establishment of growing stock, but, because higher-quality trees would be planted, the total amount of biomass grown on the site could be significantly enhanced. Indeed, by planting improved stock, the site index for the same tree species can be increased from, say, 20 m on a 50-year basis to perhaps 28 m, or by 40%.[3] This might translate into an increase in the amount of carbon stored on a site of perhaps 30% compared to allowing natural regeneration with 'non-improved' trees. If the carbon credits created in this fashion are subsequently sold, this constitutes one benefit (others include non-market values related to, e.g., ecosystem services such as wildlife habitat) to set against the costs of such a program. The point is that, without faster-growing varieties created as a result of human intervention, it is not possible to store additional carbon in what would otherwise be unmanaged forestlands.

To date, there has been little in the way of genetically-engineered trees, with the exception of hybrid poplar. The reason has to do with the time required for trees to grow – the time required is simply too long, except for hybrid poplar, to provide the payoffs needed by private genomic firms. Perhaps there is room for public research on transgenic tree species, for example, to develop a pine that is more resistant to attacks by mountain pine beetle. Likewise, other tree species might be genetically modified to ward off spruce budworm and other diseases and pests. Carbon uptake could well be a payoff in these instances.

FEEDING THE GLOBE: FOOD SECURITY AND AGRO-BIOTECHNOLOGY

I began an academic career at the University of Saskatchewan in the Department of Agricultural Economics working on agricultural issues relevant to Saskatchewan. At the time, agricultural

[2] This statement is based on discussions with Canadian Forest Service economists, Brian Peters and Kurt Niquidet (May 18, 2011). Thompson et al. (1992) and van Kooten et al. (1992) came to a similar conclusion in the context of restocking NSR lands, which is not the same as the situation here. However, these authors found that, with the exception of good quality sites and on the basis of future commercial harvest benefits, economic feasibility of restocking NSR sites was questionable.

[3] The site index is defined as the expected height of trees at a particular age.

economists were concerned with the widespread practice of summer fallow (which conserved moisture but resulted in increased soil erosion and salinity), conversion of wetlands to cropland, the depopulation of the province's rural landscape as farm size continued to increase (so farmers could take advantage of economies of size and thereby earn a living comparable to that in the non-farm sector), marketing boards, transportation of grain to export markets, and trade. Certainly, there were other issues but, for some reason, these are the ones that I ended up doing work on at one time or other. It was an interesting time, but also a time when production agriculture was considered passé – the agricultural research community had been so successful in raising global output that concern about food scarcity had disappeared and schools of agriculture were in decline (including Departments of Agricultural Economics). Emphasis shifted from production to the environment and food safety, with agricultural economics morphing into agricultural and resource economics or food and resource economics, or something else. The same happened to Faculties/Colleges of Agriculture, which became Faculties/Colleges of Life Sciences, Resources and Biotechnology, and so on. I moved on to work in areas of forestry, wildlife conservation and energy.

As the editor of the *Canadian Journal of Agricultural Economics* the past five years, I managed to get myself back to agricultural economics. I started work again on farm management and wetlands protection (which I last contributed to in 1995), and recently completed work with PhD students on rural-urban conflicts and organic farming. In January 2011, I attended an agricultural conference in Ottawa where Robert Thompson, a professor at the University of Illinois and a Senior Fellow at the Chicago Council on Global Affairs, gave a talk on the global food crisis. I thought we had solved that problem by the 1990s. Indeed, that was the reason why agriculture had been in decline – public funding for research into agricultural production problems had fallen and been increasingly relegated to the private sector. One consequence was the concomitant decline in aid to developing countries for agricultural research.[4]

What was going on? Let's investigate some of the numbers. The United Nations predicts that the

[4] According to Robert Thompson (pers. communication), global foreign aid to poor countries for agricultural development dropped from 17% to 3% of foreign aid budgets between 1980 and 2005. In the 1980s, 25% of U.S. foreign aid went to agriculture; this fell to 6% by 1990 and 1% by 2009. The share of the World Bank's lending going to agriculture fell from 30% in 1978 to 16% in 1988 to 8% in 2006. Disturbingly, the share of investments in agricultural research also fell.

world's population will slowly increase from 6.9 billion in 2010 to about 9.3 billion people in 2050. This amounts to a 35 percent increase in the number of people that need to be fed, or an annual increase in global population of 0.7 percent (which is not that high). The majority of this increase will come about in Africa, because populations in rich countries are projected to decline during this period. Unfortunately, the African continent is least equipped to feed a rapidly growing population.

Nonetheless, global per capita incomes are projected by the United Nations to increase from $3962 in 2000 to somewhere between $7250 and $21,450 (measured in constant 1990 $US) by 2050, with the gap between rich and poor declining as well (IPCC 2001, pp.13-20). Based on UN projections, the ratio of per capita incomes in rich countries to per capita incomes in poor countries is expected to fall from the current 16.1 to between 2.8 and 6.6 by 2050 (IPCC 2001, pp.13-20). Thus, global per capita incomes are forecast to grow by 1.2 to 3.4 percent per year.

The implication of these two factors for food security is obvious: a much larger population with a lot more income results in a magnified demand for food, especially grains that are fed to animals, because richer people consume more animal protein. How is this demand for food to be satisfied in the future?

Trends in Agricultural Output

Consider first the increase in the global production of the four major grains – wheat, maize/corn, rice and soybeans – over the period 1961 to 2009. From Figure 1, we see that wheat and rice production have increased threefold from about 200 million metric tons (Mt) to 600 Mt, while maize/corn output has increased by a factor of four (200 Mt to 800 Mt) and soybean output by more than 800% (albeit from nearly zero) to 230 Mt. In Appendix A, we provide data for each of these crops for the following major producing countries: the United States, China, India, Canada, Brazil, Argentina, Australia and the countries of the European Union.

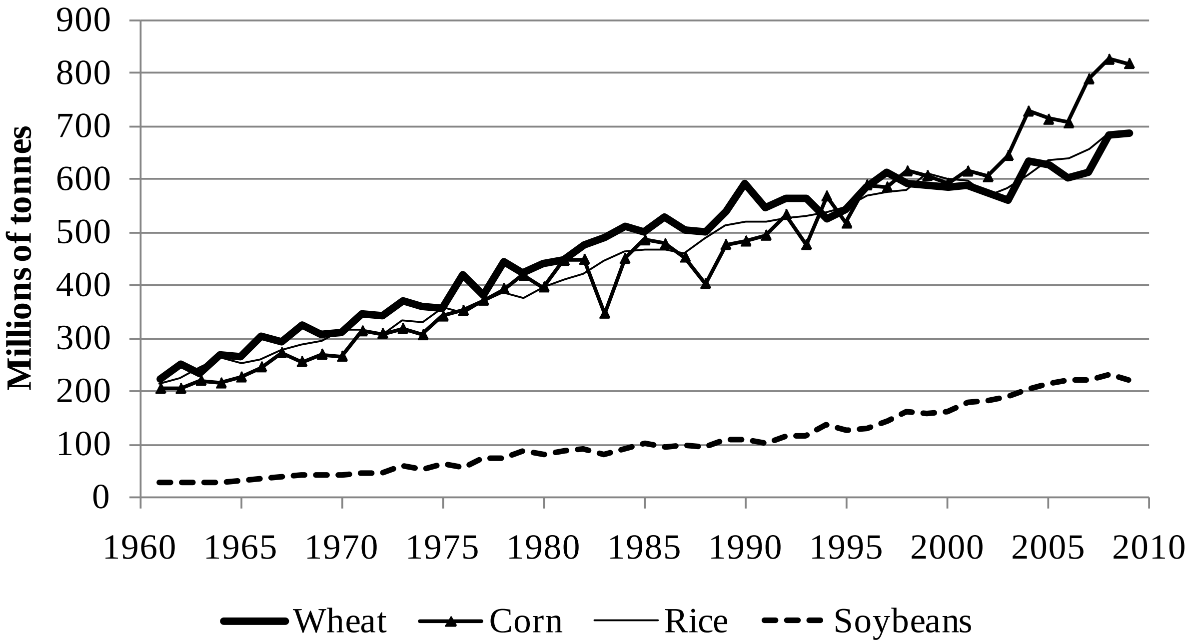

Figure 1: Global Production of Wheat, Maize (Corn), Rice and Soybeans (mil t), 1961-2009
Source: USDA (2011)

The increase in production is the result of several factors, but primarily by expanding the extensive margin of production by cropping areas previously in wetlands, forest, pasture and native grasslands, and the intensive margin using irrigation, increased chemicals, more frequent planting (e.g., more crops per year, less summer fallow) and higher-yielding varieties.[5] Crop breeding has been extremely important in helping countries increase agricultural production. Not only did crop breeding produce grains that provided higher yields and resistance to certain diseases, but also ones that could be planted in drier, colder climates thus extending the ability to grow crops in regions where they could not previously be planted.

Given that land is limited and there are conflicts at the extensive margin between forestry and agriculture, and between agriculture and nature, it is important to consider how fast yields increased over the same period as production. This is done in Figure 2. Again, data disaggregated by major producing countries are provided in Appendix A.

[5] See van Kooten and Folmer (2004, pp.38-41) for discussion of extensive and intensive margins of cultivation in agriculture and forestry.

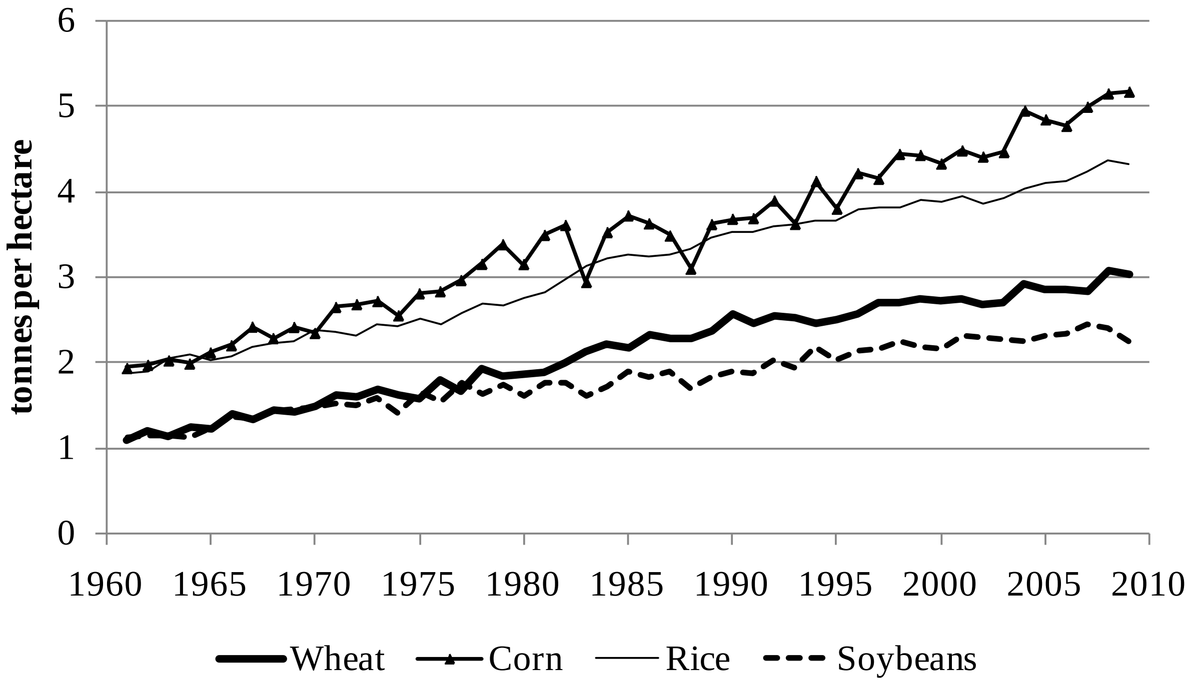

Figure 2: Trend in Yields Wheat, Maize (Corn), Rice and Soybeans (t/ha), 1961-2009
Source: USDA (2011)

Agricultural productivity increased in all regions of the globe, except Africa. If we look at the annual per hectare output of cereal grains, we see that, over a period of nearly 50 years, sub-Saharan Africa appears to have been left behind by the first Green Revolution (Figure 3). While crop yields increased by 255% in developed countries, and by 292% and 263% respectively in the Asia-Pacific region and Latin America, they increased by only 70% in sub-Saharan Africa.

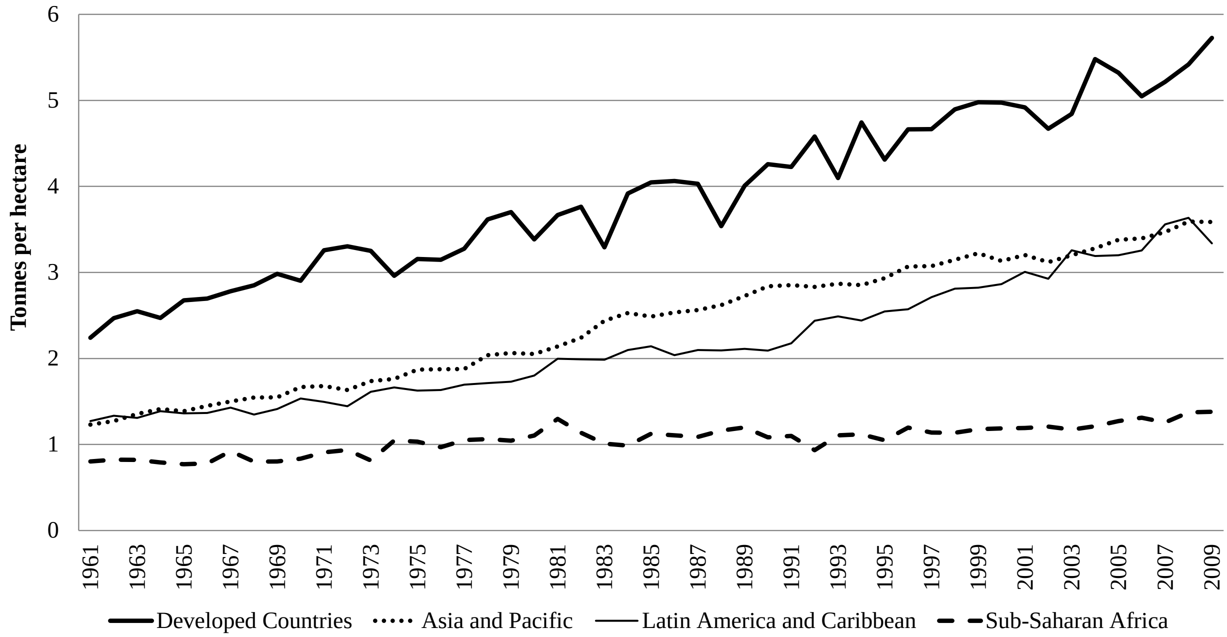

Figure 3: Trend in Cereal Yields by Region (t/ha), 1961-2009
Source: FAO (2011)

While wheat yields accounted for 90% of increase in global wheat production over the period 1961-2009, two-thirds of the increase in maize/corn production was due to yield increases and 72% of the rise in rice production. However, less than one-quarter of the expansion in soybean output could be attributed to yield improvements. This is seen in the massive increase in soybean production in Brazil and Argentina, which came about as a result of bringing new (marginal) land under cultivation (Figure A4). More than one-third of the increase in global rice production, and nearly half of the improvement in global rice yields, can be attributed to India and especially China (Figures A3 and A7).

If the trends in Figures 1 and 2 would continue for the next 40 years, the world should not have trouble feeding a growing population. However, there are several mitigating circumstances as the evidence suggests that rates of growth in both output and yield may be declining (Huang et al. 2002). The slopes of the wheat and soybean curves have flattened considerably since the early 1980s, although those of rice and maize/corn much less so. There are several reasons for this. First, increases in yields from transferring production techniques from the developed to the developing countries appear to have been exhausted. Second, the yields associated with greater use of fertilizers, water and other inputs also appear to have reached their limits.

Third, in some agricultural systems, such as the wheat-rice system in the Punjab, falling levels of soil organic matter and natural phosphorous are reducing yields. While some of this can be replenished using different crop rotations and bringing phosphorous from off site, the former will reduce yields in any event and the latter may be too expensive leading again to crop rotations with lower yields. Essentially, some crop production may be required as green manure – an investment to improve the soil quality.

Fourth, rising disease and insect resistance to fungicides, insecticides and so on results in greater crop loss.

Finally, the yield gap between experimental plots and actual experience has narrowed significantly over the past decades as a result of extension activities that encourage farmers to adopt the latest varieties and teach them appropriate farm management techniques. This is indicated in Table 1 for four crops, two of which were discussed above. Notice that the difference between actual and potential yields is almost non-existent in the richest countries, that some improvement is still possible in the emerging countries in Asia and South America, where expansion of cultivation continues, but that the gap remains large in sub-Saharan Africa.

Table 1: Yield Gap: Current Yield Relative to Estimated Potential Yield from Field Trials

Region	Maize/Corn	Soybean	Palm Oil	Sugarcane
Asia (excluding West Asia)	0.62	0.47	0.74	0.68
Europe	0.81	0.84	n.a.	n.a.
N. Africa & West Asia	0.62	0.91	n.a.	0.95
North America	0.89	0.77	n.a.	0.72
Oceania	1.02	1.05	0.60	0.91
South America	0.65	0.67	0.87	0.93
Sub-Saharan Africa	0.20	0.32	0.32	0.54

Source: Deininger et al. (2011, p.82)
n.a. signifies not applicable.

In Europe, North America, Oceania and part of Asia, landowners have adapted to vagaries in precipitation by planting crop varieties that are more tolerant of dry periods and through various management techniques (including irrigation and summer fallow) that enable production of crops despite low or even zero precipitation. However, in semi-favorable, rain-fed cropping regions in Latin America, Asia and particularly Africa, adaptive plant breeding, extension of agronomic practices and farm management techniques, and investments in public infrastructure are needed to overcome some of the large constraints to successful crop production (Huang et al. 2002). The situation is worse in marginal areas characterized by climate stress (mainly drought), fragile soils and no infrastructure. Norman Borlaug's Green Revolution simply passed by these regions. Yet, these semi-favorable and unfavorable regions can contribute to future crop production, but they cannot overcome the gap between anticipated demand and supply using current techniques and crop varieties based on plant breeding.

Non-agricultural Factors Affecting Food Security

There are other factors that affect food security. In an effort to reduce emissions of carbon dioxide, governments in Europe and North America have implemented a variety of biofuel initiatives, including subsidies to firms that produce biofuels and targets and mandates for biofuel content in gasoline and diesel. Sugar cane, beet sugar and corn can be used to make ethanol, while canola, soybeans and other oils are used for biodiesel. Research is ongoing to determine the viability of using cellulosic fiber as biofuel. One problem with biofuels is that the CO_2 savings are often rather small.

Nobel laureate Paul Crutzen examined only the impact on global warming of increased use of nitrogen (N) fertilizer associated with the production of energy crops for biofuels. He found that, "depending on N content, the current use of several agricultural crops for energy production, at current total nitrogen use efficiencies, can lead to N_2O emissions large enough to cause climate warming instead of cooling by 'saved fossil CO_2'" (Crutzen et al. 2008, p.393). Given current nitrogen-use efficiencies, the increased nitrogen emissions from growing energy crops offset the reduction in CO_2 emissions from the gasoline that the biofuel replaces. If ethanol came from sugar cane, the contribution of the biofuel to global warming was between 0.5 to 0.9, where a value above 1.0 indicates increased release of greenhouse gases (greater warming rather than cooling); if ethanol came from corn, the warming factor was 0.9-1.5; but, if the biofuel came from canola, it resulted in no benefit as the greenhouse gases released exceeded those associated with the fuel that was replaced (factor of 1.0-1.7). Only if the nitrogen use efficiency could be increased from about 0.4 to 0.6 might maize-ethanol or canola-biodiesel be climate neutral or beneficial.

Another problem with biofuels is that they increase the CO_2 released to produce the same amount of energy. In Europe, for example, biodiesel produced from canola has an indirect carbon footprint of 150.3 kg per gigajoule, compared with 100.3 kg of carbon per GJ for ethanol produced from sugar beet. In contrast, conventional diesel or gasoline releases only 85 kg of carbon per GJ (including CO_2 released during refining). This compares with carbon footprints of 82.3 and 73.6 kg per GJ for imports of ethanol from Latin American sugar cane and from Southeast Asian palm oil, respectively.[6]

Demand for energy crops also reduces the cultivated area devoted to food production as land is diverted into energy crops (Searchinger et al. 2008). Food prices have risen partly as a result of the diversion of grains to biofuels. In 2004, two percent of world grain production was used to produce biofuels, while virtually no vegetable oils (e.g., corn, canola) were diverted to biofuels. As a result of government policies, 6.5% of world grain production and 8% of vegetable oils went to produce biofuels in 2010, with governments hoping to triple this amount by 2020.[7] Clearly, this will have an impact on food prices, especially harming those who spend about half of their incomes on food. It will encourage deforestation and cultivation of native grasslands as crop production expands onto increasingly marginal lands. This reduces wildlife habitat and thereby biodiversity.

While the objective of biofuel policies is to reduce global warming and its negative impacts on developing countries in particular, it leads instead to increased deaths among the globe's poorest people as higher food prices raise incidents of malnutrition and starvation. Indeed, Goklany (2011) estimates that biofuel production in 2010 alone led to some 50,000 to 190,000 additional deaths.

Prospects for Increasing Agricultural Output Sans Genetically-Modified Crops

As already noted, there are only a few pathways to enhance crop production: expansion of cultivated land, greater use of inputs (fertilizers, water, etc.), and higher-yielding plant varieties. The Green Revolution came about as a result of all three, and these factors can be relied upon for

[6] See “Once-hidden EU report reveals damage from biodiesel” by P. Harrison, April 21, 2010 at: http://www.reuters.com/assets/print?aid=USTRE63K2CB20100421 (viewed May 3, 2010).

[7] See "How biofuels contribute to the food crisis" by T. Searchinger, February 11, 2011, at: http://www.washingtonpost.com/wp-dyn/content/article/2011/02/10/AR2011021006323.html (viewed March 2, 2011).

expanded production in the future.

Consider first the expansion of cultivated land. Brazil is considered to have more potential cropland than any other country in the world – some 300 million hectares of which only 50 million ha are currently cultivated.[8] It has more arable land that receives 975 mm or more of precipitation than the entire African continent. Crop production on Brazil's *cerrado* (savanna) was made possible through public investments to reduce soil acidity (applying 14 million tons of lime annually in the late 1990s rising to over 20 million tons in 2003-2004), and because of publicly-funded research to produce tropical varieties of soybeans and other grains.[9] As a result, Brazil expanded its cropland by one-third between 1996 and 2010. Clearly, it can increase cultivated area by a great deal more. North America, Russia, Indian and China also have large areas of uncultivated arable land that could be suitable for crop production, but nothing on the same scale as Brazil. Further, large investments will be required to bring such marginal land into crop production, while environmental costs will not be insignificant.

When it comes to more intensive use of inputs, it is important to recognize that some 16 percent of the gain in cereal yields ascribed to the Green Revolution in agriculture came from the increase in atmospheric CO_2 (Idso and Singer 2009, pp.362-381). Yields are projected to increase by as much again if atmospheric CO_2 were to double from pre-industrial times (see Levitt and Dubner 2009).[10] Ignoring CO_2, there remains the possibility of expanding global crop production simply by enabling farmers in poor nations to apply higher levels of chemicals on their lands, both fertilizers and pesticides. However, adequate roads, railways, storage facilities and so on are often needed to facilitate access to markets; lack of such infrastructure can be a formidable barrier to expanding crop production, leading to lower input use and relatively large crop losses (perhaps as great as 40%). Investments in infrastructure, improvements in the types of chemicals that are applied, and expansion of irrigated lands can enhance crop production in many developing countries, and especially in Africa which the Green Revolution pretty well by-

[8] Information in this paragraph comes from *The Economist*, "The miracle of the cerrado", April 26, 2010.

[9] It is important to note that, during the summer cropping season, crops in northern (and southern) regions experience much longer days (hours of sunlight) than a crop experiences in the tropics. It is often necessary, therefore, to develop new varieties of a crop for it to be successful in a developing country. While the same is true of tropical crops being adapted to higher latitudes, research funding is more readily available for the latter than the former.

[10] Based on their readings, Levitt and Dubner (2009) suggest that yields could increase by some 70%.

passed.

Finally, plant breeders will continue to find new varieties of crops that have higher yields, are more tolerant of drought and saline soils, and/or grow in regions beyond their current range. These discoveries will complement the expansion of agricultural lands and more intensive use of inputs.

Nonetheless, it is not clear whether the traditional pathways can be relied on to keep up with the growing demand for food and bioenergy. As noted earlier, the limits of global food output are within sight and these limits, in the view of many commentators, appear less than desirable. Currently, some 800 million people are undernourished and six million children die annually of malnutrition. To prevent food prices from rising significantly in the future, which would greatly add to levels of malnutrition, it will be necessary to plant genetically-engineered (genetically-modified) crops. Genetic engineering offers the ability to increase crop output while reducing the impact of farming on the environment.

Implementing Agro-Biotechnology: Genetically-Modified Crops

In agriculture, genetic engineering of crops works as follows. With traditional crop breeding, a parent plant with some desired characteristic (a desired gene) is cross-bred with another plant that lacks this gene (but perhaps has other desired characteristics). The offspring has many genes common to the two parents. Subsequently, it takes several generations of additional breeding to remove the unwanted genes. Genetic engineering does this in one step: the desired gene is removed from the chromosome of the first parent and inserted into the second plant. The final result is a plant that has the desired gene but not unwanted genes that would then have to be removed through additional breeding. In addition to inserting genes from the same species, genetic engineering permits scientists to insert genes from other species into the chromosomes of a plant.

Perhaps it is not surprising that political acceptance remains a major obstacle to genetically-modified (GM) or transgenic crops. The reason could possibly lie with the adoption of the Precautionary Principle in Article 130R(3) on the environment in the 1992 Maastricht Treaty that created the European Union (Adler 2011). The precautionary principle was subsequently adopted in the Cartagena Biosafety Protocol (2000) dealing with GM plants as part of the UN's

Environmental Programme's Convention on Biodiversity. The Cartagena Protocol allows governments to limit imports of living GM crops and seeds as long as there is any doubt whatsoever about its adverse impact on the environment (or humans). That is, the standard for accepting GM plants is overwhelmingly against their acceptance.

The precautionary principle is defined as follows: "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically".[11] Hahn and Sunstein (2005), Sunstein (2005) and Adler (2011), among others, have pointed out the logical inconsistency of the precautionary principle. For example, a decision based on the precautionary principle would prevent China from building nuclear power plants, even though doing so would reduce health problems associated with pollution from coal-fired power plants, deaths from coal mining, and emissions of CO_2 that contribute to climate change. Yet, if China relied only on nuclear power, a decision to mine coal and use it to generate electricity would be squashed on the basis of the precautionary principle – that electricity generated from coal could lead to adverse environmental consequences and that it is therefore preferable to rely on nuclear power. If the precautionary principle is to be taken seriously, it would thus provide no direction for decision making. By balancing costs against benefits, and perhaps applying the notion of a safe minimum standard, there is at least a foundation for making difficult decisions (see Hahn and Sunstein 2005).[12]

Following on the heels of the Cartagena Protocol, the EU defined transgenic or GM organisms as follows: "'GMO' means an organism, with the exception of human beings, in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural recombination" – Article 2(2) of EU Directive 2001/18/EC5 (Herring 2008). It is interesting to

[11] Statement adopted by 31 individuals at the Wingspread Conference, Racine, Wisconsin, 23-25 January 1998 (http://www.gdrc.org/u-gov/precaution-3.html as viewed February 25, 2010).

[12] The safe minimum standard (SMS) argues as follows: Apply expected values or Monte Carlo simulation (with relevant probability distributions) for addressing risk in cost-benefit analysis. Then, if the discounted expected benefits of a policy exceed the discounted costs, the policy should be undertaken. If the policy results in a potential irreversibility, however, it should not be undertaken unless the cost of not doing so is unacceptably large (as is the case with GM crops where many face unnecessary starvation in the absence of such crops). The SMS criterion is itself controversial because it essentially implies abandonment of cost-benefit analysis, but it at least permits tradeoffs to be made, which is not the case with the precautionary principle (see van Kooten 2011, Chapter 6, for discussion).

note that there is nothing natural about traditional crop breeding – neither mating nor recombination of plant genetic material occurs naturally. Beginning in the mid-20th century, long before agro-biotechnology, "mutagenesis using radiation or chemicals, induced polyploidy, protoplast fusion and wide crosses of plants that do not normally sexually reproduce" (Herring 2008) became common plant breeding techniques that modified the genetics of plants. Nonetheless, while accepting a range of genetically modified products outside of food, as well as genetically modified foods that were produced by 'traditional' crop breeding practices and whose safety was as questionable as products from genetic engineering, the EU opposed GM crops with adverse consequences for low-income countries, particularly those in Africa.

In August 2002, a shipload of GM corn was sent to Zambia to help alleviate famine, but it was turned back because of fear that some of the corn would be planted. If the corn was planted, Zambia would no longer be able to export farm products into European markets. Zimbabwe, Mozambique and Malawi likewise rejected U.S. food aid despite starving citizens. Yet, U.S. citizens consumed the very same variety of corn and the UN had been distributing it in Africa since 1996 as part of its World Food Programme (Paarlberg 2003).

Beginning in 1998 and with the support of international environmental NGOs, such as Greenpeace, activists in India attempted to block the use of Monsanto's *Bt* cotton, which enables plants to express *Bacillus thuringiensis* (*Bt*) protoxins from their tissue thereby conferring insect resistance and reducing the need for pesticides. Despite arguments by intellectuals, academics, environmentalists and others that higher-cost *Bt* cotton would lead Indian peasants into a debt and that the Indian government should ban GM cotton, peasants enthusiastically embraced the crop because it led to higher net returns despite the higher cost of GM seed (Herring 2006).[13] Although the European position on GM crops has been a major hurdle in achieving agreement on agriculture in the World Trade Organization's (WTO's) Doha Round of international trade talks, domestic markets in India and China are sufficiently large that these developing countries can ignore EU protestations. The same is not true of Africa, which depends on sales of farm products to Europe.

[13] This is evident from Table 2 as well, although India has been more reticent about expanding area planted to other GM crops. Information on planting of GM crops and genetically engineered agricultural products can be found at http://www.gmo-compass.org/eng/home/ (accessed June 7, 2011).

In 2002, 99 percent of the land planted to GM crops was located in Canada, the U.S., Argentina and Brazil (although it was illegal to do so in the latter). Since then, countries in Europe and elsewhere have increasingly planted GM varieties, although Europe continues to oppose GM crops. This is seen in Table 2 which provides area planted to GM crops in various locations; as of 2009, less than 100,000 ha of GM crops had been planted in Europe. However, as noted by Herring (2008), data on transgenic crops do not include illegal plantings in places like Thailand, Pakistan and Vietnam, or even Europe. Transgenic crops are grown in many developing countries, with expensive and highly-regulated seeds often acquired illicitly – grown illegally and smuggled across borders.

Table 2: Area Planted to Genetically-Modified Crops by Country, 2007

Rank	Country	Area (mil ha)	Types of crops
1	USA	57.7	Soybean, Maize, Cotton, Canola, Squash, Papaya, Alfalfa
2	Argentina	19.1	Soybean, Maize, Cotton
3	Brazil	15	Soybean, Cotton
4	Canada	7	Canola, Maize, Soybean
5	India	6.2	Cotton
6	China	3.8	Cotton, Tomato, Poplar, Petunia, Papaya, Sweet Pepper
7	Paraguay	2.6	Soybean
8	South Africa	1.8	Maize, Soybean, Cotton
9	Uruguay	0.5	Soybean, Maize
10	Philippines	0.3	Maize
11	Australia	0.1	Cotton
12	Spain	0.1	Maize
13	Mexico	0.1	Cotton, Soybean
14	Columbia	<0.05	Cotton, Carnation
15	Chile	<0.05	Maize, Soybean, Canola
16	France	<0.05	Maize
17	Honduras	<0.05	Maize
18	Czech Rep.	<0.05	Maize
19	Portugal	<0.05	Maize
20	Germany	<0.05	Maize
21	Slovakia	<0.05	Maize
22	Romania	<0.05	Maize
23	Poland	<0.05	Maize

Source: http://www.gmo-compass.org/eng/home/ (accessed June 7, 2011)

International agricultural agencies, such as the FAO, World Bank and the Consultative Group on

International Agricultural Research (CGIAR),[14] which should be promoting GM crops, have adopted the European standpoint and put up hurdles to greater use of GM crops (see Paarlberg 2003). Environmental non-governmental organizations (ENGOs) have also adopted the EU's position regarding GM crops and lobbied governments to stop funding agro-biotechnology research, including, in particular, research in developing countries. Biotechnology research at CGIAR's international agricultural research centers was one casualty, for example. Paarlberg (2003) cites that case where biotechnology research at the International Rice Research Institute was halted and eventually only two scientists out of some 800 at the Institute were involved in anything related to GM rice. While government-sponsored research declined, research on transgenic crops by the private sector ramped up. This led to the situation where environmentalists subsequently tried to prevent farmers from buying GM seeds from companies such as Monsanto because private companies used their monopoly position to exploit farmers (see Herring 2006, 2008; Paarlberg 2008).

Benefits of Genetically Engineered Crops

The benefits of GM crops are captured not only by the farmer or landowner, but also by society more generally. The vast majority of planted GM crops include a gene that makes them resistant to herbicides. For example, 'Roundup' is a non-discriminatory herbicide that kills grasses and broad-leafed plants. Its main ingredient is glyphosate, which is the most widely used herbicide in the U.S. and the most sold herbicide globally since 1980; it is made by Monsanto. The company subsequently developed a GM variety of corn that can survive glyphosate applications, thereby enabling farmers to use zero tillage agriculture. Crops are planted directly into the soil without ploughing to control weeds, thereby reducing soil erosion and runoff of nitrogen from fertilizer into surface waters.

As noted above, *Bt* cotton and *Bt* corn/maize contain a gene that makes them resistant to insects; for example, *Bt* maize resists the European corn borer. Insect and disease resistant of *Bt* maize, *Bt* potato, *Bt* cotton and so on reduce insecticide use, thereby reducing farmers' exposure to potentially harmful chemicals and reducing chemical residuals in the environment. At the same time, the gain in reduced costs of purchasing and applying chemicals and the increase in yields

[14] A list of the CGIAR international agricultural research centers and their locations are provided in Appendix B.

(due to reduced crop loss) more than offset the higher seed costs.

More recent agro-biotechnology developments have combined plants' ability to withstand herbicides while protecting against insects. Research is looking into methods that increase yields, make plants more drought (and moisture) tolerant, increase resistance of crops to saline soils, and so forth. This enables the expansion of crop production into areas that do not now support tree growth or productive grassland.

Transgenic crops also provide non-food benefits, with an estimated 90% of the enzymes used in large-scale commercial applications derived from biotechnology. Products include those used in detergents, textiles, pulp and paper manufacturing, leather tanning, metals, fuels, and mineral processing. Some of the non-food products derived from agro-biotechnology are indicated in Table 3.

Table 3: Examples of the Diversity of Non-Food Products Derived through Agricultural Biotechnology

Apples, Grapes & Cabbage	Corn, Trees, Grasses & Soybeans	Potatoes & Bananas
Plant chemicals to enhance nutrition and fight diseases	Ethanol, lubricants, medicines, Vaccines inks, dyes, paints, soaps, detergents, adhesives, particle board, industrial chemicals, textiles, varnishes, and biopolymers	Vaccine

Source: Shelton et al. (2010)

Agro-biotechnology that increases crop yields also prevents the conversion of forestlands and native grasslands to cultivation. In essence, enhanced production shifts the extensive margin of cultivation inwards, reducing the rents cropping of marginal lands. This also leads to the protection of wildlife habitat, wild spaces and so on.

Private versus Public Role in Agro-Biotechnology

There is a large debate about the role of the private versus public sector in agro-biotechnology. We have seen how lobbying by ENGOs to reduce government support of GM research created an expanded role for private firms. Of course, there is nothing inherent in biotechnology that says it must be done by private sector, although the success of agro-biotechnology firms such as Monsanto indicates that private companies can provide the types of GM crops that benefit both farmers and society more broadly, even in developing countries as illustrated by the case of *Bt* cotton in India. However, government sponsored and directed research can be of tremendous importance in developing countries, especially with regards to marginal areas in Africa. The private sector is unlikely to invest in biotechnology research and development (R&D) aimed at crops in marginal areas that the first Green Revolution largely by-passed. Research on millet, cassava, beans and sorghum is less likely to be conducted by the private sector as rents to such crops are inherently low. Further, governments are more likely to be interested in bio-fortification of food (e.g., with vitamin A) for poor, undernourished consumers.

In addition to government sponsored transgenic crop R&D in developing countries, the public sector has a role in providing education (especially of women), infrastructure (roads, railways, communications), and most particularly good governance and rule of law that clarify and protect private ownership of farmland (providing collateral for loans), facilitate banking services, and so on.

CONCLUSIONS

Developing countries have greatest need to exploit the power of modern biology to ensure food security. While genetic engineering will not solve all problems of 21st century agriculture, it would be unconscionable to deprive the world's poor of the potential benefits to them. Despite efforts of environmentalists and the precautionary principle, there is no credible evidence that applying genetic engineering in agriculture is dangerous to either food safety or environmental quality.

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APPENDIX A

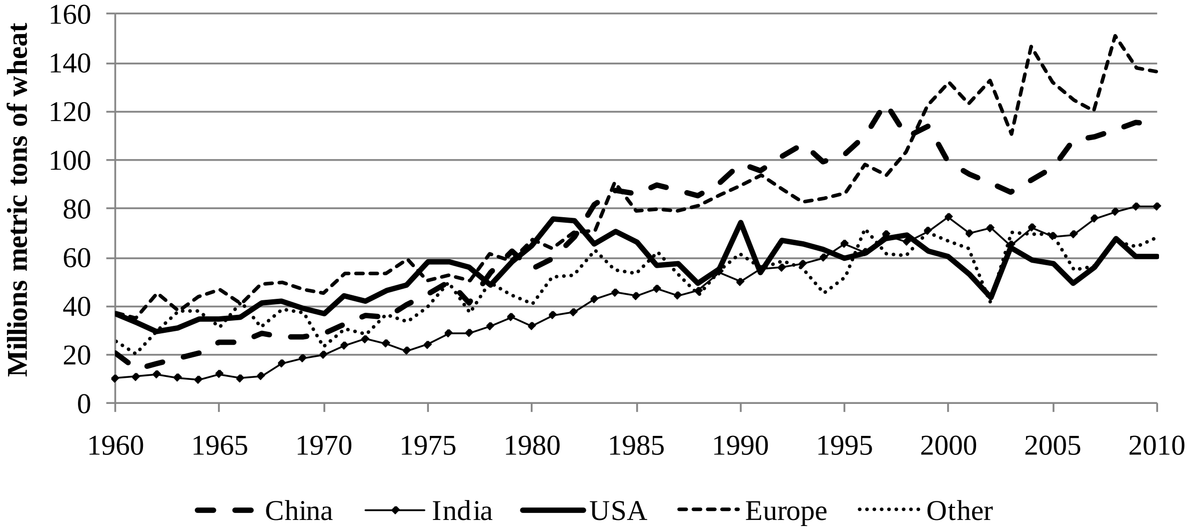

Figure A1: Expansion of Wheat Production, Selected Countries, 1960-2010
Source: USDA (2011)

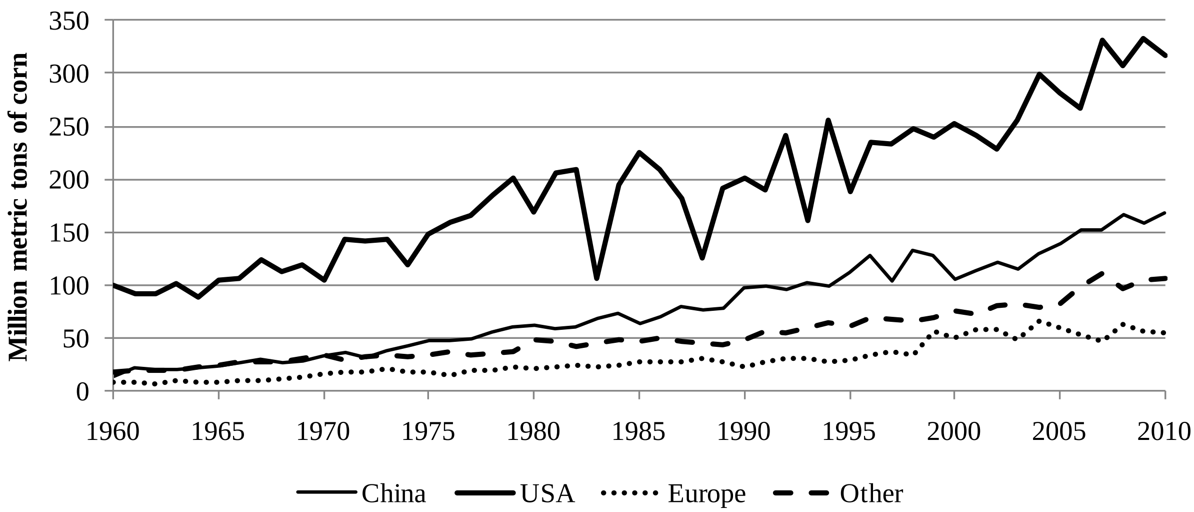

Figure A2: Expansion of Maize (Corn) Production, Various Countries, 1960-2010
Source: USDA (2011)

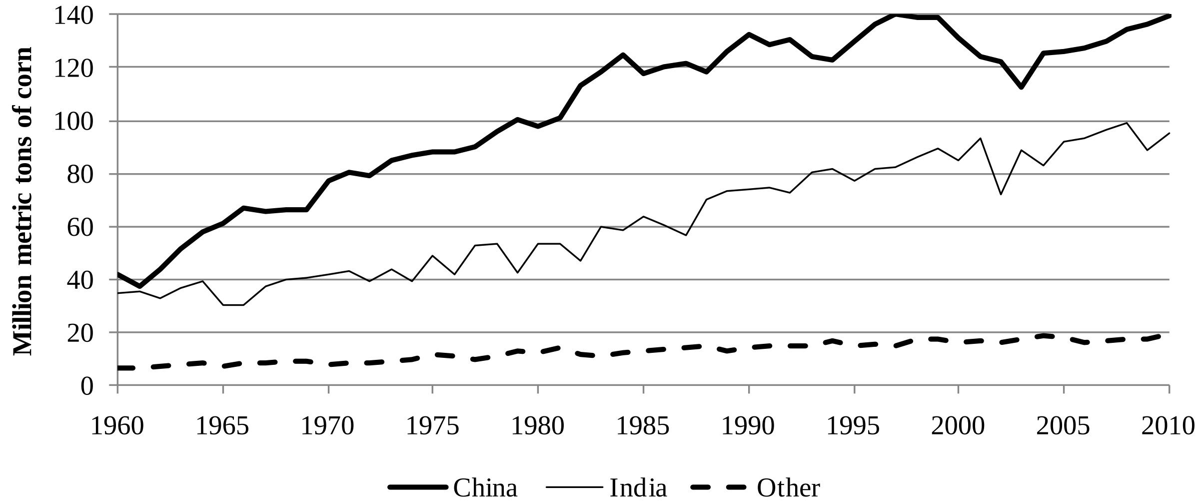

Figure A3: Expansion of Rice Production, Selected Countries, 1960-2010
Source: USDA (2011)

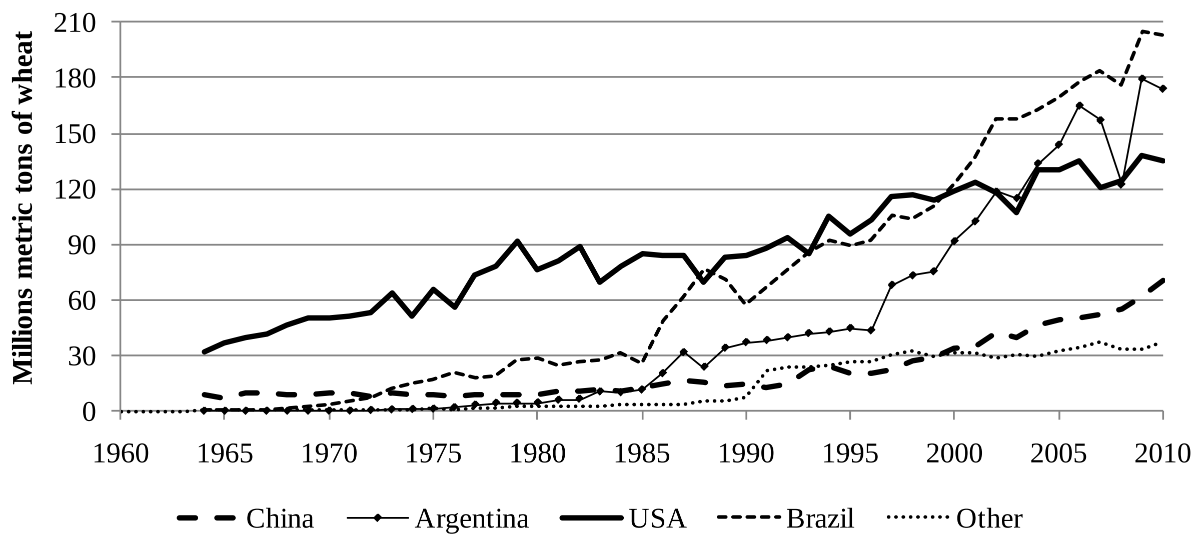

Figure A4: Expansion of Soybean Production, Selected Countries, 1960-2010
Source: USDA (2011)

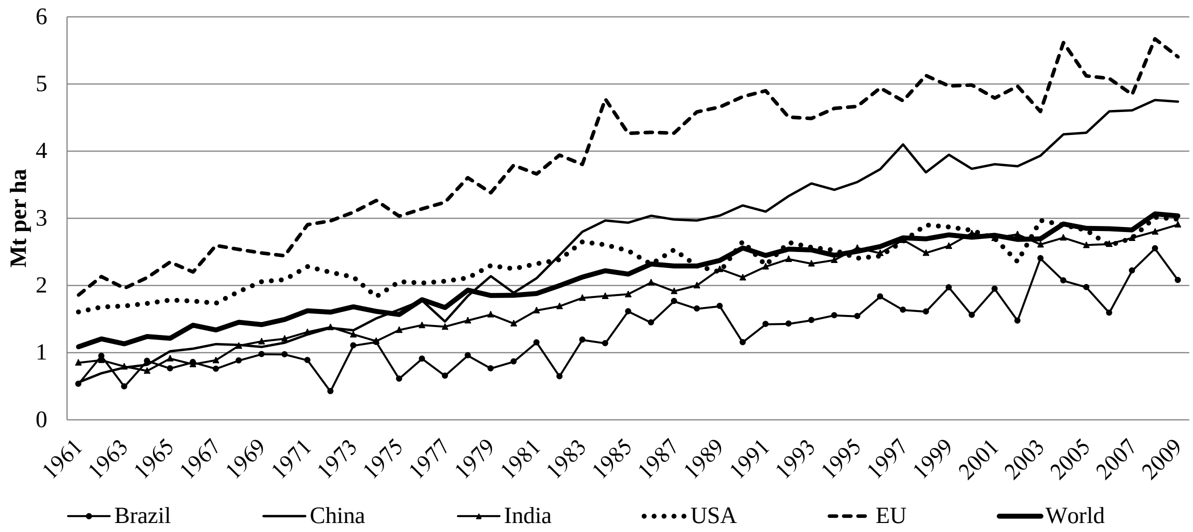

Figure A5: Growth in Wheat Yields, Global and Selected Countries, 1961-2009
Source: FAO (2011)

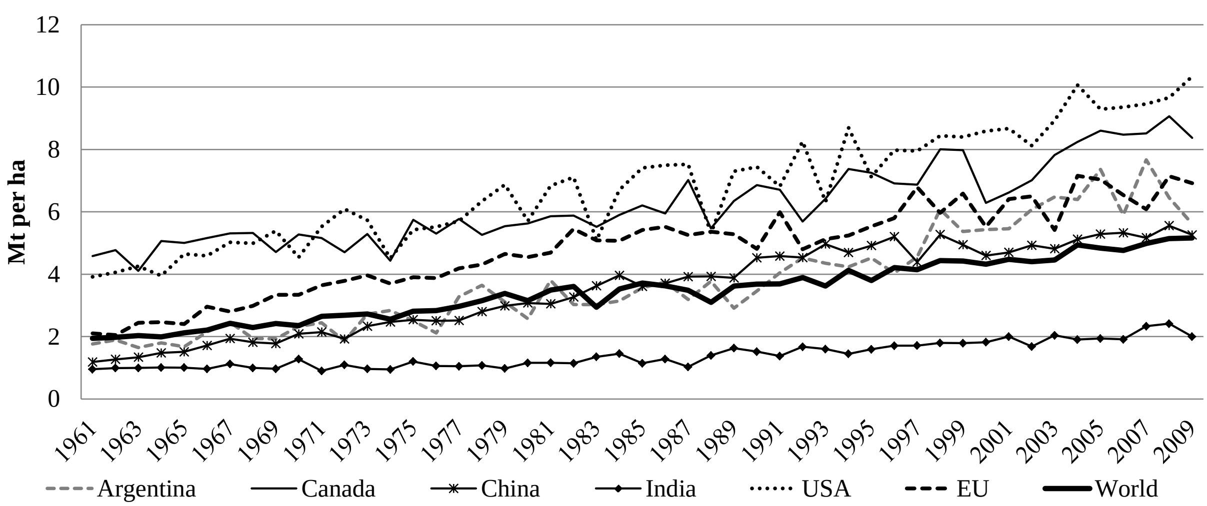

Figure A6: Growth in Maize/Corn Yields, Global and Selected Countries, 1961-2009
Source: FAO (2011)

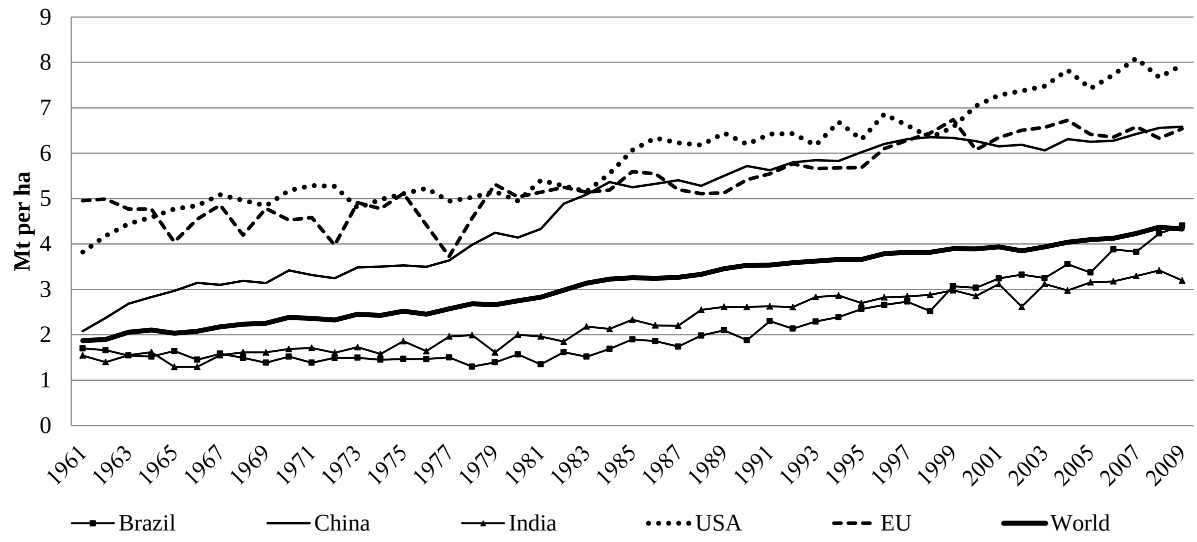

Figure A7: Growth in Rice Yields, Global and Selected Countries, 1961-2009
Source: FAO (2011)

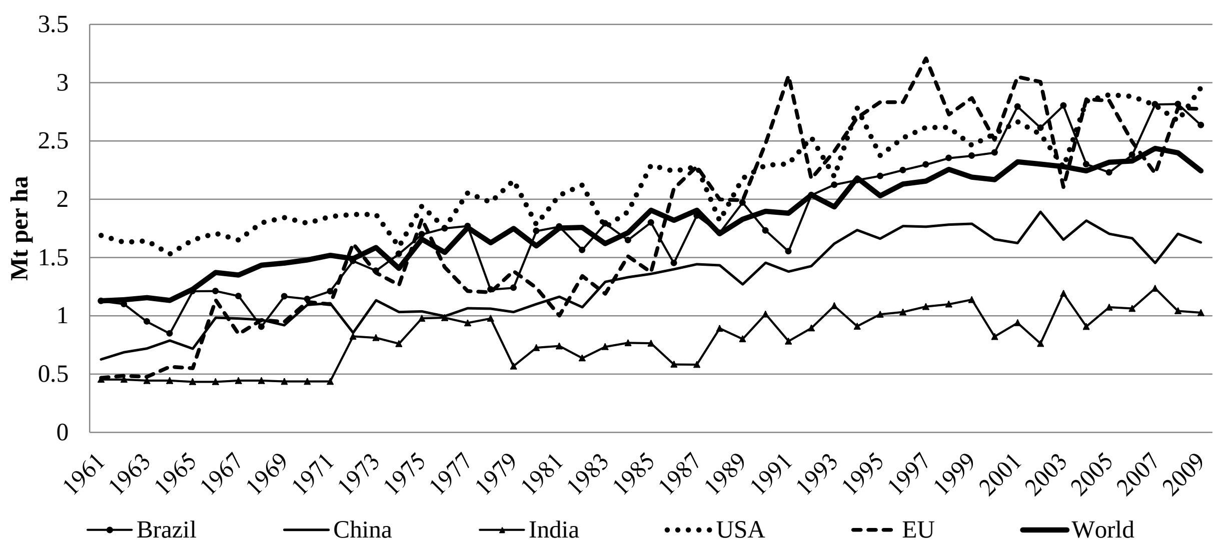

Figure A8: Growth in Soybean Yields, Global and Selected Countries, 1961-2009
Source: FAO (2011)

APPENDIX B

List of CGIAR's International Agricultural Research Centers

1. Africa Rice Center (WARDA)
2. Bioversity International
3. Centro Internacional de Agricultura Tropical (CIAT)
4. Center for International Forestry Research (CIFOR)
5. Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT)
6. Centro Internacional de la Papa (CIP)
7. International Center for Agricultural Research in the Dry Areas (ICARDA)
8. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
9. International Food Policy Research Institute (IFPRI)
10. International Institute of Tropical Agriculture (IITA)
11. International Livestock Research Institute (ILRI)
12. International Rice Research Institute (IRRI)
13. International Water Management Institute (IWMI)
14. World Agroforestry Centre (ICRAF)
15. WorldFish Center

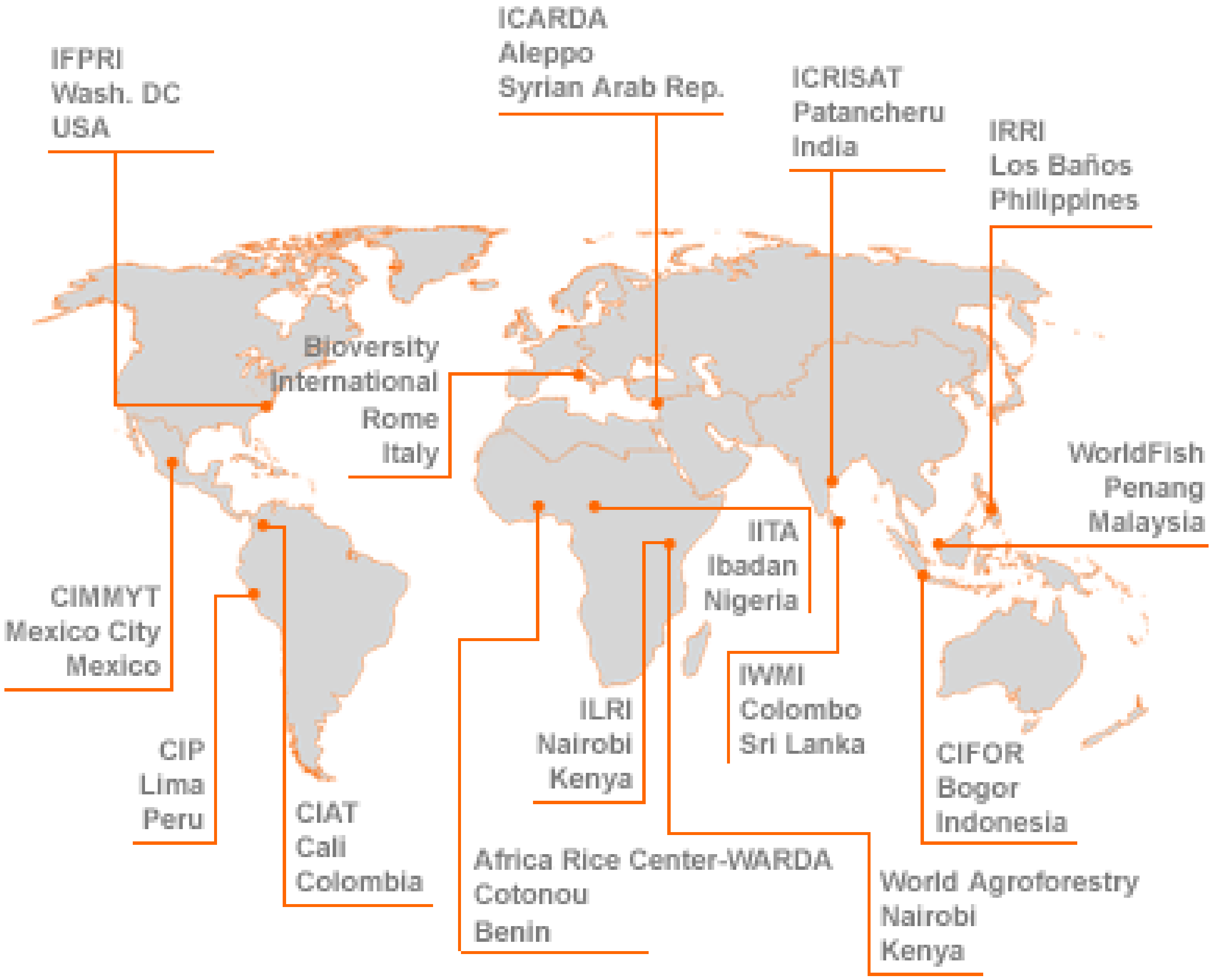

Figure B1: Location of CGIAR International Agricultural Research Centers
(Source: Robert Thompson)