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Mark W. Rosegrant, Anthony J. Cavalieri:
Bioenergy and Agro-biotechnology

Externe Expertise für das WBGU-Hauptgutachten
"Welt im Wandel: Zukunftsfähige Bioenergie und
nachhaltige Landnutzung"

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Bioenergy and Agro-biotechnology

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Executive Summary

- Use of the IFPRI (International Food Policy Research Institute) IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) model to explore scenarios related to use of GMO (genetically modified organisms) technologies to increase crop are presented. These results indicate that we are entering a period of increased food prices. Lack of land and water availability means that increases in crop production will have to come from yield increases rather that from bringing additional land into production. GMO technologies can increase production and reduce the effect of higher prices on the number of malnourished people in the developing world.

- Expanded use of crops for biofuels will result in increased demand for existing crops and land beyond the levels predicted in the models.

- Advances in biotechnology will continue at a rapid rate because of: 1) continued improvements of the basic tools of biotechnology and genomics driven by human health applications but readily applicable to plant species, 2) complete genome sequencing of many of the crops used for biofuels, 3) improved molecular marker technology, and 4) application of first generation commercialized genes to additional crops.

- Continued application of plant breeding, marker assisted breeding and biotechnology will result in increased rates of improvement in crop yield, adaptation and usefulness for biofuel production. Rates of improvement for most crops will increase but will remain in the 1 to 2 percent per year range.

- Commercial opportunities will have a large effect on the level of research spending for different crops resulting in different rates of improvement. Progress in maize will be the greatest because of private investments in maize improvement exceeding US$1 billion/yr. Soybean and canola investment will also drive higher rates of progress. Private funding will be concentrated on markets in the developed world; and public funding will be required for developing world farmers.

- Crops such as cassava, sugarcane and oil palm will be impacted by biotechnology by 2015. However, technical difficulties with these crops and low levels of research investment will result in slower progress.

- Despite historically high rates of improvement in all of the crops discussed, the demand for biofuels will outstrip the gains of productivity because of policy decisions and subsidies and the relative competitiveness compared with other sources of energy. This will result in implications for global food prices and will have significant impacts on the developing world.

- Dedicated energy crops are only now being identified. Many of the top candidates, chosen for their high biomass yields, are not domesticated and are only now being improved. A few species such as switchgrass, *Miscanthus*, *Jatropha*, poplar and various types of sorghum appear promising. Traditional breeding should result in rapid improvement since these species have not been extensively selected for yield or adaptation.

- Biotechnology is being applied to dedicated energy crops for herbicide resistance, insect resistance, abiotic stress tolerance, biofuels yield and production of processing enzymes. Efficient methods for transformation and gene expression in these species are being developed. Lack of basic knowledge of the genetics and molecular biology of these species make this challenging. Genes commercialized in maize and other commercial food crops can be used in dedicated energy crops.

- Venture capital funding is currently available to support companies involved in improving dedicated energy crops through breeding and biotechnology. Investments by large established companies in the energy and chemicals sectors are also supporting the development of the industry.

- Longer term, production of biofuels from dedicated, cellulosic energy crops as well as crop residues holds great promise. However, several technical problems must be solved. There are currently no commercial biofuels plants that use cellulosic materials. Biotechnology represents an important option for increasing the viability of biomass based fuels, whether from crop residues or dedicated energy crops.

- The horizon for genetic modification (GM) impact on dedicated energy crops will be from 2015-2025. The need for these improved crops assumes that technical challenges to using cellulose and lignin for biofuels production can be solved.

- The most important impact of biotechnology on biofuels in the next 5 years will be on microorganisms involved in the processing of biomass to biofuels. Development and improvement of enzymes used for digesting cellulose, hemicellulose and lignin into sugars and other simpler components are essential. Improvements in the efficiency and yield of fermentation will also continue. Significant levels of public and private investment make technical success likely.

- Synthetic biology, while still in the early stages of development, will be useful for biofuel production in the 10-20 year time frame.

- While most of the scientific effort to improve crops for biofuel production is located in the developed world, meaningful scientific capacity also exists in China, India and Brazil. Crop specific capability also exists in developing countries with national interest in specific crops (sugarcane-Brazil, oil palm-Malaysia, *Jatropha*-India, etc.).

- Extensive experience with GM food crops since the mid 1990's is highly relevant to developing regulatory systems for GM biofuels crops. Regulatory issues for biofuels crops are less related to food safety (toxicity, allergenicity) and more related to environmental concerns including containment of transgenes, gene flow to natural populations of wild relatives and invasiveness of biofuels crops.

- It is unlikely that the use of biotechnology for the development of crops for energy use will have a significant impact on discussions or policy related to acceptance of GM technology in the near term. However, failure of crop production to keep up with demand could result in food cost increases and consideration of biotechnology's role in meeting the demand.

- Crops for biofuels use, including those developed through biotechnology should, in theory, be of value to large and small farmers. However, as is the case with food crops, small farmers in the developing world do not have access to improved seeds and the related inputs that may be required for profitable production. Additionally, the high cost of processing plants will favor large farmers and countries with the appropriate infrastructure to move crops to the processor and to distribute the resulting fuel to buyers.

- Biotechnology will contribute to increases in crop productivity which should help ameliorate the competition for different land uses (food vs. fuel) but the demand for biofuels will likely outpace the improvements in productivity so that food prices will rise and additional land will be needed for crop production.

- Extensive use of biofuels will require much more land dedicated to agriculture. This might include more productive use of marginal land. The value of fuel relative to food will determine whether the most productive lands might also be used for fuel crops.

- While pursuing research and development in agro-biotechnology for bioenergy crops is worthwhile, this work will necessarily build on breeding and crop management research. Required crops will need to be broadly adapted for production and use as fuel feedstocks. High costs of regulatory approval of biotechnology traits mean that where non-GM solutions for crop improvement are available they will be used preferentially. Transgenic approaches will only be justified in those cases where valuable traits are not available through conventional methods and adequate markets exist.

- The results of our study suggest several policy recommendations. First, use of food crops for biofuels will cause rising food prices and have a negative effect on the number of malnourished people. Policies such as subsidies, tariffs, and blending mandates should not encourage the use of food crops for fuel. Second, biotechnology can increase the productivity of crops and with appropriate regulatory and biosafety regimes should be encouraged to solve the problems related to increasing crop yields. Third, use of biomass, from crop residues and dedicated energy crops, to make biofuels should be encouraged particularly by solving technical problems related to the economical use of these materials. Fourth, low public funding of crop improvement research has limited crop productivity. Increased public funding and policies that encourage private funding of crop improvement including through the use of biotechnology should be encouraged.

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I. Introduction

Global population is expected to increase from 6.1 billion in 2000 to 7.6 billion in 2020, reaching 9.1 billion in 2050. With this growth in human population, there will be greater pressure on agricultural production, land, fuel, and other primary services. One potential response to augment agricultural production is expanded application of biotechnology for crop improvement. However major food commodities like maize, wheat, soybean among others are now being utilized as sources of bioenergy. The debate on agro-biotechnology, specifically the use of GMOs in plant breeding, has gained a renewed public interest with the emergence of crop based bioenergy. The prospect of yield increases and increased stress tolerance in plants could alleviate competition among different land uses. At the same time biotechnology promises options for plants being specifically modified for the efficient production of fuels. This paper seeks to address the following questions in order to assess risks and opportunities of agro-biotechnology in the field of bioenergy.

The main questions are: *How can agro-biotechnology influence global sustainable plant production? To what extent can biotechnology (in particular the use of GMOs for food and non-food production) decrease the potential of land-use competition by increasing yields? What is the range of expected yield improvements that can be found in existing assessments? What may be the risks? Can biotechnology increase the potential for competition between different land uses, i.e. due to crowding out effects or biosafety concerns?*

This paper provides insights to these questions based on research studies and analysis of scenarios of food supply and demand. It is divided into two major sections, 1) bioenergy, land-use and food security, and 2) the impact of biotechnology on crop use for bioenergy and economic development. The first section presents baseline and zero-GMO scenario development, followed by discussion of the application of biotechnology to biofuel crops, agro-biotechnology directions, and role of biotechnology in biofuel processing. The second section deals with research capacity for agro-biotechnology, risks of global use of agro-biotechnology and recommends policies to develop sustainable bioenergy development.

II. Scenario Development for Baseline and Zero-GMO Scenarios

In this section we explore the potential contribution of GMO to future food supply, demand and food security. This is done using a scenario approach that compares a baseline scenario that incorporates our assessment of the likely contribution of GMO to yield productivity growth in crops and livestock to an alternative scenario that eliminates the GMO contribution to productivity. IFPRI developed a model that offers a methodology for analyzing alternative scenarios for global food demand, supply and trade. A brief description of this model is provided in Box 1.

Box 1 - IMPACT Model Methodology

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model is a representation of a competitive world agricultural market for 30 crop and livestock commodities, including cereals, soybeans, cotton, roots and tubers, meats, milk, eggs, oils, sugar/sweeteners, fruits/vegetables, and fish. It is specified as a set of 115 countries and regions within each of which supply, demand, and prices for agricultural commodities are determined. The country and regional agricultural submodels are linked through trade, a specification that highlights the interdependence of countries and commodities in global agricultural markets. The model uses a system of supply and demand elasticities incorporated into a series of linear and

IMPACT model was used to generate projections that explore the future role of biotechnology, specifically GMO or transgenic breeding on food supply and demand. These projections were based on results from IMPACT food supply, demand, net trade, and malnutrition. This study used 2000 as the base year and makes projections until 2050. Demand for food crops for biofuel use or land for dedicated energy crops can have a profound effect on the outcomes of the models. Obviously, increased demand for biofuels has a large effect on the outcomes on prices, food availability and resulting impacts on poor people. The additional demand for biofuel use also increases the role of biotechnology in meeting the additional demand.

World food markets will become tighter, with increasing scarcity, as indicated by a projected increase in world food prices for key cereals and meat under the reference projections.

The baseline scenario shows that we are entering a period of structural change in which food prices are likely to stay higher than in the past decades. As shown in Figures 1 and 2 real world prices of most cereals and meat are projected to increase in the coming decades, reversing the trend of declining real prices from the past several decades. Maize, rice, and wheat prices are projected to increase by 24-41 percent in the baseline scenario, and prices for beef, pork, and poultry increase by 9-11 percent (Figures 1-2)[3]. This will, in turn, dampen food demand of poor consumers in all regions and will adversely impact food security and human well-being. Greater scarcity will be driven by both demand and supply factors. Rapid growth in meat and milk demand in most of the developing world will put strong demand pressure on maize and other coarse grains as feed. Population growth and recovery and strengthening of economic growth in Sub-Saharan Africa (SSA) will drive relatively fast growth in regional demand for food. In developing Asia, rising incomes and rapid urbanization will change the composition of cereal demand and per capita food consumption of maize and coarse grains will decline as consumers shift to wheat and rice. As incomes rise further and lifestyles change with urbanization, there will be a secondary shift from rice to wheat in Asia. Demand for wheat and rice will be boosted by growing consumption in SSA with increasing income growth. Strong growth in demand for biofuels produced from maize, sugar, and other food crops will put further upward pressure on

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[3] The IMPACT model generates projections of real world prices of commodities, with a base year of 2000 as a deflator. Projected real prices are therefore lower than current money prices that reflect substantial inflation. As shown in the figure, the model captures a significant share of the increase in real prices since 2000.

prices. These trends will lead to an extraordinary increase in the importance of developing countries in global food markets.

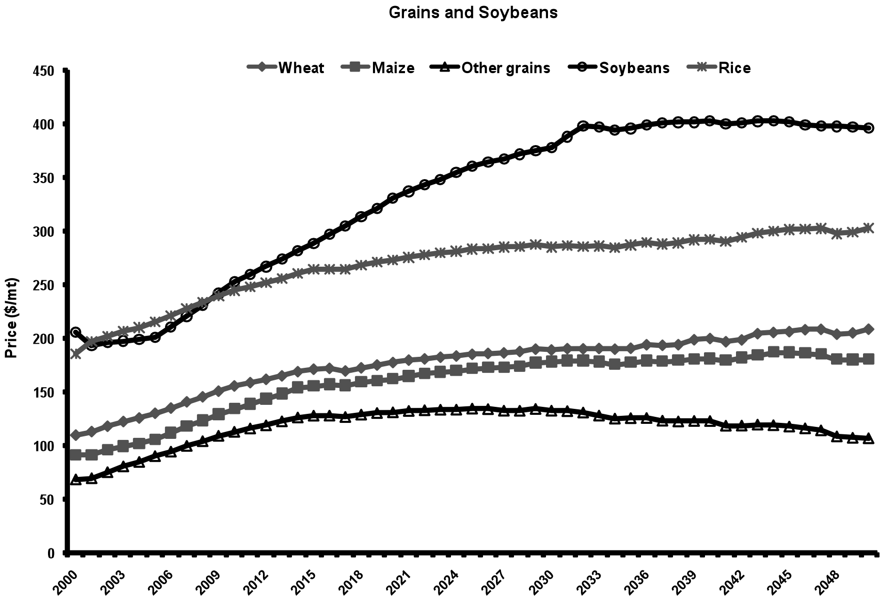


Figure 1. World prices of grains and soybeans for baseline scenario, 2000-2050.

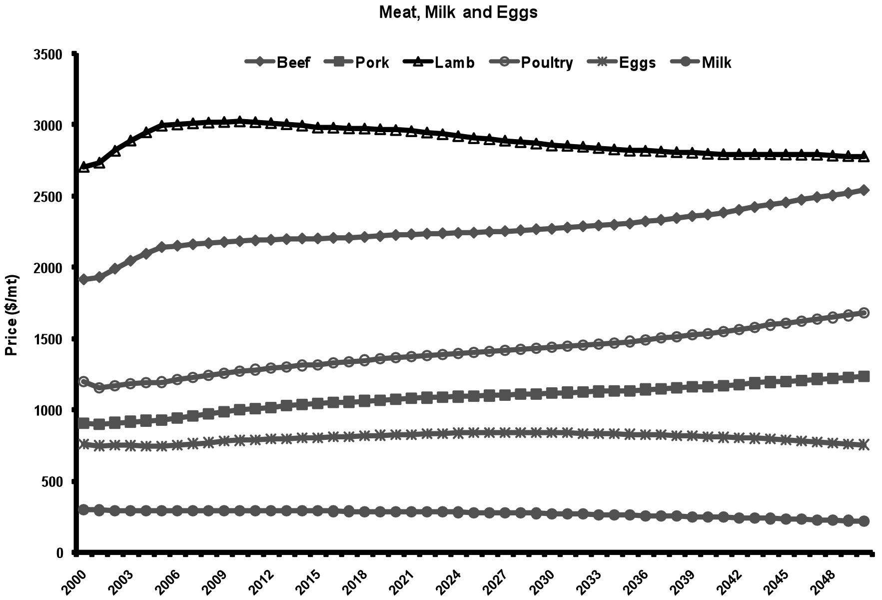


Figure 2. World prices of meat, milk and eggs for baseline scenario, 2000-2050.

On the supply side, water scarcity will increasingly constrain production. There will be virtually no increase in water available for agriculture due to little increase in supply and rapid shift of water from agriculture in key water-scarce agricultural regions in China, India, and Central, West Asia and North Africa (CWANA). Increases in the efficiency with which water is used could mitigate scarcity in some cases. Climate change will increase heat and drought stress in some regions. In many countries in Asia and Latin America where relatively high crop yields have already been achieved through high rates of input use, it will be difficult to achieve further yield gains. Declining availability of water will limit land that can be profitably brought under cultivation. Expansion in crop area will contribute very little to future production growth.

The relationships between animal numbers and yield for meat commodities is presented in Figure 3 while area growth and yield for cereals by region is presented in Figure 4. Details of these figures are given in Table 1. Analysis of the results showed a decline in area for cereals except in Latin America and Caribbean (LAC) and SSA, the latter of which is expanding to relatively poor quality land. The projected slow growth in crop area places the burden of meeting future cereal demand on crop yield growth. Yield growth in both developed and developing countries will slow when compared to the past two decades although there will be considerable variation by commodity and country.

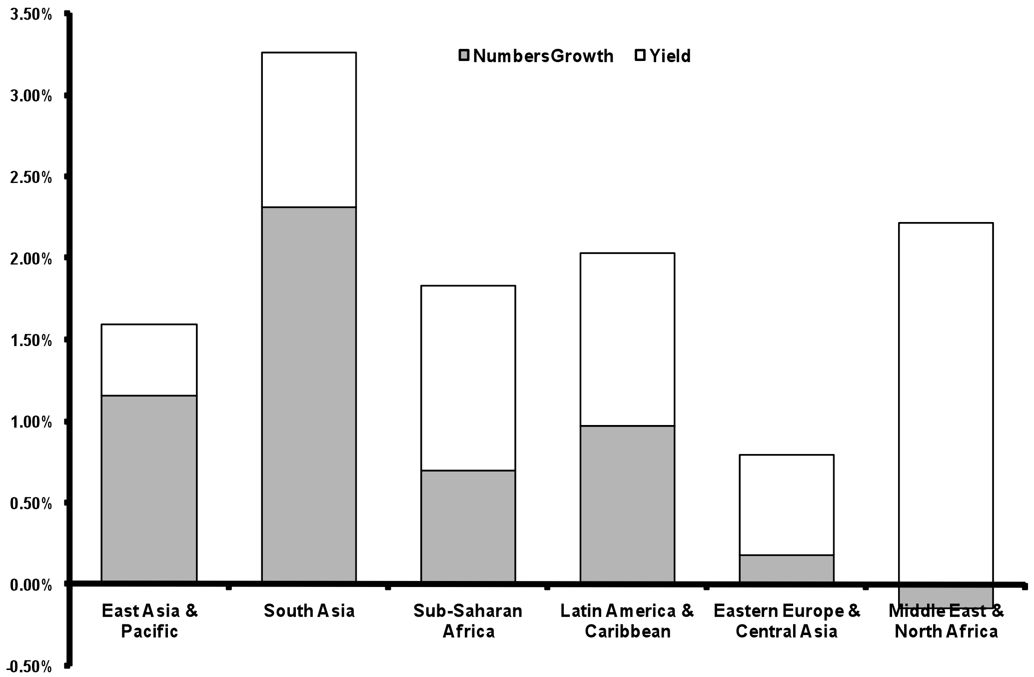


Figure 3. Production growth rate (%) for meat commodities in different regions under baseline scenario, 2050

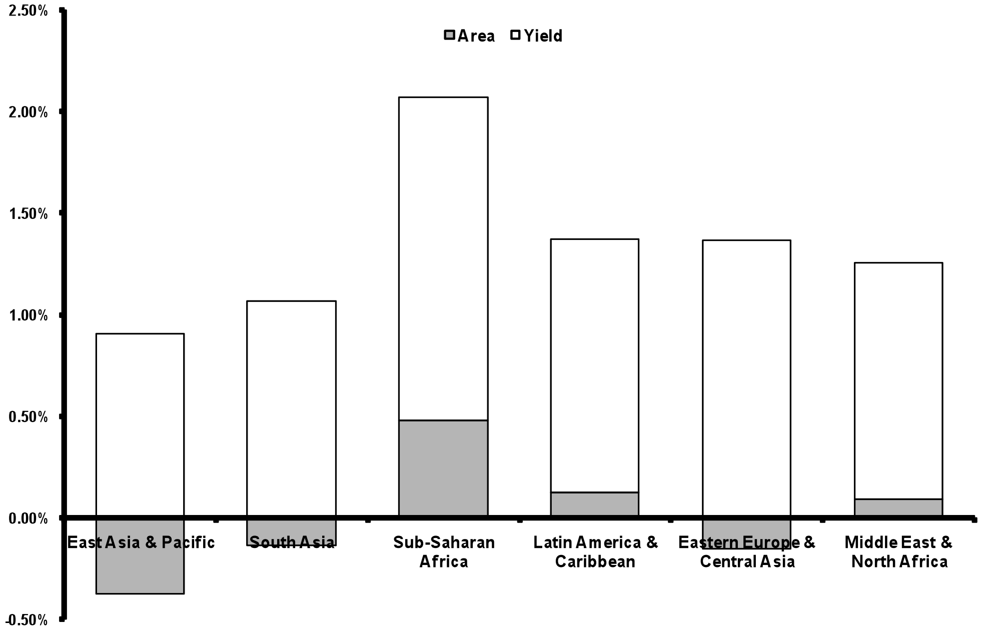
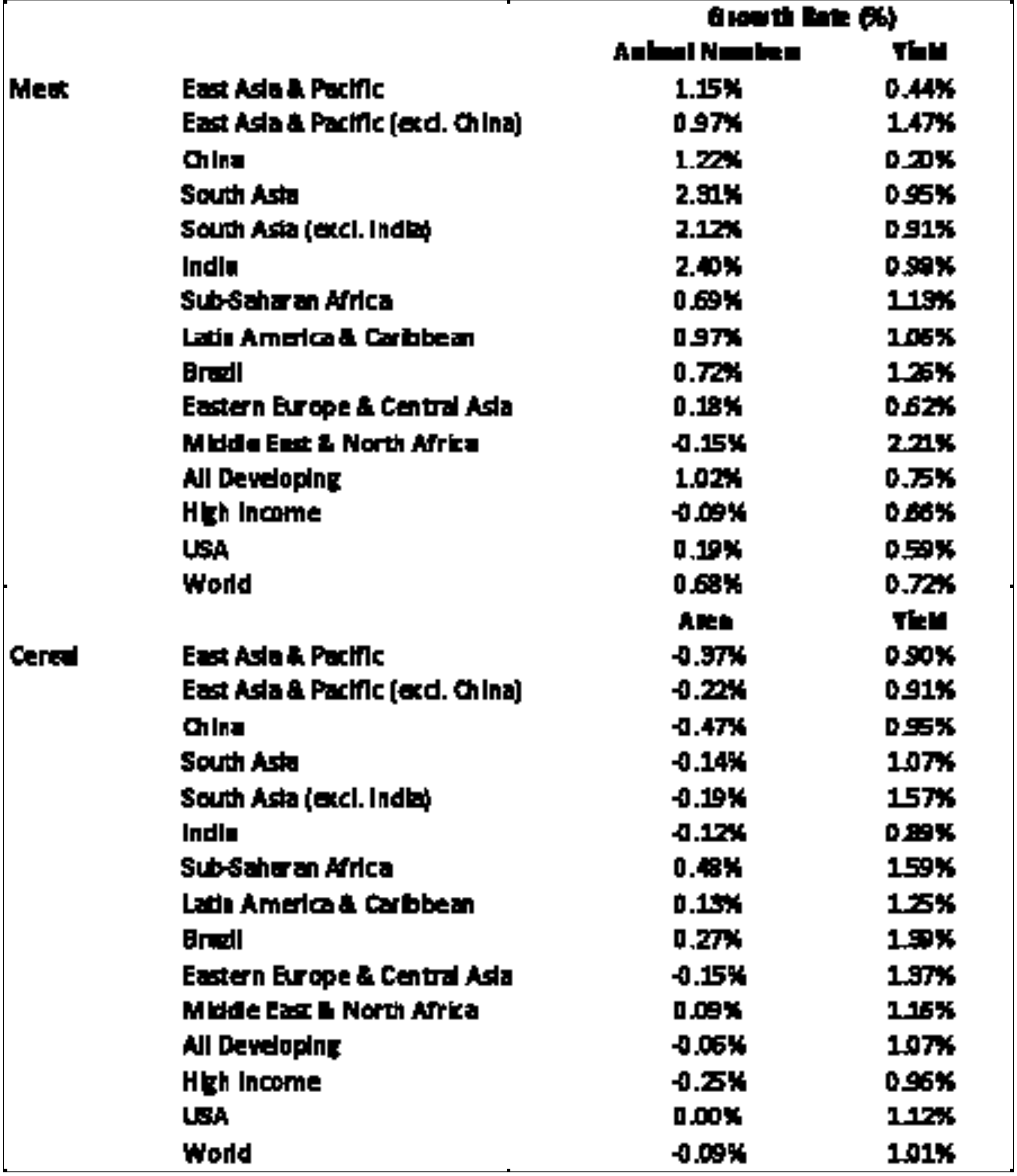


Figure 4. Production growth rate (%) for cereals in different regions under baseline scenario, 2050

Table 1. Yield, animal numbers and area growth rates in different regions (annual growth rate in percent).



		Growth Rate (%)	
		Animal Numbers	Yield
Meat	East Asia & Pacific	1.15%	0.44%
	East Asia & Pacific (excl. China)	0.97%	1.47%
	China	1.22%	0.20%
	South Asia	2.31%	0.95%
	South Asia (excl. India)	2.12%	0.91%
	India	2.40%	0.98%
	Sub-Saharan Africa	0.69%	1.13%
	Latin America & Caribbean	0.97%	1.06%
	Brazil	0.72%	1.26%
	Eastern Europe & Central Asia	0.18%	0.62%
	Middle East & North Africa	-0.15%	2.21%
	All Developing	1.02%	0.75%
	High Income	-0.09%	0.66%
	USA	0.19%	0.59%
	World	0.68%	0.72%
		Area	Yield
Cereal	East Asia & Pacific	-0.97%	0.90%
	East Asia & Pacific (excl. China)	-0.22%	0.91%
	China	-0.47%	0.95%
	South Asia	-0.14%	1.07%
	South Asia (excl. India)	-0.19%	1.57%
	India	-0.12%	0.89%
	Sub-Saharan Africa	0.48%	1.59%
	Latin America & Caribbean	0.13%	1.25%
	Brazil	0.27%	1.99%
	Eastern Europe & Central Asia	-0.15%	1.37%
	Middle East & North Africa	0.09%	1.16%
	All Developing	-0.06%	1.07%
	High Income	-0.25%	0.96%
	USA	0.00%	1.12%
	World	-0.09%	1.01%

There will be only slow improvement in food security in the reference world

The substantial increase in food prices will cause relatively slow growth in calorie consumption, with both direct price impacts and reductions in real incomes for poor consumers who spend a large share of their income on food. This in turn contributes to slow improvement in food security for the poor in many regions. The number of malnourished children was calculated from estimated relationship between percentage of malnourished children and average per capita calorie consumption, the percentage of females with access to secondary education, the quality of maternal and child care (estimated as the status of women relative to men indicated by the ratio of female to male life expectancy at birth), and health and sanitation (estimated as the percentage of the population with access to treated surface water or untreated but uncontaminated water from another source). In the reference run, childhood malnutrition (children of up to 60 months) will continue to decline, but very slowly, with numbers remaining far above the levels targeted by the Millennium Development Goals. Childhood malnutrition is projected to decline from 147 million children in 2000 to 138 million children by 2025 and 104 million children by 2050. The decline in numbers of malnourished children between 2000 and 2050 will be fastest in East Asia and Pacific at 56 percent, followed by Middle East and North Africa at 46 percent, and LAC at 40 percent (Figure 5). Despite improvements, South Asia is projected to still have one-half of the world's malnourished children in 2050. Progress is slowest in SSA—despite relatively rapid income growth and significant area and yield growth as well as substantial progress in supporting services that influence well-being outcomes, such as female secondary education, and access to clean drinking water—by 2050, there will actually be a very slight increase of less than 1 percent in the number of malnourished children in SSA.

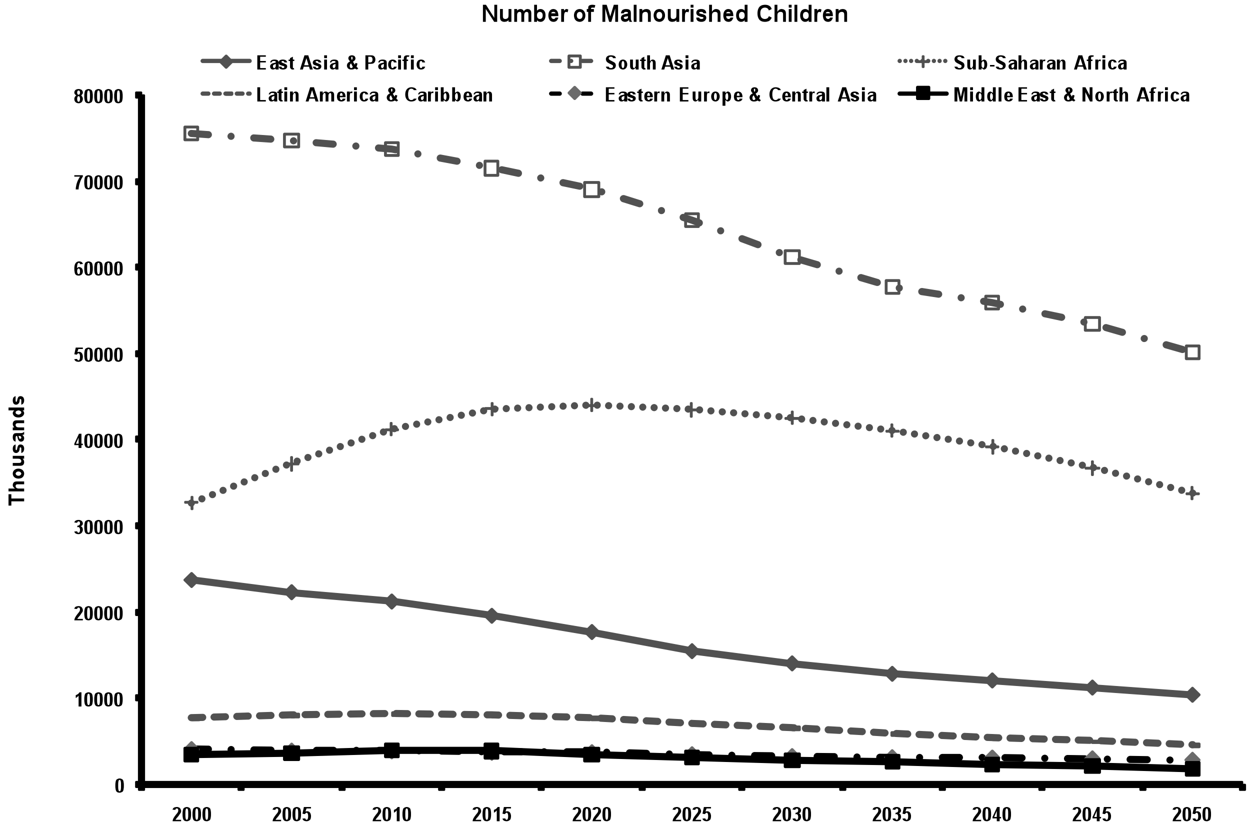


Figure 5. Number of malnourished children in developing countries, 2000-2050.

Productivity growth in the baseline projections

A key assumption in these projections is the rate of yield growth due to technological change. These estimates provide an assessment of the contribution of a number of factors, including conventional breeding (assisted by molecular markers, cell tissue culture, and other tools of biotechnology); genetic modification or transgenic breeding. A principal assumption is that non-price supply (area and yield) projections cannot be assumed to remain constant over the projections period, so growth rate estimates are individually specified over ten-year periods: 2000-05; 2005-10; 2010-15, and so on through 2045-50. Estimated projections are consistent with historical experience of slowing rates of public investments in agricultural research and rural infrastructure. Hence, projected future yield trends account for reduced yield growth that occurred across major commodities in most regions over recent decades, but also reflect best estimates of likely changes in trends and investments. Modern inputs such as fertilizers are accounted for in price effects in the yield response function and as complementary inputs with irrigation and modern varieties generated by research. Ex-post and ex-ante studies of agricultural research priority setting, syntheses of sources of agricultural productivity growth studies, examination of the role of industrialization on technological change growth, and "expert opinion" to generate projected time path of yield growth were applied as part of the methodology. Yield growth projections also account for expected effects of environmental degradation on yields.

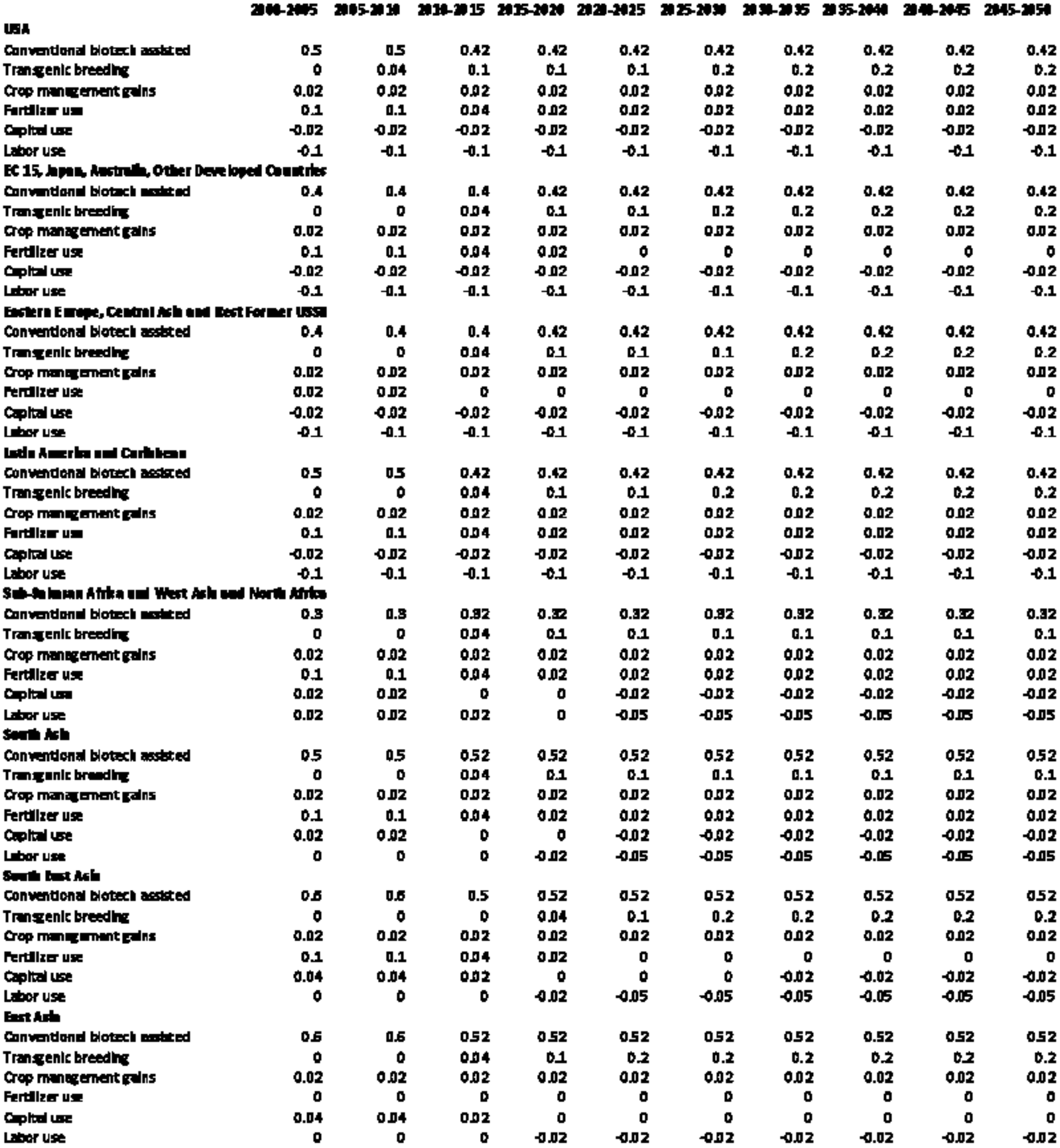
Based on this assessment, yield estimates show a gradually increasing contribution to growth from GMO within the baseline scenario. Estimates of the contribution of GMO to yield improvement are made for all crops and livestock. Tables 2-4 present examples of these projected yield contributions for rice, maize and wheat, respectively. Positive yield responses in rice were demonstrated by the increase in contribution from transgenic breeding in USA as shown in Table 2. Other countries followed the same trend over time. A similar pattern with significant productivity increase was observed in maize (Table 3) and wheat (Table 4). Of the three commodities, maize has the highest yield contribution using transgenic breeding particularly in developing countries. Inputs such as the level of investment and potential that GMOs adoption will likely continue are critical to the higher contributions to maize productivity than for rice or wheat. Moreover, projections showed that improvement in yield for these commodities will progress across countries and in time assuming gradual increase in public acceptance of transgenic cultivars, coordinated with improved financial grants and research support by private sector, international organizations, non-government and government agencies, and academia.

Projections of food supply and demand with zero contribution from GMO

The explicit assessment of the role of GMO in future productivity growth in the baseline scenario allows us to assess the impact of a reduction in this contribution. In this section we examine the impact of a scenario in which the contribution of GMO to productivity growth is set to zero beginning in 2010. This of course represents the maximum impact of removal of GMO as a tool for agricultural productivity growth. If there is a slowdown in GMO contribution relative to the baseline, the impacts would fall between the baseline and the zero-GMO scenario. In the remainder of this section we assess the impact of GMO by comparing the results from these two scenarios.

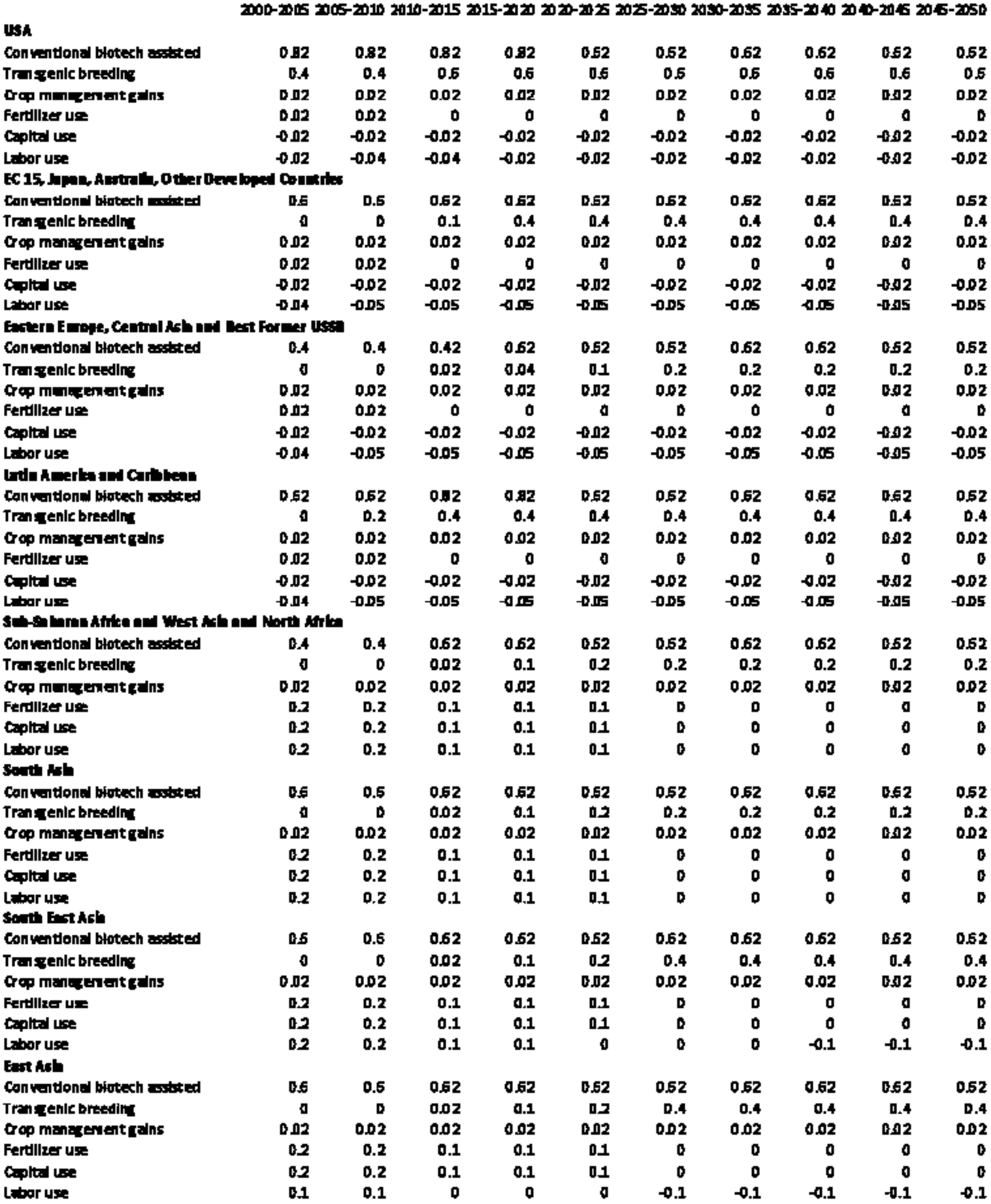
Figure 6 shows the projected impact on real world food prices in 2050 under zero-GMO scenario in 2050. Among agricultural commodities, real price of maize will be most affected, with a 51 percent increase in 2050 in the zero-GMO scenario compared to baseline price as shown in Figure 6. This was followed by other grains at 42 percent, soybean at 37 percent and cotton and sweet potato and yam both at 31 percent price increase. The greater impact of the zero-GMO scenario on maize, soybean and cotton prices are indicative of the highest potential gains from GMO estimated for the baseline scenario. With growing population and income growth, there is also greater pressure to produce maize and soybean for food and feed. Competing demand for food and feed necessitates higher efficiency of crop production to manage escalating commodity prices.

Table 2. Rice contribution to yield growth from GMO, 2000-2050.



	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
USA										
Conventional biotech assisted	0.5	0.5	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Transgenic breeding	0	0.04	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
EC 15, Japan, Australia, Other Developed Countries										
Conventional biotech assisted	0.4	0.4	0.4	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Transgenic breeding	0	0	0.04	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.02	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Eastern Europe, Central Asia and Rest Former USSR										
Conventional biotech assisted	0.4	0.4	0.4	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Transgenic breeding	0	0	0.04	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.02	0.02	0	0	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Latin America and Caribbean										
Conventional biotech assisted	0.5	0.5	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Transgenic breeding	0	0	0.04	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Sub-Saharan Africa and West Asia and North Africa										
Conventional biotech assisted	0.3	0.3	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Transgenic breeding	0	0	0.04	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Capital use	0.02	0.02	0	0	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	0.02	0.02	0.02	0	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
South Asia										
Conventional biotech assisted	0.5	0.5	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Transgenic breeding	0	0	0.04	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Capital use	0.02	0.02	0	0	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	0	0	0	-0.02	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
South East Asia										
Conventional biotech assisted	0.6	0.6	0.5	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Transgenic breeding	0	0	0	0.04	0.1	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.02	0	0	0	0	0	0
Capital use	0.04	0.04	0.02	0	0	0	-0.02	-0.02	-0.02	-0.02
Labor use	0	0	0	-0.02	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
East Asia										
Conventional biotech assisted	0.6	0.6	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Transgenic breeding	0	0	0.04	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0	0	0	0	0	0	0	0	0	0
Capital use	0.04	0.04	0.02	0	0	0	0	0	0	0
Labor use	0	0	0	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02

Table 3. Maize contribution to yield growth from GMO, 2000-2050.



	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
USA										
Conventional biotech assisted	0.82	0.82	0.82	0.82	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.02	0.02	0	0	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.02	-0.04	-0.04	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
EC 15, Japan, Australia, Other Developed Countries										
Conventional biotech assisted	0.6	0.6	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.02	0.02	0	0	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.04	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Eastern Europe, Central Asia and Rest Former USSR										
Conventional biotech assisted	0.4	0.4	0.42	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0	0.02	0.04	0.1	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.02	0.02	0	0	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.04	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Latin America and Caribbean										
Conventional biotech assisted	0.62	0.62	0.82	0.82	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.02	0.02	0	0	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.04	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Sub-Saharan Africa and West Asia and North Africa										
Conventional biotech assisted	0.4	0.4	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0	0.02	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Capital use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Labor use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
South Asia										
Conventional biotech assisted	0.6	0.6	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0	0.02	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Capital use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Labor use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
South East Asia										
Conventional biotech assisted	0.6	0.6	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0	0.02	0.1	0.2	0.4	0.4	0.4	0.4	0.4
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Capital use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Labor use	0.2	0.2	0.1	0.1	0	0	0	-0.1	-0.1	-0.1
East Asia										
Conventional biotech assisted	0.6	0.6	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Transgenic breeding	0	0	0.02	0.1	0.2	0.4	0.4	0.4	0.4	0.4
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Capital use	0.2	0.2	0.1	0.1	0.1	0	0	0	0	0
Labor use	0.1	0.1	0	0	0	-0.1	-0.1	-0.1	-0.1	-0.1

Table 4. Wheat contribution to yield growth from GMO, 2000-2050.

	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
USA										
Conventional biotech assisted	0.5	0.52	0.54	0.54	0.54	0.44	0.44	0.44	0.44	0.44
Transgenic breeding	0	0	0.04	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.08	0.08	0.04	0.02	0	0	0	0
Capital use	-0.02	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Labor use	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
EC 15, Japan, Australia, Other Developed Countries										
Conventional biotech assisted	0.4	0.42	0.42	0.42	0.42	0.34	0.34	0.34	0.24	0.24
Transgenic breeding	0	0	0.04	0.1	0.14	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.04	0.04	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Eastern Europe, Central Asia and Rest Former USSR										
Conventional biotech assisted	0	0	0	0.04	0.06	0.12	0.12	0.12	0.12	0.12
Transgenic breeding	0	0	0	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.04	0.04	0	0	0	0	0	0
Capital use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Latin America and Caribbean										
Conventional biotech assisted	0.5	0.5	0.5	0.52	0.52	0.52	0.42	0.42	0.22	0.22
Transgenic breeding	0	0	0.04	0.1	0.14	0.2	0.2	0.2	0.2	0.2
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.06	0.06	0.04	0	0	0	0	0
Capital use	0	0	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Labor use	0	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Sub-Saharan Africa and West Asia and North Africa										
Conventional biotech assisted	0.1	0.1	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Transgenic breeding	0	0	0	0	0.02	0.04	0.1	0.1	0.1	0.1
Crop management gains	0.02	0.02	0.1	0.1	0.1	0	0	0	0	0
Fertilizer use	0.1	0.1	0.06	0.06	0.06	0.02	0.02	0.02	0.02	0.02
Capital use	0.02	0.02	0.02	0.02	0.02	0	0	0	-0.02	-0.02
Labor use	0.02	0.02	0.02	0.02	0.02	0	0	0	-0.02	-0.02
South Asia										
Conventional biotech assisted	0.6	0.6	0.52	0.52	0.52	0.42	0.42	0.42	0.32	0.32
Transgenic breeding	0	0	0.02	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.06	0.04	0.02	0	0	0	0	0
Capital use	0.02	0.02	0	0	0	0	0	0	0	0
Labor use	0.02	0.02	0	0	0	0	-0.02	-0.02	-0.02	-0.02
South East Asia and East Asia										
Conventional biotech assisted	0.6	0.6	0.62	0.52	0.52	0.52	0.42	0.42	0.32	0.22
Transgenic breeding	0	0	0.02	0.02	0.04	0.04	0.1	0.1	0.1	0.1
Crop management gains	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fertilizer use	0.1	0.1	0.06	0.04	0.02	0	0	0	0	0
Capital use	0.02	0.02	0	0	0	0	0	0	-0.02	-0.02
Labor use	0.02	0.02	0	0	0	0	-0.02	-0.02	-0.02	-0.02

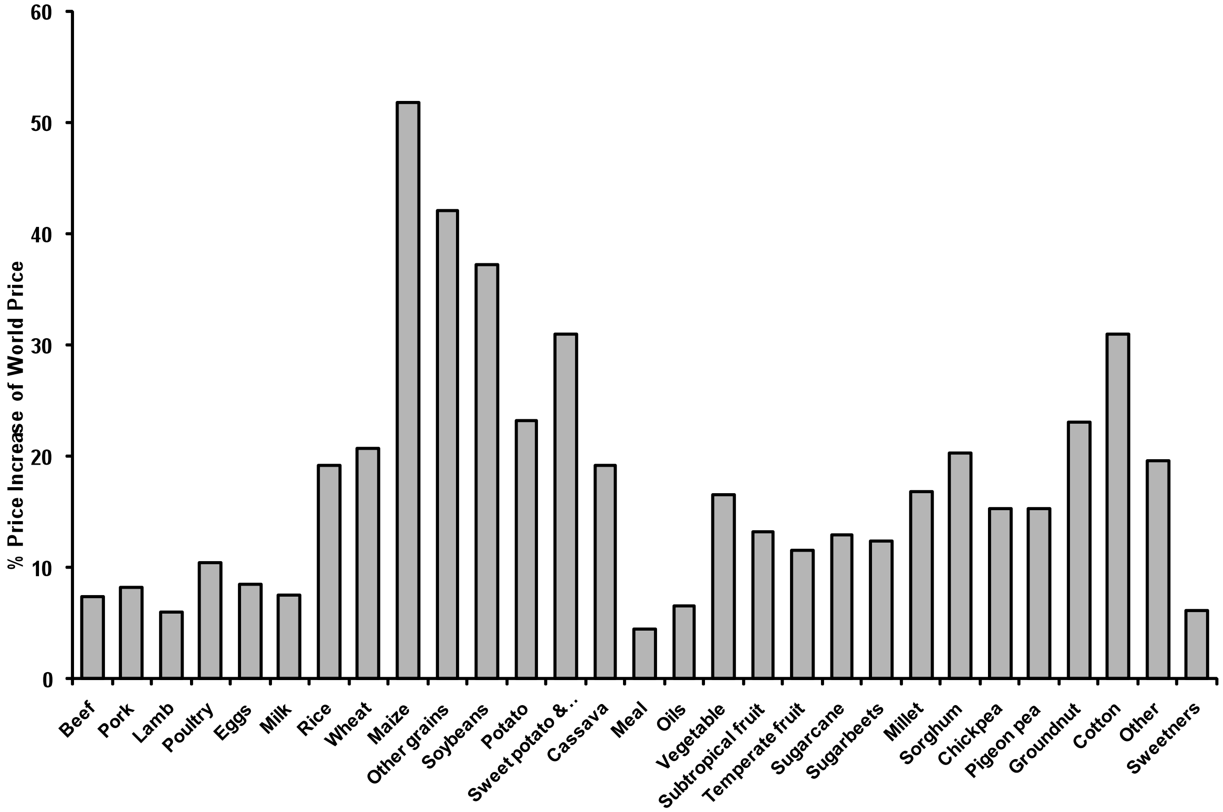


Figure 6. World price change (%) of zero-GMO scenario compared to baseline price in 2050.

Meanwhile, price increases of meat commodities like beef, pork, lamb and poultry ranged from 6 to 11 percent in 2050 compared to the baseline, reflecting the smaller role of GMO in the baseline projections.

A comparison of projected real world prices of rice, maize and cassava is given in Figure 7 to show the trajectory of prices. Even under the baseline, rice shows considerable increasing real price from US$186 per mt in 2000 to US$303 per mt in 2050 for baseline scenario, and will peak at US$331 per mt in 2050 for zero-GMO. Maize has a similar trend but more dramatic increase - baseline scenario has a doubling rise in price from US$91 per mt in 2000 to US$181 per mt in 2050, and worsening at US$274 per mt in 2050 for the zero-GMO scenario. Cassava has a different trend, where price declines in later years in the baseline scenario due to declining demand growth, but still shows higher prices in 2050 for zero-GMO scenario.

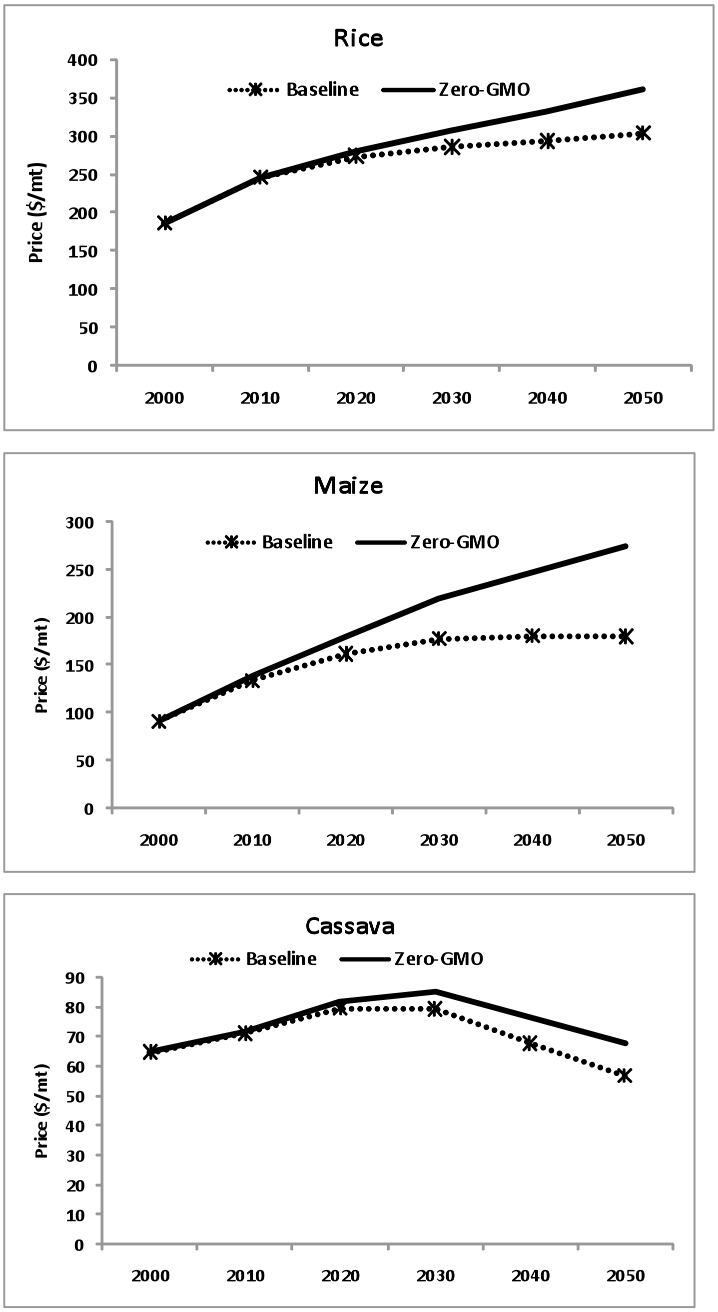


Figure 7. World prices of rice, maize and cassava under baseline and zero-GMO scenarios, 2000-2050

Cereal consumption

Cereal food consumption in different regions is presented in Figure 8 for baseline and zero-GMO scenarios. With changing patterns of demand due to income growth, urbanization, and Westernization of diets, East, South Asia and Pacific gave the highest decline in cereal consumption at less than 18 kg/person per year under baseline scenario and 23 kg/person per year under zero-GMO in 2000-2050. Most significantly, because of the slower productivity growth and higher food prices, the projected growth in per capita cereal food consumption in SSA is cut in half under the zero-GMO scenario, from 20 kg/person per year baseline scenario to 11 kg/person per year in zero-GMO scenario in 2000-2050.

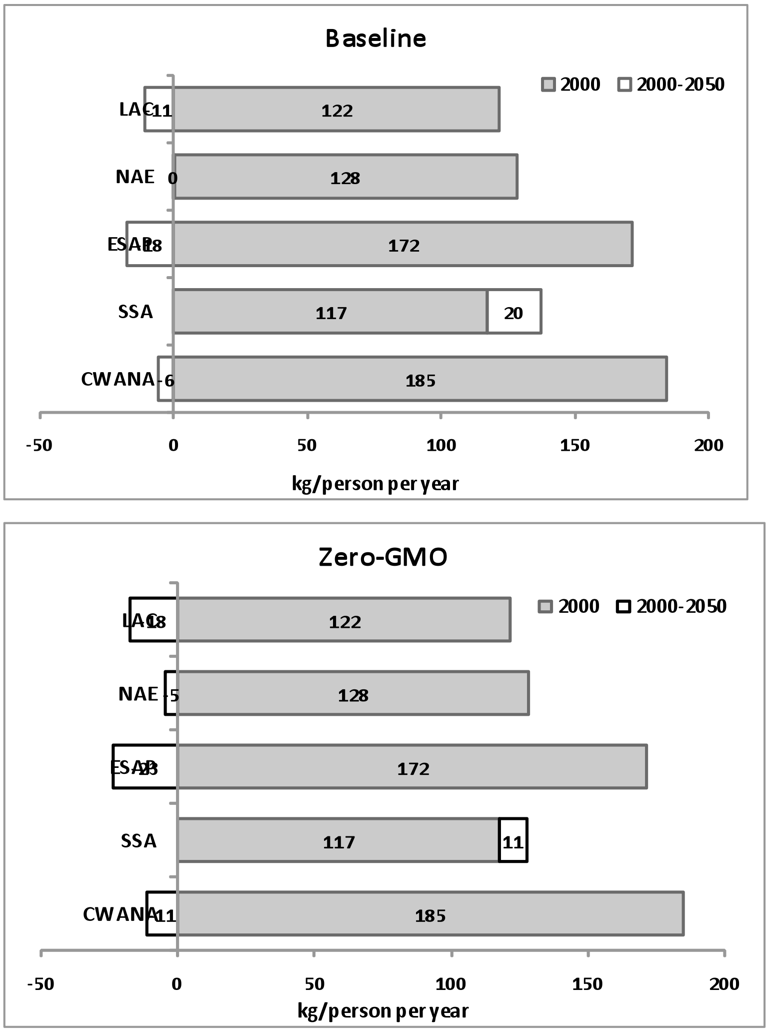
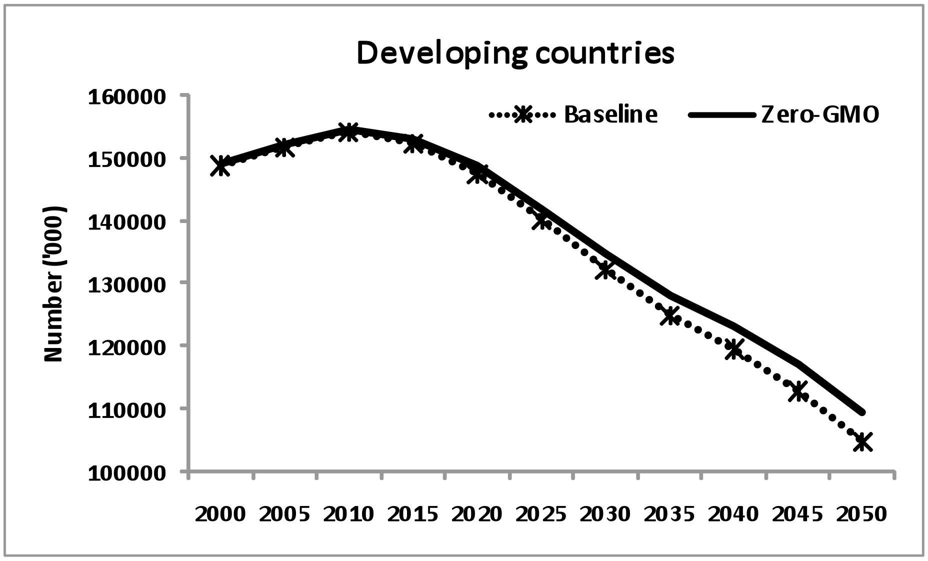


Figure 8. Cereal consumption in different regions between baseline and zero-GMO scenarios, 2000 and 2050.

Total malnutrition

Total malnourished children were calculated under baseline and zero-GMO scenarios. Figure 9 shows that zero-GMO scenario results in an increase of 2 million malnourished children in SSA and nearly 5 million in developing as a whole, thus signifying a serious negative impact on human well-being if GMOs do not contribute to future growth in agricultural productivity.



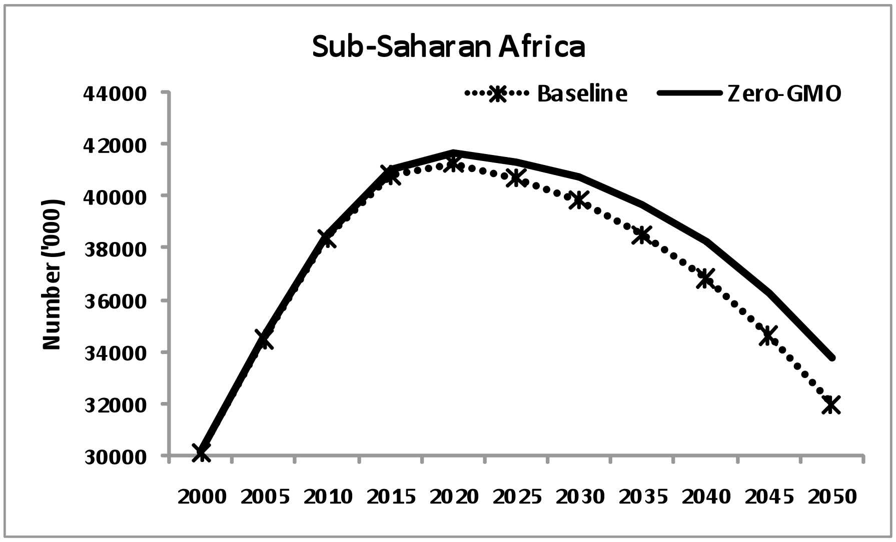


Figure 9. Number of malnourished children in developing countries and Sub-Saharan Africa under baseline and zero-GMO scenarios, 2000-2050

III. Application of Biotechnology to Food and Biofuel Crops

Findings from the modeling demonstrate the need for increasing crop yields to meet food needs in the coming decades and that biotechnology can contribute to meeting those needs. This section will summarize the state of biotechnology application to the main crops of interest for biofuels, many of which are also among the world's most important food crops. Production of ethanol from starch crops and biodiesel from oil crops is based on established technologies. Research focused on using cellulose and other plant biomass components for biofuels is spawning a generation of dedicated energy crops. For purposes of this discussion we group biofuels crops into three categories: 1) food/energy crops supported by an active private research sector including maize, soybean and canola; 2) food/energy crops with limited resources for genetic improvement including sugarcane, cassava and oil palm; and 3) dedicated energy/biomass crops including switchgrass, *Miscanthus*, sorghum and *Jatropha*.

The application of plant breeding and biotechnology for crop improvement has been concentrated on widely grown, commercial crops primarily maize, soybean, cotton, and canola. Breeding and research in these crops is supported by the private investment of the seed industry. Crop cultivars with transgenic traits have been broadly commercialized in the last 12 years. In 2007, transgenic varieties, most containing insect and/or herbicide resistance traits, were grown on 114.3 million hectares (ha). The US leads in adoption of transgenics with 50.5 percent of the transgenic crop area. Argentina, Brazil, Canada, India and China grew 45 percent of the total area devoted to transgenics (James 2007). Cultivars with transgenic traits for disease resistance, abiotic stress resistance, nutritional enhancement, modified oil and grain yield will be released in the next 5 to 10 years (BASF, Dow AgroSciences, Monsanto, Pioneer Hi-Bred, Syngenta, websites). Expansion of GM technologies beyond large commodity crops in industrialized countries is occurring more slowly. Several crops, particularly transgenic cotton, have been successfully adopted by small farmers in India and China (James 2007).

Many of the challenges of using crops for biofuels production can be addressed through biotechnology. Crops must necessarily be adapted for growth in a wide variety of environments making biotechnological approaches for crop adaptation of value in biofuels crops as well as food and fiber crops. Introduction of specific traits related to crop use for biofuels can increase the economic feasibility of a crop's use by raising productivity or increasing the efficiency of processing. Some authors have argued that widespread biofuels production from crops will, in fact, require a transgenic approach. Crops have not been selected for use as biofuel feedstocks through domestication and breeding, and Gressel (2007) points out that the "quickest, most efficient, and often, the only way to convert plants to biofuels feedstocks is biotechnologically".

Current status of biotechnology application to maize, soybeans and canola

Application of plant breeding over many years has resulted in high, consistent yields of maize, soybeans and canola in the developed world and in a number of developing countries with good growing conditions including Brazil, Argentina and China. Even so, yields remain low in much of Africa, Asia and Latin America because of unimproved germplasm, poor soil nutrition, abiotic stresses and pests. While much of our discussion focuses on the application of biotechnology to crops, it is important to note that in many parts of the world there is significant opportunity to increase crop productivity through conventional approaches.

Maize, soybean and canola cultivars containing transgenes for insect resistance and herbicide resistance have been available for 5-12 years and have been widely adopted by farmers (James 2007). The current product pipeline for transgenic traits in maize, soybean and canola is summarized in Table 5.

Table 5. Commercial transgenic trait pipeline for maize, soybean and canola.

	Maize	Soybean	Canola
Insect resistance	1	2	5
Herbicide resistance	1	1	1
Disease resistance	4	2	3
Abiotic stress tolerance	3	3	3
N use efficiency	4	4	5
Yield	3	2	3
Biofuel yield	3	2	4
Biofuel processing traits	2	3	4

1. Commercially available
2. Commercially available by 2010
3. Commercially available 2010-2015
4. Commercially available 2015-2020
5. No current program

(BASF, Dow AgroSciences, Monsanto, Pioneer Hi-Bred Intl., Syngenta websites)

Genes for agronomically important traits such as, disease resistance, drought tolerance salinity tolerance, heat tolerance and yield have been identified and are in various levels of field testing. Cultivars containing these traits are projected to be commercialized by seed companies in the markets where genetically modified (GM) products are currently accepted (BASF, Dow AgroSciences, Monsanto, Pioneer Hi-Bred Intl., Syngenta websites). Commercial breeding programs routinely incorporate the use of molecular marker based approaches to incorporate transgenes and improve the efficiency of selection for multiple gene traits in these crops.

Most of the major research-driven seed companies are also marketing conventional maize hybrids identified for use in ethanol production (Monsanto, Pioneer Hi-Bred Intl., and Syngenta websites). Yield of starch is the most important trait in maize hybrids used for ethanol production while oil content is the most important trait for biodiesel production from oil crops. Transgenic approaches for increasing starch in maize or oil in soybean and canola, as well as, modifying oil profile for biofuel use are also in the company pipelines (Monsanto, Pioneer Hi-Bred Intl., Syngenta websites). Syngenta has developed a transgenic maize containing amylase that converts starch to sugar for the production of ethanol. The trait is currently in regulatory review and should be released before 2010 (Syngenta website).

Private research spending by the commercial seed companies to improve maize, soybean and canola for farmers in the developed world exceeds US$1 billion/year (BASF, Dow AgroSciences, Monsanto, Pioneer Hi-Bred Intl., Syngenta websites). The rate of private research spending has increased dramatically in the last 20 years. Since the results of this spending take many years to produce new products, it is likely that the rate of yield improvement in commercially important food crops will increase. Research spending for these three crops in the developing world will remain modest. The Consultative Group on International Agricultural Research (CGIAR) spending on maize is less than US$35 million/yr (CIMMYT 2007). Rapid rates of yield improvement could be realized with increased research for the developing world since yield levels in many developing countries are low and proven technologies are readily available. Opportunities for raising yield levels through improved seed coupled with increased fertilizer use are particularly high in Africa (Morris et al. 2007).

Currently, grain is harvested and leaves, stems and other plant parts (stover) are returned to the soil. Use of stover or biomass for biofuel production could complement grain production in maize. Numerous programs are developing maize stover more suited to ethanol production (Dhugga 2007). Sustainability issues exist since stover would no longer be returned to the soil increasing the chances of erosion and decreasing soil tilth (Wilhelm et al. 2007). Use of this biomass from crop stover is subject to many of the issues related to use dedicated energy crops and will be discussed at length in the section on cellulosic crops.

Biotechnology applications to sugarcane, cassava and oil palm

Sugarcane, cassava, oil palm are tropical food crops with high suitability for biofuel use. Relative to maize, soybean and canola, they have not been the target of significant research spending for breeding or biotechnology. Table 6 summarizes the current status of transgenic crop development in these three crops.

Table 6. Availability of transgenic sugarcane, cassava and oil palm to farmers

	Sugarcane	Cassava	Oil Palm
Insect resistance	3	3	3
Herbicide resistance	3	5	3
Disease resistance	4	4	4
Abiotic stress tolerance	3	4	4
N use efficiency	5	5	5
Yield	4	4	5
Biofuel yield	4	4	5
Biofuel processing trait	4	4	5

1. Commercially available
2. Commercially available by 2010
3. Commercially available 2010-2015
4. Commercially available 2015-2020
5. No current program

(Gressel 2007, Murphy 2007, Lakshmanan et al. 2005, Syngenta website)

Sugarcane

Sugarcane is broadly adapted to the tropics and is grown on 20 million hectares in more than 90 countries. Sugarcane represents the most successful and widely used biofuel crop. Brazil has extensive experience in substituting sugarcane ethanol for petroleum for transportation fuel beginning in the 1970's with the initial oil shocks and continuing to the present (Nass et al.

2007). Sugarcane is recognized as the most energy efficient crop based ethanol source. Popular sugarcane varieties are inter-specific hybrids. The crop is characterized by a narrow gene pool, complex genome, poor fertility (seed set) and long breeding times (Lakshmanan et al. 2005). Given the difficulties of working with sugarcane and the relatively small size of the research investment, large increases in productivity are likely to come slowly. Sugarcane, which has been selected for biomass instead of sugar yield, is referred to as energy cane. Waste sugarcane biomass (bagasse) which is currently used for firing ethanol plants, could increase the already high energy efficiency of sugarcane, if cellulosic ethanol becomes a commercial reality.

Molecular marker based approaches for improving sugarcane are being used to study crop diversity within sugarcane varieties. Introgression of quantitative trait loci (QTL) can also be facilitated through the use of markers. Eyespot susceptibility and rust resistance, two single major gene traits have been mapped in sugarcane. QTL's for traits related to sucrose content have also been identified (Lakshmanan et al. 2005).

The large size of the sugarcane genome has limited efforts at DNA sequencing to expressed sequence tags (EST's) or genes that code for proteins. Brazilian researchers have generated more than 250,000 EST's that mark 33,000 unique genes. Microarray technologies that identify gene expression for large numbers of genes are also being applied to identify genes involved in disease resistance and carbohydrate metabolism (Lakshmanan et al 2005; Vittore et al. 2003).

Considerable progress has been made in developing transformation systems for sugarcane. Biolistics is currently the preferred method for transforming sugarcane although simpler insertion patterns from Agrobacterium mediated transformation make it attractive as well. An array of genes including those for plant architecture, abiotic stress, nitrogen use, virus resistance, fungal disease resistance, insect resistance, herbicide resistance and sugar content are being field tested (Bur. Sugar Expt. Stations 2008; Snyman 2004; Lakshmanan et al. 2005). In spite of the relatively efficient transformation systems a number of challenges exist including genotype dependent transformation and limited numbers of useful promoters (Lakshmanan et al. 2005).

A number of programs use biotechnology to improve sugarcane (Nass et al. 2007). Two private companies, Copersucar and Canavalis, and two public organizations, Ridesa (Planalsucar) and Instituto Agronomico, lead the sugarcane breeding efforts in Brazil. These programs have large germplasm collections with significant screening capability and are building molecular and genomic toolkits to improve program efficiency (Nass et al. 2007).

Overall, the industry lacks extensive experience in developing transgenic cultivars and will likely encounter many challenges in providing transgenic varieties to farmers. Timelines for farmer access to approved sugarcane cultivars will be in the 5-10 year timeframe with significant acreage delayed beyond 2015.

Cassava

Cassava roots produce virtually pure starch. Hydrolyzing starch to sugar for fermentation to ethanol is straightforward. As a major crop of poor farmers, special consideration is needed when considering cassava use for biofuels. A number of countries are exploring this possibility, particularly as a domestic fuel source and a mechanism for adding value to the cassava crop. The International Center for Tropical Agriculture (CIAT) has led the exploration of these possibilities (Biopact 2007a).

Cassava improvement is technically challenging. Cassava does not reproduce true to type from seed and there is strong inbreeding depression. In spite of these challenges, improvement has been made through traditional breeding. Biotechnology has also been applied to some of the problems of cassava. Tissue culture to produce “clean stakes” or sterile planting material is particularly valuable (Aerni 2006). Transformation systems have been developed, and it is possible to insert genes into cassava and regenerate plants. Interest has been focused on insect (whitefly and stem borer) resistance, African Cassava mosaic virus disease resistance, nutritional quality, starch composition and post harvest quality (Aerni 2006). Development of transgenic cassava plants with bacterial enzymes involved in starch accumulation increased the biomass of above ground portions and starch in roots suggesting that biofuels yields could be increased by increasing the starch yield (Ihemere et al. 2006). Since there is a limited commercial market for cassava, levels of research spending for breeding and biotechnology tend to be small. Most research has been done at the CGIAR centers, particularly CIAT, the Donald Danforth Plant Science Center and at universities funded through governments, foundations and other public sources. Formation of the Cassava Biotechnology Network has coordinated efforts and improved the effectiveness of biotechnology research in cassava (Aerni 2006).

Oil Palm

Oil palm is the most productive oil crop in the world with current yields around 4 tons per hectare. Fruit is produced throughout the year, and trees have a productive life of 25-30 years (Murphy 2007). While oil palm has been an important source of edible oils, recent demand for biodiesel in Europe has resulted in extensive planting of oil palm plantations in the tropics, particularly Malaysia and other parts of Southeast Asia (Rosenthal 2007). Palm oil has been a relatively low value commodity which has limited incentives to improve yield through conventional methods. Improved management could easily double yields and trees improved through breeding yield in excess of 10 tones per hectare. Yield potential, estimated from individual trees exceeds 60 tones per hectare (Murphy 2007).

Since oil palms do not produce seed for 6-7 years, molecular marker breeding approaches are quite valuable for making early selections. Tissue culture has also been used for mass clonal propagation. This technique allows a breeder to select a tree with desirable traits and propagate it immediately without waiting for seed production. Clonal propagation has been applied at the commercial plantation scale and is now an important tool. However, variation introduced through tissue culture has resulted in problems and requires management (Murphy 2007). In spite of limited resources for the application of biotechnology to oil palm, a workable transformation system exists. Transgenics containing the bacterial insect resistance gene (Bt) have been developed although they are many years away from farmer adoption (Lee et al 2006). The two major pests of oil palm, basal stem rot, caused by the fungus *Ganoderma lucidum* and the rhinoceros beetle, could both be addressed by a transgenic approach in the future. A partnership between Synthetic Genomics, a US based genomics company and the Asiatic Centre for Genome Technology, a wholly owned subsidiary of the Asiatic Berhan, an oil palm plantation company, was recently announced to sequence the genome of the oil palm (Biopact 2007b).

Palm oil can be used to produce biodiesel. Palm oil biodiesel is comprised of long chain, unsaturated fatty acids which tend to congeal in cold weather. Currently, energy-requiring chemical methods are used to solve this problem. It has been suggested that a biotechnology approach involving antisense or RNAi approaches to knock out the elongase enzymes would result in shorter chain fatty acids and that desaturates could be added to increase double bonds and fluidity of the fuel (Gressel 2008). While this is technically feasible, we are not aware of groups taking this approach in oil palm.

Developing dedicated energy crops for cellulosic biofuels

Considerable resources are being devoted to developing commercial methods to produce biofuels from biomass. Many potential sources for biomass exist including unused crop materials like stalks and leaves, waste from forestry operations and crops (or species) grown specifically for cellulose and other biomass components (dedicated energy crops). There is considerable enthusiasm for dedicated energy crops, and many species are being evaluated for this purpose (Houghton et al. 2006; Perlack et al. 2005). Initial planning documents have identified an "ideal" biomass crop as having the following attributes: C4 photosynthesis, long canopy duration, recycles nutrients to roots, clean burning, low input, sterile (non-invasive), winter standing, easily removed, high water use efficiency, no known pests or diseases and harvestability using existing farm equipment (Houghton et al. 2006). Studies have concluded that dedicated energy crop production will be commercially viable by 2020 (Houghton et al. 2006).

Global differences in growing conditions and agroecology will result in many species being used for biofuels. We will concentrate on a subset that seems most likely to be of widespread importance and to be impacted by biotechnology. These include switchgrass (*Panicum virgatum*), *Miscanthus* (Miscanthus giganteus), sorghum (*Sorghum bicolor*) and *Jatropha curcas*. It is important to understand that switchgrass, *Miscanthus*, and *Jatropha*, are not actually crops. They have not been domesticated through thousands of years of selection and have only been improved in recent years. That doesn't mean that significant progress is unlikely, only that the starting point is different than crops like maize and sugarcane. Dedicated energy crops have been chosen for biofuels use by researchers and companies because of their high levels of biomass production and adaptation to a number of relatively temperate growing areas. One of the major challenges for cellulosic biofuels is the sustainable production of biomass while using the least possible land (Lynd et al. 2008). Most have the advantage of being perennial and storing carbon in the roots over many years. Perennial crops fix carbon over a longer part of the year than annuals and will also limit soil erosion (Houghton et al. 2006). It is also possible that some biofuels will be produced from perennials grown in natural mixtures that approximate natural ecosystems (Tilman et al. 2006). Many people in the industry feel that the requirement for high biomass production will preclude these systems unless the use of more natural species mixes are driven by government programs that provide farmers with payment for the additional ecosystem services these systems provide such as water purification, wildlife habitat and carbon storage.

The current enthusiasm for biofuels has resulted in private venture capital funding for start up biotechnology companies devoted to developing these species. This is coupled with government sponsored research to improve the crops and develop techniques for profitably processing the biomass into fuel (Waltz 2008).

Switchgrass

Switchgrass is a native American grass with average biomass yields of 5.5 to 8.0 dry tons/acre. Selected clones produce more than 8 tons/acre. The highest yields have exceeded 15 tons/acre, demonstrating its suitability as a biomass crop and the potential for improvement through plant breeding (Perlack et al. 2005; Schmer et al. 2007). Several breeding programs currently exist within universities and as part of public private partnerships (Samuel Roberts Noble Foundation and Ceres Biotechnology Inc.). Breeding targets include biomass yield and seed health and germination. These programs are developing breeding lines and finished cultivars of switchgrass. There is also interest in genetic systems that will allow development of hybrid switchgrass.

There are a number of approaches that use biotechnology to improve switchgrass. Significant sequencing of the expressed genes of switchgrass has resulted in 12,000 sequenced genes which are being evaluated for their effects on biomass composition and biofuel conversion traits (Ceres Company website). Transformation systems have been developed for switchgrass and transgenics for drought tolerance, salinity tolerance, and herbicide resistance are in the early stages of product development.

Processing efficiency for biomass is a critical factor determining the eventual commercial feasibility of cellulosic biofuels. Several companies are working to engineer plants to contain genes for enzymes that will digest the cellulose and other cell wall compounds. Precise expression of these genes will be required so that the enzymes are produced in a controlled way following harvest. Inducible promoters for this purpose are well understood and will be an important component of these systems. These promoters might be turned on by temperature, pH, or specific chemicals (Edenspace System Corp. website). This *in planta* approach could result in a crop with greater value. Genes for reduced lignin have also been identified.

While programs using biotechnology to improve switchgrass are promising, several hurdles exist. Switchgrass is not widely grown and agronomic systems are currently in the development stage. Widespread demand for biomass for biofuels is also at least five years away. Conventional cultivars of switchgrass with reasonable levels of environmental adaptation and adequate yields are still in the development stage. GM cultivars will be developed concurrently with conventional improvements in the species; however, transgenic traits in switchgrass will not impact production for at least 10 years.

Research on switchgrass is currently funded by public sources primarily in the US. Additional capital is available from private sources and at least three venture capital supported companies (Ceres Biotechnology Inc., Mendel Biotechnology Inc. (in partnership with Monsanto) and Edenspace Bioscience Systems) have improvement of dedicated energy crops as their mission (Ceres Biotechnology, Edenspace Systems Corp. and Mendel Biotechnology websites).

Miscanthus

Miscanthus is a large perennial grass related to sugarcane. It grows well in temperate climates and is capable of producing biomass yields in the range of 15-20 dry tons/acre (Somerville 2007). Limited breeding programs for *Miscanthus* have existed for 20 years including programs in the private sector (Tinplant Biotechnik und Pflanzenvermehrung GmbH recently bought by

Mendel Biotechnology Inc., Mendel Biotechnology website). Breeding programs have focused on increasing genetic diversity, finding alternatives to propagation by rhizomes, stress resistance and suitability for biofuel use (Mendel Biotechnology website).

Limited programs to apply biotechnology to improve *Miscanthus* exist. Transformation systems exist for inserting genes in *Miscanthus*. There are only limited reports of production of transgenic *Miscanthus*. Mendel Biotechnology is applying genes discovered in their large scale screening programs with *Arabidopsis* to *Miscanthus*. In particular transcription factors, genetic components that control expression of large numbers of genes, are being used to increase drought tolerance and other abiotic stress traits (Mendel Biotechnology company website). As is the case for switchgrass, the application of breeding and biotechnology to the improvement of *Miscanthus* is very promising; however, the timelines tend to be long with transgenic varieties unlikely to be released before 2015-2020.

Sorghum forage for biomass

Sorghum is currently being genetically engineered as part of a program to improve the nutritional character of the crop. The Bill and Melinda Gates Foundation has funded a public private consortium of Africa Harvest and Pioneer Hi-Bred Intl. to use biotechnology to increase vitamin A levels in the crop (Neonda 2008). Agrobacterium mediated transformation is effective for inserting genes into sorghum (Zhao et al. 2000). Ceres Biotechnology and Texas A&M University are pursuing a molecular marker based approach for producing high biomass types of sorghum (Ceres Biotechnology company website).

ICRISAT has initiated a project for use of sweet sorghum for ethanol production. Grain is still used for food, but sugar from stalks is used for ethanol. Stalk sugar yield and modification of planting dates for year round production are the traits under selection through breeding. The project is collaboration between ICRISAT and Rusni Distilleries in India and is supported by the Government of India (Bradshaw 2007).

Jatropha curcas

Jatropha is a drought and pest resistant tropical shrub. It produces 30% seed weight as oil that can readily be made into biodiesel. *Jatropha* has been the recipient of considerable attention as well as some hype as a potential biofuel crop that can be grown on marginal land, while providing fuel and substantial employment of the poor (Fairless 2007; Frances et al. 2005; Gressel 2007, www.jatrophaworld.org/). *Jatropha* plantation seed yields range from 0.5 to 12 tons/yr/ha with average yield of 5 tons/yr/ha (Francis et al. 2005). As is the case with other non-food, dedicated energy crops *Jatropha* is not a domesticated species nor has it been subject to long term breeding. Considerable improvement will come as the result of optimizing agronomic parameters for production and for simple selection and multiplication of desirable individual plants (Francis et al. 2005). Archer Daniels Midland Company, Bayer CropScience and Daimler announced plans to cooperate to develop Jatropha as a biofuel indicating involvement of large multinational companies in addition to governments and others focused on smallholder farmers (Bayer CropScience website 2008).

Application of biotechnology to improve *Jatropha* is not an initial priority although there are potential advantages. *Jatropha* is a perennial shrub with a long life cycle and would benefit from molecular marker based selection schemes that allow selection for important traits early in the life cycle. *Jatropha* also contains several classes of toxic molecules including curcin, a toxic protein related to ricin from castor beans and phorbol esters, making the plants poisonous and the meal unfit for human or animal consumption. Production of these toxic compounds could be reduced or eliminated with the use of transgenic antisense or RNAi approaches for gene knockouts. Growth type, for instance dwarfing, non-shattering and low branching types could also be generated through transgenic approaches although traditional selection might accomplish the same thing more rapidly (Gressel 2007). Transformation of *Jatropha* has been reported although the efficiency is relatively low (Li et al. 2007).

Jatropha represents an attractive potential biofuel crop. Its ability to grow on marginal soils in the tropics with limited inputs make it an ideal species for poor farmers and plantations are being grown in Africa, Central and South America as well as Asia (Somerville 2007). However, it appears that the early enthusiasm may be tempered over the coming few years by many lessons related to the economics of the species, the agronomic requirements and the differences between domesticated crops and wild species. *Jatropha* shares these challenges with a number of other wild species being considered for biofuels production including castor bean, *Pongamia pinnata*, *Calophyllum inophyllum*, *Simarouba glauca* and other species (Azam et al. 2005). While there are clear applications for biotechnology, the many inexpensive and technically attainable approaches should and will be pursued first. The limited resources for *Jatropha* improvement also make biotechnology a low priority. Meaningful impacts of biotechnology on *Jatropha* production likely lie beyond 2020.

IV. Agro-biotechnology Direction

The extent to which biotechnology is applied to crops for biofuels use is determined by a number of factors. Among the most important is the rate of discovery of improvements of the individual techniques used for gene discovery, insertion and regulation. This topic is reviewed in this section.

High throughput technologies

Plants and animals, including humans, share common genetic material. Technologies including DNA sequencers, chip-based gene expression technologies, molecular markers and many others that have been developed for application to human medicine are being applied to crop plants. Interest in genetic characterization of humans for personalized medicine is providing additional incentives for rapid, cheap DNA sequencing. Researchers recently announced the complete genome sequencing of a human individual in less than 2 months and at a cost of less than $1 million US. This compares to a similar sequence produced in 2007 with conventional technology for $100 million (Wheeler et al. 2008). The ability to apply discoveries resulting from medical research to improve crop plants results in a significant boost to the more modest direct funding for plant molecular biology research and has the potential to speed crop improvement through biotechnology.

Continued improvements in technology will make genome sequencing of crops routine and inexpensive. The US National Plant Genome Initiative goal is to produce a complete genome sequence for a plant species for US$1000 by 2013. It is likely that this goal will be met (Comm. Natl. Plant Genome Init. 2008) resulting in complete genome sequences for all of the crops considered in this paper by 2015. Complete or draft genome sequences for *Arabidopsis thaliana* (the most important plant model system), rice, poplar, grape, papaya and maize are now available (Comm. Natl. Plant Genome Init. 2008; Ming et al. 2008). Complete genome sequences for soybean, sorghum and canola will be available by 2009, and sequences for sugarcane, cassava, oil palm, switchgrass, *Miscanthus* and *Jatropha* by 2015 (Comm. Natl. Plant Genome Init. 2008; *Brassica* Genome Gateway 2008).

Complete genome sequence data from *Arabidopsis* and rice is especially valuable as these species are important model systems for plant research. Information at the DNA level has many similarities across all plant species making it possible to apply discoveries in simple model systems to more important crops. In addition, *Arabidopsis* is closely related to canola; and rice is closely related to other grasses such as maize, sorghum, sugarcane, switchgrass and *Miscanthus*. While complete genome sequences are valuable, significant efforts to identify the genes coding for proteins are underway in a number of species where complete sequences do not yet exist. Genome sequences for important pests and pathogens of crops have also been completed and will be valuable for devising strategies for engineering insect and disease resistance in crop plants (Comm. Natl. Plant Genome Init. 2008).

Crop genome sequencing initiatives have also increased the understanding of how gene expression is regulated. Successful genetic engineering requires knowledge of when and how specific genes can be turned on and off within plants. Promoters, transcription factors and small RNA's controlling gene expression are necessary for engineering traits controlled by multiple genes including drought resistance and yield (Bhatnagar-Mathur et al 2007).

DNA sequencing programs are also essential for the development of efficient DNA based breeding tools referred to as molecular marker technologies. Molecular markers are small pieces of DNA that can be associated with the genes responsible for important traits making selection much more efficient. Improvements in molecular marker technologies have increased the resolution of marker based breeding while reducing the costs. As researchers have transitioned from early marker systems to more robust and inexpensive systems (RFLP's to RAPD's to microsatellites, to SNP's) applications to breeding approaches have increased (Murphy 2007; Comm. Natl. Plant Genome Init. 2008). Marker assisted breeding is now used to predict crosses, select for difficult to screen single genes, breed for complexly inherited traits (quantitative trait loci QTL's) and introgress transgenes. DNA based diagnostics can also be used to improve the efficiency of plant breeding programs. Rapid, inexpensive screening of disease causing organisms improves the efficiency of breeding programs selecting for disease resistance.

High through-put technologies, often referred to as "omics" technologies, can be used to understand gene expression and the translation of gene sequences to proteins as well as the regulation of metabolites within plant organs or whole plants. Gene and protein expression (proteomics) technologies are developing rapidly and increase the ease of gene discovery by allowing a researcher to monitor the expression of all of the genes of an organism simultaneously. Understanding the total metabolic make up of a crop species (metabolomics) at various stages of development has important implications for biofuels production by allowing understanding and modification of key metabolic pathways. Plants manufacture the compounds used in biofuels production in discrete enzyme mediated steps. Characterizing the products of these steps allows researchers to modify the products by modifying the genes that code for these enzymes (DellaPenna and Last 2008).

The numbers of genes for use in transgenic cultivars should increase rapidly over the coming years as the results of the application of these technologies are increasingly available. In addition to single genes of value, understanding of traits controlled by multiple genes is increasing rapidly meaning that it will be possible to engineer more complex and important traits like drought resistance or nutrient use efficiency.

Transformation technologies

Transformation systems are used to introduce genes into plants. An ideal transformation system is 1) efficient, 2) inexpensive, 3) effective across all cultivars of a crop, 4) able to generate simple, targeted insertions (for ease of regulatory characterization) and 5) capable of working without interfering with other aspects of the plant's biology. As the pace of gene discovery increases and more well characterized genes for important traits are available, transformation systems are increasingly valuable. Transformation systems exist for all of the crops discussed in this paper, however their efficiency and genotype independence varies widely. Currently, no single transformation system works efficiently across species and genotypes. Existing approaches, such as *Agrobacterium* or biolistics transformation, must be adapted to each individual species and genotype.

Efficient proprietary transformation systems developed by private companies have been adequate for generating commercial GM cultivars of maize, soybean and canola. However, these systems are still somewhat genotype dependent and significant event screening is required to be sure that resulting varieties are only changed for the gene of interest. Development of transformation systems for other crops has lagged behind. A number of transformation systems are available to the public sector. Most other molecular tools for genetic engineering are available for application to crops for biofuel use. Significant progress in discovering useful promoters for regulating gene expression continues to be made.

Gene and trait discovery

Numerous programs for discovering important genes for food and fuel production now exist. Multinational seed companies continue to make large research investments to use biotechnology for improving maize, soybean, canola and cotton. The size and focus of these programs means that the industry will lead the field with the steady release of new transgenic traits in cultivars of maize, soybean, cotton and canola. While these crops are likely to be impacted by new transgenes first, the impact of biotechnology is likely to spread to additional crops and to developing countries. Genes that have been discovered and commercialized in maize, soybean, cotton and canola can be used in additional crops at much lower cost, assuming intellectual property issues can be solved. Patents on the first generation genes will begin to expire in the next 5-10 years.

Development of transgenic varieties of crops for poor farmers has been supported by the public sector working with CGIAR centers and through public private partnerships. Companies have donated transgenes and other technologies for use in developing countries including drought resistance for Africa (Monsanto, CIMMYT), insect resistance for Africa (Syngenta, CIMMYT), and nutritional traits (Syngenta, Pioneer Hi-Bred and Africa Harvest). Funding for development of these transgenic crops has come from various government organizations and private foundations including USAID, DFID, Rockefeller Foundation, and Bill and Melinda Gates Foundation and the Syngenta Foundation.

Biotechnology for biofuel

The basic molecular tools for genetic engineering of plant species for biofuel use have been in use for food crop improvement for many years (James 2007). Biotechnology application to biofuels production is an active research area in the public and private sectors. Improvements in crop productivity, crop suitability and biofuels processing are all within the realm of proven biotechnological approaches. Biotechnology can be used to improve the crop to make it more productive or more suitable to biofuels use. Biotechnology can also be applied to the microbes involved in processing biomass into biofuels. Below we consider the possibilities of addressing the traits that make crops more valuable for biofuel use.

Crop productivity: The measure of a crop's usefulness for biofuel production is closely related to its yield, whether it is starch, oil, or biomass yield. Historically, plant breeding has been the primary approach for improving yield across growing environments. Initial application of biotechnology has been aimed at single gene traits; and while insect resistance has improved yields in some situations, approaches to improve yield directly with the tools of biotechnology are still being developed. A crop's ability to produce yield across many different growing environments is complex and can be affected by many different genes. The genes involved in determining yield potential, their importance and expression patterns vary widely depending on the crop and growing environment. Even so, genes affecting yield directly have been identified and are being evaluated in the field (BASF, Monsanto, Pioneer Hi-Bred Intl. Syngenta websites).

Photosynthesis: Despite the obvious association of photosynthesis and yield, attempts to improve the efficiency of photosynthesis have largely been unsuccessful. Research continues to identify approaches that could reduce the inefficiencies of C_3 photosynthesis or even convert C_3 crops such as rice to more efficient C_4 photosynthesis (Normile 2006). The technical hurdles for this approach are very high and it is probably unrealistic to assume that these types of improvement will be available in the next 10 years.

Hybrid vigor: Hybridization is a successful approach for increasing yield in maize, sorghum and canola. The potential for hybridization in other biofuels crops exists although extensive research funding has not been available for this purpose. Companies such as Mendel Biotechnology and

Ceres Biotechnology are targeting hybridization of dedicated energy crops (Mendel Biotechnology Ceres Biotechnology company websites).

Abiotic stress tolerance: In most growing environments, environmental stresses such as drought, heat, cold or salinity result in yields that are below the crop's potential. Improving abiotic stress tolerance improves the yield a farmer realizes. Research in *Arabidopsis* and rice has resulted in identification of many genes associated with various types of stress tolerance (Ceres Biotechnology, Mendel Biotechnology websites). In most cases, characterization has been made in greenhouse or growth chamber conditions often under highly artificial conditions (Bhatnagar-Mathur 2007). These genes must now be associated with changes in crop tolerance to abiotic stresses in the field. Several of the larger seed companies report field tests of drought tolerant transgenic varieties (BASF, Monsanto, Pioneer Hi-Bred Intl. websites).

Nutrient use: Genes have also been identified that appear to improve the efficiency with which plants use nitrogen and phosphorous. As is the case with abiotic stress tolerance, only a few of these genes have been characterized in realistic field conditions (Monsanto, Pioneer Hi-Bred Intl. websites).

Enhanced biomass production: Biomass production can be increased if a plant continues to grow vegetatively and does not flower. The switch from vegetative growth to flowering is under genetic control. Modifying these genes so that additional vegetative growth occurs before flowering could result in increased biomass for biofuel use. It would also modify the harvest index, that is, the ratio of plant material to grain or seed. There has been rapid scientific progress, particularly in model species like *Arabidopsis* in understanding the molecular mechanisms controlling flowering and other developmental changes. This knowledge should be applicable to crop plants (Gressel 2007).

Preparing the crop for biofuel processing Opportunities exist to modify the structural make up of plants so that they can be processed into biofuels more efficiently. Understanding of fundamental aspects of plant biology, particularly the biochemistry of plant cell walls, is required for designing and processing crops for biofuel production (Somerville 2007). Plant cell walls and consequently, biomass is composed of three main components, cellulose, hemicellulose and lignin (Somerville 2007). Knowledge of cell wall structure and enzymology suggest a number of approaches to modify the cellular and biochemical structure of energy crops so they are more amenable to digestion during processing (Himmel et al. 2007). Lignin is a complex insoluble plant cell wall component that contributes to the plant's structure and resilience and is the second most abundant material (after cellulose) on earth. Lignin content in plants has been reduced by genetic modification in maize and poplar (Sticklen 2007). Initial results indicate that lignin content can be reduced making cellulose more accessible to breakdown during processing. Sticklen (2007) concluded that while this field is developing rapidly there are still significant questions about the control of lignin production and the overall regulation of cell wall composition. Concerns about the unintended consequences of modifying cell walls on the plant's survival and vigor will need to be addressed before the feasibility of these approaches can be evaluated (Dhugga 2007; Himmel et al. 2007; Sticklen 2007).

Several approaches exist to improve a crop's usefulness as a biofuel feedstock. Plants have been engineered to produce enzymes involved in processing of biofuels. Adding cellulases and other genes that can be turned on at the appropriate time can result in the plant producing the enzymes that begin the processing of cellulose to sugar while the plant is still intact. Transgenic hydrolase enzymes including cellulase, hemicellulase and endo-glucanase from bacteria have been expressed in corn and rice and effectively hydrolyze cellulose suggesting that they can be used to replace added industrial enzymes. Preliminary investigations indicate that the addition of these enzymes did not result in detrimental effects to the plant's growth and development (Sticklen 2007). Sticklen (2007) hypothesized that "plant-produced hydrolysis enzymes must be cheaper than the same produced in microbes. The ideal scenario would be to produce designer biomass crops that express their own cell wall hydrolysis enzymes and have less lignin or more easily deconstructable lignin residues" (Sticklen 2006). This may be as realistic as producing single designer microbes that secrete all of the necessary hydrolysis enzymes and also utilize all sugars in an "integrated bioprocessing" for fermentation (Dhugga 2007; Lynd et al. 2005).

V. Role of Biotechnology in Biofuel Processing including Synthetic Biology of Microorganisms

Producing biofuels from plant materials requires processes geared to the biochemical make up of the starting materials. Microbes are commonly used in industrial processing of crop materials to produce biofuels. The biological processes of these microbes (breakdown of cellulose and other molecules to sugar, fermentation of sugar to yield ethanol or butanol etc.) are involved in the step wise process of converting plant materials to biofuels. Microbial enzymes determine the range of plant materials usable for biofuels and economics of production of biofuels from various crops. Processing of plant materials is conducted by microbes in contained vessels therefore many of the concerns about use of genetic engineering in crops do not exist in the case of confined, modified microbes.

<u>Starch to ethanol</u>: Since most plants, with the exception of sugarcane or sugar beet, do not store meaningful amounts of sugar, methods are required to break down the carbohydrate storage and structural products that plants do produce. Starch is produced in many plants as a storage form of carbon and energy. Maize and cassava produce large amounts of starch in seeds (maize) or roots (cassava). Starch is composed of long chains of sugar molecules, which can be hydrolyzed to simple sugars using microbial enzymes. Sugar produced in this way can then be fermented to ethanol. Opportunities exist to genetically engineer organisms producing starch hydrolyzing enzymes.

<u>Biomass</u>: The major hurdle for the development of a cellulosic biomass fuel industry is the high cost of processing biomass (Lynd et al. 2008). The United States government has recently provided support to private companies building pilot plants that produce ethanol from crop cellulose (US Dept. of Energy 2007). Commercially successful biofuels plants that use biomass (cellulose) as a starting material are estimated to be at least 5 years in the future and commercial success is not ensured.

Plants produce cell walls that give them their form and structural integrity as well as protect them from insects and disease organisms. Cell walls are extremely complex, however three components predominate, cellulose (45 percent), hemicellulose (30 percent) and lignin (25 percent). The complex structure of cell wall material as well as other natural structural features of plants, including epidermal tissue and epicuticular waxes, the arrangement of vascular bundles, the amount of cell wall thickening and the degree of lignification make biomass "recalcitrant" to breakdown and fermentation (Himmel et al. 2007). Refining biomass to produce fuel requires three major processes, thermochemical pretreatment, enzymatic hydrolysis and sugar fermentation to ethanol or other fuels. Thermochemical pretreatment breaks down the biomass, disrupts lignin and converts hemicellulose to simple sugars which can be hydrolyzed or fermented (Himmel et al. 2007). Cellulose is exposed and can then be hydrolyzed by cellulase enzymes that produce individual sugar molecules that can then be fermented. This process is harsh and energy inefficient. Opportunities to substitute economical enzymatic processes could improve this step substantially (Houghton et al. 2006). The slow kinetics of hemicellulases and cellulases currently limit the efficiency of cellulosic biofuel production. The current cost of cellulase for cellulosic ethanol production is approximately five times the cost of all enzymes used in making ethanol from starch. In addition to genetically engineering energy crops to contain hydrolase genes (described above), several approaches for improving the enzymes and microorganisms used in the refinery process is a promising approach to improving biofuel production efficiency (Houghton et al. 2006; Himmel et al. 2006). Many bacteria and fungi produce hemicellulases, cellulases and other enzymes involved in cell wall degradation. Screening for more efficient organisms and protein engineering (shuffling) of known enzymes are both viable approaches (Himmel et al. 2006). The possibility exists to combine several of the processing steps; however, this will require enzymes that in addition to breaking down the cell wall components also have wider ranges of thermal tolerance and are not inhibited to the breakdown or end products of the process (Houghton 2006).

Lignin presents special problems for bioprocessing of biomass. The lignin and hemicellulose fractions of the cell wall are more difficult to break down and do not readily yield six carbon sugars that can be fermented. Several approaches to dealing with lignin have been proposed including the *in planta* examples discussed above. Research is also being directed at identifying biochemical approaches to metabolize lignin and hemicellulose so that usable products might be produced from these molecules as well. These organisms exist (Himmel et al. 2006) and are identifiable through bacterial and fungal sequencing programs. A much broader range of sugars can be fermented by organisms such as *Saccharomyces*, *E. coli*, *Xymomonas* and *Pichia*, all of which show promising results for use in fermentation (Somerville 2007). These organisms produce enzymes that ferment a broader array of five and six carbon sugars. Since the microorganisms used for fermentation cannot survive at ethanol levels greater than 10-15 percent, distillation must be used to remove the remaining water and achieve high concentrations of ethanol. The use of genetic engineering to increase the tolerance to ethanol of the organisms used in fermentation is an active field of research. The possibility to "engineer a single organism to secrete all the necessary enzymes and utilize all the available sugars in a process referred to as integrated bioprocessing" represents a goal that many recognize as achievable (Somerville 2007).

Synthetic biology

Synthetic biology involves the design and synthesis of new biological parts, systems or organisms or the redesign of existing biological systems for specific purposes. Of particular interest is developing microbes to produce biofuels. Synthetic biology can be used to create organisms that metabolize terrestrial plant feedstocks and create novel compounds such as liquid hydrocarbons. Photosynthetic organisms created through synthetic biology can also convert sunlight directly into molecules that are useful as fuel (Huntley and Redalje 2007; Brenner et al. 2006). There are advantages to organisms that can produce liquid hydrocarbons or butanol as fuel as both have important advantages over ethanol as transportation fuels. Savage et al (2008) calculated that it would require 4.3 percent of US land or 22 percent of US cropland to meet transportation fuel needs. Redesigning organisms that produce biofuels could "increase efficiency, decrease cost and enable a transition to a sustainable energy economy that is largely independent of fossil fuels" (Savage 2008).

These authors outline several modifications that would allow microorganisms to produce fuels such as butanol or ethanol by engineering *Clostridia acetobutylicum*. These modifications include engineering the organisms to excrete cellulases and preferentially produce butanol by over expressing the genes involved in butanol production. Genetic engineering of *Escherichia coli* is routine. Additions, deletions and changes in large number of genes can result in organisms that can perform a number of new functions. Use of a malleable organism such as *E.*

coli as a starting point would result in a synthetic organism that could take biomass to hydrocarbon (Savage et al. 2008). A study on the feasibility of microorganisms for energy production found that "microbes present a great opportunity for energy science since they are simpler than plants, have smaller genomes and proteomes and are easier to manipulate and culture" and microorganisms represent "enormous biodiversity" and a "broad palette of starting points for engineering" (Brenner et al. 2006). Brenner et al. (2006) also identified the low efficiency of biofuel production from microorganisms as the major technical application for the field of synthetic biology.

Several companies have been formed to use synthetic biology to produce biofuels. LS9 is using synthetic biology to engineer microorganisms to produce hydrocarbons in a process that involves adding microbial, plant and animal genes to bacteria (LS9 Company website). Amyris Biotechnologies has entered into a partnership with the Brazilian sugar firm Crystalsev to make hydrocarbon fuels using sugar from sugar cane (Amyris Biotechnologies company website)

VI. Research Capacity for Agro-biotechnology Applied to Biofuel Crops

Research capacity in agro-biotechnology is concentrated in developed countries particularly the US, Canada, Europe and Australia (FAO 2004). The development of the commercial biotechnology industry accounts for much of the know-how for developing transgenic cultivars. Companies that have been active in developing transgenic food and fiber crops are now investing in crop improvement for biofuels use. Monsanto, DuPont, Syngenta, Dow and Bayer are all working to develop crop cultivars for biofuel use. Energy companies particularly BP and Chevron are collaborating with biotechnology companies to apply biotechnology to dedicated energy crops. BP and DuPont recently announced a collaboration to develop bio-butanol, a second generation biofuel (DuPont Company website). Private investment in start up companies in the energy technology area increased ten times between 1999 and 2006 with energy biotechnology accounting for a significant portion (Lynd et al. 2008). Private companies working to provide enzymes for biofuel production include Verenium, Dyadic International, Novozymes and Genencor while more than 20 companies have entered the cellulosic ethanol field (Waltz 2008).

The large private investment in crop-based biofuels in the developed countries is supported by a large publicly funded research enterprise. University and other public researchers are active in basic molecular biology, plant biochemistry and physiology, the basic sciences necessary for a rapidly developing agro-biotechnology capacity. Public sector researchers are also active in gene discovery and evaluation of transgenic plants particularly in greenhouse and growth chamber experiments. Much of the public sector work uses *Arabidopsis* as a model system (Comm. Natl. Plant Genome Init. 2008).

In addition to basic research capacity and development of transgenic food and fiber crops, funding for biofuel crops is now an area of major interest. The US Department of Energy (DOE) is providing more than a billion dollars in funding for lignocellulose ethanol projects for biofuels in 2007 (Waltz 2008). In 2007, BP, University of California at Berkeley, Lawrence Berkeley National Laboratories and the University of Illinois announced the formation of a US$500 million biofuels initiative, most of which will be focused on applying biotechnology to crops and processing (BP Company website 2007)

In the developing world, capacity is also increasing, particularly in China, India and Brazil. China has expressed large scale ambitions in ethanol production and intends to meet its goals without using food crops (Waltz 2008). Sinopec, China's state owned oil company is investing US$5 billion on oil palm and Jatropha plantations and production plants in Indonesia (Biofuels Intl. 2008). China has also announced plans to launch a 5 year, US$1.4 billion crop biotechnology program. This would increase current agro-biotechnology spending by five times (Jia 2008). This research spending would be concentrated on food production but nonetheless would increase the biotechnology research capacity and make it relatively easy to expand efforts to biofuels. Brazil, the leading producer of sugarcane ethanol, is also expanding biotechnology research on crops. EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), the Brazilian agricultural research organization has considerable expertise in crop improvement. Canavieiria Technology Center is leading a Brazilian effort to sequence 50,000 sugarcane genes (Vittore et al. 2003).

The CGIAR system provides crop improvement expertise in support of developing improved crop varieties for poor farmers. The CGIAR centers have some biotechnology capacity although this has not been a focus for the centers. Limited work has also been carried out on crops for biofuels use, particularly sorghum and cassava (Biopact 2007a; Bradshaw 2007). Countries with specific interest in individual biofuel crops have initiated biotechnology efforts. Malaysia and Indonesia are increasing research to improve oil palm using biotechnology. India has been the leader in research related to *Jatropha*.

VII. Risks of the Global Use of Agro-biotechnology for Bioenergy

Risks arising from new plant generation

Regulatory and biosafety evaluation of GM biofuels crops will be required as has been the case for food and fiber crops. Traits of interest for improving crops for biofuel use are largely related to yield and productivity as is the case with genes of interest for food crops. It will be impossible to completely segregate crops grown for biofuel use from the same crops grown for food. Therefore, biosafety evaluations should assume that genes from GM biofuels crops might occasionally enter the food chain. In some crops that are intended for biofuels use the profitability of the crop can be increased if some of the crop, particularly the protein fraction, which is not usable for biofuels, is sold as livestock feed. This is currently the case with soybean and maize. This means that the crops that can be used for food and biofuels will not be subject to a completely different evaluation of acceptability. Food crops that are also used for biofuels such as maize, soybean, canola, sugarcane, cassava and oil palm will need to be evaluated for food safety (toxicity and allergenicity) as if they were food crops. Dedicated energy crops that do not enter the food chain, and cannot cross with food crops, such as switchgrass, *Miscanthus* and *Jatropha* are not subject to concerns about food safety unless they are fed to animals.

All GM crops should be evaluated for likelihood of gene flow to wild relatives. Transfer of desirable genes for biofuels crops, such as high productivity, rapid growth, nutrient use or abiotic stress resistance, to wild relatives could result in wild populations with significant advantages within natural habitats. Perhaps the greatest risk from biofuels crops is that they become establishing as invasive weeds. This possibility is being addressed by creating cultivars that are sterile and will not produce seed (Mendel Biotechnology company website). Regulatory evaluation of invasiveness of transgenic biofuels crops will also be necessary.

Processing enzymes, such as cellulase or other hydrolytic enzymes that are introduced into crop plants through biotechnology will be under the control of inducible promoters and presumable will not be expressed in the field. Even if they were expressed, this type of enzyme is unlikely to have effects in humans or other animals although this possibility should be considered.

Acceptance of GM crops

The controversy over GM crops has continued for more than 12 years. The basis for opposition to GM crops varies. Broad consideration of ethical and social impacts of GM crops has become a part of the discussion of GM acceptance (Melo-Martin and Meghani 2008). We focus on the particular impacts of GM biofuels crops on human health and the environment. These concerns apply equally to biofuels crops as they have to food crops. Objections related to food safety, toxicity and allergenicity are less relevant with dedicated energy crops since they are not intended for human consumption; however, the two uses are not totally independent.

Genes for traits of interest to consumers including genes for nutritional qualities, increased antioxidants, decreased allergens, increased shelf life and processing characteristics are in advanced stages of product development (Dow AgroSciences, Monsanto, Pioneer Hi-Bred Intl. Syngenta websites). While these traits are largely unrelated to biofuels, their attractiveness to consumers may increase the level of GM acceptance.

Concerns of some environmental groups about GM food crops on the basis of gene flow to wild relatives and other long term ecological concerns apply equally to biofuels crops. Despite evidence that GM insect and herbicide resistance traits have reduced the amount of agricultural chemical use and the impact of insecticides on biodiversity (Cattaneo et al. 2006), these findings have had little effect on GM crop acceptance.

Additional demand for food crops for growing populations, changing diets and biofuels is increasing the cost of food as well as the pressure to bring additional lands into agricultural production. It is possible that these pressures will influence the discussion of GM acceptance. To date, this discussion has occurred in an environment of cheap and adequate food allowing opponents' leeway to ignore crop productivity. A serious food crisis might well force consideration of the opportunities for increasing production through agro-biotechnology. Cropping systems that are generally believed to be more sustainable, such as organic, offer similar yields as conventional farming but do not offer options for increasing productivity on a given hectare in an ongoing way (Posner et al. 2008).

Groups who oppose GM crops have not indicated a change in position when considering crops for biofuels use. Rather many of these organizations have opposed crop based biofuels particularly those made from food crops. Additionally, there is a high level of concern about land conversion for oil palm and soybean to be used for biofuel production.

Several cross-stakeholder initiatives to address the sustainability of crop based biofuels have recently formed including the Roundtable on Sustainable Biofuels (RSB) and the Roundtable on Sustainable Palm Oil. The RSB is currently developing global principles for sustainable biofuels production and has produced a version that addresses the use of biotechnology with the following principle "if biotechnologies are used in biofuels production, they shall improve the social and/or environmental performance of biofuels, and always be consistent with national and international biosafety and transparency protocols" (Roundtable on Sustainable Biofuels 2008). Attention to approaches for improving the sustainability of agriculture is growing and collaborative efforts to bring environmental groups, growers and agribusiness together have been formed recently including the Keystone Initiative for Sustainable Production Agriculture and the Sustainable Food Laboratory. An initiative to address these issues in dedicated energy crops has been formed under the facilitation of the Meridian Institute. These initiatives provide hope that the discussions of commercial production agriculture and sustainable agriculture will not remain separate. The need for high productivity to meet the demand for food and fuels combined with concerns about increased land use for agriculture will drive a common approach to providing high productivity sustainably.

Experience with GM crop regulation and acceptance

Since the initial introduction of transgenic crops in the US in 1996, significant experience has been gained with the issues related to the technology, risks and appropriate regulatory approaches (FAO 2004). Fifty two countries have granted regulatory approvals. Over 114 million hectares of transgenic crops were produced in 2007. Only a handful of countries have banned GM crops outright. Maize, soybean, cotton and canola represented the most extensive plantings of transgenic crops, although transgenic squash, papaya, alfalfa, tomato, poplar, petunia, and sweet pepper have been grown (James 2007). Systematic collection and analysis of data describing the experience with GM crops in the US to address long term benefits and impact has not occurred. This type of monitoring and analysis could be funded by government organizations to increase the scientific basis of the discussion of GM crops (Marvier et al. 2008).

Many countries now have regulatory frameworks and biosafety protocols for GM crops. In addition, officials in these programs have years of experience and have had the chance to refine the first generation of regulations. Many countries, particularly in the developing world, have not implemented regulatory frameworks for any type of GM crop. The opportunity to approve biofuel crops may serve as an additional impetus for developing and implementing the necessary biosafety framework.

Differences for large and small scale farmers

Crops improved through biotechnology are relatively farm scale neutral (FAO 2004). However, in the case of crops improved for biofuel use, several factors favor application of the technology for large farmers. Research spending to develop biofuels crops grown in the developed world including maize, soybean and canola is much greater that the spending on sugarcane, oil palm, cassava and *Jatropha*. Consequently, improvements are likely to accrue to large farmers sooner than to small farmers in the developing world. Many countries in the developing world with large numbers of small farmers also lack regulatory systems and technical capacity that allow review and approval of transgenic crops even if they are available (FAO 2004). Finally, current versions of biofuel production facilities are large, centralized and capital intensive. Countries lacking roads and other forms of infrastructure and access to capital are likely to be at a disadvantage in developing biofuel industries. Attention to developing more appropriately scaled production facilities may address this inequity.

Will biotechnology increase or reduce the potential for competition between land uses (food v. fuel) due to crowding out effects or biosafety concerns?

There is considerable concern about the effects of diverting significant portions of the US corn crop to ethanol production. More than one fourth of the 2007 US corn crop was used in ethanol production contributing to the run up in commodity prices. US government subsidies of corn and ethanol producers and the resulting impacts on food prices for the poor have been challenged

(Runge and Senauer 2007). Increasing maize area for ethanol production will also contribute to nitrogen export when compared to natural lands or other less nitrogen intensive crops (Donner and Kucharik 2008).

Initial studies on conversion of natural lands to crop production for biofuels indicate that more CO_2 is released than the biofuels would provide. Use of waste biomass or biomass grown on degraded or abandoned agricultural lands offers greenhouse gas advantages (Fargione et al. 2008; Searchinger et al. 2008). Increased cropland devoted to biofuels crops and increased biofuels plants will also have significant negative effects on water use and quality (Committee on Water Implications of Biofuels Production in the United States 2007).

The results of our modeling indicates that increase demand for due to larger populations, increased wealth and changing diets will result in serious pressure on global agricultural systems. The additional pressure from biofuels increases the need to maximize sustainable production. Agro biotechnology can contribute to increasing productivity and reducing inputs for crop production. It can also play a critical role in the development new biofuels crops and in improving the efficiency and cost effectiveness of processing biomass sources of biofuel feedstocks. It is unlikely that the improvements in productivity and new crops contributed by biotechnology will be adequate to meet increasing demands for food and fuel without bringing new land into production.

VIII. Recommended Policies Needed to Develop/Accompany Sustainable Bioenergy Development

The findings of this study allow us to recommend a number of policies.

- While private investment for yield improvement for a small number of crops for the developed world has increased, public investment in plant breeding and biotechnology has decreased. There is a strong need for increased public investment in conventional and GM approaches to crop improvement. International crop improvement centers and national programs are underfunded. As a result, known technologies have not been implemented in many developing countries. Additionally, rates of crop improvement have lagged far behind what has been achieved in certain areas.
- Policies that favor private sector investment in crop improvement for the developing world are critical. These include 1) decreasing the bureaucratic hurdles to business formation 2) development of infrastructure that enables production and distribution of improved seeds and other agricultural inputs 3) development of appropriate regulatory and biosafety protocols for introduction of transgenic cultivars and 4) reform or improvement of intellectual property rights that would encourage private investment in crop improvement.
- Policies that support the development of public private partnerships to increase access to advanced crop improvement technologies to poor farmers where conditions are not yet adequate to promote private commercial seed companies.
- Policies are needed that provide funding for low cost, localized processing of crops for biofuels use could improve local markets for poor farmers and allow participation in the biofuels market.
- Policies that increase the potential of producing dedicated energy crops on marginal land should be encouraged. Dedicated energy crops can provide environmental services in additional to food production, such as reduction in soil erosion, soil carbon storage and water purification. Policies that recognize and compensate farmers for providing these additional services will increase the sustainability of biofuel crop production.
- Competition of crop demand for food and fuel can be reduced by policies that encourage the development of processes that allow economical use of biomass (cellulose,

hemicellulose and lignin) for biofuels production. These policies could facilitate use of non food parts of crops (stalks, leaves etc.) for fuel and will allow the commercialization of perennial, highly productive energy crops. In addition, the development of a biomass fuel industry will reduce some of the pressure to use grain of starch crops for fuels production.

- Policies that subsidize biofuel production from food crops should be discouraged.
- More open international trade of crop based biofuel could encourage the use of crops with the most energy efficient profiles. Reduction in tariffs would also promote trade from those countries where crop biofuel production was more efficient.

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