Technology and Innovation in World Agriculture: Prospects for 2010-2019

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Abstract

The objective of this paper is to assess prospects for increasing agricultural productivity through advances in technology and innovation in farming techniques for developed and selective developing and transition countries over 2010-2019. Over this period of time, the net impact of climate change is expected to be small, perhaps positive on cereal yields. However, environmental concerns (carbon dioxide release from bringing new lands into crop production and erosion on marginal lands brought into crop production, additional agricultural chemicals applied, and less biodiversity) may grow if meeting future demand for food, feed, fiber and bio-fuels require the conversion of forests and pastureland to cropping. The paper first provides a review of agricultural TFP growth for OECD countries and other large developing or transition economies. Second, a discussion of the organization of science and technology for agriculture is presented. Third, new agricultural technologies for cereal, oilseed, and potato production and for livestock production are discussed and their impacts assessed. Fourth, the contributions of public and private agricultural research capital to agricultural productivity are summarized. Fifth, prospects for new agricultural technologies primarily developed by the private sector over the next decade are described and evaluated. Although not everything is rosy for future developments of agricultural technologies for farmers in developed countries to 2019, the combined efforts of public and private agricultural research will provide a steady stream of new crop and to a lesser extent livestock technologies for farmers over this time period.

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Over the past two decades, the average annual growth rate of world agricultural product demand has been roughly 2.1 percent and of agricultural product supply has been 3.1 percent. The real price of food decreased by 55 percent over 1980 to 1992; remained relatively unchanged to 2005 and then rose at more than 10 percent per year to early 2008 (Helbling et al. 2008). Then, real corn, wheat, rice and crude oil prices rose rapidly and spiked in mid-2008. The rise of food (and feed prices) choked off demand and created food insecurity in developing countries (FAO 2008a,b), and high oil and gas prices caused consumers in developed counties to reduce their driving and greatly reduce to demand for large fuel inefficient cars and truck. However, during July to January 2009, real food and energy prices fell back roughly to 2007 levels (World Bank 2009, p. 4).[1]

This decade long run up in real oil prices stimulated efforts of the US and some other major oil importers to seek out alternative sources of energy. There are primarily two issues: First, concerns exist about the security of domestic fossil fuel supplies in developed oil importing countries. Second, interest is growing in counteracting global warming through increased use of bio-energy (Von Witzke, et al. 2008). New alternatives include the use of corn (US), sugar cane (Brazil) and wheat (EU) to produce ethanol and oilseeds, rapeseed/canola and sunflower in the EU and soybeans in the US, to produce biodiesel. However, with the exception of bio-ethanol made from sugar cane in Brazil, bio-energy is not competitive with fossil fuel at present prices and technologies. Hence, it is government market regulations through subsidies and alternative fuel mandates that is driving the rapid growth in bio-energy. For example, the US has mandated the use of 7.5 million gallons of bio-ethanol by 2012 and have extended several favorable incentives. The US has a long term 50 cent per gallon subsidy on the use of ethanol to create a gasoline blend of

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[1] See Appendix Figure 1 and 2 for more information on real prices of crude oil and gas.

85% gasoline and 15% ethanol, and renewable energy standards, which require annually increasing levels of biofuels production to reach 36 billion gallons by 2022 (Energy Independence and Security Act of 2007). Also, the European Union has set a goal of 5.75 percent use of bio-fuels in transportation by 2010 and 10 percent by 2020. Hence, bio-fuel mandates are now driving the bio-fuel markets.

The expanded demand for bio-energy has been a major factor in the reversal of the long-term downward trend in grain and oilseed prices, roughly since 2005. As recent as 2005, US ethanol production consumed only 2 percent of US corn production but is projected to consume 32 percent of the 2008 crop. It has caused food consumers to substitute from corn to other cereals such as rice and wheat and from soybean, canola, and sunflower oils to other fats and oils. On the supply side, the higher grain and oil seed prices have caused farmers to shift some land out of food crops (wheat, rice and other production) to crops used for feed and ethanol and biodiesel production (corn, sugar cane, canola, sunflowers and soybeans). These demand and supply side effects have also tended to increase the price of wheat, rice and also of grain-fed livestock and of other oilseeds because of the competition for farmland.

An IFPRI study by Rosegrant suggests that likely future crude oil prices, the rapid increase in global biofuels production and demand will push global corn and oilseed prices up by 30-40 percent by 2020 (Rosegrant 2008), and some scholars have suggested that this trend could starve the world's poor (Runge and Senauer 2007; World Bank 2008, p. 96-98). Even with some moderation in crude oil, grain, and oilseed prices over July-December 2008, the long-term trend in the real price of crude oil and energy will be upward, and this will keep pressure on cereal and oilseed prices, given the relatively inefficient means of producing biofuels currently and the mandates to substitute biofuels for transportation fuels.

In developed countries, only very modest increases in farm land area can be anticipated to 2019. Conversion of land to cropland causes environmental problems. First, each acre converted, including forests, to cropland would release CO_2 previously sequestered roughly proportional to the duration of the uncultivated period (Spink et al. 2009). Bringing set-aside, CRP or other marginal lands into production would also increase soil and water erosion and reduce biodiversity. Hence, increases in crop yields and more generally agricultural productivity seem to be a more attractive alternative for meeting growing demand for agricultural products.

Introduction and improvements in GMOs is one technology with potential to increase agricultural productivity significantly in the future. The GM crop revolution that started in the mid-90s has great potential for expanding the supply of food and feed in the world with given land area, but resistance to these new crops in some high income countries (Western Europe and to a lesser extent in Japan) has not only limited the growth in the supply of food there but also interfered with the adoption of GMOs in most developing countries (Paarlberg 2008), except for Argentina, China, Brazil, South Africa and India. Advances in GM crop technologies with single transgene insertions became frontier technology starting in 1996 when Monsanto, Pioneer, and Delta and Pineland began supplying GM canola, cotton, corn and soybean varieties to farmers in North America. Figure 2 shows the adoption pattern over 1996-2007 for the US where in 2007, over 90% of soybean acreage was planted to herbicide tolerant (HT) soybean varieties, and more than 50% of the corn and cotton acreage were planted to HT, insect resistant (IR) or HT and IR varieties.

Another option is new technology to increase productivity of semi-arid lands with long periods of drought and infrequent abundant rainfall, such as exists in Australia. Here new drought tolerant perennials are being tested as a substitute for annual crops: perennial wheat and new grasses and legumes that could more efficiently use the small and variable amounts of available water (Future Farm Industries).

Consumer and environmental groups, especially in Europe, have resisted GMOs. They emphasize possible food safety problems, negative impacts on the environment either through reduced biodiversity or out-crossing to create super weeds, and ethical concerns that arise from messing with nature (Friends of the Earth 2001; Greenpeace International 2001a, 2001b, 2001c, 2003, 2006). Although there is at best weak scientific support for any of these concerns, significant consumer resistance persists. GM crop technology is a technology that could significantly increase the future world supply of food, feed, fiber and bio-fuel stocks and help offset the impact of growing demand for cereals and oil seeds for biofuels.

The objective of this paper is to assess prospects for increasing agricultural productivity through advances in technology and innovation in farming techniques for developed and select developing countries over 2010-2019. Over this period of time, the net impact of climate change is expected to be small, perhaps positive on cereal yields. Increased agricultural productivity, for example, as represented in high crop yields is one alternative to bringing new lands into production. However, environmental concerns would grow if future production requires conversion of forests and pasture land to cropping, which increases green house gas emissions and reduces biodiversity (von Witzke et al. 2008; Spink et al. 2009).[2] The paper first provides a review of agriculture sector TFP growth for OECD countries and select large developing or transition economies. Second, a discussion of the organization of science and technology for agriculture is presented. Third, new agricultural technologies for cereal, oilseed and select vegetable crops and for livestock production are discussed and their impacts assessed. Fourth, the contributions of public and private agricultural research capital to agricultural productivity are summarized. Fifth, the prospects for new agricultural technologies over the next decade are summarized and assessed. Finally, a summary and conclusions are presented.

Review of Total Factor Productivity for Agriculture

Based upon data for various country groups since 1990, total factor productivity growth for the agricultural sector, i.e., the rate of growth of an index of farm outputs less the rate of growth of

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[2] Each acre converted to cropland releases carbon dioxide previously sequestered, with the release being proportional to the length of the uncultivated period.

inputs under the control of farmers, has tended to be lower during 2000-2006 than during 1990-2000, but this does not occur for all regions (Table 1). This evidence is taken from a major study by Fuglie (2008). For Western Europe (17 countries), the agricultural sector annual average TFP growth rate was 1.98 percent over 1990-1999 and 1.49 percent over 2000-2006, but the decline in agricultural productivity from the first to the second period was especially large in Denmark and France. For a selective set of Central European Transition Economies now belonging to OECD and the EU, the average growth of agricultural TFP was 0.7 percent over 1990-1999 and a lower -0.02 percent in 2000-2006; for North America, from 2.10 percent over 1990-1999 to a lower 1.74 percent over 2000-2006; high income Oceania from 2.23 percent in 1990-1999 to -0.23 over 2000-2006. Also, in large developing and transition countries, the growth rate for agricultural TFP was 3.12 percent over 1990-1999 and only slightly lower 2.87 percent over 2000-2006, but this rate of growth for the latter period is quite high.

Groups of countries going against this negative TFP growth trend are Developed Northeast Asian countries (Japan and Korea) where agricultural sector TFP growth increased from 2.49 percent over 1990-1999 to 3.13 percent over 2000-2006, and for Turkey from 0.7 percent over 1990-1999 to 1.2 percent over 2000-2006. Perhaps the most surprising agricultural TFP growth performance over the past almost two decades has been the developed Northeast Asian region (Japan and Korea) and that of the large developing and transition countries (Argentina, Brazil, China, India and Russia). Moreover, for Brazil, China, and Russia the rate of agricultural sector TFP growth has exceeded 3 percent for both periods. Among these large countries, India stands out for its slow agricultural TFP growth of roughly 1.5 percent in both periods (Table 1).

It has sometimes been argued that the benefits of agricultural TFP growth come at some cost; in particular, degradation of the environment and in some cases more subtle horizon pollution. One route to increasing crop yields has been to increase the intensity of farming through higher rates of chemical fertilizer and pesticide applications, but these chemicals can pollute surface and ground water, the air and agricultural workers. However, increasing crop yields have reduced the amount of total land in crop production, especially that of highly erodible cropland and land from deforestation, and this has reduced the amount of soil erosion and ecological damage, which is a frequently unobserved benefit of these new agricultural technologies. Attempts to incorporate these types of externalities associated with new agricultural technologies in TFP measures have been slow. For example, it is very difficult to obtain objective measures of pollutants and then to value their social damage/benefit (Antle and McGuckin 1993, p. 175-220).

Some recent research at the USDA has shown that new agricultural technologies adopted by US farmers over the past three decades have greatly reduced environmental pollution of earlier technologies. Ball et al. (2004) incorporates the impact on human health and aquatic life of pesticide pollution in the US into state agricultural TFP indexes, 1960-1996. Their study shows that over 1960-1972 US agricultural productivity is roughly 4 percent lower due to environmental degradation, but over 1973-1996, the environmentally friendly TFP index grows substantially faster than for the conventional agricultural TFP index—an average of 2.3 percent higher for the 1984-1996 period. The reason is that over 1960-1972 new agricultural technologies frequently caused negative externalities on labor and aquatic life, but since the early 1970s, new agricultural technologies have become increasingly friendly to these organisms since new environmental protection legislation and efforts intensified. Although some find the US record of conventional agricultural TFP growth amazing, TFP growth adjusted for environmental problems is a much larger 5 percent per year over 1984-1996.

For developed countries, the high agricultural sector TFP growth for North America and Northeast Asia are telling. They reflect a long term record of investment in public agricultural research and complementary private sector R&D and private sector development and marketing of new technologies to farmers. In North America the regulatory process brings oversight but is not especially stifling of new agricultural technologies. Given that GMOs have been developed and marketed by the private sector for corn, soybeans, cotton and canola in North America, and these crops, except for canola, are not grown in large acreage in the EU, TFP growth in the EU is being slowed here. In the future, GMOs will be developed for food crops, and continued resistance by the EU to them will further retard agricultural productivity growth in the EU relative to North America (Argentina, Brazil, China, and India). Although TFP growth in Russia has been substantial over the past decade, its R&D system for agriculture remains primitive and its poor relations with western private agricultural corporations will slow their access to new agricultural technologies and they do not have the scientific capacity and infrastructure to undertake new developments themselves over the over the next decade.

Relationship between Science (Research) and Agricultural Technology (Development)

Organized research and development (R&D) in the public and private sectors are the main source of new agricultural technologies and increased agricultural productivity over the long term. However, efficient organization of R&D for the creation of new useful technologies continues to be debated. First, roughly a half century ago, the "linear model of innovation" was proposed by Bush (1945) and vigorously defended by the Reagan administration as late as the mid-80s. This model postulated that innovation starts with basic research, followed by applied research and then development and ends with product or process diffusion (Figure 3). This model was amenable to statistical collection of data and to use in political discussions of public research funding. It, however, provided the misleading implication that funding of basic research is the source of basic and applied discoveries that are needed to create new technologies for farmers and others. Also, it contained the naïve assumption that researchers' choice of work is unaffected by the problems faced by farmers and other end-users of technologies. It also ignored the fact that many successful engineering principles are without sound basic science underpinnings.

A significant advance in the modeling of this relationship can be obtained by postulating a bi-directional relationship among basic science, applied science and technology development

(Figure 4). In this model, it is now possible for the problems and needs of end-users of technologies to be channeled to those who are engaged in research, to affect the direction of future research and in some cases, to lead to fruitful discoveries or innovations. Conceptually, this is a more powerful and realistic model of the relationship between research and technology. Now, pouring money into discoveries at the basic science level is not the only route to new technologies, although it may still be one of the most important. Moreover, the relative importance of applied research is elevated because it is likely to be the first line of effort to solve problems with end-users' existing technologies.

With advances in science, new fields of specialization have developed in basic or general sciences and in applied sciences, which open the model to new horizontal and vertical linkages. For example, Huffman and Evenson (2006a) hypothesize that a type of science, called pre-invention science, exists, and it is very important to technology development (Figure 5). The general or core sciences tend to be inward-looking and make little effort to forge horizontal or vertical linkages in pursuing discoveries. However, for sustainable discoveries and inventions to occur, Huffman and Evenson (2006a) postulate that pre-invention science seeks downstream linkages to core or general sciences for fundamental information needed for successful discoveries, but also upstream linkages to applied sciences for problems needing solutions. Their model also inserts a new level of activity in the organization of research and development—extension activities. In particular, in the US, the federal, state, and local governments finance public agriculture extension to disseminate information to farmers in the agricultural and natural resource areas. Hence, public (and private) extension activities enhance information flows that are useful in the adoption of new technologies. In this H-E model, discovery and invention at various levels are required for long term sustainability of an R&D system for agriculture.

New Technologies for Field Crops and Their Impacts

In developed countries, there have been a wide range of technical advances for agriculture—genetic improvement, chemical fertilizers and pesticides, farm equipment and machinery, and cultural and management practices. Research in both the public and private sectors has been the primary source of new technologies, with the private sector becoming increasingly involved in new technology development and marketing and being the exclusive source of GM crops in OECD countries.

Genetic Improvement

In OECD countries, corn and small grains, mainly wheat, and rice are the key cereals and soybean, canola/oilseed-rape and sunflower are the main oil crops. The public and private sectors have played very different roles in the genetic improvement of these crops. Starting with the development of commercial hybrid double-cross seed corn varieties by the public sector in the 1930s, the private sector has assumed an increasing role in genetic improvement and seed reproduction in developed countries. A significant innovation in the 1960s was the change from double-cross to single-cross corn hybrids. This change provided greater concentration of superior genes for performance in the best varieties, and with new methods of seed production, the cost of single-cross hybrid seed corn to farmers was reduced. Although the public sector continued for three decades to develop inbred lines that were heavily used by the private sector for commercial hybrid seed corn production, the private sector had largely taken complete control of inbred line development by the mid-1980s (Huffman 1984; Huffman and Evenson 1993, p. 150-160). Commercial hybrid corn varieties have gone through stiff selection for strong emergence of seedling, drought and heat tolerance, standability, high grain yield, and rapid fall dry-down.

Wheat is the leading cereal crop grown in the European Union, and North America and Australia are also major producers. In the EU wheat is grown on relatively good soils under a temperate climate and adequate rainfall. France and Germany are the EU leading producers. Furthermore, there is an anticipated significant increased in demand for wheat in the EU for ethanol production (von Witzke 2008). In North America, wheat is grown mostly in low rainfall areas that limit production potential. In

Australia, wheat is grown under even more adverse rainfall conditions. New research underway there is attempting to develop perennial wheat varieties that would over time out yield annual wheat varieties. The idea is that perennial wheat would establish a more extensive root system that would give it greater drought tolerance (Future Farm Industries).

New wheat and other small grain variety developments have been largely a public research sector activity, and starting in the mid-60s, new wheat varietal development also included dwarf varieties with CIMMYT ancestry (Huffman and Evenson 1993, p. 167-177; Pardey et al. 1996; Heisey 2003) and dwarf rice varieties for the International Rice Research Institute (IRRI). The dwarf wheat and rice varieties had major advantages of reduced tendency for lodging (plant being flattened by high wind and rainfall) and putting a larger share of total energy produced into grain yield rather than into straw yield. Over the 20th century, the value of straw as an output of small grains was steadily declining in developing countries relative to the value of grain yield.

Rice is the third leading source of calories for humans, and Japan is the leading producer of rice in the OECD. Varieties developed at IRRI have been a resource available to the Japanese scientists and seed industry for improving their rice varieties (Evenson and Gollin 2003, p. 19-21; Hossain et al. 2003). Japanese grows paddy rice—which is in irrigated lowland or flooded lands. The rice seeds are started in a nursery, the fields are leveled, tilled, fertilized, and flooded, and then the rice seedlings are transplanted into the nutrient rich soggy soil (Yamaji 2008). The need to transplant rice seedling is an added labor expense, but the paddy rice yields much better than upland dry-land rice (Fujiki 1999). Also, rice seeds that are sown on flooded fields develop a very weak root structure that can be easily upended by strong wind. Paddy rice production in Japan does create environmental concerns with flood waters taking up some of nutrients from the soil, and the Japanese have been working to reduce negative environmental events associated with paddy rice production.

The increased demand for oils during World War II boosted soybean oil prices dramatically and provided a major financial incentive for farmers in the US to increase been production. US production of soybeans in 1950 was 300 million bushels (Huffman 1987). Early soybean improvement research was undertaken in the US South by the USDA and a few private companies, but in the Midwest, the USDA and selected State Agricultural Experiment Stations undertook this work. Because the soybean plant had served as a hay crop in some regions during the early part of the last century, seed yield was slow to increase. After 1950, soybean improvement focused on improving seed yield and oil content. This included research to control pests, e.g., cyst nematodes and aphids. Soybeans are extremely photoperiod or day-length sensitive. This sensitivity means that any soybean variety performs well only within a relatively small geo-climatic area. However, in the US Midwest, research was undertaken to extend the soybean growing region North and West by developing new varieties (Huffman and Evenson 1993, p. 162-163. Also, improved weed control was important to increasing seed yields.

The soybean plant is self-pollinated, hybridization is very expensive, and commercial hybrids have not been developed. Hence, until the mid-90s, farmers were able to save their own soybean seed and plant or re-sell it to other farmers. The main obsolesces of a variety in this era were due to evolving pest resistance and development of new superior varieties. In fact over the 1970s and 1980s, US farmers were planting an increasing share of new seed each crop year (Huffman and Evenson 1993, 162-167). First in Argentina and later in Brazil, farmers have had access to this new soybean technology.

Pest Control

Agricultural Chemicals. Although insecticides and fungicides have been available to farmers extending back into the 1930s, herbicides became available and adopted by farmers in the 1960s. Insect and fungal problems tend to be affected by particular environmental conditions, which frequently contain a random component. Some pest problems have become more severe due to new cultural practices adopted by farmers, e.g., single cropping or cropping under short rotations. Over this time period, applied research and development, largely in the private sector, have supplied farmers with new chemical pesticides. For more than five decades a menu of insecticides has been supplied by private firms to farmers, and they have been used heavily by farmers to help control insects, for example in corn, cotton, and horticultural crops. However, the widespread use of a particular insecticide to control a particular insect eventually leads to the development of tolerance/resistance by the target insect, as it adapts to the new environment. Farmers frequently respond by increasing the frequency and/or quantity of insecticides applied (Zilberman 2004; Coelho 2009). For example, in the US South before GM insect control, cotton farmers frequently made 10 or more applications of highly toxic insecticides (pyrethroids) in an attempt to control the budworm-bollworm complex (Fack-Zepeda et al 2000). More generally, organochlorides have been used to control insects, even though they tend to accumulate in soil sediments and plant and animal tissues over time, being especially a problem in large mammals and humans, and therefore, to persist in the environment for a long time.

In developed countries where the real price of farm labor has increased substantially and chemical companies have been innovative in developing new chemical herbicides, farmers have frequently adopted chemical herbicides to help control weeds. Weeds are a perennial problem in farming, and these early herbicides either killed all plants, or selectively kill all grasses or all broadleaf weeds. These new herbicides save on labor for hand weeding and on labor, machinery and fuel needed for field cultivation of crops. Plants exhibit varying levels of tolerance to herbicides. Some plants are highly sensitive and can be damaged or killed by very low doses of certain herbicides, while plants that have high tolerance can be unaffected by a herbicide that kills other plants. Over the past four decades, farmers in developed countries have frequently adopted chemical herbicides developed by the private sector to control weeds and to substitute for hand weeding or mechanical weeding.

Integrated Pest Management (IPM). In the 1980s, agronomists and entomologists cooperated to develop a new insect control system, called integrated pest management (IPM). The objective of IPM is to reduce pesticide use, improve farmers' profits and provide regulations to protect human health and the environment. In the US, these public programs are two-pronged: to provide safe, low cost food and a high quality environment (Carlson and Wetzstein 1993, p. 268). In IPM, farmers attempt to break the cycle of increasing tolerance by adopting a mixed strategy to control target, for example, insects—more diverse crop rotations, introduction of biological controls such as natural enemies, retaining untreated pest refuge areas, scouting to assess intensity of pest infestations, and limited chemical pesticide use. However, over the past decade, genetic modification that introduces genes into plants to produce substances that are toxic to target insects has been a new type technology available to farmers for biological control of insects (Fernandez-Cornejo and McBride 2002).

GM Control. New genetically engineered or GM crop varieties developed in the 1990s built upon prior discoveries of DNA in 1953, a gene splicing technique in 1973, and the Cohen and Boyer gene splicing patent in 1977. GM varieties for more than a decade have been developed by the transfer of genes from soil bacteria into commercial varieties, creating transgenic plants. One type of GM trait is insect resistance (IR) obtained by insertion of *Bacillus thuringiensis* (Bt), a soil bacteria that is toxic to some insects. When a vulnerable insect eats a plant part containing Bt it dies. For example, Bt cotton is relatively effective in killing tobacco budworms, and less effective in controlling the cotton bollworm. Early IR corn varieties provided resistance primarily to the European corn borer and were somewhat protective towards the corn earworm, the Southwestern corn borer, and to a lesser extent, the cornstalk borer (Fernandez-Cornejo and McBride 2002). Hence, GM IR crop varieties have emerged as another solution to farmers' plant insect pest problems in corn and cotton (Figure 2).

Herbicide tolerance is a second GM trait that has proved valuable to farmers. With HT genetically engineered into a crop variety, the plant is resistant to a particular commercial herbicide; for example, Monsanto's Round Up, which contains the active ingredient glyphosate (Fernandez-Cornejo and McBride 2002). When a farmer plants a HT crop variety, he may carry out the planting with minimal seedbed preparation. Roughly one month after emergence of the crop and accompanying weeds, the farmer applies the commercial herbicide Roundup, which kills all of the plants in the field, except for the HT plants. In a few weeks, the fields are weed-free. An attractive feature of the HT technology is that it is not sensitive to modest deviations in the application date, which is a major advantage to farmers that have off-farm jobs, other competing uses for their time, or face uncertain rainy weather conditions. Because farmers always face weed problems in their fields and plants like the soybean are not competitive against tall weeds, HT soybean varieties have become very successful in the United States (Figure 2) and canola varieties in Canada.

In contrast, corn is a strong competitor against weeds, and early adoption of HT corn varieties was much slower than for soybean varieties. Likewise, European corn borer infestation is random, not occurring every year. Hence IR for European corn resistance has not been as popular with farmers as HT (Figure 2). Recent development of GM protection against corn rootworm occurred by making roots of GM plants taste bad to the rootworm. Given this bad taste, the rootworm starts to crawl away to find another source of food, but its energy reserve is low, and it generally dies of starvation before reaching another food source. In many corn growing areas, the rootworm is a persistent problem and rootworm tolerant varieties are valuable to farmers in these areas.

Over the past decade, new private-sector developed GM herbicide tolerant (HT) crop varieties and have been supplied they to farmers in North America and a few other countries (Argentina and later Brazil). When plants carry the HT gene, they will survive and be minimally affected by application of a particular herbicide, while at the same time killing targeted weeds (Fernandez-Cornejo and McBride 2002). To farmers, currently available HT crops represent an innovation that allows them to simplify herbicide application to a single broad-spectrum herbicide, thereby simplifying farm management decision making; for example, farmers have rapidly adopted HT soybean varieties in the US.

The current frontier of GM corn varieties is with a triple stack of GM traits. For example, Monsanto-DeKalb have for the past two-three years marketed corn varieties with a second generation IR trait primarily to control European corn borers, IP trait to primarily control corn rootworm and an a HT trait. Bt for corn borer resistant varieties results in stronger stocks and less stock breakage. The insect protection for rootworm is not the standard Bt trait, but instead, it is one where the protected corn root contains a chemical that tastes bad to the rootworm and causes the rootworm to crawl away to find a new root to attack. However, its energy reserve is low and it dies before reaching food. Figure 6 displays the soil profile down to approximately three feet. The soil profiles for both of these plants were infested with corn rootworm. The soil profile on the left is for a corn plant that does not contain protection against the rootworm and the profile on the right does contain Monsanto-DeKalb’s rootworm protection. One can see from visual inspection that the root structure for the plant on the right is dramatically more extensive throughout the soil profile than for the plant on the left.

Improved root structures accomplish several things that are important to corn grain yields. First, it provides a root structure that can easily take up water and nutrients from the soil, and this advantage grows when the tasselling and silking period receives below average rainfall. The superior root structure is also insurance against high wind and wind-driven rainfall that otherwise would cause stock breakage, lodging and twisting which make harvesting difficult and increase field losses. This root structure also enables the corn plant to better withstand the stress of higher plant populations—which is one method for increasing corn yields. Clearly, improved root structures from HP for rootworm are a major advantage in below average rainfall periods, although it is not called the drought tolerant trait.

Energy and Tillage Practices

With advances in soil sciences and the rapid rise in energy prices during the mid-1970s, farmers, aided by applied researchers in public universities, re-examined tillage practices for potential cost savings. Farmers had, for over a century, relied on the mould board plow as a major tool for preparing seedbeds for row crops or small grains following legumes and grasses. This instrument cuts the soil to a depth of 6-12 inches and then turns the surface material (say dead or green plant materials) under. The exposed soil was then disked and harrowed to create a fine, firm seedbed for planting. However, plowing required large amount of energy in terms of horsepower. With one bottom plows, two horses or mules provided the horsepower to turn the soil, but as gasoline tractors started to replace horses in the US in 1910 and the process was largely completed by 1960 (Olmstead and Rhodes 2001), plows became larger, with two to six cutting shears. In particular, during the 1950s and 1960s larger horsepower tractors were developed and adopted by some US farmers. Roughly 15 drawbar-horsepower were required per cutting shear, or tractors with at least 100 horsepower were required to pull a five to six-bottom plow cutting eight to ten inches deep. These larger horsepower tractors were also used to pull larger tandem disks, 16-24 feet wide, to further break-up the soil structure. The shift to large horsepower tractors in the US peaked with the high real prices of grain and oilseeds in the 1970s; but as reduced- and no-till farming practices were adopted starting in the late 70s, super large tractors were no longer needed for field preparation for three decades. Huffman and Evenson (2001) show that public agricultural research and education and private agricultural research and market prices are important determinants of structural change (farm size, crop and livestock specialization, and part-time farming) in US agriculture during the post-War II period.

With the higher energy prices of the 1970s, applied scientists and farmers in North America re-examined alternative methods of seedbed preparation. They found that in most soils and climates, the use of the mould board plows and heavy disks could be eliminated from the technologies of seedbed preparation and replaced with a once-over with a new field cultivator-harrow that stirred the top three or four inches of the soil leaving crop residue on the surface, or by no-till seedbed preparation. With no-till farming, a broad spectrum herbicide, such as Round Up, was applied to a field first to kill all of the weeds on the surface. With reduced or no-till seedbed preparation, there was a need for new stronger seed planters.[3] Surprisingly, reduced tillage and no-till farming were found generally to produce similar crop yields as with the earlier more intensive seedbed preparation, but with significantly less energy, labor and machinery services. It also reduced soil and water erosion and led to more efficient use of soil moisture, which is an advantage in most areas that are under dry-land farming. Although these new tillage practices had obvious savings, they

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[3] Rahm and Huffman (1984) show that the adoption rate was conditioned by soil type and precipitation. Also, in the U.S., the Food, Agriculture, Conservation and Trade Act of 1990 prohibited farmers from using intensive tillage practices for seedbed preparation when the land was classified as being highly erodible.

also increased the demand for chemical herbicides and specialized no-till equipment, including heavy planters, and more recently HT crops.

In Japan, Europe, Argentina and the US where land is relatively flat and water is abundant, the mould board plow remains the primary tool for field preparation for row crops and for small grains following hay crops. The much lower rate of reduced- and no-till farming here seems to reflect the greater intensity of farming and abundance of precipitation. In Spain where much of the farmland receives low rainfall, there is higher frequency of reduced and no-till farming. Also, in the Canadian Prairie Providences and in Australia, dry-land famers have adopted reduced and no-till farming as a means of obtaining more efficient use of water and speeding up planting.

Plant Populations

The evolving genetic potential of crop varieties has resulted in dramatically higher seeding rates. It is widely accepted that the corn grain yield per corn plant has not changed much over the past 50 years, but the amount of grain yield per acre has increased dramatically. Why is this? Hybrids can now tolerate their neighbors' better, less abiotic stress, than in the past, and are able to withstand higher plant densities when placed in narrower rows while still producing roughly one ear per plant. In the Corn Belt in the 1950s, hybrid corn was planted in 40 inch rows and achieved about 14,000 plants per acre. By 1980, the plant populations had increased to 20,000 plants per acre (Padgitt 1982) and by 1990 to 22,000 (Huffman 2006). As plant populations increased, the distance between plants in a row became an issue worth investigating. Farmers using plant populations over 24,000 per acre found an advantage to narrower row width, 30 inches (versus 40 inches) for corn, and with these narrower rows, plant populations have moved up to about 30,000 per acre in 2007.

Plant populations for wheat and rice are relatively high compared to corn. Wheat is normally planted with a grain drill with two to six inches between pseudo-rows, but high plant populations are used when rainfall levels are high or in the case of paddy rice. Paddy rice, which is hand planted, has very high plant populations. Relative to other grains, a high labor cost exists for transplanted rice.

In the Corn Belt during the 1950s and 1960s, soybeans were planted in 40 inch rows. Over time the row width came down to 30 inches by 1990, and with the 1990 farm bill, US farmers who grew soybeans on highly erodible cropland had to apply uniform, solid or drill seeding of soybeans. Those farmers who were not planting soybeans on highly erodible land have further reduced their row width to 15 and in some cases to 7.5 inches in the Corn Belt. With current technology, 100,000 soybean plants per acre in row width of 30 inches or less provide optimal plant population for soybean yields (DeBruin and Pedersen 2007). These changes have resulted in increased soybean plant populations, but the average percentage increase is less than for hybrid corn.

Planting and Harvesting Equipment

Field crop production in developed countries today has been reduced largely to two operations; planting and harvesting. Fifty years ago when a large share of farms in developed countries were small (80-240 acres of cropland), seed corn planters were small, 2- or 4-40 inch row planters. The size of grain farms has increased dramatically in North America, Australia, Argentina, and Brazil, and as this has occurred the farm machinery companies have produced ever larger machinery. Today, large North American farms have available to them large new developed sophisticated 24-30 inch row (30-20 inch or 48-15 inch rows for soybeans) planters that plant seeds with high spacing accuracy, depth control and firm seed-soil contact for rapid germination. Corn planters of the 1950s might have also applied starter fertilizer, but new planters today also can apply starter fertilizer and pre-emergent herbicide. Also, the new modern planters have the capacity to be linked to GPS to more accurately control planting rates and fertilizer and pesticide application rates. Moreover, these planters can be quickly folded into an easily transportable piece of farm equipment. These new planters are major labor-saving devices or raise labor productivity.

In countries with dryland farming, e.g., Europe, where farm and field sizes have remained small, row-crop planters remain small. The technology of grain drills for small grains and oilseeds has not changed very quickly over time. The main changes have been to accommodate large field sizes in dry land areas of North America, Australia, Argentina, Brazil and Russia.

In Japan, the fields for paddy rice are relatively small and the acreage farmed by each farmer is also modest in size. However, the Japanese have developed and adopted small scale tractors and tillers to assist with field preparation. Power rice planters have been developed to replace hand planting or re-planting, and small combines have been developed and adopted for harvesting rice

In 50 years, the technology available for harvesting of corn in North America has been converted from two-row tractor-mounted or drawn pickers to 12- and 16-row self-propelled corn combines. These new corn combines have electrically controlled smooth feeding of stocks, low ear loss, large 150-350 bushel grain tanks and easy maintenance. On these new combines, corn heads can be replaced by a cutting bar for small grain and oil seed crops. The size of the cutting bar available has increased from 12 feet in the 1960s to 30 or even 40 feet today, and the wide cutting bars or platforms are somewhat flexible so that they can better follow the terrain of the land from which small grains and oilseeds are being harvested. This reduces seed loses in harvesting and damage from picking up dirt and rocks. Also, new combines have steadily improved threshing effectiveness relative to earlier combines. On new combines, it is possible to have yield monitors and also have the potential for use of GPS data by the combine's computer such that the combine is computer-guided through the field while adjusting the height of picker and cutting bars and maintaining peak harvesting speed. New self-propelled combines with enclosed comfortable cabs and GPS controls permit farmers to harvest more grain with less of their own energy and less fatigue, which permits longer work days. Hence, these new self-propelled harvesting combines are major labor-saving or labor-augmenting devices relative to the early vintage pull-type and small open self-propelled combines and corn pickers. Larger tractors, planters, and combines have been a major factor raising labor productivity in agriculture in North and South America and Australia.

More on GM Crop Utilization

Starting in 1995, GM crop varieties were first planted in North American and Europe. After a series of unrelated food scares in Europe during the late 1990s, the EU countries placed a moratorium on approval of new GM crop varieties. This left the U.S. and Canada as the early leaders in GM crop use. Even in these countries, the GM technology has been successful for cotton, which is a fiber and oil seed crop, and for soybean and canola, which are oilseed crops, and corn, which is mostly used for livestock feed. In the case of vegetable oils made from GM soybean or canola, the refining process for these oils removes all of the GM content. Hence, consumers have little to fear from the use of GM technology in the production of these crops. Various kinds of fears have slowed the sale and adoption of GM small grains, such as wheat, barley, rye and rice, which are used heavily for food.

The U.S. has been the leader in adopting GM soybean, cotton and corn varieties. In 1995, no significant acreage of U.S. field crops was planted to biotech crop varieties, and in 1996 the rate of adoption was low, being higher for Bt cotton and HT soybeans than for HT corn and cotton or Bt corn (Figure 2). Bt cotton has been adopted in some areas of the South, but not in other areas where insect problems, including tolerance to chemical insecticides, were less severe. The HT cotton adoption rate surpassed Bt cotton adoption by 1998, reflecting the fact that weeds are a persistent problem in cotton, and HT cotton experienced higher adoption rates than Bt cotton through 2007.

Although the U.S. adoption rate for HT soybeans was initially lower than for Bt cotton, HT soybean varieties have experienced very rapid adoption rates over 1997-2007, except for a brief setback in 2000. The adoption rate in 2007 was about 90 percent of planted acres. HT and IR corn varieties were adopted more slowly by U.S. farmers, but by 2007, HT and IR corn variety adoption rates had reached about 50 percent (figure 2). In the U.S. in 1996, biotech crop variety shares for planted acres were 17 percent for cotton, 7 percent for soybeans and 4 percent for corn. But in 2007, these shares had increased to 91 percent for soybeans, 87 percent for cotton and 73 percent for corn. For non-hybrid GM crops, farmers must sign a waiver when they purchase the seed that they will not save or sell seed from their harvest.[4]

Evidence of Field Crop Yield Improvement

Crop yields are of much interest to farmers, agronomists, and economists, but they are also of interest to scholar and public officials who are interested in meeting future demand for food, feed, fiber and biofuels. The reason is that if additional arable land in developed countries is quite limited, the primary means of increasing grain, oilseed, and fiber production is to increase crop yields per acre of land. However, crop yields may change over time for a variety of reasons; only one of which is improvement in genetic potential.

In studies of crop improvement, a lingering issue is how to express yield improvement-- bushels per acre (kilograms per hectare) per year or as a percentage change in yield per year, which is a pure number. Although some scholars have fitted and reported results from regressing ln yields on an annual trend, these results tend to show that average annual yield increases as percentage are *declining over time* (World Bank 2008). But if yield improvement is summarized in bushels per acre (tons per hectare), yield improvement is more likely to be increasing over time. An issue is which procedure is appropriate for indexing crop improvement or innovation.

There are four main factors to consider in decided how to quantify crop yield improvement. First, advances in science and technology are measured by counts of the *best* of scientists' discoveries and inventors' inventions, e.g., these discoveries and inventions must be superior to existing ones, and furthermore, discovery/invention of inferior technologies do not count as advances in science and technology (Levitt 1995, Huffman and Just 2000). This is the main reason that experiment stations and seed companies release only a fraction of the total number of test varieties or crosses that they produce and evaluate (Huffman and Evenson 1993, pp. 152-179;

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[4] With hybrid corn, saved seed is a poor performer and hybridization provides natural intellectual property right protection.

Evenson and Gollin 2003). Second, the count of creative events is in units of number of discoveries and innovations per year, and change in creative events over time is measured as change in absolute number of events, and not in terms of percentage change in events. The reason is that new discoveries or inventions are certainly not easier to achieve than past ones and will be more difficult, if the discovery and innovative potential is not restored by advances in basic/core and pre-invention sciences (Huffman and Evenson 2006, pp. 49-52; Evenson and Gollin 2003). Third, yield increases cannot be attributed wholly to crop varietal improvement because other crop technologies may also be changing simultaneously, e.g., increased plant population, increased fertilizer application, and improved planting and harvesting equipment. Fourth, for comparison purposes, changes in crop yields must be measured in units that can be easily and accurately interpreted, i.e., units with orders of magnitude that are easy to comprehend, for example, in bushels per acre or in kilograms per hectare (per year).

In the following sub-section, I consider a select set of field crop yields from major growing areas in developed countries: corn in Iowa, Wheat in Kansas and France, rice in Japan, and soybeans (an oil crop) in Iowa. These area are representative of much broader areas.

(Hybrid) Corn. Turning to the Iowa data on state average corn yields, we see little increase in corn yields over 1866 to 1930, and roughly a two bushel per acre per year increase over 1958-2007 (see Figure 7, the trend). During 1866-1930, when farmers planted open-pollinated corn varieties, the state average corn yield increased at only six one-hundredth of a bushel per year (note: 1 bu per acre equals 62 kilograms per hectare). During this era, farmers saved the best-looking ears from their harvest, dried and stored them and then in the spring shelled the kernels and planted them. Iowa average corn yield in 1930 at the dawn of the hybrid corn revolution was only 39 bushels per acre. The introduction and adoption of double-cross hybrid corn varieties started in Iowa about 1930 (Griliches 1960; Huffman and Evenson 1993) and reached 90 percent of harvested acres by 1940. These hybrid varieties were developed largely by private seed companies, e.g., Pioneer Hi-Bred, but were supported by public

(USDA and State Agricultural Experiment Station) inbred line development up to the mid-80s (Huffman 1984). With the adoption of these early hybrids, the yield trend moved sharply upward, increasing at an average of 0.8 bushels per acre per year over 1930-1958, and the state average yield was 58 bushels per acre in 1958. New superior single-cross hybrid corn varieties were introduced and adopted in Iowa starting in 1958, and they provided an additional boost to the trend in Iowa average corn yields—2.3 bushels per acre per year over 1958-1970 (Duvick 1984). Over 1970 to 2007, the trend increase in Iowa average corn yields has been at 1.9 bushels per acre per year, with the state average yield exceeding 165 bushels per acre in 2007. However, the state average yields in 2004-2007 were somewhat above the trend line, suggesting that a new era of large high increases in Iowa average corn yields might be occurring. This may be due to private seed company sale of the triple stacked GM corn varieties: Bt for corn borer resistance, IP for corn rootworm and herbicide tolerance. Hence, the performance of Iowa's corn yields over the last half century is truly amazing.

Wheat. Wheat yield are presented for Kansa, the leading wheat growing state of the US and where wheat is grown in rain fed semi-arid conditions, and for France, the leading producer of wheat in the EU and where wheat is grown under temperate abundant rainfall conditions. Figure 9 shows that over 1900 to 1950, very little improvement in Kansas state average wheat yields occurred— a trend rate of increase of only three one-hundredth of a bushel per year (Figure 8), and state average wheat yields were only 15.5 bushels per acre in 1950. Early Kansas wheat varieties were largely imports from Europe, e.g., Turkey variety, but by 1924, the Kansas Agricultural Experiment station emerged as a successful developer of new hard red winter wheat varieties. By 1949, 77 percent of Kansas hard red winter wheat acreage were planted to public sector developed varieties (from Kansas and largely adjoining states of Nebraska and Oklahoma). See Huffman and Evenson (1993, pp. 169-173). However, the rate of genetic improvement in Kansas wheat varieties over this period roughly offset the biological erosion of yield potential due to the evolution of pests.

Over 1950-2007, the trend in Kansas state average wheat yields is steadily at one-half bushel per acre per year, and the average yield in 2007 was 44 bushels per acre. Over 1949 to 1974, Kansas-bred wheat varieties were replaced by varieties bred by the Nebraska Agricultural Experiment Station. In particular, in 1969, 66 percent of the Kansas hard red winter wheat area was planted to varieties developed in adjacent states. However, over 1969 to 1984, varieties developed by the Kansas Agricultural Experiment Station reigned supreme. Furthermore, over 1980 to 1992, Pardey et al. show that CIMMYT ancestry was of growing importance to wheat varietal development in the US Central Plains, including Kansas, but this influence peaked at 20 percent in 1992. This difference in source of leading Kansas grown wheat varieties after 1950 has not affected its trend yield increase.

Wheat yields in France average 41.5 bushels per acre in 1960 and have a strong linear trend upward over 1961-2007 at 1.55 bushels per acre per year. The predicted wheat yield based on the linear trend is 113 bushels per acre in 2007. However, a review of Figure 9 shows that wheat yield increases in France may have slowed since the mid-00s (Figure 9). Clearly, French wheat yields have improved much faster than in Kansas. This comparison makes clear how the use of lower quality land for wheat production requires many more acres to grow the same quantity of wheat, but even in Europe, marginal lands may need to be brought into wheat production as more wheat is diverted to produce ethanol.

Rice. Paddy rice production in Japan, Korea and Brazil is intensive farming. Japanese country wide average rice yields were 78 bushels per acre in 1960 and increased to 117 bushels per acre in 2007. Furthermore, Figure 10 shows that the trend rate of increase in average yields is 0.53 bushels per acre per yield. Thus, although paddy rice is intensive agriculture on good quality land in Japan, the average rate of yield increase compares favorably to dry land low resource input wheat in Kansas, and far behind dry land resource abundant corn yields in Iowa and wheat in France.

Soybeans. Soybean production is the leading source of vegetable oil North, South America and China. The planting of significant acreage to soybeans in the Corn Belt started as a result of the need for substitutes for animal fats during World War II. Iowa average soybean yields were 22 bushels per acre in 1950, and Figure 11 shows that a linear trend fits the Iowa average soybean yield data well over the approximately 60 year period since then. The average tend rate of increase is 0.47 bushels per acre per year, and the yield in 2008 is 49 bushels per acre. In contrast to hybrid corn, the development of new soybean varieties for the Corn Belt was primarily by the public sector up to the mid-1970s (Huffman 1987). The US passed a Plant Variety Protect Act in 1970, and it provided weak intellectual property protection to new soybean varieties. The law provided that novelty be awarded to varieties that had achieved a certain degree of homogeneity or stability over generations. Holders of a Plant Variety Protection Certificates (PVPCs) can exclude others from commercial reproduction of protected seed (Huffman and Evenson 1993, p. 138-144). A large absolute and relative number of PVPCs were issued to the private sector on soybean varieties over 1971-2002 (Huffman and Evenson 1993, p. 145, 2006, p. 163). These varieties gradually replaced public sector varieties, and by 1991 US soybean growers used newly purchased seed on 70 percent of their harvested acres with 50 percent being private sector varieties (Huffman 2006).

Starting in 1996, varieties containing GM herbicide tolerance became available to Midwestern farmers, and the private sector required farmers to sign a contract that they would not save their own seed for planting nor would they save seed and sell it to others for growing. From this perspective, it is interesting that the same linear trend performs equally well for the 1996-2007 period when HT soybean varieties were being rapidly adopted by farmers as for the earlier pre-GM period 1950-1995.

In conclusion, the dramatic difference in public-private sector contributions to development of wheat and rice varieties compared to corn varieties seem to be due to the following reasons: (i) the low rainfall in the wheat growing area of Kansas and other Great Plains states (and Canada and Australia) relative to substantial summer rainfall in the Corn Belt and (ii) wheat being a self-pollinated plant where hybridization has been relatively unsuccessful relative to hybridization of corn. The breeders of hybrids benefit from the inherently strong nature of intellectual property rights that arise from the fact that seed from a hybrid performs poorly relative to the parent. These property rights have been strengthen since the mid-80s by new DNA finger-printing methods, which permit more precise identification of genetic origins.

More about the Current Frontier in Field Crop Production

There is no doubt that genetic improvement has been a major factor pushing corn yields of major corn growing areas to their current levels. In the US where the frontier has been pushed the farthest, genetic improvements have been largely in the private sector and due to: (i) breeding for improved yield per se, (ii) breeding for multiple stress resistance as reflected in tolerance to stressful emergence (the struggle of the seedling to emerge successfully); better stock, leaf and root structures (which are key to energy absorption and nutrient and water uptake); greater resistance to insects, weeds and fungal diseases; and increased plant population (which has doubled in 40 years), and (iii) new GM hybrid corn varieties with the triple stack of herbicide tolerance for weeds, Bt for corn borers and rootworm protection.

Changes in non-genetic factors have also contributed to corn yield improvement in the US Corn Belt. Those with farm origins include: adoption and perfection of reduced and no-till farming, increased plant population, better farm equipment, including yield monitors and GPS guide nutrient and pesticide application, and better management. If I were to judge the relative importance of these two forces for change in hybrid corn yields, I would allocate 50 percent to genetic improvement and 50 percent to non-genetic factors at the farm level.

The big story in oilseed production is the successful introduction and adoption by farmers of GM herbicide tolerance. Farmers in the US, Canada, Argentina and Brazil have had high rates of adoption and diffusion of HT soybean and canola varieties among farmers. However, it seems that in the US the rate of yield improvement of soybeans has not changed over the GM variety era versus the pre-GM variety period.

Yield improvement in dry land winter wheat varieties can be split into genetic and non-genetic factors, too. The genetic factors include the development of semi-dwarf varieties that put energy into grain, not stems, and breeding for multiple stresses. These include abiotic stress of drought resistance, low N tolerance, and winter cold tolerance and biotic stress of leaf rust, aphids, karnal bunt and other diseases. Improvements in non-genetic factors include higher rates of fertilizer application, better moisture management (shift from fallow periods to no-till field preparation), better weed control, improved crop rotation, improved harvesting equipment and better farm management. In Australia, where wheat is grown under very low and variable rainfall conditions, new research is attempting to develop perennial wheat varieties that would over time out yield annual wheat varieties. The idea is that perennial wheat would establish a more extensive root system that would give it greater drought tolerance (Future Farm Industries).

Wheat yield improvement in both dry land and irrigated wheat (and rice) has undoubtedly been retarded by the fact that GM wheat (rice) varieties have not come to market. The primary reason for this outcome is the concern that it will be heavily discounted or barred by major importers. The reason for this is the fact that wheat (rice), as opposed to corn grain, is largely used for food consumption while (yellow dent) corn grain is used primarily for livestock feed or high fructose corn syrup. GM crops used for oil or sweeter largely do not face the same barrier. The reason is that oils are a pure lipid or fat and high fructose syrup is a pure sweetener, and in the refining of the raw materials all impurities, including residual DNA carrying GM, are boiled away. Hence, oil or sweetener made from GM and non GM crops have the same chemical structure. Individuals might still have environmental concerns about these GM oilseeds, but any nutritional or health concerns are eliminated.

Why has Europe been so slow to adopt GM crop technology? In one sense, the major crops produced in these countries are ones where GM technology has not yet come to market. Also, under the Common Agricultural Policy, consumers in Europe do not expect to gain much from GM input traits. This, however, could change if the European Parliament were to ban the use of the most commonly used insecticides (Coelho 2009; Spink et al. 2009). The health concerns with the commonly used European chemical insecticides and fungicides are due to the likely disruption of the endocrine system of humans as well as insects and associated nerve damage. The pest control concern is with growing resistance of insects and fungi to approved chemical pesticides when they are used widely. In addition, IMP frequently requires the use of a wide range of chemicals to control insects. Another possibility is that banning these pesticides would increase the profits of the pharmaceutical companies for developing new and safer pesticides, and with some lag new pesticides would be available to farmers. The upshot of these circumstances is that Europe may finally see a major advantage to IR crop varieties, because of their safer biological control nature, otherwise pharmaceutical companies will see new incentives to develop safer pesticides.

New Technologies for Horticultural Crops

The presentation focuses on potato and tomato with secondary emphasis on other vegetables and fruits.

Genetic Improvement

For potatoes, other vegetables and fruits, public and private research has focused on protection-maintenance and biological efficiency, e.g., see Huffman and Evenson (1993, p. 114). Protection-maintenance research is needed for continued pest control. Irrespective of the type of pest control undertaken, some of the pests evolve over time so that they become resistant to the pest control practice, including pesticides. If new alternatives are not under continued development, new pests will over-run the protection and crop yields may decline. Insect resistance is especially important in the production of fresh fruits and vegetables because insect damage makes most produce salable for a much reduced processing price. Improvements in biological efficiency include changing the configuration of leaves so as to incept a larger share of the light from the sun, increased efficiency of water use, and conversion of a larger share of total plant energy into the parts to be consumed.

Potato. The potato has been grown for over 8,000 years, starting in South America, and it is the leading non-grain-based source of calories in OECD countries. However, Vos (1992) claims that increases in yield per se in potato varieties has been unimportant over more than a century up to 1990. Public and private research has instead focused on controlling major pest problems, including late blight (*Phytophthora*), wart, Colorado potato beetle, and potato cyst nematodes. Late blight has been a serious threat to potato yields since the Irish potato famine of 1845-46. The blight is caused by fungi that is carried by the wind and can hit the potato plant early or late, rapidly killing the potato vines and cutting off energy to the roots and tubers. Breeding for resistance to *Phytophthora* occurred during 1900 to 1970, and several resistant varieties were developed. However, each of these varieties was only a temporary solution because the target pest mutated once resistant varieties were widely grown by producers. Spraying with fumigants is another means of *Phytophthora* control, for example, in the Netherlands, 60 percent of applied pesticides to potato and other crops are soil fumigants (Vos 1992). Moreover, potato ranks second to onion in Dutch agriculture for its rate of application of pesticides. A third alternative is to reduce the frequency of potato in a crop rotation—e.g., a change from continuous potato cropping to planting potatoes one year in two or three.[5] In addition, the likelihood of potato cyst nematodes and fungus *Rhizoctonia solani* is also reduced by lowering the frequency of potato in a crop rotation.[6] However, a low frequency of potato in a crop rotation does not insure control of other soil-born pests, such as root knot, nematodes and the fungus *Verticillium dahliae* because they may be carried by other host plants. For example, the latter pest shows increased frequency when leguminous crops are included in the crop rotation (Vos 1992).

In the Netherlands and other major commercial growing areas research on potato improvement has shifted to improved net potato yield of high quality potatoes (Peeten 2009). The emphasis is on both internal (starch and dry matter content) and external (size, shape, color,

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[5] Both late blight and potato cyst nematodes are high risks in continuous cropping of potato.

[6] Other controls for potato cyst nematodes are resistant potato varieties, plant new seed potatoes that have been tested for absence of infestation, and partial soil sterilization with nematicides.

grading). New potato varieties tend to yield a larger share of potatoes with desirable attributes and lower share of waste.

The Colorado potato beetle is a leaf-eater which can defoliate the above ground parts of the plant. The chlorinated hydrocarbon DDT, which became available after World War II, was quite effective. However, DDT became a banned pesticide in the 1970s with the discovery that it polluted ground water and accumulated in the food chain. Other chemical controls for the beetle are less effective, and this led Monsanto to discover, test, and develop the Russet Burbank New Leaf Potato, which was released for sale to farmers in the US in 1994. Control of the beetle was obtained by genetic modification, which provided a new type of biological control and dramatically reduced the need for chemical insecticide application to potato fields. However, with some resistance to GM foods in the US in the mid-90s and a variety of food scares unrelated to GMOs in Europe in the late 90s, the market for GM potato dried up. In particular, the US fast food industry and the supermarket chains failed to purchases or distribute the product, and it was withdrawn from the market by Monsanto in 1999. However, GM pest control in food crops, such as potato, may warrant a serious re-examination as the public bans more chemical insecticides.

Continued resistance to transgenic GM crops, which transfer one or more genes across species, for example from soil bacteria to hybrid corn varieties, and large genetic diversity in some vegetable crops have provided the opportunity for the development of new crop varieties that use intragenic rather than transgenic GM technology. Intragenic GM technology transfers genes within a species, and the potato is an ideal crop for the new technology. The potato has been grown by farmers for 8,000 years, starting in Andes of Peru and spreading to areas that have diverse geo-climatic, food and economic needs. Although the potato has a diverse genome, it is difficult to manipulate using conventional plant breeding techniques. For example, it is propagated by planting a small piece of potato with an eye or tiny sprout on it and not by planting a seed. Scientists have discovered genes for high antioxidant and vitamin C levels and low-acrylamide levels in primitive potato varieties, and GM methods can be used move these traits into commercial varieties (Colson et al. 2009; Rommens et al. 2008).[7] Thereby, genomic and metabolic pathway discoveries can be rapidly introduced into established commercial varieties to fast-track the breeding process for potato, tomato and perhaps other crops (Rommens et al. 2004). These intragenic GM methods are expected to be important to future development of other related vegetable crops, e.g., tomato.

Tomato. The tomato is the second leading (fruit or) vegetable for consumption in OECD countries. There are primarily two types of tomatoes, those for the fresh market consumption, where color and taste are important, and those for the processing market, where solids content and ease of harvest are most important. Over the past three decades fresh market tomato varieties have been developed that are medium sized, firm when purchased by the consumer, and generally flavorful. To reduce disease and insect pest problems, these tomato plants are tied to individual wooden stakes or to lines strung between stakes (which is a labor-intensive operation).

Controlled-environment tomatoes (greenhouse and hydroponically grown) that are harvested when vine ripened for the fresh market have experienced rapid growth since 1999. In the past, these tomatoes have been largely grown in the Netherlands, Canada and Israel, but more recently in the US. These tomatoes have greater uniformity than open-air fresh-market tomatoes, and it is claimed, improved taste. Many are being marketed “on-vine” in clusters to convey an appearance of freshness to consumers. The hand labor in the hothouse is somewhat different from that for traditional open-air staked tomatoes and can approach year-round work.

Tomato breeding has produced new tomato varieties for processing that are grown near the ground in open fields and can be hand or mechanically harvested. With the invention, adoption and diffusion of the mechanical tomato harvester in California in the late 1960s-early 1970s (Schmitz and Seckler 1970), processed tomato varieties have been bred for a pear or cylinder shape, high-

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[7] Acrylamide is produced in starch foods that are baked, roasted or fried at higher temperatures. However, Acrylamide derivates are a potential cause of cancer and some other serious diseases in humans. New low-acrylamide potato contain approximately a 20 fold reduction in acrylamide (Rommens et al. 2008).

solids content, uniformity in ripening date, and generally tough skins. With these attributes, they are less susceptible to pests while growing near the ground and easily harvested with a mechanical tomato harvester.

Early attempts to develop a GM product-enhanced tomato variety failed. The first GM tomato, named the Flavr-Savr tomato, was invented, tested, developed and marketed by Calgene to US farmers in 1994, and they were marketed as GM and were sold in US grocery stores in the summer of 1994. The Flavr-Savr tomatoes did extend shelf life by about a week relative to mature green harvested tomatoes. They initially sold relatively well at first and were in about 2,500 US stores by June 1995, but it became apparent that their performance did not match expectations. First, the genes for delayed ripening were inserted into a tomato variety that was best suited for processing, not fresh consumption, and it bruised relatively easily, contrary to its development objective. Second, contrary to expectations, it had a bland taste relative to conventional winter tomatoes. Third, the new tomato variety was suited to California's dry summer growing conditions but not to the humid winter tomato growing regions of Florida where it was expected to have its main advantage. As a result, it was susceptible to Florida's tomato fungal diseases. Fourth, the retail price was more than two times higher than conventional fresh market tomatoes. Hence, a number of factors contributed to the failure of the Flavr-Savr tomato in the US market (Alcamo 1999, p. 256-257, Soil Association 2007).

At the same time, Zeneca produced a related high-solids GM tomato for use in purees and soups, obtained approval for sale in the UK and began marketing in 1996 under the brand names Safeway Double Concentrated Tomato Puree and Sainsbury's California Tomato Puree. These products were sold at a lower per unit price than purees from conventional tomatoes and were marketed in larger containers to make the product appear to consumers as a "better value." By 1999, the GM puree had captured up to 60 percent of the processed tomato market share in the UK. However, when unrelated food scares (e.g., BSE in sheep and cattle, dioxin in livestock feed) started to unfold in the UK in the late 1990s, Zeneca's GM high-solid tomato varieties were a casualty, and they were withdrawn from the market (Soil Association 2007). Thus, Zeneca's GM tomato varieties also had a short product life.

Cultural Practices

For specialty crops such as potato and other vegetables and fruits, major technical advances have been associated with raised seed beds, drip irrigation, fertigation, plastic mulch and/or climate-controlled green houses (Huffman 2002). Irrigation is an important supplement to natural precipitation for most high value fresh vegetable crops. Although flood, moving rig, or center pivot irrigation systems have been used for field irrigating horticultural crops, they are being replaced by drip irrigation, which is a water- and labor-saving way to irrigate plants. Hoses with regularly spaced drip holes are laid permanently (or temporarily) at the center of beds. When the water is turned on, the drip system delivers water at the root base of the growing plants. This dramatically reduces water percolation out of the root zone and from evaporation, as in flood, moving rig, or center pivot irrigation systems. Also, it dramatically reduces the amount of labor used relative to that with irrigation from portable surface pipes, which increases labor productivity.

Fertigation uses the same drip irrigation system to deliver liquid fertilizer efficiently to the roots of growing plants, especially in fresh vegetable production. With this method of application, a farmer usually starts the growing season by applying dry fertilizer before planting vegetables and then supplements during the later growing season with fertigation. A positive externality of fertigation is reduced water pollution from leaching and runoff of agricultural chemicals.

Plastic mulch is frequently used with raised and rounded seedbeds to produce fresh tomatoes, other vegetables and strawberries. This plastic mulch is placed on raised or rounded seedbeds. Long clear (or sometimes black) sheets of plastic are laid over the entire bed, pierced only where the young seedlings or plants are planted. Plastic mulch reduces weed growth, promotes desired plant growth, especially in hot-season plants like tomatoes, and blocks micro-organisms from moving from the soil to the growing plants. It reduces the need for hand weeding, herbicides, fungicides, and other plant protection measures. In northern latitudes in the summer or for winter crops, plastic also raises the soil temperature, reduces water evaporation and increases the total photosynthetic activity in most plants.

Since the mid-90s, controlled-environment tomatoes have been grown hydroponically in green houses in the Netherlands and then spread to Israel, Canada and the US. These plants obtain all of their nutrients from a liquid solution surrounding the roots of growing plants. The hand labor in the greenhouses is somewhat different from that for traditional open-air staked tomatoes and can approach full-time year-round work. These tomatoes have been attractive to consumers because of their greater uniformity than open-air tomatoes and, it is claimed, improved taste. Many of these tomatoes are being marketed "on-vine" in clusters to convey an appearance of freshness to consumers. US production of hydroponic tomatoes is now replacing the traditional Netherlands, Canada and Israel sources.

Harvesting the produce from ripe crops, especially fruits and vegetables, has historically been labor intensive, hard and sometimes backbreaking work. Harvesting ranges from stoop-labor for vegetables such as strawberries, lettuce, asparagus, broccoli and tomatoes to standing on ladders to pick fruits such as citrus (oranges, grapefruits, lemons, limes), apples, peaches, cherries, pears and avocadoes. Labor-saving mechanization for these crops can be classified as labor aids (e.g., back-saving devices), labor-saving machines (e.g., tree shakers), and automation (e.g., electronic eyes that replace human eyes for selecting and harvesting crops) (see Martin 2006).

The most dramatic labor-saving mechanization in fruit and vegetable production continues to be the harvester for harvesting tomatoes for processing (Schmitz and Seckler 1970). It was developed in the early 1960s by the University of California and spread rapidly in the processed tomato industry of California after the end of the Bracero program in 1964. Before the harvester, workers hand-picked ripe tomatoes, placing them into boxes weighing about 50 pounds when full.

These boxes were then carried to the ends of rows where they were dumped into specially designed trucks. In their place, the mechanical tomato harvester operates much like a conventional small-grain combine, cutting the plants off near ground level and pulling them into a separator, where the tomatoes are shaken off the vines and sorted by gravity through a screen onto rolling conveyor belts. Until the early 1990s, four to six workers were needed to ride on the machines and undertake hazardous hand-sorting, getting rid of chunks of dirt and green tomatoes so as to have a truck load of high-quality ripe tomatoes. During this era, payments to growers were frequently docked for excessive dirt and green tomatoes that accompanied ripe tomatoes delivered to processing plants.

During the early 1990s electronic sorters were developed and attached to mechanical tomato harvesters. These electric-eye sorters were a major technical advance (Huffman 2002). They sense the color of material on rolling conveyor belts and use air pressure to blow green tomatoes and chunks of dirt off the belts. The remaining ripe tomatoes are then elevated into wagons or trucks. The electronic sorters have reduced the amount of hazardous hand-sorting and the number of workers riding on the tomato-harvesting machines, also eliminating the green tomatoes and dirt from loads of ripe tomatoes. The net result of the new processed tomato harvesting technology was that harvesting labor costs declined from 50 percent to 15 percent of the cost of producing processed tomatoes.

Mechanical harvesters somewhat similar to the tomato harvester have been invented, developed and marketed to some producers of soft fruit (e.g., cherries, peaches, plums) and hard fruit (e.g., apples) for processing and for nuts. These harvesters have one motorized part that grips the tree and shakes it hard enough to make virtually all of the nuts or fruit fall off, either onto the ground (nuts) or onto a sloping canvas (fruit). Conveyors can be used to move fruit into boxes. After harvesting, the gripping part of the machine releases and moves to the next tree. These machines greatly reduce the labor needed for harvesting and eliminate the hazardous work of harvesting trees from ladders.

Shake-and-catch machines harvest most tree nuts, and are used to harvest some tree fruits for processing, such as cling peaches for canning and Florida oranges for juice. Other fruit crops whose harvest has been largely mechanized are mid- and low-end wine grapes and prunes (dried plums). In each case, machines were improved as they were introduced and then diffused rapidly as processors changed their machinery to deal with machine-harvested crops.

In some commodities, innovations in mechanical aids rather than harvesting machines or genetics are making jobs easier and workers more productive. Advanced methods for harvesting lettuce, celery and broccoli involves hand-harvesting and placement of the produce on a slow-moving conveyor belt by workers who follow behind a work-table that is slowly pulled through the field of produce. This eliminates the need for workers to carry heavy loads of vegetables to trucks, and makes the work accessible to more women and older workers, and less likely to cause back injuries. A similar conveyor belt harvesting system has been introduced and is spreading through strawberry harvesting fields. Again, this worker-aid has eliminated the need to carry heavy flats of berries to pickup stations. In California, raisin grapes have been traditionally harvested by hand and left on paper trays in the field to dry, but new raisin grape varieties are trellised so that the ripe fruit can dry on the vine (DOV method of production) and then be harvested mechanically. Since the fruit is relatively dry when harvested mechanically, bruises and blemishes are less of a concern than for fresh produce (Green and Martin 2008). Many leafy vegetables, such as spinach, are cut by new band-blade machines, and a new machine has been invented for harvesting fresh-market asparagus, which eliminates stoop labor.

Tree shakers are an innovation to harvesting of some fruits and nut crops. A major problem with adopting tree shakers for crops like apple, avocado, peach and pear is the lack of uniform ripening of the produce, and excessive damage to the ripe harvested fruit and sometimes to harvested trees themselves. Moreover, for citrus fruits, trees of ripe fruit must be sprayed with a chemical to loosen the fruit so that they can easily be detached and shaken off without damaging the trees.[8] However, most modern fresh fruit packers and processors are not set up to handle crops that include significant amounts of damaged fruit. Moreover, mechanical harvesting is easier when trees are short, and can only be accomplished by planting new dwarf trees at high density. For example in Washington State, delicious apples ripen uniformly but the trees are spaced far apart because they are more than a decade old, but this makes mechanical harvesting inefficient. With newer varieties, such as Fugi and Gala, the growers have planted trees that are dwarfs and are pruned to grow on trellises, which position the fruit ideally for mechanical picking. However, existing varieties do not ripen uniformly and generally need picking four or more times, so mechanical harvesting in again inefficient (Green and Martin 2008).

Yield Improvement

My discussion of vegetable yield improvement focuses on the potato. The Netherlands is recognized as a center of intensive, high yielding potatoes, and the yield data that I report are for Dutch average potato yields over 1961 to 2007 (FAO 2009). Figure 12 graphs these potato yields in tons per acre against time and also includes the trend yield.[9] Dutch average potato yields in 1961 were 471 bushels per acre, and over roughly a half century has increased at a trend of 4.6 bushels per acre to 2007 of 667 bushels per acre. Hence, the increase in Dutch average potato yields is larger relative to the Iowa corn.[10]

Technical Advances in Livestock Production

Technical advances in livestock production are a result of genetic improvement of animals, improved disease control, improved structures and improved management practices. Huffman and Evenson (2006, pp. 252-253), Narrod and Fuglie (2000), and Yu (2008) describe how the

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[8] For example, it takes a 20 pound pull to dislodge oranges from their tree. In Southwest Florida, orange harvesting in highly mechanized but in other areas hand harvesting from ladders is the dominate technology. Recent high orange prices have slowed mechanization (Green and Martin 2008).

[9] These are ware, starch and seed potatoes.

[10] One notable difference between potato and corn grain is the water content. Number 2 yellow corn is standardized to 14 percent moisture content. In contrast, potatoes are 72-75 percent water (FAO 2009).

technologies of U.S. livestock production have changed. Steady improvements in animal genetics have occurred with the use of artificial insemination, which is now widespread and pervasive in modern dairy, swine and poultry breeding and production. Modern animal breeding strives for a high proportion of lean meat in prime cuts. Cross-breeding was a new technique in swine production in the 1950-60s, but it has since spread to beef herds as a means to improve genetics for rapid growth and quality attributes of meat. Livestock production in the U.S., Spain, the Netherlands, Denmark, Belgium and Germany have become specialized into large units for broilers and layers and also cattle finishing in the US, which reduces labor intensity. Since diseases can spread rapidly under high animal populations, preventive disease control is important to low cost production. However, animal rights groups have been lobbying in Europe and the US for low density-production methods.

The largest dairy herds in OECD countries are in the US West and South—Florida, Arizona and California—where herd sizes are 5,000-10,000 cows. Extremely large dairy herds have not been adopted in the US Upper Midwest and New York and in Europe where herd sizes are typically still 100-200 cows. Switzerland and Norway have even smaller average dairy cow herd sizes, but these cow herds are a major input into agro-tourism, i.e., making the rural summer countryside look appealing to tourists. Totally automated dairy cow feeding and milking exists in some advanced European countries, but not in the US where relatively cheap Hispanic immigrant farm workers have been integrated into factory-type specialized livestock operations. An advantage to labor in large livestock operations is that a specialized worker can sometimes be paid full time to perform an important task, e.g., artificial insemination, and perhaps obtain higher earnings than if they performed a diverse set of farming activities that included artificial insemination (Yu 2008).

Organic Agriculture

Organic foods have become a niche market in developed countries, and a potential source of demand for boutique agriculture (von Witzke et al. 2008). However, organic farming is relatively land intensive and regressive in its technology used. Organic farmers frequently use technologies that were popular with conventional farmers roughly 50 years ago in developed countries. Relative to modern farming technologies of today, which were described in the previous sections of the paper, organic farming technology can be characterized as low purchased input, mixed farming with joint crop and livestock production, free-range livestock and poultry production and long or complex cropping rotations (ERS 2008; OECD 2003). For example, organic farmers use livestock manures rather than commercial fertilizer for soil nutrients; biological and cultural practices including crop rotation to control pests rather than chemical pesticides or genetic modification; free range dairy cows, poultry, and swine lifestyle rather than confined housing and feeding operations; and are prohibited from using prophylactic pharmaceuticals in livestock and poultry feed and/or drinking water and the use of growth hormones in livestock, including bovine growth hormone (BGH) in dairy cows (European Commission 2007, 2009).[11]

It is also alleged that organic farming methods are environmentally friend, sustainable, and support small family farmers. Although a recent OECD (2003) report concludes that organic farming might be more environmentally friendly than conventional agriculture, crop and livestock productivity are lower and more variable and, hence, the production of the same amount of food requires using more land (and labor), which are disadvantages when considering the future global demand for food, feed, fiber and bio-fuels (OECD 2006; McBride and Greene 2007; von Witzke et al. 2008). If supplying organic foods to food markets in developed countries requires the deforestation of land in the tropic and farming more highly erodible land occurs, organic agricultural may be net environmentally harmful. Also, the use of animal manures rather than chemical fertilizers increases food safety risks because of possible salmonella contamination of fresh vegetables and high bacterial counts in unpasteurized milk; and the more intensive use of good

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[11] Farm level technology and animal welfare issues are sometimes in conflict. However, the EU has established minimum standards governing the welfare of farmed animals. It has also laid down specific rules for laying hens, caves and pigs, and by 2012, the practice of keeping laying hens in cages will be prohibited.

farm management and more labor in general increases the costs of agricultural products. Hence, consumers must pay a premium relative to non-organic produce in order for organic production to be profitable to farmers (Dimitri and Oberholtzer 2006), although some farmers might substitute additional personal satisfaction from their organic farming lifestyle for some amount of negative farm profits.[12]

Organic agricultural production has expanded significantly over the past decades as a result of growing demand by consumers in OECD countries, but it still accounts for less than 10 percent of food produced and consumed. Although European farmers may find a niche in supplying organic crop and livestock products and Australia and New Zealand in livestock products (von Witzke et al. 2008), the structure of organic production and marketing in North America has changed. Early on production and distribution was dominated by small family farmers serving a local, largely, farmers market but with significant growth in the market large farms are not producing organic produce here and serving large grocery stores and supermarket chains with fresh organic fruits and vegetables, milk and sometimes meat. Overall, low agricultural productivity under organic farming and the need for using more total land to meet world food demand are major negative factors for the future of organic agriculture.

Productivity Analysis

Given that new agricultural technologies are sources of agricultural productivity, economists have examined the contribution of past investments in public and private agricultural research to new technologies and agricultural productivity. Let us assume that aggregate agricultural of a given state/province/nation can be adequately summarized by an aggregate production function

(1) $Y = \mathrm{F}(X, K, \mu)$

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[12] The EU actively promotes the growth of the organic sector with a wide variety of policies designed to increased the amount of land farmed organically, including government standards and certification, conversion and support payments for organic farmers, targets for land use under organic management, and policies supporting research, education, and marketing. The U.S. government largely takes a free market approach to organic farming (Dimitri and Oberrholtzer 2006).

where Y is an index of agricultural outputs of all farms in a geographical area; F( ) is some plausible algebraic form of the aggregate production function, X is an index of conventional inputs of land, labor, equipment, breeding stock, buildings and materials; K is the current state of agricultural technology; and μ represents all other factors (Huffman 2009).

Under special conditions, total factor productivity can be written as

(2) $\ln TFP = \ln(Y/X) = G[W(\mathbf{B})R, t, \nu]$

where G( ) is a production function for agricultural technologies or total factor productivity of a given geographic area, R is a vector of current and lagged values of real agricultural research expenditures that produces discoveries and innovations impacting the techniques available to farmers for a geographic area. W(**B**)R is a lag operator representation of research capital

(3) $W(\mathbf{B})\mathbf{R} = w_0 R_t + w_1 R_{t-1} + w_2 R_{t-2} + w_3 R_{t-3} + w_4 R_{t-4} + w_5 R_{t-5} + \ldots + w_m R_{t-m}$,

t is a time trend to capture purely trend dominated factors affecting state TFP. ν represents other factors that affect the technology available to farmers in a given state, for example agricultural extension and private agricultural research. A simple representation of technology capital is

(4) $K_t = [W(\mathbf{B})R_t]^{\eta} exp(\alpha + ct + \nu_{tt})$

Substituting (4) into equation (2), we obtain an econometric model of agricultural productivity that is linked to past investments in agricultural research capital

(5) $\ln TFP_t = \alpha + \eta^* \ln[W(\mathbf{B})R_t] + c^* t + \nu_t^*$.

Equation (5) clearly captures the hypothesis that a geographic area's agricultural research capital impacts its agricultural productivity, and its contribution is η^*. Moreover, in equation (5), the impact of public agricultural research capital can be estimated separately from the impact of a linear time trend and random ν_t^*. It is also highly likely that the random disturbance term ν_t^* is generated by a first-order autoregressive process, i.e., $\nu_t^* = \rho\ \nu_{t-1}^* + \varepsilon_t$, where $|\rho| \leq 1$ and ε_t is identically distributed with zero mean and constant variance (Greene 2003).

Huffman (2009) proposes the follow econometric model of state agricultural productivity in the US:

$$(6)\ \ln(TFP)_{ilt} = \beta_1 + \beta_2 \ln(RPUB)_{ilt} + \beta_3 \ln(RPUBSPILL)_{ilt} + \beta_4 \ln(EXT)_{ilt} + \beta_5 \ln(RPRI)_{ilt}$$
$$+ \beta_6 \ln(RPUB)_{ilt} \text{ x } \ln(RPUBSPILL)_{ilt} + \beta_7 \ln(RPUB)_{ilt} \text{ x } \ln(EXT)_{ilt}$$
$$+ \beta_8 \ln(RPUB)_{ilt} \text{ x } \ln(RPRI)_{ilt} + \tau\ trend + \Sigma\, \delta_l D_l + u_{ilt},$$

where TFP_{ilt} is total factor productivity in state (province) l in year t, $RPUB_{ilt}$ is public agricultural research capital in state i in region l in year t (i.e., intrastate research capital), $RPUBSPILL_{ilt}$ is public agricultural research capital spilling in state (province) i in region l in year t, EXT_{ilt} is the stock of public agricultural extension capital in state (province) i in region l in year t, and $RPRI_{ilt}$ private agricultural research capital is a state's (province's) stock of private patents of agricultural technologies. *trend* is a linear annual time trend.

Public and private agricultural research capitals are measured as weighted past real research expenditures and patents, respectively, after a brief period with zero weight. The shape of the timing weights have evolved through Evenson's research (Evenson 1967, 1968, 1980, 2001) and Huffman and Evenson (1993, 2006a,b). Moreover, Griliches (1998) concludes that the impact of research and development on productivity or output most likely has a short gestation period, then blossoms, and eventually becomes obsolete. Our newest lag pattern conforms to his suggestions and also reduces the likelihood of reverse causation.

The exact pattern of timing weights used in measuring public agricultural research capital from real research expenditures of the USDA and state agricultural experiment station and veterinary medicine colleges in t is that in t and t – 1 a weight of zero is assigned, then a positive weight starts in year 3 and rises linearly to 0.05128207 in year 9 (7 years of rising weights), then the weight remains constant to year 15 (or a total of 7 years), and then the weights decline linearly to zero in year 35 (or after 20 years).[13] Also, see figure 13. Huffman (2009) and Huffman and Evenson (2006a,b) defined public agricultural research spillin weights using spatial or contiguity weights derived from the geo-climatic sub-region map. Finally, they measure of private agriculture research capital in t is the weighted number of agricultural patents by state over t-2 to t-18 (Huffman and Evenson 2006b).

The econometric results in Huffman (2009) shows that the percentage change in state agricultural productivity due to a 1 percent change in intrastate state public agricultural research capital is 0.140, public agricultural research capital spillin capital is 0.059, and public agricultural extension capital is 0.098. A surprising result is that private agricultural capital has a negative productivity elasticity. One explanation for this result is that there is too much private agricultural research capital, given that public and private agricultural research capital are shown to be (imperfect) substitutes. However, intrastate state public agricultural research capital and spillin public agricultural research capital from other states in the region are (imperfect) complements.

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Hence, Huffman (2009) shows public agricultural research capital—intrastate and spillin—are major determinant of agricultural productivity in the US. Similar relationships are expected in

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[13] Alston, Craig and Pardey (1998) have considered other lag structures. One might consider a symmetric quadratic shape to the timing weights over periods t-1 to t-35, but our particular trapezoidal weighting pattern is skewed to give a larger share of benefits early and fewer later, with all weighting patterns have the same area under the curve. Our approach has similarities to Bayesian lag patters (Kitagawa and Gersch 1996; Geweke and Kean 2005).

other developed countries, including the European Union. However, in an EU productivity analysis, countries would take the place of states in the US, i.e., there are most likely inter-country spillin effects, and to the extent that intra-country and spillin effects are complements, countries can successfully borrow from their neighbors. If there is a public desire to increase agricultural productivity in the future, these plans must be made today. If real public agricultural research expenditures are increased now, Huffman's study implies that the peak impact on agricultural productivity will not occur for nine years, or almost a decade later. Thus, the foundations for new agricultural technologies of 2019 are being laid today. If the common belief that real public agricultural research expenditures in the US and other developed countries have declining relative to that of the 1970s and 1980s, then predicted agricultural TFP growth a decade from now will be lower than today.

Future Prospects

New technologies in crop production are on the horizon. First, I expect the future use of second and third generation biotechnology developed by the private sector to speed up crop improvement, especially in corn, soybeans and perhaps cotton. This includes: rapid DNA sequencing followed by selection on genomic traits, marker assisted breeding including functional markers, double haploid breeding for crossing species, and random DNA markers associated with desired traits. New or enhanced agronomic traits are being inserted into corn varieties for: (i) drought resistant genes, (ii) improved protection of root structures using GM rootworm and cutworm protection, (iii) improved stock strength and ear quality by multi GM stock borer and ear worm protection, (iv) improved weed control by GM herbicide tolerances, (v) improved output traits of enhanced oil and protein continent and (iv) improved nitrogen usage at early growth stages.

In particular, the private hybrid seed corn industry has developed a stack of eight transgenes that they are testing and planning to market in 2010. It involves three transgenes for controlling above ground insects (corn borers and ear worm), three transgenes for below ground control of insects (rootworms and cutworms), and two transgenes for herbicide tolerance to glysophate and glufsomate. The package is labeled as the SmartStax. This package of multi-modes of insect protection can be expected to result in lowering the current refuge required for single-model GM pest protected varieties from 20 percent to 5 percent, which would be an advantage to farmers. It is not yet clear how Monsanto (and Dow) will price the SmartStax varieties because few farmers will benefit or be willing to pay for all eight genes, but it most likely will be quite cost effective for Monsanto to supply varieties having the complete package of eight genes, as opposed to providing varieties that contain only the transgenes that each farmer expects to need.

A very recent development has been the anticipated release of GM corn modified to have unusually high sugar content, which increases the amount of ethanol that can be produced from a bushel of corn and furthermore reduced the energy used in processing. These new corn varieties are haled by the ethanol industry but distained by the food industry.

The private seed industry has announced that they have successfully tested drought tolerant corn varieties for the US Western Great Plains. The drought tolerance is to boost yields by seven to ten percent in a one-year drought. However, this technology for drought tolerance enables the corn plant to withdraw a larger share of the moisture in the subsoil and to avoid shutting down physiological processes under water and heat stress. However, if the drought lasts for multiple years, these varieties are unlikely to have advantages beyond the first year. Since drought is a deviation of precipitation from normal, there is a significant random component to its occurrence. Also, drought can hit at any stage of the plant growth and needs different modification for each, so drought tolerance needs some refinement in its definition, e.g., drought tolerance at pollination and ear filling. Hence, the expected gain to so-called drought tolerant corn varieties may be quite low, and these varieties are not expected to be useful (or even available in the US Corn Belt). In the Corn Belt, new corn varieties with corn rootworm protection have greatly improve root structure and volume and have much greater expect value to farmers that new drought tolerance corn varieties that are on the horizon.

Over the next decade private sector developed and marketed GM technology for wheat and rice varieties remains a long shot. Hence, dry-land wheat yields in the EU, North America and South America have modest potential for future yield increases, and this technology will have more of a public sector component, although Monsanto is planning to re-enter the market with new wheat varieties over the next decade. The wheat growing areas of the EU have a relative abundance of water, but the relatively good record of recent yield increases may be difficult to maintain without the use of new technology. In the EU, public research is beginning to breed into wheat early canopy closure, early stem extension, better nutrient capture and conversion, improved light conversion, increased conversion of dry matter to grain, better water capture and conversion and sustainable protection against pests and diseases (Spink et al. 2009). This will, however, be very difficult without using GM technology. Wheat production is the US and Canada is largely low-resource input agriculture, and new varieties have been developed primarily by public sector research sometimes using CIMMYT wheat germplasm. Over the next decade the trend rate of yield increases, which are modest, are expected. The potential exists for HT wheat, most likely to become available to farmers in China first followed by North America.

In Australia where long periods of drought are common, traditional approaches to drought tolerant crops seem ineffective. Researchers there are attempting to develop perennial wheat varieties, including salt tolerant ones, which will over time yield significantly more grain than annual wheat varieties. This might occur because of more effective use of water over time. However, this technology has not been completely tested. There is also an attempt to introduce new perennial plants, e.g., chicory, wild relatives of lucerne, cocksfoot, and birdsfoot trefoil, as a pasture crop for cattle and sheep. The goal is to increase the carrying capacity of grazing lands (Future Farm Industries).

Paddy rice production in Japan (and elsewhere) is high input agriculture, but the trend rate of increase in Japanese yields is modest, compared to corn in the US and wheat in Europe. Genetic engineering would be one method to accelerate yield increases. However, salinity and environmental problems seem to have greater priority than yield increases per se in Japan.

Farming practices are also expected to change over the next decade: increased plant populations, better farm management, better information management, and greater use of internet for technical and market information. Improved root structures are a major requirement for higher plant populations in field crops, especially corn because it reduces plant stress.

The private seed industry has set as a goal doubling corn, soybean and cotton yields in the US by 2030. For corn, this translates into Iowa state average yields increasing from roughly 150 bushels per acre to 300 bushels per acre.[14] For example, average corn yield increases would need to be 3 times the trend growth over 1970 to 2007 or about 6 bushels per acre per year. This is clearly an ambitious goal, but it might be possible in corn varieties, given the large investment of the public and private sectors and CIMMYT is corn genetics. I remain skeptical for the other two crops. However, yield increases of these magnitudes would greatly change the need for additional land need to meet future demand for food, feed, fiber and biofuels.

Research is underway that will increase soybean yields per se (intrinsic yield). Soybean germplasm has been identified that will significantly increase soybean yields in conjunction with second generation HT. The target increase is 6 to 10 percent yield increase compared to elite conventional soybean varieties. Soybean and canola varieties in North American are over 90 percent HT, and I expect other oilseed crops to come under competitive pressure to incorporate GM for HT because of the indistinguishable nature of the oils. I believe this information will become common knowledge over the next decade and consumer resistance will gradually moderate.

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[14] This goal is most likely related to an anticipated growth in demand for the use of corn and soybean to produce biofuels.

The potential for future benefits from GM potato varieties developed by the private sector are large and likely to be realized by 2019 in OECD countries, Argentina, Brazil, China and perhaps Russia. New GM varieties for late blight and Colorado potato beetle resistance would create valuable biological pest resistance to all sizes of potato farms, including home plots/gardens. Also, new GM traits for product-enhanced potato varieties will be released for sale to farmers in the near future. They are expected to contain high levels of anti-oxidants and vitamin C and low acrylamide levels.

The use of second and third generation GM crop technologies of the future is expected to be a major factor in reducing the rate of environmental degradation caused by chemical pesticides in agricultural production in OECD countries and in Argentina, Brazil, China and perhaps Russia. Agricultural productivity is expected to continue to increase at significant rates, and to be a major alternative to increasing the area of cropland.

One note of pessimism is that new technologies developed and marketed by the private sector may be quick successful in increasing crop yields of cereal, oilseed and select vegetable crops, but they may not always increase agricultural productivity. The reason is that the private sector is developing and marketing new agricultural technologies with expectations of at least normal profits. This means that the prices of new enhanced performance seeds (and other technologies) will carry higher price tags than conventional ones. However, for the private companies to make a profit on these new technologies they must sell them in large quantities and this means they must share the surplus with farmers who use them, otherwise there will not be repeat or large sales (Huffman 2006; Moschini and Lapan 1997). For a quantification of the sharing, see the research on the adoption of GM cotton by Falck-Zepeda et al.(2000a,b) and on soybeans by Moschini et al. (2000) .

Summary and Conclusions

Technologies available to farmers are continuously changing. However, agricultural productivity which is a reflection of the adoption and diffusion of successful technologies has slowed over 2000-2006 relative to the 1990s in the EU, North America, in high income Oceania and in large developing or transition economies. Among developed countries, an exception to this pattern is Northeast Asia-Developed countries, which experienced larger agricultural TFP growth in the latter period.

Models of the organization of research and development have advanced over the past two decades from a linear model where basic research is the only source of discoveries needed for applied research and new technology development. The first step was to introduce a bi-directional relationship, such that problems faced by users of technologies could be the source of the research problems that stimulated scientists working in applied and basic sciences. More recently, a multi-directional and multi-layered model has been developed, which contains horizontal linkages at a given level of science and technology as well as vertical linkages. A successful R&D system for agriculture is now widely accepted to have simultaneous efforts at all layers of science and technology and with feedback from farmers and other end users. Having the public sector invest only in applied research is not sufficient for long term productivity, and although developed countries can borrow some research discoveries and innovations from other countries, they must undertake some research in order to borrow effectively.

New technologies have been developed for crops, and they have steadily improve crop yields in major cereals—corn, wheat, and rice—and oil seeds—soybeans and canola. These yield increases have been the result of efforts to improve yield per se and to more effectively control insects, weeds, fungi and diseases. Pest control was first achieved by the replacement of mechanical and hand weeding with chemical herbicide applications. Integrated pest management was introduced in the 1980s to more effectively break pest cycles while at the same time reduce the agricultural chemical load on the environment. In the mid-90s, new genetically engineered (GM) crop varieties became available to farmers in North American and insect resistant (IR) crop varieties were developed they replaced insect control through chemicals insecticides. New herbicide tolerant (HT) crops have replaced mechanical and hand weeding in North and South America. This new GM technology was achieved by using transgenes—moving genes across species—and this led to some resistance by environmental groups to the new technology. However, GM technology has been quite successful in soybeans (HT), corn (IR/IP, HT), cotton (HT, IR), and canola (HT) varieties planted in North American, South America, China, and India. In the US, GM crop varieties are now into second generation technologies, and third generation technologies are in the pipeline for the coming decade.

Cultural practices have also changed for field crops. In North and South America, farmers have reduced the energy required in seedbed preparation by shifting to reduced-tillage and no-till farming in the 1970s and this adoption has continued. Plant populations of all field crops have been increased as plants were bred to better withstand this stress. Where farm and field sizes have expanded rapidly, new planting and harvesting equipment have increased greatly in size, effectiveness in harvesting grain, and in comfort to the operator, raising labor productivity. In Europe and Japan, where farm sizes have remained small, the size of planting and harvesting equipment has changed very little.

With world concerns about environmental harm from bringing new lands into cropping to meet future needs for food, feed, fiber and bio-fuels, new interest is focused on improving crop yields, because increasing crop yields may be a more environmentally friendly alternative than increasing cropped area. Historic yield data were summarized for corn, wheat, and rice, which are the major cereal crops in the OECD. The performance of state average corn yields in the US Midwest has been spectacular over the past half century—a trend rate of increase of almost 2 bushels per acre per year, and the Iowa average corn yield is approximately 165 per acre. Moreover, the yield trend may be increasing since the mid-00s. Wheat is the dominate cereal crop in Europe, and the upward trend is strong at 1.55 bushels per acre per year over a half-century for France, the leading wheat producer in the EU. The current wheat yields are about 110 bushels per acre, and it is significantly below trend yield. Wheat in the US Great Plains, Canada and Australia are grown under semi-arid low resource conditions, and the trend in wheat yields in these areas has been much lower. For example in Kansas, the leading US wheat producing state, the trend in the state average wheat yield is only 0.51 bushels per acre per year over the last half century, but the trend is steady The current state average wheat yield in Kansas is about 45 bushels per acre. Rice production in Japan, Korea and Brazil is largely in paddies under intensive agricultural conditions. However, the yield trend in Japanese paddy rice is a modest 0.52 bushels per acre per year, but the current average yield is 117 bushels per acre. Hence, hybrid corn has been an amazing crop in terms of its long term potential to respond to modern science and technology—breeding and new cultural practices. Much of this past research has been undertaken by private seed companies. Wheat and rice seed production has been less profitable for seed companies because of their open pollinated nature and because GM wheat has not yet been accepted by major importing countries.

The leading oilseed crop in North and South American and China is soybean. The trend rate of increase in soybean yields in the US Midwest has been steadily upward but at a modest rate relative to corn. For example in Iowa, the state average rate of increase in soybean yields over the past half century is 0.47 bushels per acre per year, and there is no evidence of a change in trend due to the shift of farmers to annual newly purchased seed in the 1980s and early 1990s and to GM/HT varieties starting in the mid-90s. Current IA state average soybean yields are 49 bushels per acre.

The discussion of technologies for horticultural crops was limited primarily to potatoes, the fourth leading source of human calories and tomatoes, which is the second largest vegetable crop in developed countries. As compared to cereals, the leading focus of research on horticultural crops is controlling pests—sometimes called maintenance research. Pests for these, as well as for other crops, evolve to become resistance to genetic and chemical pest controls, so research must be continually underway in order to maintain yields over the long run. Central and Northern Europe and South American are the largest producers of potatoes. A two year crop rotation has been shown to be effective in controlling most pests in potato, including late blight or *Phytophthora*. The Netherlands is widely recognized as having the most advanced technology for potato production, and their average rate of yield increase is 4.6 bushels (0.14 tons) per acre per year, and current average yields are about 667 bushels per acre.

GM potatoes have been developed and marketed in the US. The first attempt in the mid-90s was for IR to the Colorado potato beetle. The technology was effective and greatly reduced the application of chemical pesticides. However, this technology was not accepted by the US retail food chains. In the mid-00s, new GM potatoes have been developed using intragenic GM methods—using bioengineering to move genes a long distance within the potato genome. This is a major advantage because the potato genome is very difficult to manipulate using convention plant breeding methods. Furthermore, the intrargenic GM technology has focused on introducing product -enhance consumer attributes into commercial potato varieties. This technology has received approval in the US, shown to be valued in food experiments and holds excellent future potential.

Tomatoes are broadly of two types—those grown for the fresh market and those grown for processing. Research has successfully raised the solids content of tomatoes and made them a size and toughness to withstand mechanical harvesting. GM tomatoes that were developed and sold in the mid-90s, having extended shelf life and high solids, failed due to inferior varieties, being over priced and to not directly related food scares in Europe in the late 90s.

New cultural practices for tomatoes include raised seed beds, plastic mulch, fertigation, and climate-controlled green houses production. The new green house tomatoes have been attractive to consumers because of their uniform. Many are marketed “on-vine” in clusters to convey an appearance of freshness to consumers.

Technical improvements in livestock production are a result of genetic improvement of animals, improved disease control, improved structures and improved management practices. The diffusion of artificial insemination in almost all farm animals has been a major factor for incrasing the rate of livestock improvement. Beef cattle and hogs have also been improved through selective cross breeding. The OECD countries are examples of the largest and smallest dairy herds—with the US-CA herds exceeding 10,000 cows and Switzerland and Norway having herds of 20-30 cows. The large herds of Holstein breed cows are most efficient at producing low fat milk, but the small herds of Switzerland and Norway are an integral part of agro-tourism, where they are heavily subsidized to produce milk in the mountains and hillsides in the summer months.

Organic farming is meeting a niche market provided by a subclass of consumers in OECD countries. Although it is low on purchased inputs, high land intensity and regressive in technology used, organic produce is frequently marketed as being of superior quality to conventionally grown produce. This is frequently an incorrect perception. Organic farming increases the amount of land needed to produce a given amount of food, which is a concern for meeting world food demand of the future. However, Europe and Oceana seem to have a comparative advantage in this type of boutique agriculture.

New technologies are in the pipeline for the next decade. The second and third generation GM crop varieties promise to significantly increase crop yields for corn and soybeans and to a lesser extent, cotton and canola. Wheat and rice yields are being held back by the failure to adopt GM technology, even in North America. I expect that China will be the first country to adopt GM wheat (and a number of other new GM crops) and the US, Canada, and Argentina will quickly follow pursuit. If the EU carries through on its ban on important pesticides for agricultural use, this will increase the pressure on the EU to accept GMOs for IR and possibly HT.

Although new GM drought tolerant cereals are attracting a lot of attention, I am pessimistic about their long run potential. The main reasons are that drought can occur at any stage of the plant growth and development process, meaning that drought resistant at all plant growth phases is impossible and when drought occurs in the protected phase its advantage is only for a single year of drought in an otherwise normal weather pattern. But, many areas face extended years of drought—Australia, U.S. Great Plains, Africa—and the current technology has little advantage there. The new third generation corn varieties developed for the US which have IR for three below grown pests have great potential for improving root structures and root volume of the corn plants, which indirectly improves drought tolerance, but also improves nutrient uptake, standability against strong wind and rain and reduces stock breakage, which makes harvesting easier and grain loss in harvesting less. The expected benefit from these HT traits will exceed by a sizeable margin expected payoff to drought tolerant corn varieties in the US Corn Belt. Moreover, the drought tolerant corn for the US is for land in the Western Great Plains which is of low quality and best used for non-cropping purposes.

New research shows that public and private agricultural research capital and public agricultural extension are major determinants of agricultural productivity. The strongest evidence is from state data for the US over 1970-1999, but the general results seem likely to hold for other developed countries. Given that investments in public (and private) agricultural research have their impacts with a long lag, now is the time to significantly increase public expenditures on agricultural research in order to make agricultural productivity significantly higher a decade from now. However, the general consensus is that real public expenditures on agricultural research in OECD countries has been declining rather than increasing, and rates of growth in agricultural productivity may decline over the next decade. Private sector agricultural R&D expenditures have been growing much faster than public agricultural research expenditures, and even through some of my research shows that they are substitutes, they are not perfect substitutes. Moreover, new technologies developed and successful marketed by the private sector might not improve agricultural productivity, although they increase crop yields.

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Figure 1

Trends in Real Wheat, Rice, Corn and Crude Oil Prices, Jan. 2000-Jan. 2009

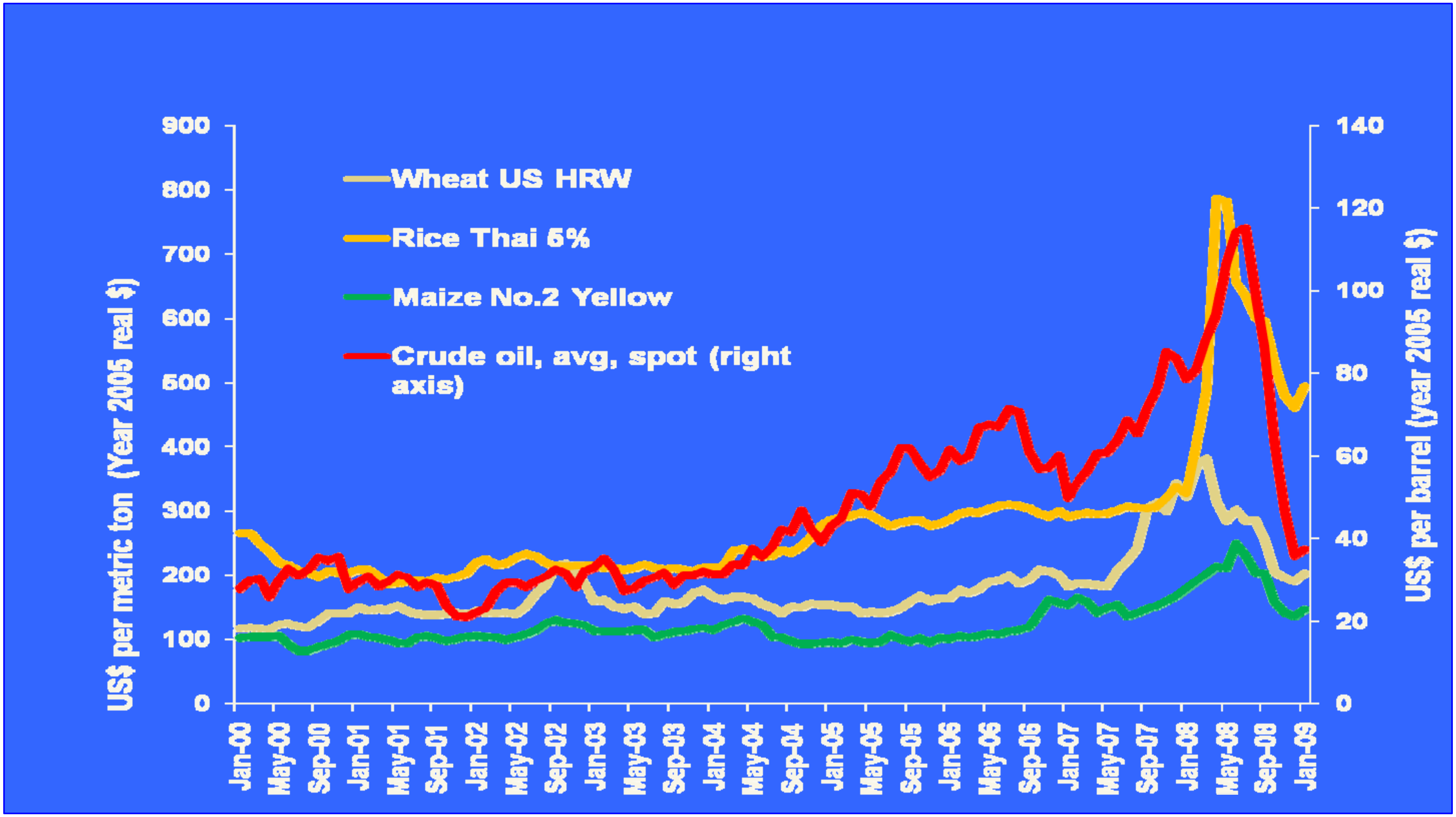
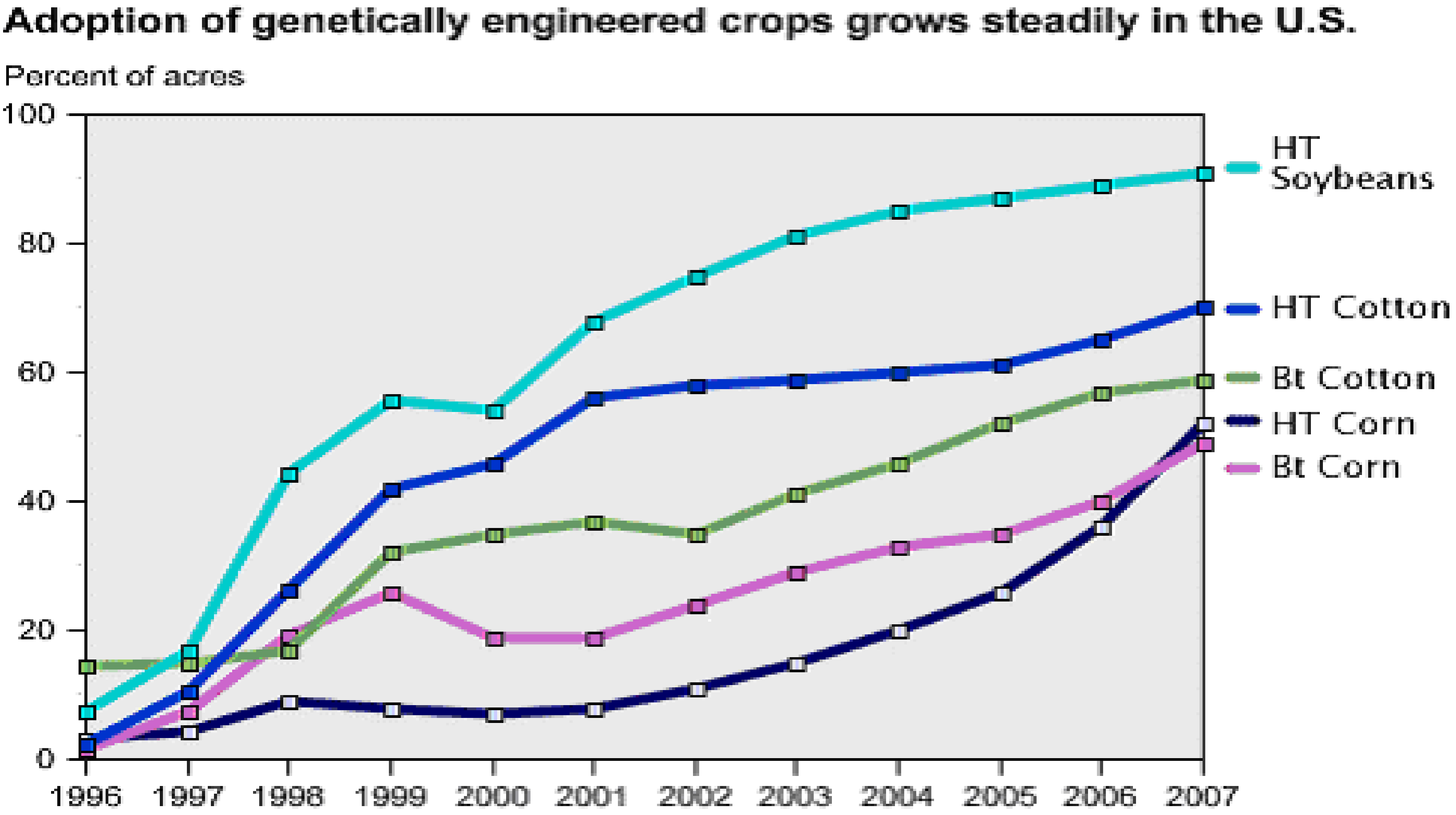


Figure 2



Adoption of genetically engineered crops grows steadily in the U.S.

Figure 3

The Linear Model of Research and Development

Basic Research = Discoveries that are new knowledge about fundamental scientific relationships

Applied Research = Inventions with potential practical usefulness to society

Technology Development = New products and processes

Source: Bush (1945)

Figure 4

Bi-Directional Linear Model of Research and Development

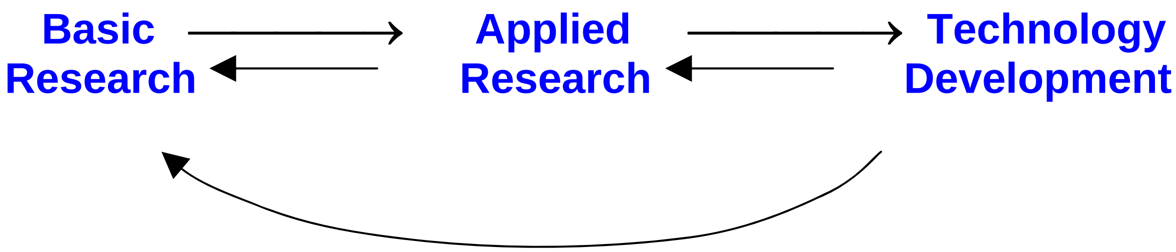


Figure 5. The New Multidirectional Relationship for Agriculture

Layer/Activity	Linkages	User and Use Types	Linkages
I. FINAL USERS (Source of clientele problems)	⇕	Producers/Governments/Consumers	⇕
II. EXTENSION (Public and private)	⇕	⇔ Information dissemination ⇔	⇕
III. PRODUCTS FROM INNOVATION (Agri-industrial development)	⇧	Farm & household inputs, management & information systems, institutions	⇧
		Major Areas of R&D for Agriculture Physical Sciences/Chemical Sciences/Biological Sciences/Social Sciences	⇩
IV. TECHNOLOGY INVENTION (Public and private research)	⇩	⇔ Particular applied science fields ⇔	⇕
V. PRE-INVENTION SCIENCES (University and public agency research primarily)	⇩	⇔ Particular pre-invention science fields ⇔	⇩
VI. GENERAL OR CORE SCIENCES (University and public agency research primarily)	⇕	Particular general/basic science fields	

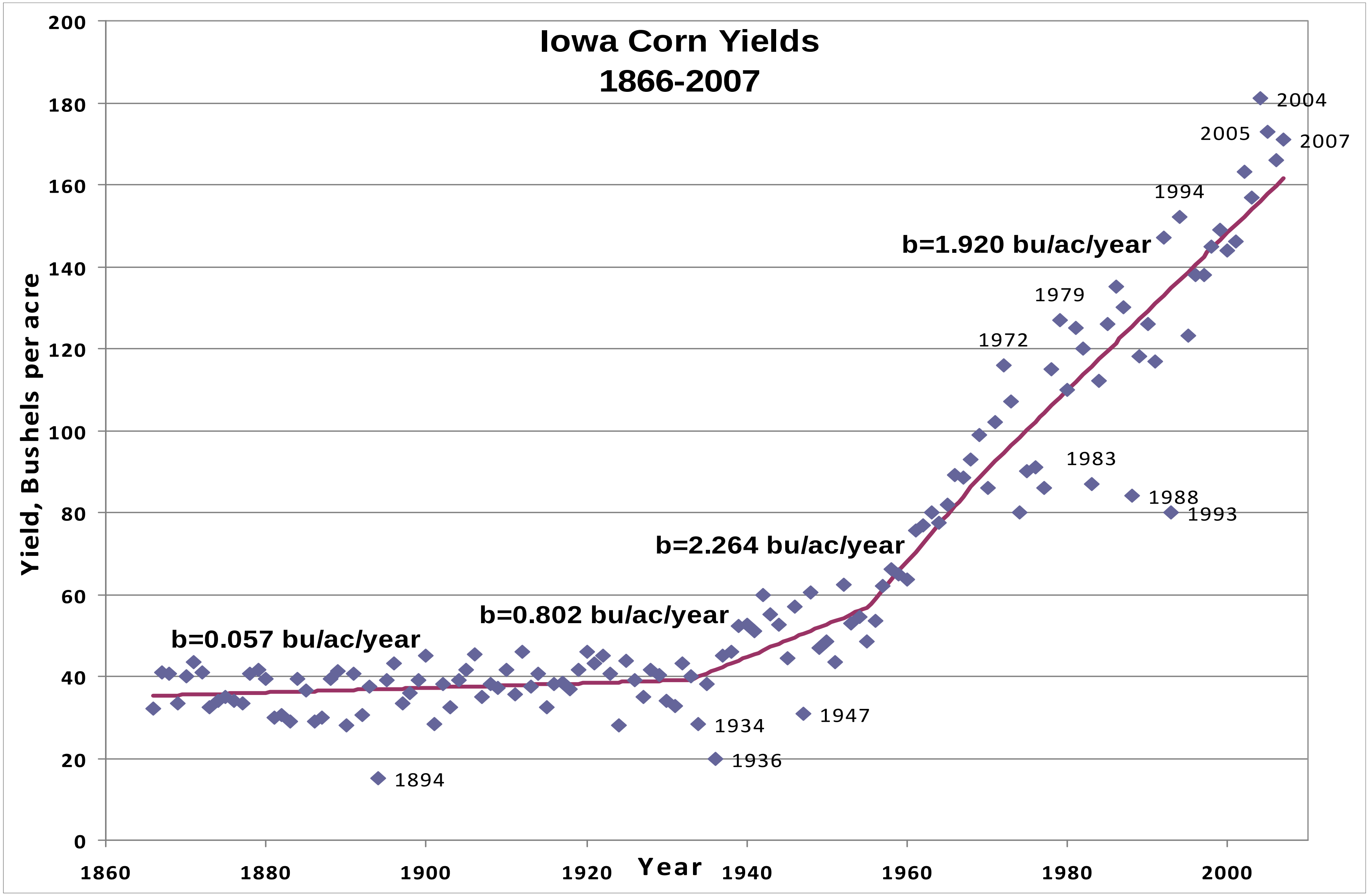
[a] Arrows indicate the direction of linkages, upstream, downstream, or horizontal.

Source: Adapted from Huffman and Evenson, *Science for Agriculture*, 2006a.

Figure 6

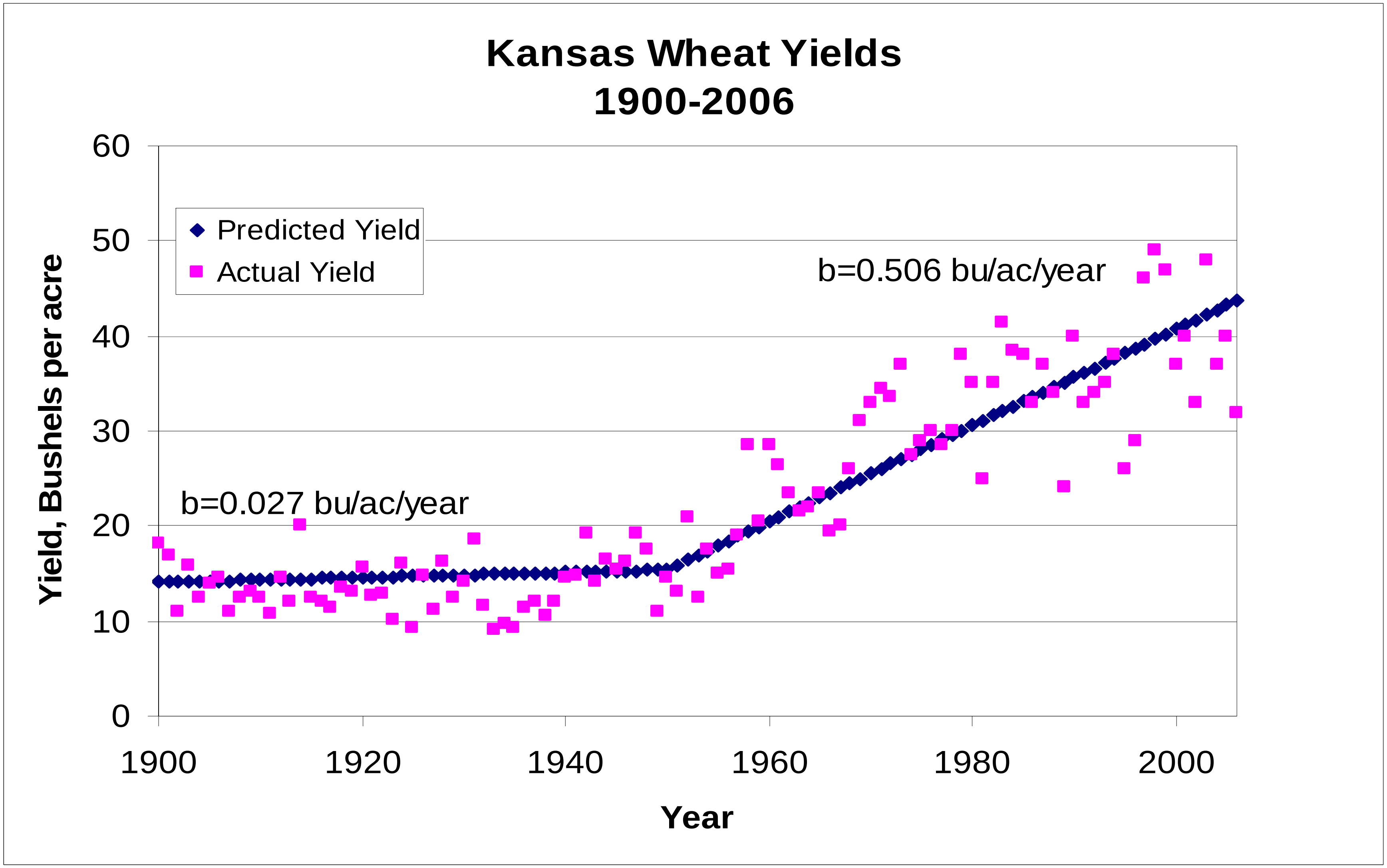
Rootworm infested corn and soil profiles for unprotected and insect resistant rootworm protected varieties

Figure 7



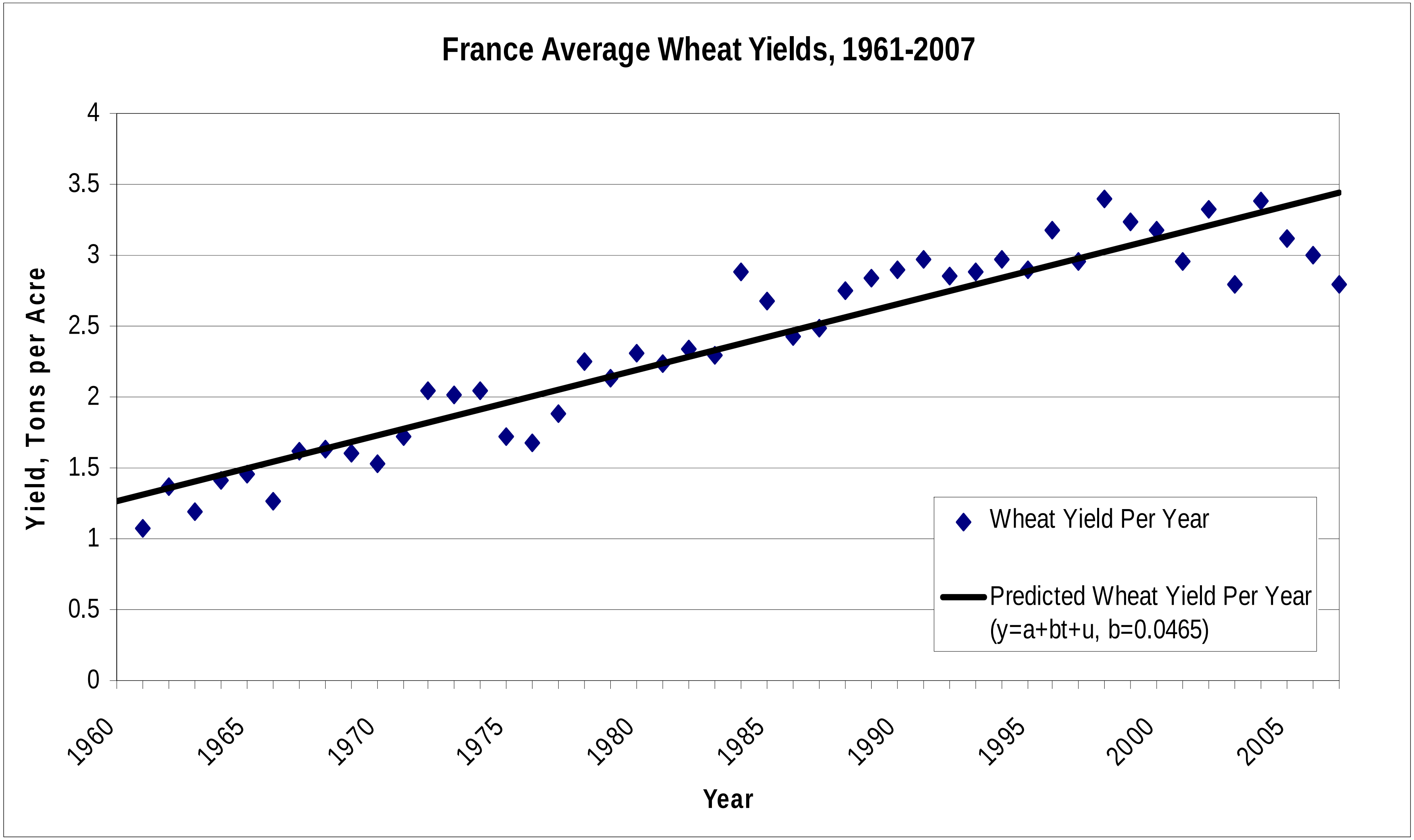
Source: Kendall Lamkey and the Iowa Agricultural Experiment Station

Figure 8



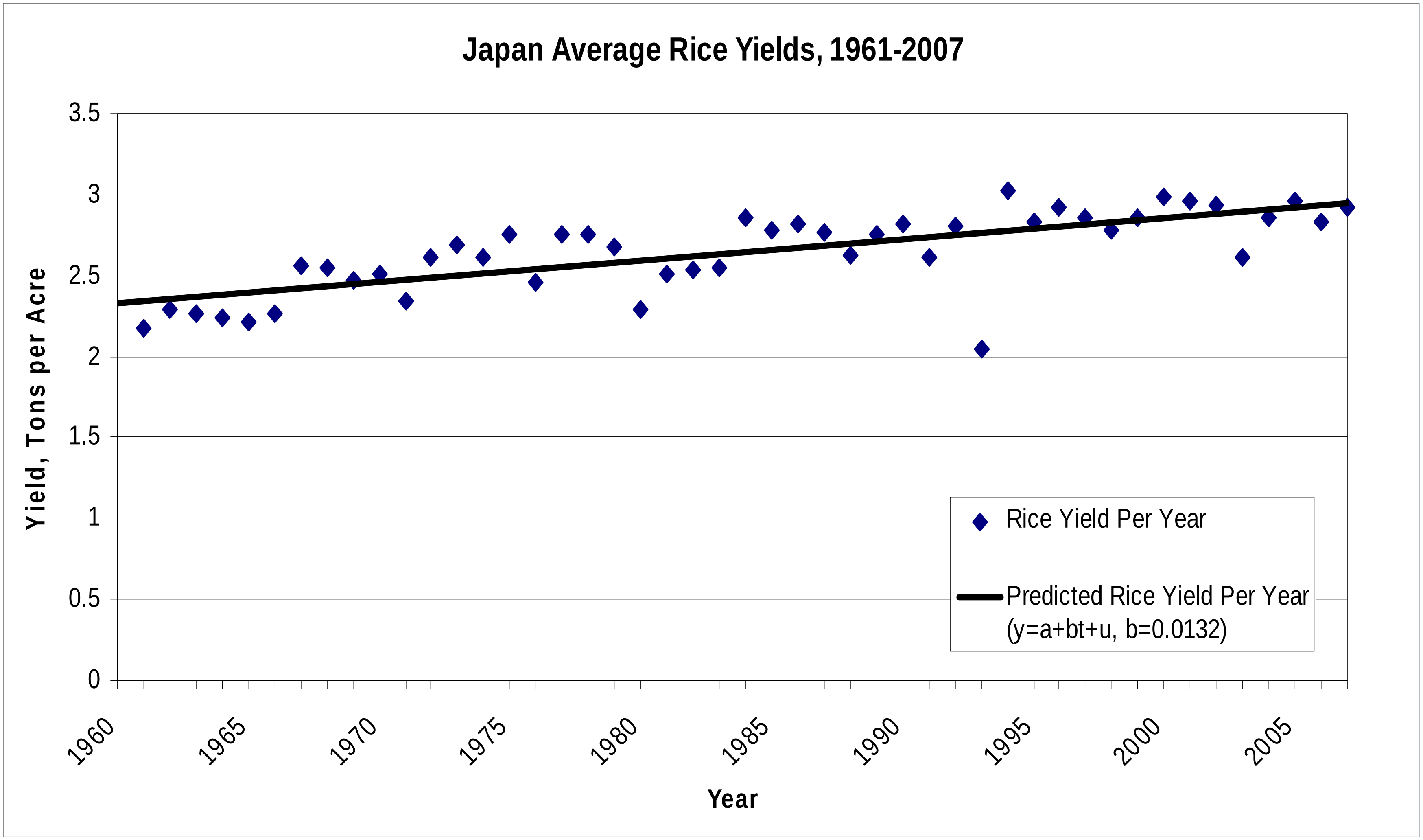
Source: Kansas Agricultural Experiment Station

Figure 9



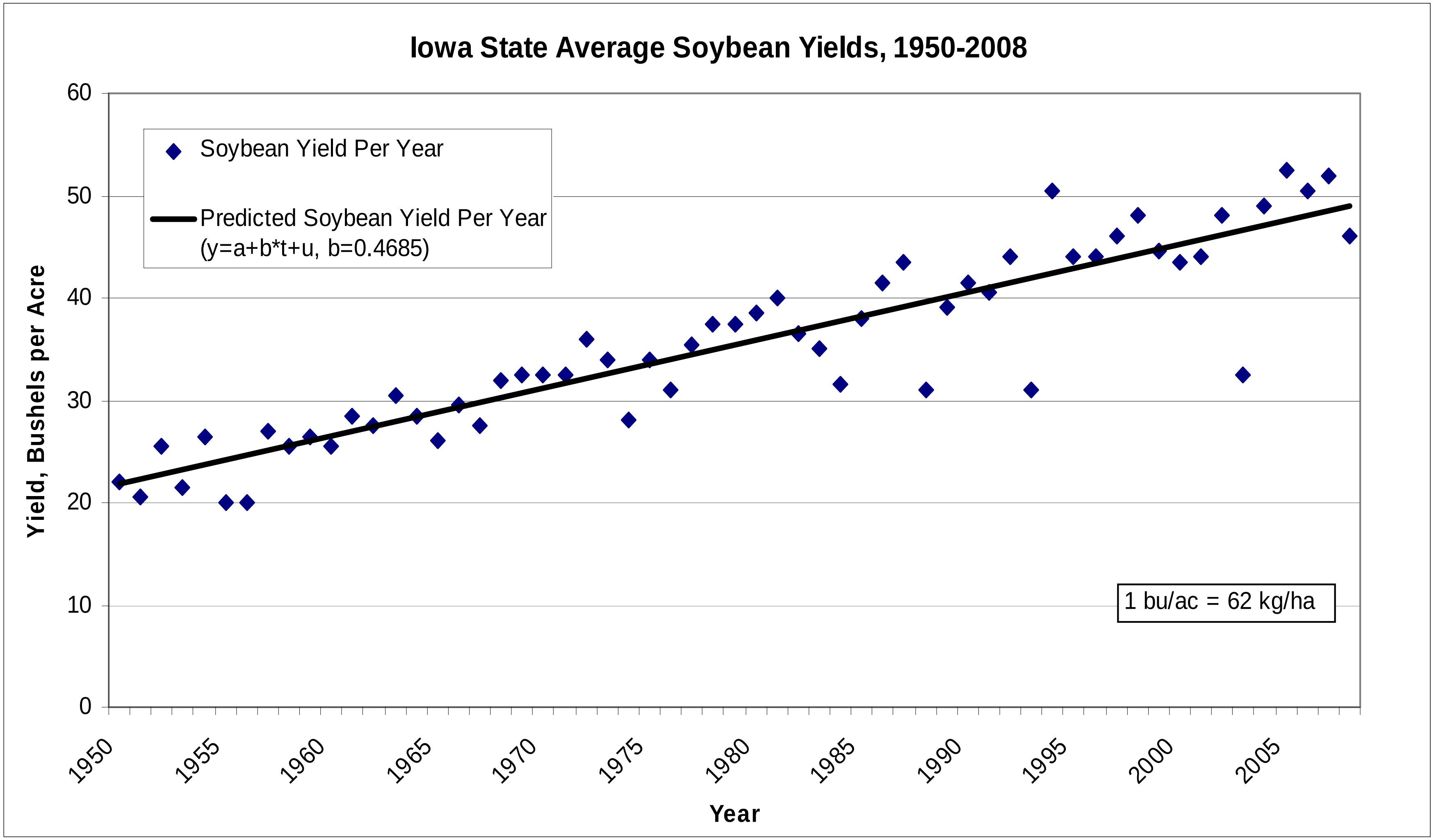
Note: One ton of wheat = 33.3 bushels. Average yield increase is 1.55 bushels per acre per year.
Source: FAO

Figure 10



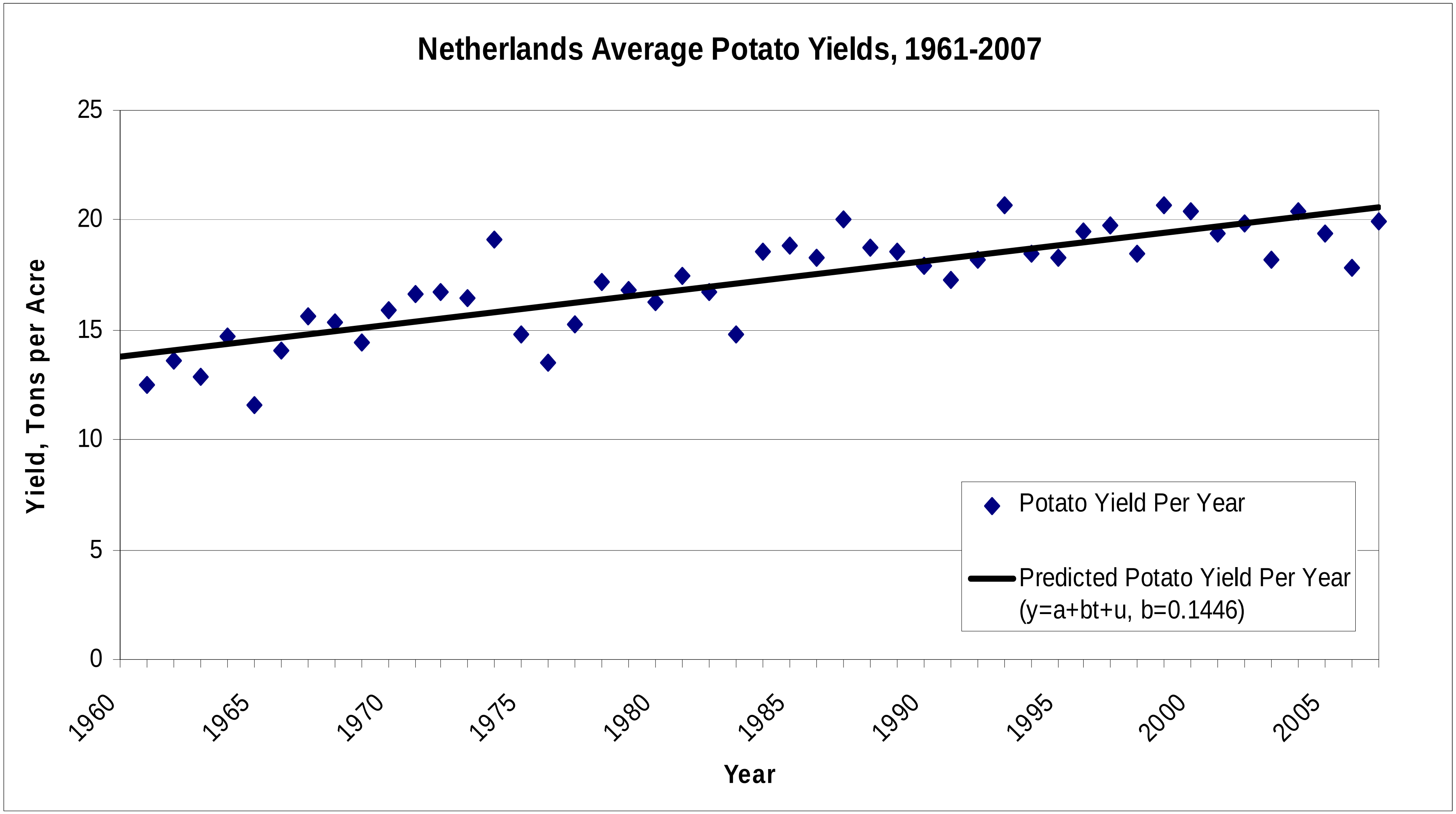
Note: One ton of rice = 33.3 bushels. The trend rate of increase in paddy rice yield is 0.528 bushels per acre per year.
Source: FAO

Figure 11



Note: The trend rate of increase of soybean IA soybean yield is 0.47 bushels per acre per year.
Source: USDA, NASS.

Figure 12



Note: The trend rate of increase is 4.6 bushels per acre per year.
Source: FAO

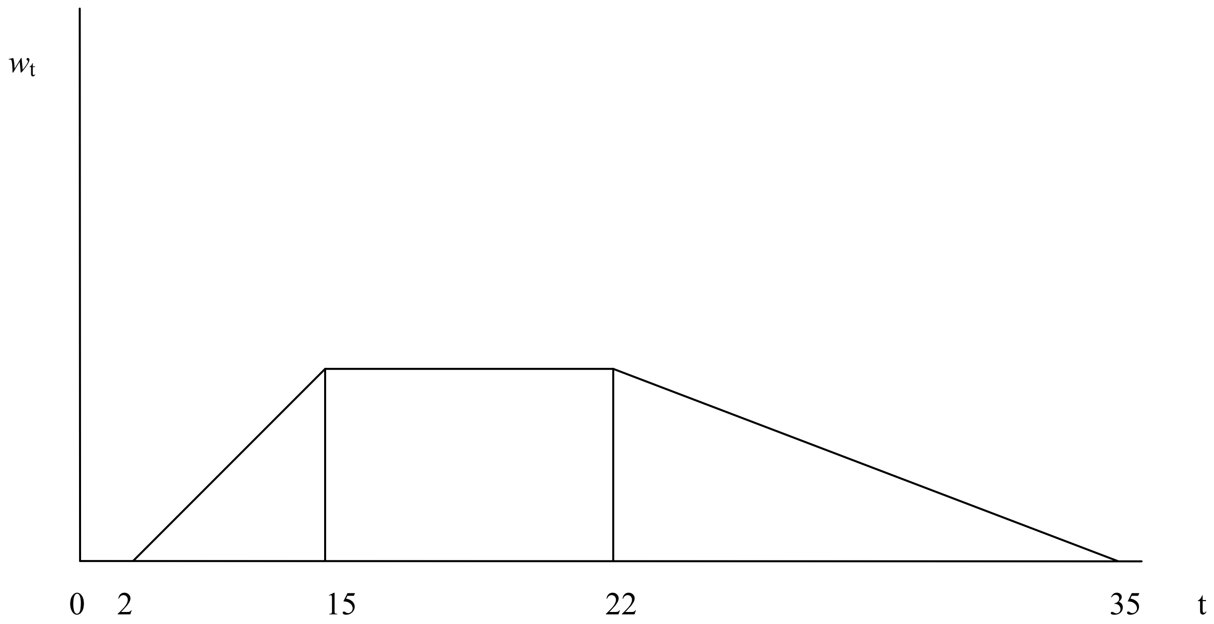


Figure 13. Timing weights (trapezoidal)

Table 1. Size and Agricultural Total Factor Productivity Growth: Selective Countries 1990-2006

Region – Country	**Ag TFP Growth (%)**		**Average Outputs 2004-2006 2000 US$ bil.**
	1990-99	**2000-06**	
Western Europe			
Finland	1.9	2.9	1.89
Sweden	1.2	0.7	2.69
Norway	0.5	-0.4	1.16
Denmark	2.9	1.5	5.40
Germany	2.8	2.5	30.18
Netherlands	1.4	1.3	9.51
Belgium – Luxemburg	2.4	-0.1	5.08
Austria	1.9	1.6	3.60
Switzerland	1.0	0.6	2.24
France	2.3	1.2	35.78
Italy	1.8	2.1	25.74
Greece	1.6	0.3	6.60
Spain	1.9	1.4	24.73
Portugal	1.7	1.7	3.33
United Kingdom	0.8	0.9	15.01
Ireland	0.9	0.3	3.81
Iceland	0.8	1.6	0.07
Sub-total	(1.98)	(1.49)	(176.82)
Select Central European			
Czech & Slov Republics	1.4	0.2	5.29
Hungary	-0.4	1.4	5.73
Poland	0.3	-0.6	16.25
Sub-total	(0.37)	(-0.02)	(27.27)
Asia			
Turkey	0.7	1.2	26.93
North America			
Canada	2.1	2.9	22.34
United States	2.1	1.6	181.99
Sub-total	(2.10)	(1.74)	(204.33)
High Income Oceania			
Australia	2.6	-0.6	20.23
New Zealand	1.3	0.7	7.91
Sub-total	(2.23)	(-0.23)	(28.14)
Northeast Asia -Developed			
Japan	2.0	3.1	15.86
Korea	3.4	3.2	8.41
Sub-total	(2.49)	(3.13)	(24.27)

Table 1 (cont'd)			
Region – Country	**Ag TFP Growth (%)**		**Average Outputs 2004-2006 2000 US$ bil.**
	1990-99	**2000-06**	
Large Developing or Transition Countries			
Argentina	2.1	1.7	28.99
Brazil	3.0	3.7	85.87
China	3.8	3.2	386.83
India	1.7	1.4	159.27
Russia	3.2	4.6	41.48
Sub-total	(3.12)	(2.87)	(702.44)

Source: Fuglie (2008).

Appendix

Figure 1

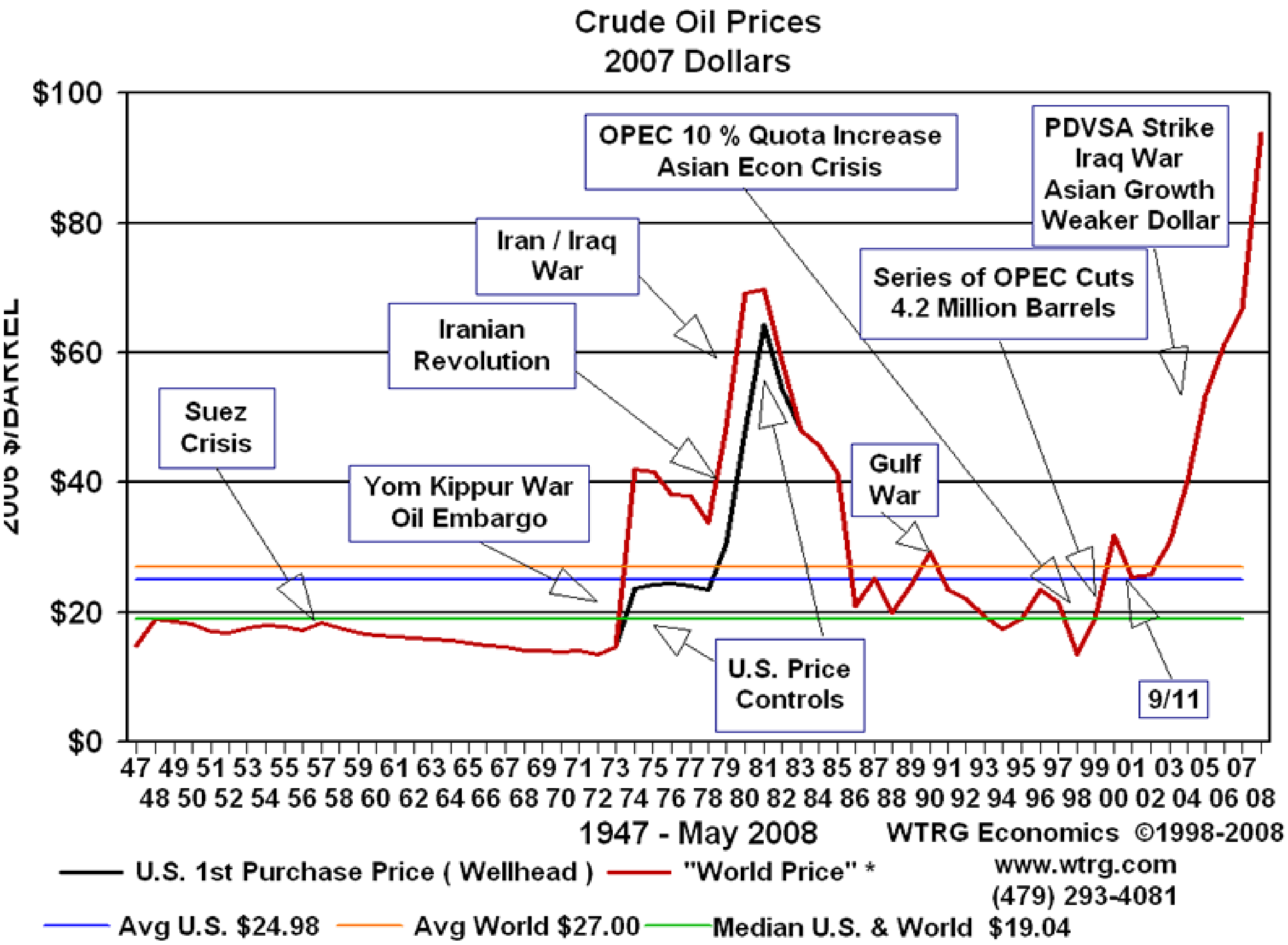


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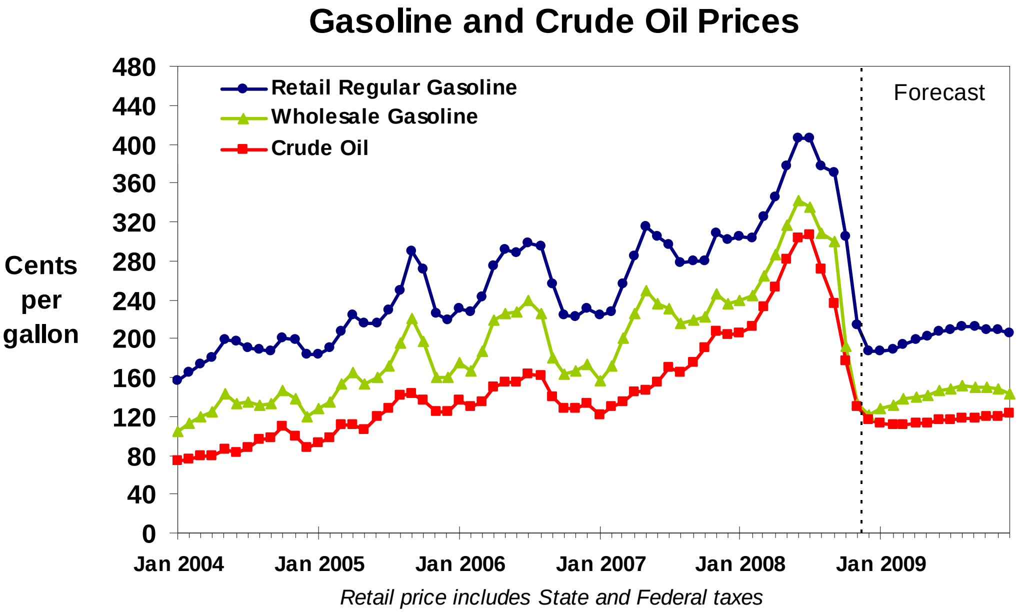
Figure 2



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