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Long-term Global Agricultural Output Supply-Demand Balance and Real Farm and Food Prices

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Abstract: Global food demand is estimated from population projections of the United Nations and food supply is projected from Food and Agriculture Organization yield data to quantify the global food supply-demand balance for 2025 and 2050. The eight food categories examined account for 95 percent of global food consumption.

Results indicate that the historic era of secularly falling real food prices is over. The real price of corn, for example, is not expected to fall over the next four decades at the annual rate of 1.3 percent that it fell annually from 1960 to 2006. The analysis foresees future real food prices fluctuating around a flat or rising trend. Slowed national economic growth from flat or rising real food prices may be little more than an irritant for consumers in affluent countries, but will entail severe hardship for consumers in the many countries currently troubled by poverty and hunger.

Opportunities exist to expand food output by adding cropland in Brazil and irrigation in Africa, for example, but in the long term such developments will be offset by cropland removed from production by urban and industrial development, soil degradation, and the like. Although cropland can be expanded through higher real farm and food prices, higher yields rather than added cropland offer the most attractive opportunities for farm output expansion at low cost to consumers and the environment.

The slowing rate of increase in crop and livestock yields corresponds with a slowing rate of increase in public and in private agricultural research and development spending. The world will not have the luxury of curtailing spending on agricultural technology and rejecting promising technologies such as genetically modified organisms (GMOs) if is to keep real food costs from rising. Productive new cropland, irrigation, genetically modified varieties, and other technologies will be hard pressed indeed to match the massive historic gains from hybrid varieties, irrigation, synthetic fertilizers, and mechanization. On the demand side, subsidies to expand demand for farming resources such as biofuels will need revisiting if rising food costs are to be contained.

Keywords: World Food Supply-Demand, Food Prices, Agricultural Markets, Crop and Livestock Yields
JEL Classification: Q11, Q18

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Introduction

Historically, rising living standards have been inseparable from the declining real price of food. Falling global food prices mean that fewer resources are needed to supply food, thereby freeing resources to supply education, science, and technology that further raise living standards and quality of life. Fewer people supplying food leaves more people to supply entertainment, shelter, disease control, environmental protection, and other concomitants of a better life.

The Malthusian specter—secularly rising food costs and associated falling living standards and (in poor countries) rising poverty, disease, and hunger—has once again been raised by rising real farm and food prices in recent years. The International Monetary Fund index of food commodity prices increased 130 percent from January 2002 to July 2008 (Trostle 2008, p. 3). The rise was due to higher energy prices, biofuel production, rapid international economic growth, drought in selected countries, depreciation of the dollar, and trade restrictions by some food exporting countries. These items are important in the short run, but at issue in this analysis is the influence on real food prices of secular (long-term) changes in the global food supply-demand balance.

Whether real food prices will decline in the 21st century is now an open question. Improved transportation, communication, and more open markets have made food an international market. The international food supply-demand balance determines real food prices. Real food prices will increase in the future if global growth in demand for farm output outpaces global growth in supply. On the demand side, agricultural output has never been just for food, but it is being called upon as never before to provide biofuels and environmental amenities as well. Or real food prices could rise not just from growing demand but also from slowing supply: Environmental degradation and neglect of investment in technology and infrastructure could retard agricultural productivity gains that traditionally have driven agricultural supply.

The objective of this study is to examine whether global real farm and food prices are likely to continue to fall in the future as they have in past decades. If portents are for agricultural supply to outpace demand and hence for real food prices to continue their secular decline, then public efforts to vigorously stimulate biofuel production may be appropriate. On the other hand if under current policies the likely outlook is for rising real food prices, policymakers may wish to forego biofuel subsidies and instead redouble incentives to increase agricultural productivity through education, research, and development.

Either one of two approaches can be used to quantify the long-term global food supply-demand balance. One approach is estimation of detailed supply and demand relationships for individual commodities, countries, and policies. Such structural analysis though useful for some purposes is bedeviled with errors in quantifying interactions among components, hence errors accumulate in long-term projections. The second or predictive approach, that is used in this study, projects future food and farm supply and demand from past trends in food aggregates. The central premise is conditional: *If past trends continue, these are the most likely outcomes for 2025 and 2050.*

Global *demand* trends are measured herein by population and income projections with adjustments for rising demand for biofuels and selected other factors. However, the principal focus of this study is on farm and food *supply* trends, especially on crop and (to a lesser extent) livestock yields. The focus is on yields for several reasons. The principal mover of agricultural output has been yields; real farm prices have fallen over time and discouraged use of more land, labor, and conventional capital. Agriculture will be able to supply output at lower real cost only by increasing productivity. Yields are a useful proxy for productivity (output per aggregate input), the latter, unfortunately, is not available for global crops and livestock.

Global Agricultural Output Demand

Food demand projections depict the challenge facing world agriculture. If supply cannot move forward to keep pace with demand, the real price of food at the farm level will need to increase to discourage consumption and encourage production so that supply and demand are brought into balance.

Global agricultural demand will grow in coming decades mainly from population gains. Rising income also will add to the demand for farm output, especially in developing countries where a sizable share of income is spent on food. Biofuels, "farmaceuticals", and plastics are emerging sources of farm output demand.

Annex table 4, recognizing the different response of food and fiber demand among countries by income level, indicates that the per capita food and fiber demand growth rate from income does not change very much over time. The quite stable 0.27 percent gain per capita per year over time from rising income is explained as shown in annex table 4 by the falling income elasticity of food demand under rising global incomes offset by the rising share of global population in developing countries with relatively high (though falling) income elasticities of food demand.

Biofuels

Biofuel demand depends on economic profitability and on government subsidies and mandates for biofuel use. The federal Energy Independence and Security Act of 2007 as amended in March of 2008 mandates 9 billion gallons of vehicle ethanol fuel in 2008, 13.2 billion gallons in 2012, and 15 billion gallons in 2015.[1] The market plus current federal subsidies and tariffs on ethanol seem consistent with meeting the mandates if the price of oil is approximately $80 per barrel and the corn price is $3.77 per bushel (see Roberts 2008; Babcock 2008). Ethanol as an oxygenate is readily blended with gasoline in so-called E10, a mix with 10 percent ethanol. Opportunities for ethanol are less attractive beyond that blending opportunity. The Environmental Protection Agency allowed up to a ten percent blend of ethanol in the 140 billion gallons of gasoline consumed in the U.S. in 2008, thus potentially utilizing 14 billion gallons of ethanol. However, the U.S. Department of Agriculture's 10-year projections look to slowing growth in U.S. ethanol production (Trostle 2008, p. 9).

Kruse et al. (May 2007, p. 16) estimate that markets plus existing U.S. tax and tariff provisions would result in 12.37 billion gallons annually of U.S. ethanol production

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[1] The renewable vehicle fuel mandate calls for 36 billion gallons of ethanol for 2022, half to come from cellulosic ethanol. Technology to efficiently produce the latter is unavailable and may not be forthcoming by 2022, hence the impact of the mandate on corn ethanol use is elusive.

from 2011 to 2016, near the mandated level. However, in the absence of tax and tariff inducements and mandates, ethanol production was estimated to average only 8.61 billion gallons annually for the 2011-2016 period. U.S. biodiesel production in the same period was estimated to average 0.51 billion gallons annually with government incentives and only 0.23 billion gallons without incentives.

The economic impact of biofuel production in the intermediate to long run considered in this study is influenced by substitution among farm resources and commodities in a global context. The mandated 13.2 billion gallon ethanol target for 2012, if achieved, adds $15 billion to U.S. farm receipts--assuming $3.77 per bushel corn and 20 percent feed recovery per bushel. Assuming another $5 billion added by biodiesel from soybeans, farming receipts are raised by an estimated 6.6 percent. Considering the addition to receipts as the addition to farm output, and with a price elasticity of excess demand of -0.3 in the intermediate run (3-5 years) and –1.0 in the long run (many years), U.S. farm prices are raised 22 percent in 3-5 years and 6.6 percent in many years by biofuel production. With farm ingredients only 24 percent of retail food cost, the forgoing biofuel numbers translate into a 5 percent increase in food prices in the intermediate run and 1.6 percent in the long run.

Given that other nations (except Brazil) on average are likely to rely less than the U.S. on biofuels, the global impact of expected levels of biofuel production may be relatively less than indicated above. Thus the introduction of biofuels does not seem to unduly upset the global food supply-demand balance. To be sure, the 21 million barrel per day global gasoline industry and the equally massive global diesel industry constitute a highly elastic and almost inexhaustible demand for biofuels at high oil prices. Ethanol consumed 23 percent of U.S. corn production in 2008, but that ethanol accounted for only 3 percent of U.S. gasoline consumption. Brazil has shown that ethanol can substitute for gasoline over a considerable range of utilization, hence U.S. demand for ethanol is great indeed at oil priced above $80 per barrel. On the other hand, the limited global supply of land, water, and other farm resources implies strong market restraints on biofuel production. Limited resources to supply crops and livestock coupled with competing demands for food and fiber means that agriculture will supply only a minor share of vehicle fuels at home and abroad in the future. Among countries, Brazil is one exception to that conclusion. A recent review (Searchinger 2008, p.1) of ten biofuel studies concluded “Mandates and subsidies to produce biofuels are significantly more expensive methods than other methods of reducing greenhouse gas emissions…” In the unlikely event that policymakers accept that conclusion and withdraw subsidies, the following projections of biofuel use could be overoptimistic.

Assuming production trends follow the federal biofuel mandate, that each bushel of corn for ethanol retains 20 percent of its feeding value for livestock, and that each bushel of corn produces 2.7 gallons of ethanol, then ethanol demand adds an estimated 0.41 percentage points annually to the growth in American agricultural receipts from 2008 to 2012 and only 0.14 percentage points annually to the growth of farm receipts from 2012 to 2015. The European Union also is mandating future biofuel use; other countries may join the effort. In subsequent analysis, nonfood demands for biofuels, nutriceuticals, farmaceuticals, and the like are assumed to add 0.10 percentage points annually to global farm output demand.

Demand projections

Table 1 shows past and projected annual growth rates in farm output demand from 1961 to 2050 from population only and from all sources based on assumptions discussed above. The initial year, 1961, was chosen because several data series used in this study began with that year.

Table 1. Rate of increase and global total demand for farm output due to population only and from all sources in selected years from 1961 to 2050

Item	Year					
	Actual				Projected	
	1961	1975	2000	Variant	2025	2050
Annual increase in year,%						
Population only	1.89	1.85	1.31	Low	0.48	-0.17
				Medium	0.82	0.36
				High	1.13	0.88
Total agri. demand	--	--	--	Low	0.83	0.18
				Medium	1.17	0.71
				High	1.48	1.23
Agri. output, accumulated demand	Year 2000=100					
Population only	50	67	100	Low	124	127
				Medium	131	150
				High	138	176
Total agri. demand	--	--	100	Low	135	152
				Medium	143	179
				High	151	209

Source: Population numbers from United Nations Population Division (October 1, 2008, p. 1). After year 2000, projected world demand growth for farm output per capita is calculated as the average compound rate of growth in population plus 0.25 percent annually due to income growth (see annex table 4) and 0.10 percent annually due to sources other than food and fiber (see text).

Population numbers from the United Nations are projections—the likely world population at future points in time under specified assumptions. The numbers are not predictions of the most likely population in any particular year. Nonetheless, many demographers view the assumptions underlying the “medium” and “low” projections as most realistic and thus provide the most realistic population “predictions” (see Tweeten 2007, ch. 9). The medium population variant calls for global population to increase 0.82 percent in 2025 and 0.36 percent in 2050. World population growth rates have been slowing for some years and several experts believe that global population will have already begun to fall by mid-century as depicted by the negative growth rate –0.17 percent per year under the low population growth variant for 2050 in table 1.

If demand for farm output were proportional solely to population and the low population growth variant prevailed, demand for farm output would be only one-fourth greater in 2025 and 2050 than in 2000. A more realistic projection based on the medium population variant and including nonfood demands is that overall demand for farm products will be 143 percent of year 2000 output in 2025 and 179 percent of 2000 output in 2050 (Table 1). Thus demand could nearly double in the first half of the 21st century based on the medium UN population projection. The demand under the high population variant seems less likely. It will be necessary to return to table 1 numbers to ascertain the global agricultural supply-demand balance and resulting prices after examining supply projections in the following pages.

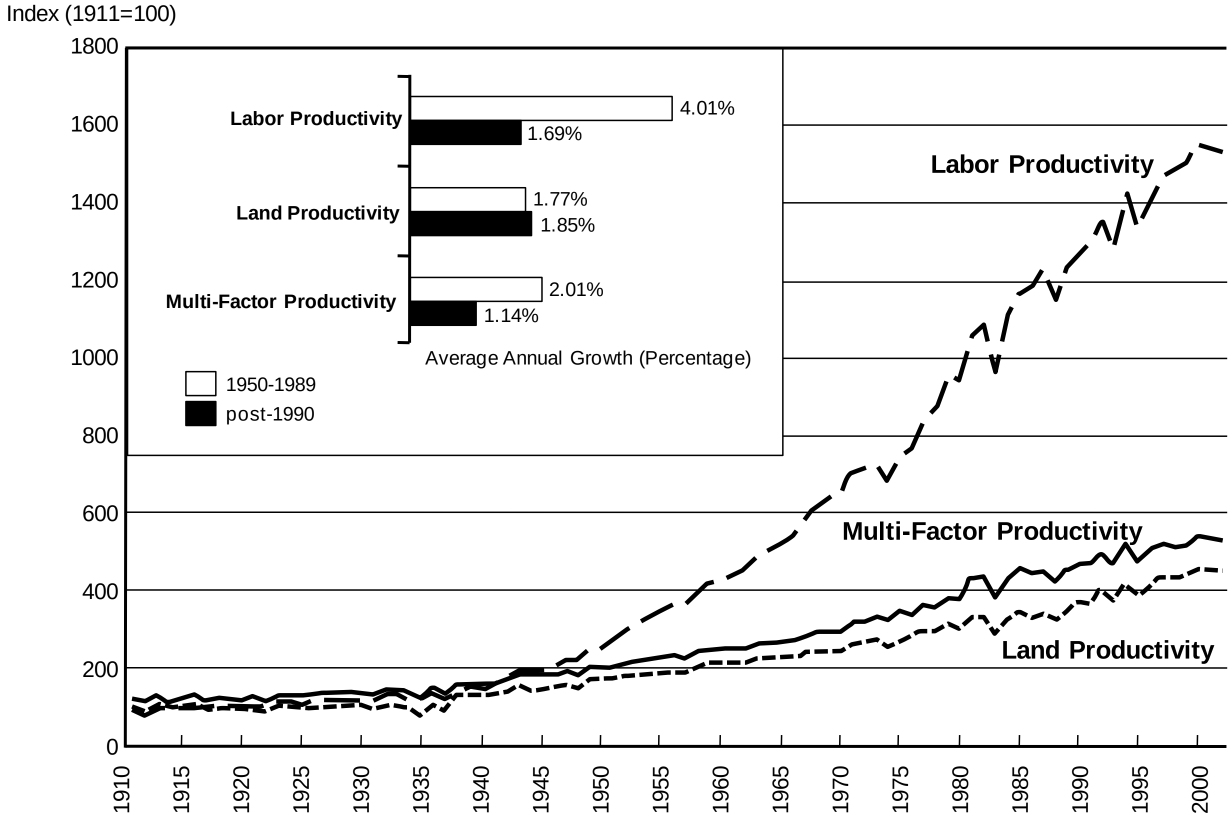
Global Agricultural Output Supply

Ideally, the outward shift of the supply curve would be measured by multi-factor productivity growth, i.e., output per unit of all production inputs. Unfortunately, agricultural productivity has not been measured for recent years or for many countries and commodities. Figure 1 from Alston and Pardey (2008) shows that the level and variation in land productivity (yield) in the United States closely aligns with multi-factor productivity. U.S. labor productivity advanced markedly in recent decades, freeing farm workers to produce other goods and services prized by consumers. But land more than labor constrains farm output, hence productivity of land is of special interest. U.S. land productivity increased 1.77 percent annually while multi-factor productivity increased 2.01 percent annually from 1950 to 1989 (see figure 1). Multi-factor productivity growth then slowed considerably, however, averaging only 1.14 percent annually from 1990 to 2002. In this study, major crop and livestock yield trends for the U.S. and the world will be examined for evidence of a continuing slowdown in productivity growth. The following paragraphs examine the potential impact of irrigation, global warming, and cropland area on agricultural output before observing historic yield trends.

Irrigation

Yields in this study are from irrigated and rainfed agriculture and from developed and developing country agriculture. Irrigation contributes mightily to farm output. Some 40 percent of agricultural production and fully 60 percent of the world's grain are from irrigated land (Meinzen-Dick and Rosegrant 2001, p. 1). Irrigated agriculture currently accounts for only 18 percent of cultivated area in developing countries but for 40 percent of the value of agricultural output (World Bank 2007, p. 182). The following analysis recognizes yield gains on irrigated cropland from improved crop varieties and technology throughout the world. Substantial rainfed land in rich and poor countries could be irrigated but rising energy costs preclude doing so in the absence of rising real farm and food prices. As the water table level drops in aquifers such as the Ganges Plain in India or the Ogallala basin underlying the southern Great Plains in the U.S., pumping water for irrigation from ever-greater depths becomes uneconomic. Formerly irrigated farmland will remain in agriculture but yields with rainfed crops will be lower. A third of irrigation relies on water behind dams. Lack of promising additional sites coupled with environmental concerns leaves modest scope for building more dams for irrigation. Extensive water use for crop irrigation and urban population has reduced water flow in the Colorado, Rio Grand, Ganges, and Nile rivers to little more than a trickle in some seasons. An increasing proportion of river flows now used for crop irrigation will be diverted to urban use in future decades.

Figure 1. Labor, land, and multi-factor agricultural productivity, U.S., 1911-2002



Source: Alston and Pardey (2008)

Large areas of China, South Asia, and the Middle East and North Africa are extracting groundwater or river water for irrigation at unsustainable levels. Groundwater overdraft in excess of sustainable levels exceeds 25 percent in China and 56 percent in parts of northwest India. These irrigated areas currently are some of the world's most productive (see World Bank 2007, p. 64).

On the other hand, opportunities to expand irrigation are promising on some of the currently most unproductive lands in the world. In Sub-Saharan Africa, irrigated agriculture is projected to double by 2030 from the 2007 level. Only 4 percent of the cultivated area in that region was irrigated in 2007, and a mere 4 million hectares had been added in the past 40 years. Lack of infrastructure (roads, bridges, etc.) and institutional support has been and will continue to be a stumbling block to expansion of irrigation in that region. Such considerations prompted the World Bank (2007, p. 64) to conclude that irrigated area in developing countries is likely to expand by only 0.2 percent annually in the developing world by 2030. Additions will be less after 2030. "Yield improvements in existing irrigated areas, rather than further expansion, will be the main source of growth in irrigated agriculture" (World Bank 2007, p. 184).

Global Warming

Global warming is expected to have minimal *overall* impact on worldwide food and fiber output but impacts will differ widely by region. Yield level and variation may be more affected than crop area by global warming. Mainly due to lower yields, Cline (2007) projects agricultural output will fall 16 percent from global warming by 2020—some 6 percent in developed countries and 20 percent in developing countries. The overall reduction could be reduced to 3 percent due to "carbon fertilization" as higher carbon dioxide levels stimulate photosynthesis. Estimates from Rosenzweig and Perry (1994) and Mendelsohn and Neuman (1999) place the loss of cereal production from global warming at up to 7 percent in developing countries offset by gains of up to 14 percent in developed countries, leaving global cereal output unchanged. A similar conclusion was reached more recently by Tubiello and Fischer (2007, pp. 1030-56) who conclude that between 1990 and 2080 global cereal output is expected to fall by only 0.6 to 0.9 percent due to global warming, other things equal. They anticipate that global warming will increase cereal production by 2.7 to 9.0 percent in developed countries but decrease cereal production by 3.3 to 7.2 percent in developing countries by 2080. Thus, unfortunately, the most severe hardship is likely to occur in the poorest countries, with cereal production falling by 18.2 to 21.1 percent in South Asia and by 3.9 to 7.5 percent in Sub-Saharan Africa (Tubiello and Fischer 2007). However, exploiting irrigation potential in Sub-Saharan Africa could offset losses from global warming on that region.

Area response

The global area in the six major crop groups in this study remained almost unchanged at 1.1 billion hectares from 1985 to 2006. However, due to rising demand from ethanol production and other factors such as rapid economic growth in China, the six-crop harvested area surged from 1,079 million hectares in 2002 to 1,155 million hectares in 2007. The latter period growth is unsustainable. The following text table shows trend area growth rates predicted by linear and double-logarithm equations estimated by ordinary least squares from annual data for years 1961 to 2007. A linear equation with six-crop area as a function of time depicts a trend growth rate of 0.46 percent for 1961 but dropping to 0.33 percent for 2050. The double log function with the dependent variable, six-crop area, and time, expressed as the year less 1900, displayed better statistical properties than the linear-in-original-values equation as measured by the statistical significance of the time variable, the adjusted R-square, and the Durbin-Watson statistic.

	Year				
Function	1961	1975	2000	2025	2050
	Trend rate of increase in six-crop area, % in year:				
Linear	0.46	0.43	0.39	0.36	0.33
Log-log	0.57	0.46	0.35	0.28	0.23

Source: Data from FAO 2008

The initial supply shift projections of this study assume no increase in crop area in 2025 and 2050 over year 2000 area. The presumption of no increase in cropland without an increase in the real price of food may seem severe given the recent rise in global cropland area. The following numbers, though sparse, highlight the challenge of even maintaining crop area in the future. Myers (1997, pp. 8-10) estimated that worldwide annual abandonment of agricultural land averages 10.75 million hectares due to soil erosion, 6.00 million hectares due to overgrazing, and another 2.00 million hectares due to water logging and salinization through irrigation. The sum of these losses, 18.75 million hectares per year, exceeds the 5 to 12 million hectares of agricultural land that the International Food Policy Institute (IFPRI 1999, p. 20) reports is lost worldwide to degradation each year. Most of that degradation is occurring in poor countries and has accelerated there in the past 50 years (IFPRI 1999, p. 2).

World Resources Institute (WRI 1996, p. 59) reports loss of 476,000 hectares of agricultural land each year due to urban development including buildings, roads, parks, airports, and reservoirs. Much of this loss of agricultural land will take place in developing countries already stretched to provide sufficient food. There, urban population is expected to double from the 1990 level to total 3.4 billion persons by year 2020 and account for virtually all the world's population growth (Pinstrup-Andersen et al. 1999, p. 5). Urbanization, however, accounts for only a small portion of the total annual estimated agricultural land loss averaging 5 to 19 million hectares.

This annual loss can be compared to prospective additions to agricultural lands. The most promising prospects are in Brazil, although selected other regions especially in Russia and Africa also offer promise—heroically assuming that needed massive investments in infrastructure, including roads and irrigation along with security and technology, can be provided. In 1990, Brazil's national institute for agricultural research, EMBRAPA, estimated that 136 million hectares of the interior *cerrado* savannah were suited for large-scale agriculture, an increase from the region's 47 million hectares utilized in 1990 (Schepf et al. 2001, p. 12). The additional 89 million hectares are feasible with treatment of the soil for acidity, aluminum toxicity, and for deficiencies in nitrogen and phosphate. The region is especially well suited to soybeans, and accounted for much of the expansion in Brazil's annual average soybean area harvested from 3.7 million hectares in 1970-74 to 12.4 million hectares in 1995-99.

The conclusion, that the world will need another Brazilian *cerrado* every four to 18 years to compensate for cropland losses from degradation and (to a much smaller extent) urbanization, is sobering. Though crude, the estimate supports our no-net-cropland-change assumption (in the absence of an increase in food real prices) when projecting long term food supply. Those who consider reasonable the area trends shown in the text table above can add 0.2 to 0.3 percentage points to the aggregate yield percentage increases for 2025 and 2050 shown later to express the total farm output supply response. It is recognized that cropland expansion carries environmental costs from deforestation, soil degradation, and water quality and species loss.

Historic yield trends[2]

U.S. crop yields are examined first because it is a major agricultural producer, is at the vanguard of technological advance, and has extensive data. Later, worldwide crop and livestock yields are examined individually and combined to form aggregate supply trends for comparison with aggregate demand trends for global farm output. Yields for the four major U.S. farm crops shown in figures 2 to 5 display considerable variation

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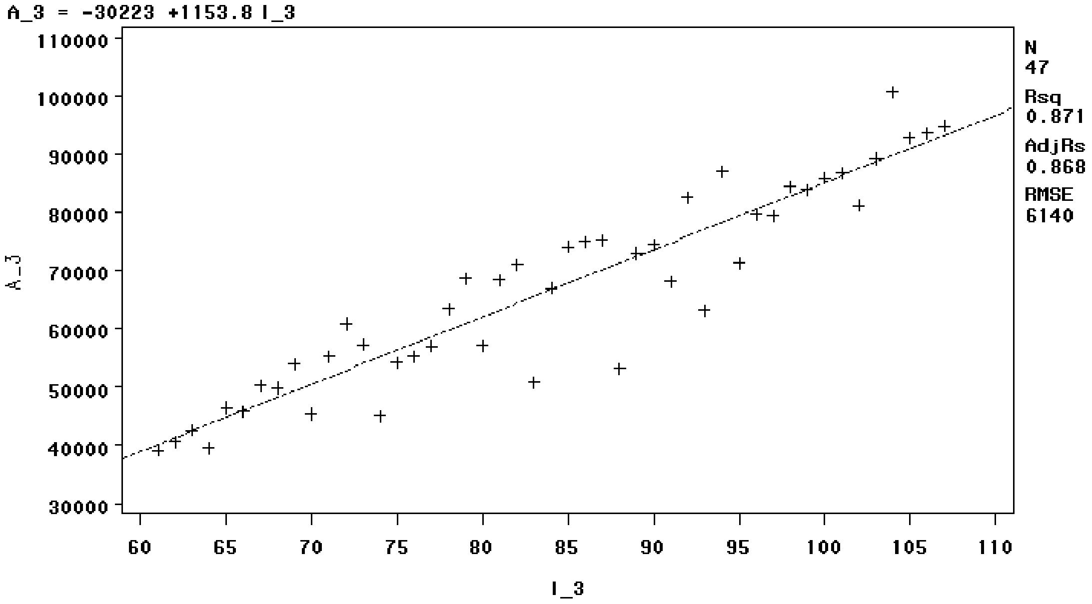
[2] All yield data are from FAO (2008).

from year to year but made sizable gains from 1961 to 2007. The figures show actual yields (+) along with a linear yield trend line. The statistical results in the annex indicate that curvilinear equations fit the data little better than the linear functions (straight lines) shown in figures 2 to 5. Annual yield gains averaged 1,154 hectograms per hectare (hg/ha) (1.8 bushels per acre) for corn, 243 to 256 hg/ha (0.4 bushels per acre) for soybeans and wheat, and 198 hg/ha (18 pounds per acre) for cotton. Cotton yields show signs of accelerating in recent years. The implications of alternative interpretation of trends are examined later.

Figures 6 to 11 show actual yields and a linear trend line for the world's major crop groups from 1961 to 2007. Except for oilcrops (soybeans, rapeseed, etc.), yields appear to be increasing along a straight line. Cereals such as corn, wheat, and rice are of special importance because they account for half of the world's diet directly and for up to two-thirds if the contributions of cereals to livestock and poultry products are considered. Two additional features of figure 6 for world cereals and figure 2 for U.S. corn are notable. First, *relative* variation in yields is much less for world cereals than for U.S. corn. A world that can share cereal output through trade has access to a rather steady supply from year to year.

Figure 2. U.S. corn yield, 1961-2007 (hectograms/hectare)



Year (Current year less 1900)

Figure 3. U.S. soybean yield, 1961-2007 (hectograms/hectare)

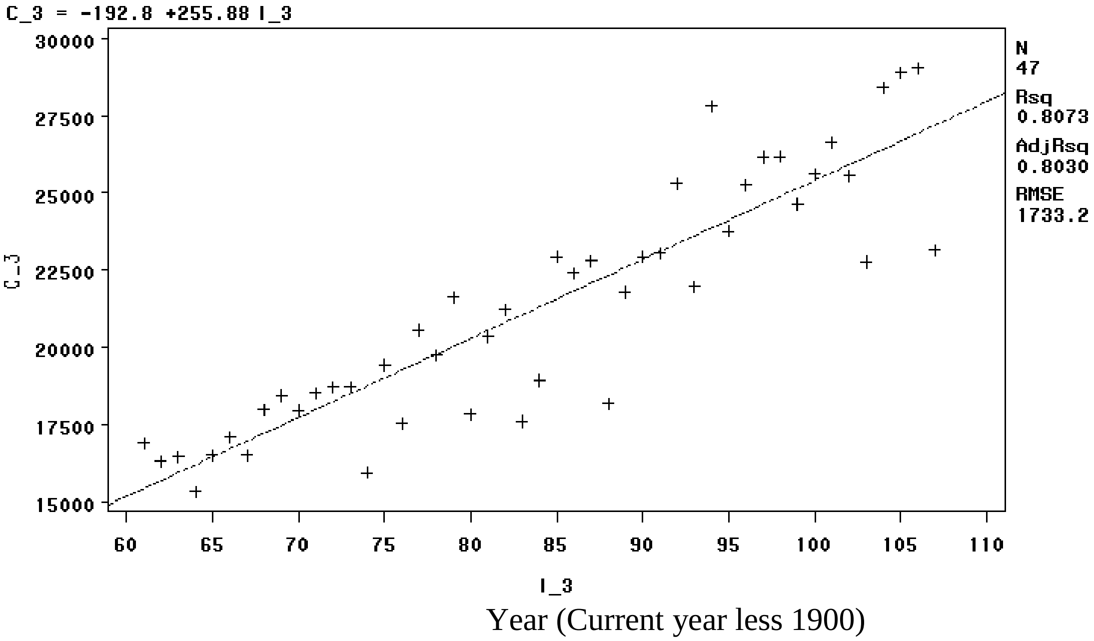


Figure 4. U.S. wheat yield, 1961-2007 (hectograms/hectare)

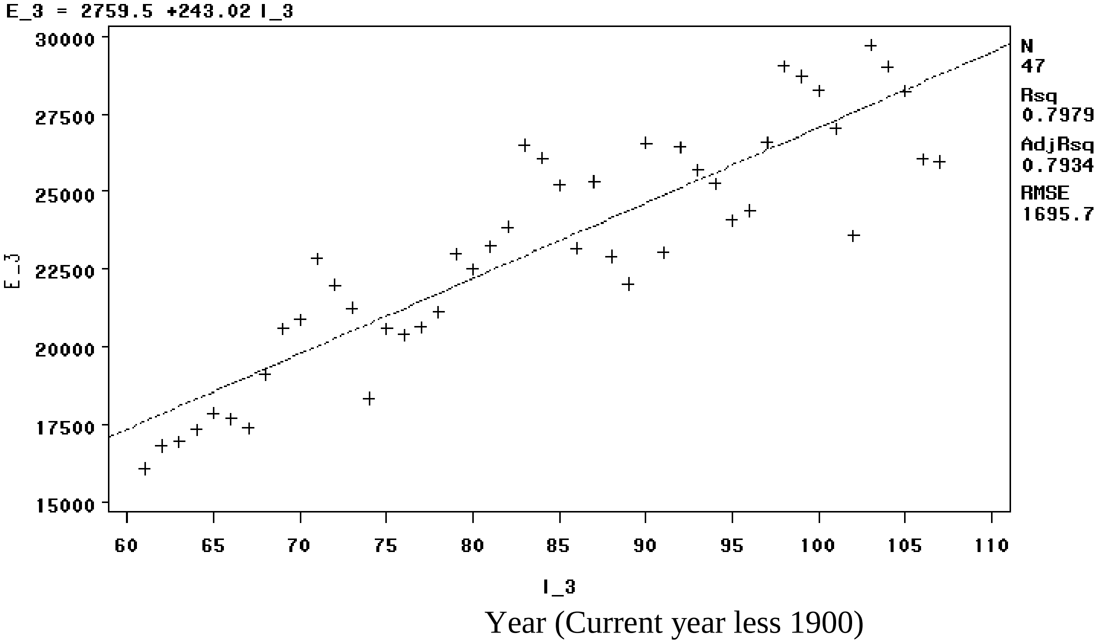
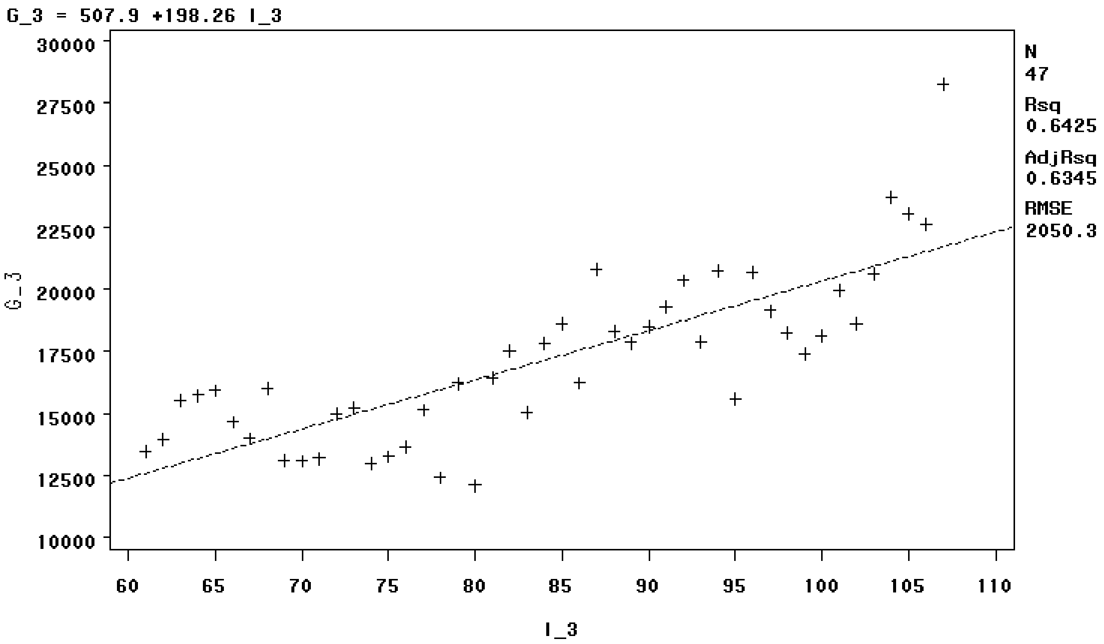
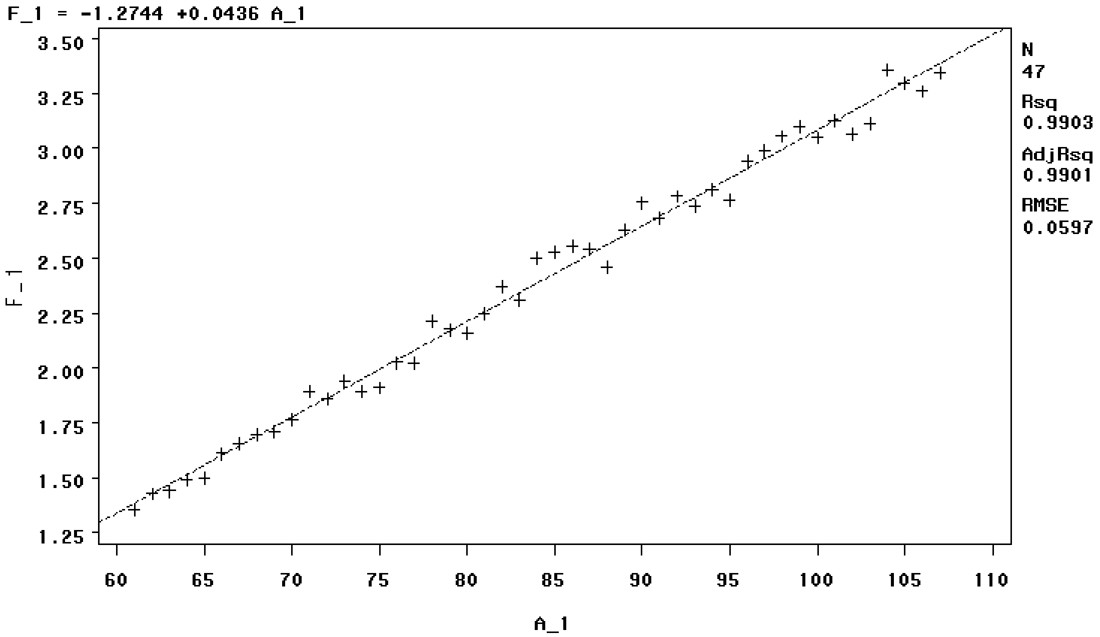


Figure 5. U.S. cotton yield, 1961-2007 (hectograms/hectare)



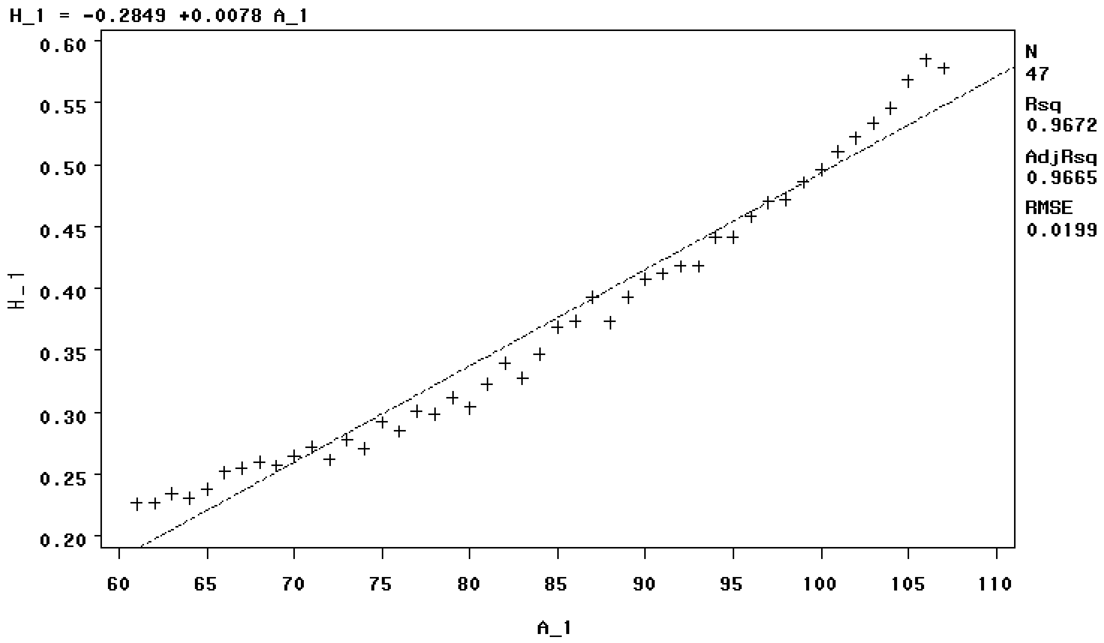
Year (Current year less 1900)

Figure 6. World cereal yield, 1961-2007 (tons/hectare)



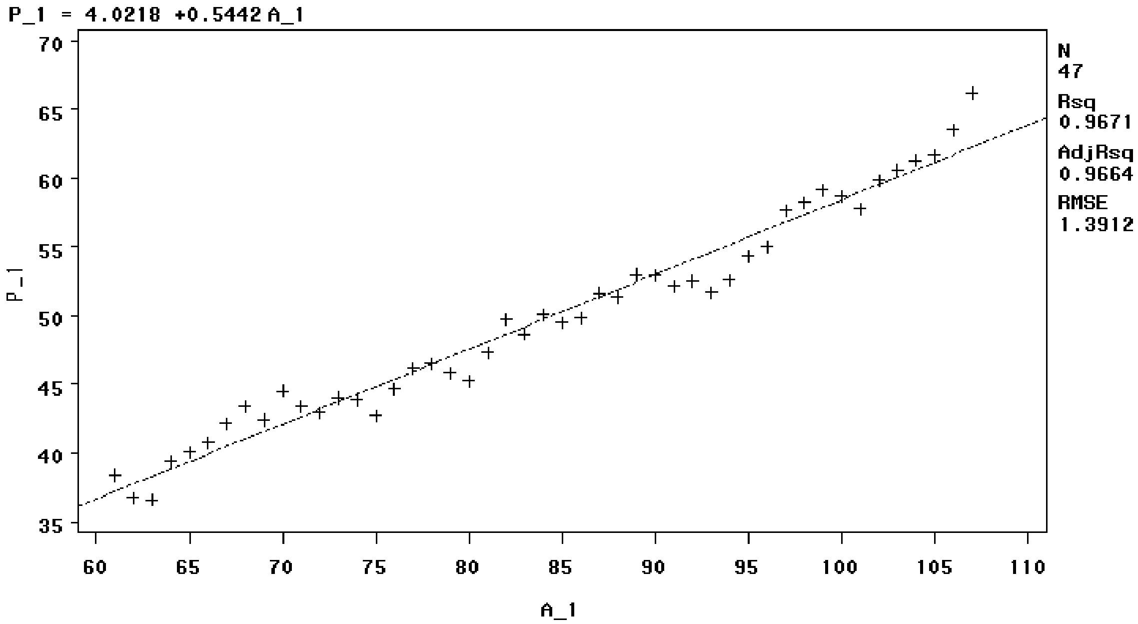
Year (Current year less 1900)

Figure 7. World oilcrop yield, 1961-2007 (tons/hectare)



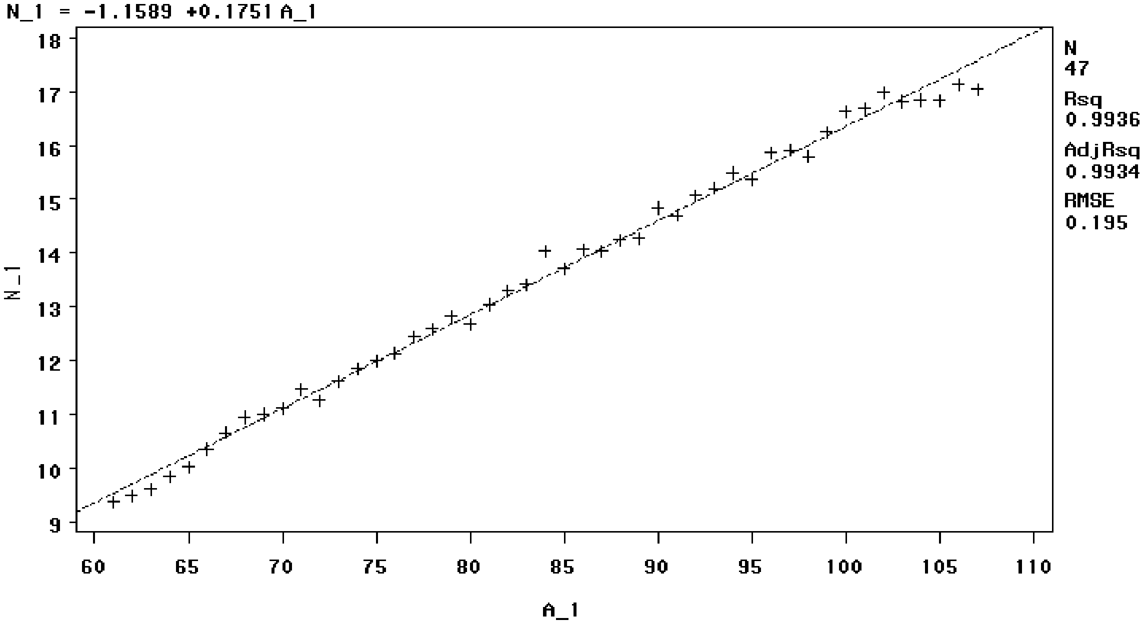
Year (Current year less 1900)

Figure 8. World sugar crop yield, 1961-2007 (tons/hectare)



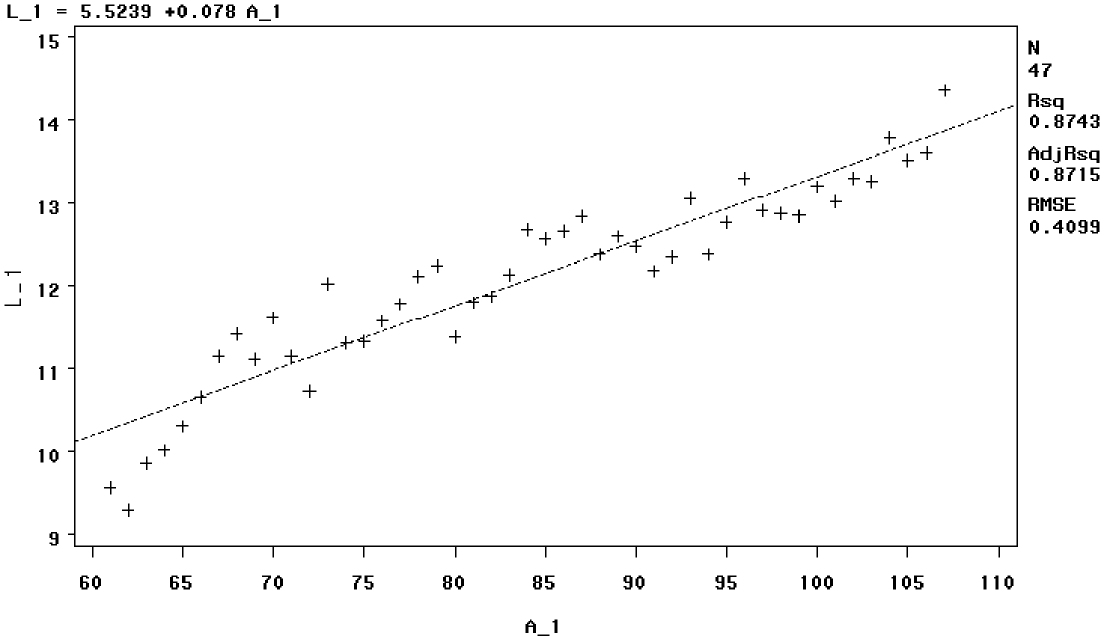
Year (Current year less 1900)

Figure 9. World vegetable and melon yield, 1961-2007 (tons/hectare)



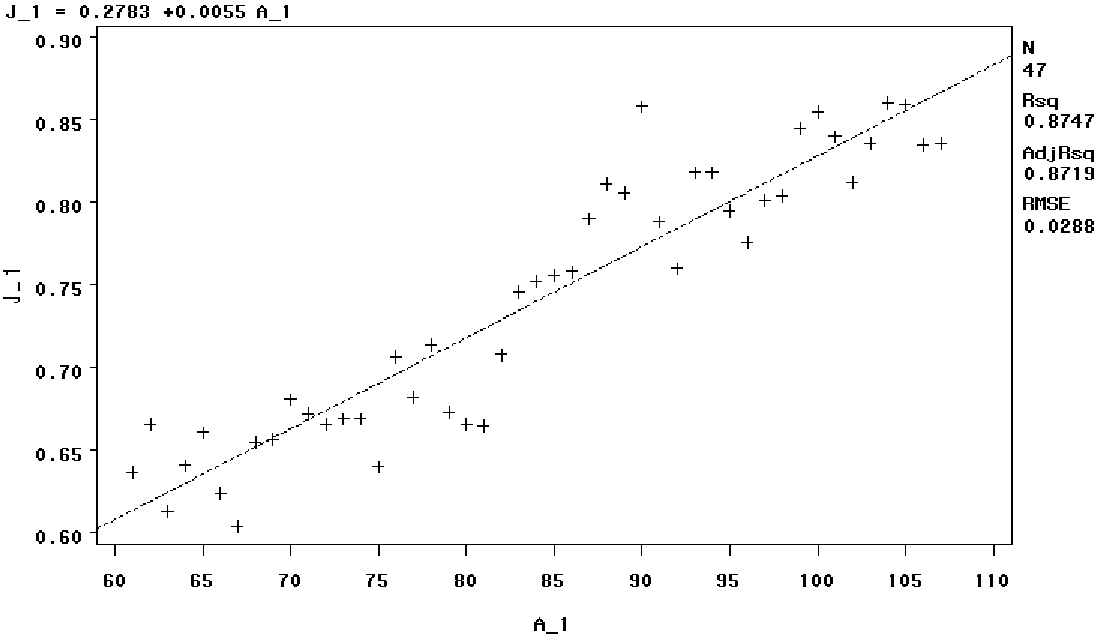
Year (Current year less 1900)

Figure 10. World root and tuber yield, 1961-2007 (tons/hectare)



Year (Current year less 1900)

Figure 11. World pulses yield, 1961-2007 (tons/hectare)



Year (Current year less 1900)

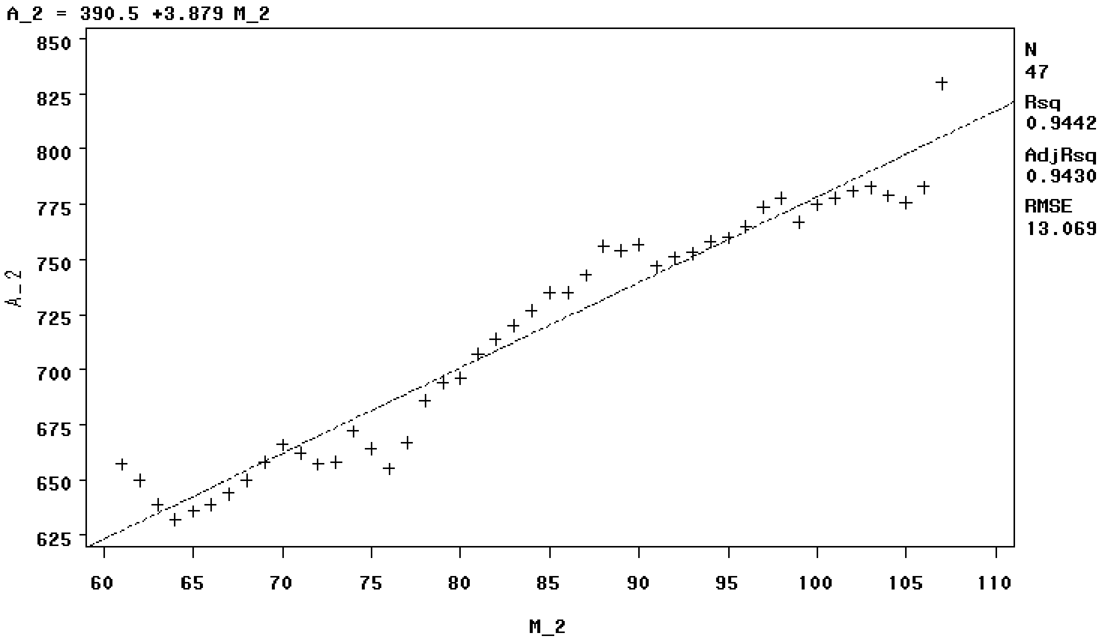
The second observation is that, compared to U.S. corn, world cereal yield annual increments are of modest size on average. Corn yields in the U.S. (figure 2) increased on average 2.6 times the rate of world cereal yield in part because some cereals such as sorghum and millet tend to be produced in arid regions of the world offering minimal yield response to improved practices with available varieties.

Recent world sugar crop yields show signs of accelerating and world vegetable and melon yields show signs of falling in recent years. It is hazardous, however, to let an interpretation from 3-4 recent years take precedence over the 47-year trend.

Historic world livestock yields are shown in figures 12 to 16 to complete the yield analysis of farm output. The concept of livestock yield is elusive because opportunities are much greater to expand livestock production by increasing the number of animals than it is to expand crop production by adding area. Furthermore, data on livestock yields are less reliable than on crop yields. Nonetheless, livestock yields such as milk per cow or eggs per hen provide clues to livestock productivity and the challenge of providing food efficiently in the future.

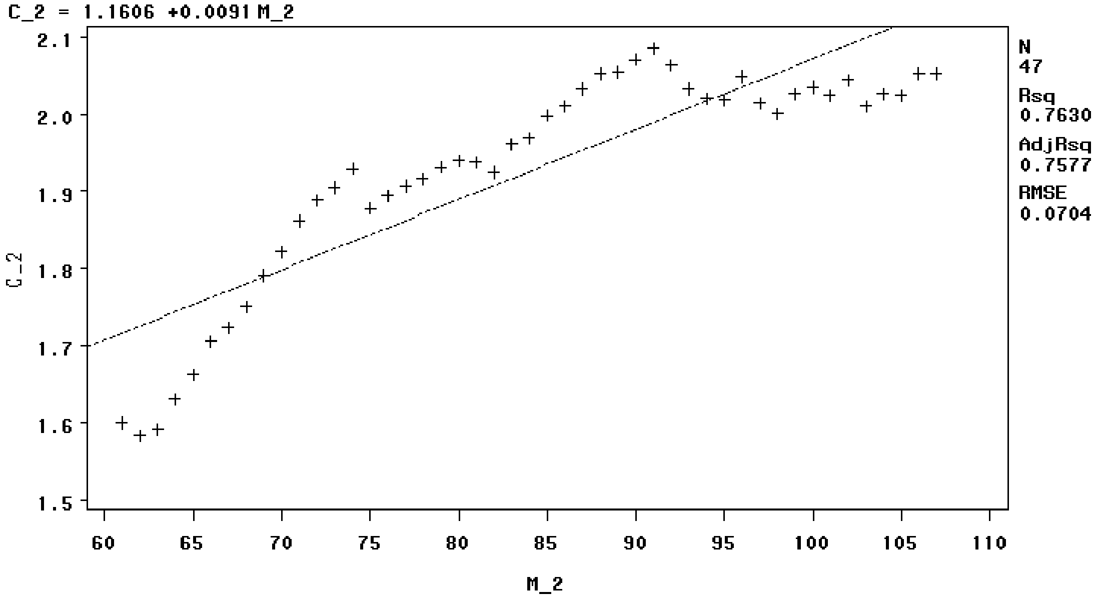
World livestock yields, like crop yields shown earlier, are increasing. The pattern of increase varies. Pig meat yields appear to be increasing at a constant rate, cattle meat and egg yields appear to be increasing at a decreasing rate, and chicken meat yields appear to be increasing at an increasing rate. The trend in milk yield per cow is erratic, perhaps due to data problems, so firm conclusions regarding trends are unwarranted. Where more accurate data are available, evidence is clear that milk per cow has increased in recent decades, thereby increasing economic efficiency and reducing real milk and milk product prices.

Figure 12. World pig meat yield, 1961-2007 (hectograms/pig)



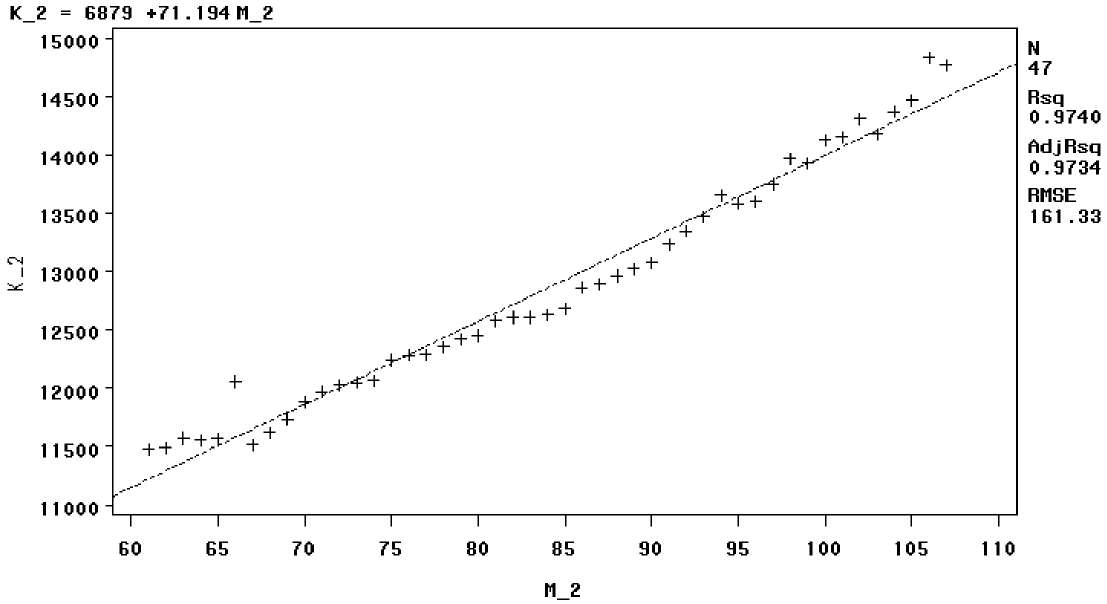
Year (Current year less 1900)

Figure 13. World cattle meat yield, 1961-2007
(tons/head)



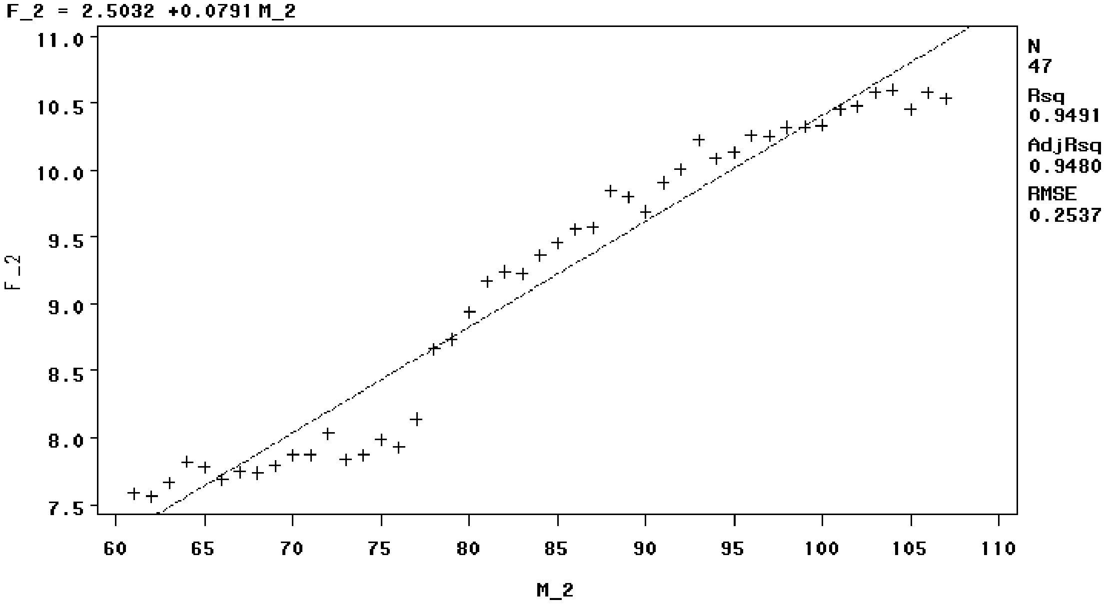
Year (Current year less 1900)

Figure 14. World chicken meat yield, 1961-2007 (hectograms/chicken)



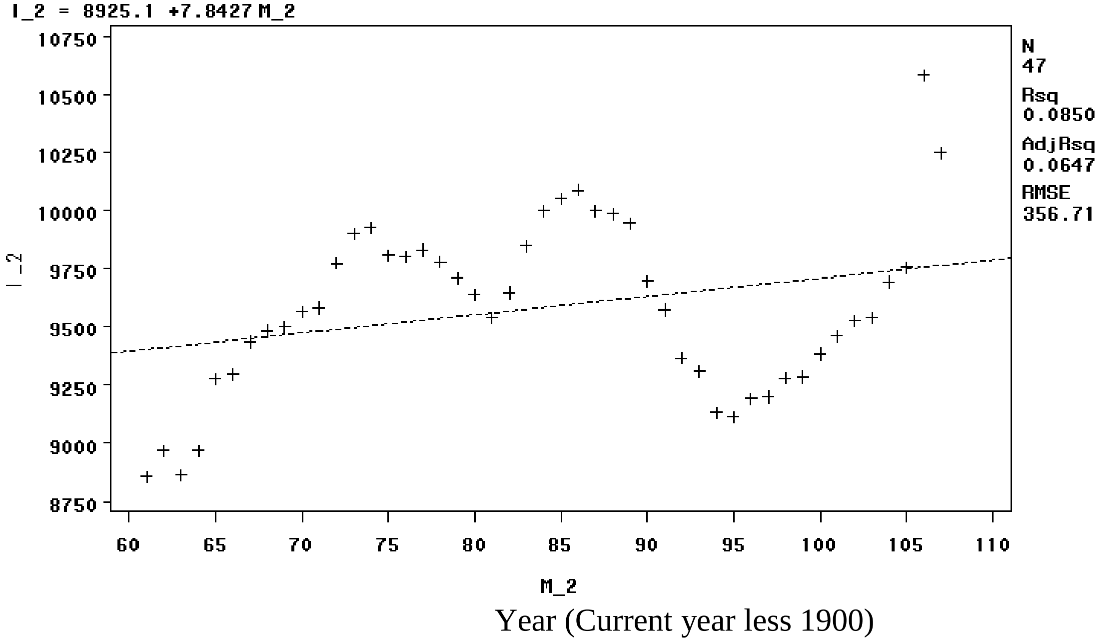
Year (Current year less 1900)

Figure 15. World egg yield, 1961-2007 (kilograms per hen)



Year (Current year less 1900)

Figure 16. World milk yield, 1961-2007 (hectograms/cow)



Future Food Supply-Demand Balances

The foregoing figures 2 to 16 do not facilitate comparison of yield growth among commodities or with respect to the rate of growth in demand for farm output. Table 2 for U.S. crops and tables 3 and 4 for world crop and livestock yields respectively (see also annex equations) facilitate comparisons in judging the world food supply-demand balance. To place the table 2 numbers in perspective, it is well to recall from table 1 that demand for the world's farm output is predicted to be increasing at a rate of 1.17 percent in 2025 and 0.71 percent in 2050 based on the UN medium population projection. Crop groups in tables 2 and 3 will need to increase at least by these rates if they are to maintain their share of overall demand growth from yield gains alone.

On the whole, results from linear equations were judged to be most acceptable based on signs and significance of coefficients, adjusted R-square, and Durbin-Watson statistic. Results from one other attractive specification were included in table 2 and subsequent tables for comparison purposes. None of the linear equations for four major U.S. crops individually or a weighted average in table 2 predicts a yield increase as high as 1.17 percent in 2025. And for 2050 only the U.S. corn yield gain of 0.81 percent exceeds the predicted world demand gain of 0.71 percent for that year. The nonlinear equations except for wheat are more optimistic than are linear equations predicting future yield prospects. Rates of increase in aggregate yields (weighted by individual crop revenue from 2001 to 2003) by 2000 are only one-third to one-half the rate of increase in 1961. Without the sizable drop in the growth rate of farm output demand due to slowing population growth as depicted in table 1, the world would be destined for sharply rising real food prices—if world yield patterns in tables 3 and 4 are similar for those for the U.S. shown in table 2.

Table 2. Predicted annual increase in U.S. major crop yields in selected years

Crop	Proportion of major crops	Annex equation number	Equation form	Predicted percent increase in yield in year:				
				1961	1975	2000	2025	2050
Corn	0.443	1.1 (Fig. 2)	Linear	2.87	2.05	1.35	1.01	0.81
		1.2	Log-log	2.42	1.97	1.48	1.18	0.98
Soybeans	0.322	2.1 (Fig. 3)	Linear	1.66	1.35	1.01	0.80	0.67
		2.2	Semi-log	1.20	1.20	1.20	1.20	1.20
Wheat	0.121	3.1 (Fig. 4)	Linear	1.38	1.16	0.90	0.73	0.62
		3.2	Quadratic	2.50	1.44	0.48	-0.19	-0.97
Cotton	0.114	4.1 (Fig. 5)	Linear	1.57	1.29	0.98	0.78	0.66
		4.2	Quadratic	-0.33	0.69	1.78	1.91	1.72
	1.000			Weighted average				
			Highest	2.29	1.66	1.35	1.22	1.09
			Linear	2.15	1.63	1.14	0.88	0.72
			Lowest	1.59	1.48	1.09	0.77	0.53

Source: See equations in annex. Yield data from FAO (2008); shares are weighted by revenue data for 2001-2003 from USDA (2008).

Global percentage yield gains

Table 3 shows global crop yield growth for selected years for eight commodity groups and in aggregate predicted by equations in the annex. Yields of commodity groups are predicted by the linear equation and by a second equation considered appropriate based on the proportion of yield variation accounted for, the autocorrelation in residuals, and the signs and significance of the coefficients.

The most notable general observation is that, like U.S. yields, world yield rates of increase have markedly slowed over time. Annual absolute increments for U.S. corn yield were much larger than for world cereal but the percentage gains are very similar because U.S. yields were higher. Based on the linear equation, the U.S. corn yield increment predicted to be 1.01 percent per year in 2025 is near the world cereal gain predicted to be 1.04 percent for the same year. In 2050, the U.S. corn yield increment predicted to be 0.81 percent matches closely the 0.83 percent increment predicted for the world. The world weighted averages of the linear yield gains over all commodities, 0.87 percent in 2025 and 0.70 percent in 2050, compare closely with the weighted average U.S. crop yield gains of 0.88 percent in 2025 and 0.72 percent in 2050.

As stated earlier, demand for farm output based on the medium population variant of the United Nations is projected to be increasing at a rate of 1.17 percent per year in 2025 and 0.71 percent per year in 2050. It is notable that all but one (vegetable oil quadratic) of the annual yield increments for individual commodity groups or for the weighted aggregate in table 3 fell short of that 1.17 percent demand growth in 2025. And the weighted average of the linear yield equation predictions, 0.70 percent in 2050, fell just short of the predicted 0.71 percent demand growth.

Table 3. Predicted annual increase in global crop and livestock yields in selected years

Crop or animal group			Predicted percent increase in yield in year:				
	Annex equation number	Equation form	1961	1975	2000	2025	2050
Cereals	5.1	Linear	3.15	2.19	1.41	1.04	0.83
	5.2	Quadratic	3.58	2.27	1.56	0.87	0.62
Meat and animal fats	11.1,12.1,13.1	Linear	0.59	0.55	0.48	0.43	0.39
	11.1,12.1,13.2	“Best”[a]	0.46	0.51	0.54	0.54	0.52
Vegetable oils	6.1	Linear	4.10	2.60	1.58	1.13	0.88
	6.2	Quadratic	1.20	2.02	2.25	1.97	1.66
Sugars	7.1	Linear	1.46	1.21	0.93	0.76	0.64
	7.2	Quadratic	0.95	1.07	1.11	1.10	1.03
Milk, eggs, fish	14.1, 15.1	Linear	0.58	0.51	0.42	0.36	0.32
	14.2, 15.2	“Best”[b]	1.50	1.24	1.10	0.80	0.58
Fruits (melons)	8.1	Linear	1.84	1.46	1.07	0.84	0.70
and vegetables	8.2	Quadratic	2.19	1.55	0.95	0.63	0.41
Roots and tubers	9.1	Linear	0.76	0.69	0.58	0.51	0.45
	9.2	Quadratic	1.25	0.52	0.35	Neg.[c]	Neg.[c]
Pulses	10.1	Linear	0.90	0.80	0.66	0.57	0.50
	10.2	Quadratic	0.91	0.80	0.66	0.55	0.48
Weighted total[d]		Highest	2.71	1.80	1.35	0.92	0.83
		Linear	2.38	1.69	1.13	0.87	0.70
		Lowest	2.03	1.61	1.11	0.74	0.54

Source: See annex.

[a] Linear equation for pig and cattle meat, quadratic equation for chicken meat.

[b] Quadratic equation for eggs per hen; cow numbers and time variables in milk per cow equation.

[c] Predicted rate negative, but assumed to be zero for weighted total of lowest rates.

[d] See weights in table 4.

The most impressive yield gains historically and in prospect are for cereals and oilseeds. Cereal yield improvements are especially notable for hybrid corn and green revolution wheat and rice. Roundup-ready soybeans and canola rape constitute notable achievements in oilseeds.

Each of the projected linear yield growth rates for the major crop groups in table 3 falls short of 1.17 percent medium demand growth rate predicted for 2025. The average of the individual crop group yield growth rates weighted by share of world diets and projected to 2025 ranges from 0.74 for the lowest projected rates to 0.92 for the highest projected growth rates. These rates are broadly in line with the low demand scenario projection, 0.83 percent in table 1, for 2025. If, optimistically, additional crop area in 2025 adds 0.20 percent to farm output growth to bring the total output growth to 1.07 percent under the linear projection in table 2, farm food ingredient growth will fall just short of medium demand growth and real food prices will not need to markedly increase. If the demand for farm output would have maintained the 1961 population growth rate of 1.89 percent annually to 2025, only the projected vegetable oil yield could have kept pace. But the weighted total yield increase over all food groups would have fallen well short of the rise in demand and the result would have been sharply rising real food prices, food shortages, and new land broken out for crop production to the detriment of the environment.

By 2050 global population growth will slow to reduce farm output demand growth from an estimated 0.18 percent (low growth) to 0.71 percent (medium growth) annually. Several predicted yield growth rates of crop groups in table 3 exceed those rates. Of interest is that the average of the linear estimates weighted by proportion of the world's diet predicts yields increasing by 0.70 percent in 2050. This balance implies that farm output demand can be met without an increase in cropland area or by higher food prices.

Table 4 shows global supply quantities in selected years from yield increases predicted by regression equations used to derive rates of increase in table 3 and shown in the annex. Based on superior theoretical and statistical properties of the estimates, a linear equation with time independent variable and a quadratic equation with time and time-square dependent were chosen to depict global supply quantities in table 4. The quadratic equations predicted modestly higher farm output from higher yields. Quadratic equations depicting accelerating yields are unrealistic as the time period is extended into the future. Whereas both linear and quadratic projections are of interest, the linear estimates are believed to best stand scrutiny.

Assuming no increase in area and linear projections, yield gains are predicted to raise vegetable oil (oilseed) output by 39 percent and meat output by only 13 percent above the 2000 level by 2025. By year 2050 and again based on linear estimates, vegetable oil output is projected to be up 79 percent and milk and egg output up 21 percent from the 2000 level. Yield gains in livestock and livestock products will fall short of demand, and livestock and poultry numbers will need to expand.

Based on the medium UN population projection, the global demand for farm output is projected to be 43 percent over the 2000 demand in 2025 but supply from increasing yields alone will increase by only 28 percent (linear model). If each percentage point of excess demand, 15 percent, raises commodity prices by 2 percent, then the real price of farm output will be 30 percent over the 2000 level.

By year 2050, demand is predicted to be 79 percent above the 2000 level whereas yields are projected to be up only 57 percent (linear model). If each of the 22 percentage points of excess demand raises commodity prices by 2 percent, then the real price of farm output would be up 44 percent by 2050 over the 2000 level. In a developed country such as the United States, farm ingredients may constitute only one-fifth of food cost and thus food cost will be up 9 percent.

Other assumptions give different outcomes. Of note is that farm product demand and supply advances from yields alone are expected to approximately balance by 2050 based on results from the quadratic yield functions. Such an outcome implies that additional crop area and higher real food prices may not be necessary but even no rise in real food prices stands in sharp contrast to the secular fall in food prices since 1960.

Table 4. Global food supply by food group and total predicted, percent of year 2000

Food group	Share of diet 2001-03	Year								
		1961		1975		2000	2025		2050	
		Linear	Quadratic	Linear	Quadratic		Linear	Quadratic	Linear	Quadratic
Cereals	0.496	45	52	65	78	100	135	155	171	187
Meat	0.108	80	82	87	88	100	113	115	126	126
Veg. oils	0.102	38	45	61	57	100	139	170	179	267
Sugar crops	0.092	64	66	77	76	100	123	132	147	173
Milk, eggs	0.069	84	81	90	94	100	110	123	121	148
Fruits, veg.	0.057	58	57	73	74	100	127	121	154	138
Roots, tuber	0.055	77	75	85	87	100	115	104	129	99
Pulses	0.021	74	74	83	83	100	117	116	133	132
Total	1.000	56	60	72	78	100	128	143	157	176

Source: FAO (2008); predictions from equations in annex tables 2 and 3

Conclusions

The foregoing analysis points to stable to rising real cost of food in future decades. This trend is a major departure from the historic trend of falling real food prices. Other observers see a similar pattern. The International Food Policy Research Institute (von Braun 2007, p. 8) projected that international food prices will rise by 26 percent for maize and 18 percent for oilseeds by 2020 over prices in 2005/2006. With greater expansion in biofuel production, the Institute projected price increases respectively of 72 percent and 44 percent over the period.

Of agricultural resources, land and associated climate, water, and location are the most fixed in supply. Opportunities exist to add to cropland in Brazil and Russia, add irrigation in Africa, and more efficiently use irrigation water, for example, but in the long term considered in this study such developments will be offset by cropland removed from production by urban and industrial development, soil degradation, and the like. These estimates of food supply-demand balance are based on constant real prices at the 2001 to 2003 level. Cropland can be expanded through higher real farm and food prices, but higher yields rather than added cropland offer the most attractive opportunities for farm output expansion at low cost to consumers and the environment.

Global farm output may need to nearly double in the first half of the 21st century to fill demand without increasing real prices. The prospect of stable or rising real food prices at the farm level is neither the basis for panic nor complacency. Complacency currently is evident. Alston and Pardey (2008) show that the slowing rate of increase in yields and multi-factor productivity in American agriculture corresponds with a slowing rate of increase in public and in private agricultural research and development spending from 1953 to 2004. The world will not have the luxury of turning down promising technologies such as genetically modified organisms (GMOs) if is to keep real food costs from rising.

The situation is dire in many developing regions of the world but most notably in Africa. Consumers in poor regions such as Africa spend a high proportion of their income on food, so a food price spike as in 2007-2008 constitutes a major hardship (see annex table 4). Still, a meager 0.5 percent of Africa's agricultural gross domestic product is spent on research to improve the productivity of farming, a small fraction of what developed countries spend to improve their agriculture.

This analysis indicates that part of the farm commodity price rise in 2007-2008 was the product of a tighter food supply-demand balance arising from long-term systemic factors that will not go away. Productive new cropland, irrigation, and genetically modified varieties will be hard pressed indeed to match the massive historic gains from hybrid varieties, irrigation, synthetic fertilizers, and mechanization. World agriculture will likely operate on a new plateau of generally high real prices in the future, but the basic market structure will remain unchanged. Buyers will bid up land prices until real returns average near historic levels—near 4 percent on investment. Variations in prices around the new plateau will continue unabated and will emanate from some new sources—such as fluctuating oil prices. Nominal returns will exceed real returns by the inflation rate; capital gains will compensate landowners for inflation.

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Annex

This annex shows the statistical model and empirical estimates used to quantify supply shifts reported in the text. Global annual yield data are from 1961 (the first available year) to 2007 (latest available year) and are from FAO (2008). U.S. price and selected other data are from the U.S. Department of Agriculture (USDA 2008). Statistical results are presented first for four major U.S. crops followed by results for world crop groups and livestock groups. The world estimates form the basis for the supply projections in the text.

Statistical model

The initial model for estimating yield in this study is:

(a) $Y^*_t = a + bP^*_t + cA_t + dT + e_t$

(b) $Y_t - Y_{t-1} = g\,(Y^*_t - Y_{t-1})$

(c) $Y_t = ag + bgP^*_t + cgA_t + dgT + (1-g)Y_{t-1} + ge_t$.

In annex equation (a), actual yield Y^*_t of a crop in year t is assumed to be a function of expected price P^*_t, area in the crop A_t, a technology variable T, and an error term e_t, the latter assumed to be normally and independently distributed with a constant variance. A structural supply model ideally would include separate exogenous variables for education, management, research, information systems, and infrastructure shifting the supply curve over time. Those variables are not available for the commodities included in the supply analysis. Because the collective trajectory of these variables changes only gradually over time, they are represented by the proxy variable T in the statistical model.[3]

Long-term true coefficients of the three independent variables P, A, and T are respectively b, c, and d. Short-term coefficients are ag, bg, and cg in equation (c). Variable A is included to reflect the depressing impact on Y of expanding production on the extensive margin to inferior land. Adjustment to the equilibrium or desired yield Y^*_t is not instantaneous: actual adjustment as depicted by the left side of equation (b) is some proportion g of the desired adjustment expressed by the term in the right side parenthesis. Substituting annex equation (a) into equation (b) gives equation (c). Equation (c) is empirically estimated assuming the commodity price expectation variable $P^*_t = 0.50\,P_{t-1} + 0.33\,P_{t-2} + 0.17\,P_{t-3}$. All prices are adjusted to "real" terms by the GDP deflator.

The above model is assumed to be recursive, with supply price and yield not simultaneously determined with demand. Rather, supply quantity is predetermined by past price and other variables.

The secular decline in real commodity prices is closely correlated with and indeed is caused by the rising productivity of resources used to produce crops. Nonstationarity and multicollinearity were evident in the variables for the U.S. in equation (c). The problem of autocorrelated residuals likely to characterize equation (c) was addressed with a first order autoregressive scheme. The first order autogression coefficient was significantly different from zero only for U.S. cotton in the equation (c) model. In that equation, the coefficient of time T was highly significant but the coefficients of the area and expected price variables were not statistically significant. In another approach to deal

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[3] Technology T is represented by the time variable, the year less 1900. That formulation (1961=61, 1962=62, etc.) is used throughout because statistical results are not invariant to the coding. In a double log equation, a time variable with 1.0 as the origin allows more curvature than with 1961 as the origin. The number 61 as the origin is an arbitrary compromise.

with nonstationarity, equation (c) without variable T was estimated in first differences and the constant term was the coefficient of T. In each of these attempts, the coefficient of A was positive or insignificant and the coefficient of price was negative or insignificant.

Empirical results indicate that the time trend (expressing a regular pattern of the influence on yields from changing technology and the like over time) has dominated yields. That domination has fully overshadowed the impact of prices and area on yields. Thus empirical estimation of structural equation (c) met with limited success. The insignificant and/or of the wrong (negative) sign on the price coefficient incorrectly implied that higher prices exert no or negative influence on yields. The insignificant and/or wrong (positive) sign on the area incorrectly implied that extending area in a crop exerts no or positive influence on yields. Refinements including expectation and adjustment models, first differences, and autoregressive least squares did not improve results for U.S. commodity supply and therefore were not attempted for the global supply equations.

Of particular interest was the trajectory of global supply shifts over time measured by various forms of variable T. Unfortunately, model refinements such as first differences were not well suited to modeling the yield trend with alternative mathematical specifications of T: as a quadratic function (T and T-square) or segmented to allow a different time trend by decade. Other specifications included a semi-logarithm (the dependent variable only in logs) function, double logarithm function, and a logarithm-inverse (dependent variable in logs, time as inverse 1/T). These specifications and a linear specification permitted commodity yield to change at a constant, increasing, or decreasing rate over time. For the most part, the linear or quadratic equations with yield a function of time-only proved superior to other specifications. Quadratic equations accounted for a high proportion of variance in yields from 1961 to 2007 in several instances but such equations (predicting that yields in the future would decline or increase at an increasing rate) were judged to be less satisfactory than linear equations when projecting to year 2050.

In short, the various specifications of (c) containing area, price, first differences, autoregressive schemes, and expectation and adjustment models did not improve predictions of commodity yield. Given the need for a predictive rather than a structural model for this analysis and given that structural refinements tended to interfere with alternative specifications of the trend variable, this analysis relies on ordinary least squares with various specifications of a trend variable to predict the movement of commodity supply over time. This simplified analysis resulted in higher projected estimates of supply quantity for 2025 and 2050 than did the more complex but unacceptable specifications of supply.

Empirical results

The supply-demand balance for food is achieved in a global market, hence it is not possible to analyze the food balance for the United States in isolation. But it is of interest to observe how yield trends in the U.S. compare with global yield trends. Statistical equations for yields of major crops in the U.S. using annual data for the 1961 to 2007 period and the modified statistical model of equation (c) are shown in annex table 1.

Annex table 1. Statistical equations of U.S. crop yields using annual data, 1961 to 2007

Dependent variable and equation	Coefficients			Adjusted R-square	Durbin-Watson
	Intercept	Time T[a]	Time square		
Corn yield (hg/ha)[b]					
1.1 Linear	-30,223	1,153.848 (66.025) [17.48]		0.869	2.502
1.2 Log-log	4.558	1.475 (0.0855) [17.25]		0.866	2.436
Soybean yield (hg/ha)					
2.1 Linear	-192.804	255.877 (18.638) [13.73]		0.803	2.089
2.2 Log yield	8.942	0.0120 (0.000842) [14.26]		0.815	2.149
Wheat yield (hg/ha)					
3.1 Linear	2,759.504	243.024 (18.234) [13.33]		0.793	1.287
3.2 Quadratic	-22,035	849.186 (239.240) [3.55]	-3.608 (1.420) [-2.54]	0.816	1.466
Cotton yield (hg/ha)					
4.1 Linear	507.897	198.261 (22.048) [8.99]		0.635	1.343
4.2 Quadratic	37,337	-702.102 (278.262) [-2.52]	5.359 (1.652) [3.24]	0.698	1.647

Source: FAOSTAT, 2008

[a] Time variable is current year minus 1900, i.e. 1961=61, 1962=62, etc. Standard errors are in parenthesis; t values are in brackets.

[b] Hg/ha is hectograms per hectare.

Statistical equation 1.1 indicates that a linear time variable accounts for a large share of the variation in U.S. corn yield over time, a result similar to that in annex table 2 for global yield. The highly significant coefficient of time (t-value 17.48) in equation 1.1 indicates that cereal yield in the nation increased on average by 1,154 hectograms per hectare per year—nearly two bushels per acre (corn equivalent) over the 1961-2007 period. Equation 1.2 estimated with yield and time in natural logarithms allowed yield to increase at a decreasing rate over time, but its statistical properties indicated no improvement over the linear model. Other specifications discussed earlier in the annex also did not improve on equation 1.1.

Linear equation 2.1 estimating U.S. soybean yield per hectare accounts for 80 percent of the variation in yield over the 1961-2007 period. The estimated annual yield gain of 256 hectograms per hectare is 23 pounds per acre per year. The semi-log equation 2.2 (with the dependent variable in natural logarithms and time in original values) allows yields to increase at a constant percentage rate and was a modest improvement over linear equation 2.1. (See the text for a plot of yields and comparison among percentage rates of growth predicted by the various annex table equations.)

Linear equation 3.1 estimates that wheat yields increased at near the rate of soybean yields over time. The quadratic equation 3.2 improves somewhat over the statistical properties of linear equation 3.1. The quadratic equation provides evidence that annual wheat yield increments have been diminishing over time.

Cotton is not a food crop, but lagging cotton yields could require more area to be planted to cotton rather than food crops. The quadratic equation 4.2 displays some statistical improvement over linear equation 4.1 in accounting for variation in cotton yields. The negative coefficient on the time variable and positive coefficient on time-square allows for yields that increased at an increasing rate in recent years. Because the acceleration in recent yields appears to be due to weather and other transitory elements, the linear equation 4.1 may be a more reliable predictor of future U.S. cotton yields than quadratic equation 4.2.

Other specifications including prices, expectation and adjustment models, and alternative functional forms did not improve on results in annex table 1.

We now turn to global yields to measure supply shifts for crops. Annex table 2 shows linear and quadratic equations, judged to be the preferred specifications based on statistical properties, for estimating yields of the six major world crop groups with annual data from 1961 to 2007.

The yield trend for cereals (corn, barley, grain sorghum, rice, wheat, etc.) is of special importance because the crop group accounts for from half to two-thirds of world food consumption, the latter proportion accounting for grains fed to livestock. Linear equation 5.1 accounts for 99 percent of the variation in global cereal yield from 1961 to 2007, based on the adjusted R-square. The highly significant statistical coefficient of time T in equation 5.1 indicates that on average the yield of cereals advanced by 43.6 kilograms/hectare per year. (The graphs of predicted linear trend yields from equations in annex table 2 and actual yields are shown in the text.) Quadratic global cereal yield equation 5.2 features statistically significant coefficients of the linear and squared time variables along with a slightly improved adjusted R-square and Durbin-Watson test. Especially of note is the negative coefficient of T-square in equation 5.2, predicting that global cereal yield is increasing at a decreasing rate.

Annex table 2. Statistical equations of global crop yields using annual data, 1961 to 2007

Dependent variable and equation	Coefficients[a]			Adjusted R-square	Durbin-Watson
	Intercept	Time T	Time-square		
Cereal yield (tons/ha)					
5.1 Linear	-1.274	0.0436 (0.000642) [67.89]		0.990	1.776
5.2 Quadratic	-1.983	0.0609 (0.00863) [7.06]	-0.000103 (0.0000512) [-2.01]	0.991	1.937
Oil crops (tons/ha)					
6.1 Linear	-0.285	0.00778 (0.000214) [36.42]		0.967	0.282
6.2 Quadratic	0.470	-0.0107 (0.00110) [-9.68]	0.000110 (0.00000656) [16.77]	0.995	1.958
Sugar crops (tons/ha)					
7.1 Linear	4.022	0.544 (0.0150) [36.38]		0.966	0.760
7.2 Quadratic	30.342	-0.0993 (0.186) [-0.53]	0.00383 (0.00111) [3.46]	0.973	0.947
Melons and vegetables(tons/ha)					
8.1 Linear	-1.159	0.178 (0.00210) [83.48]		0.993	1.193
8.2 Quadratic	-5.446	0.280 (0.0248) [11.27]	-0.000624 (0.000148) [-4.23]	0.995	1.655
Roots and tubers (tons/ha)					
9.1 Linear	5.524	0.0780 (0.00441) [17.69]		0.872	1.065
9.2 Quadratic	-1.327	0.245 (0.0565) [4.34]	-0.000997 (0.000336) [-2.97]	0.891	1.280
Pulses (tons/ha)					
10.1 Linear	0.278	0.00550 (0.000310) [[17.72]		0.872	1.081
10.2 Quadratic	0.265	0.00583 (0.00436) [1.34]	-0.00000198 (0.0000259) [-0.08]	0.869	1.081

Source: Data from FAOSTAT (2008)

[a]Time variable is year less 1900, i.e. 1961=61, 1962=62, etc. Standard errors are in parenthesis; t ratios in brackets. All coefficients on T and T-square are statistically significant at the 1 percent level or better except for those in equation 10.2, and on T in equation 7.2. The coefficient on T-square was significant at the 5 percent level in equation in equation 5.2.

The linear equation 6.1 for oil crops (soybeans, rapeseed, etc.) in annex table 2 indicates that yields are increasing on average by 7.78 kilograms/hectare per year. The oil crop yield trend is better depicted by the quadratic equation 6.2 than by the linear equation 6.1 based on the former's highly significant coefficients, higher adjusted R-square, and less evidence of autocorrelated residuals based on the Durbin-Watson statistic. Of note is that oilcrops are the only ones displaying evidence that historic yields are increasing at an increasing rate.

Linear equation 7.1 indicates that sugar crop (beet and cane) yields increased on average by 0.544 metric tons/hectare annually from 1961 to 2007. The quadratic equation 7.2 of global sugar crop yield as a function of a time variables T and T-square displays a slightly higher adjusted R-square than the linear equation but the coefficient of T in 7.2 is not statistically significant.

On average, fruits and vegetables comprise less than 6 percent of diets around the world and are represented by melon and vegetable yield equations in annex table 2. The time variable accounted for a high proportion of the variation in melon and vegetable yields from 1961 to 2007 as evident from linear equation 8.1. The highly significant coefficient of T predicted that yields increased on average 0.178 metric tons per year. The adjusted R-square and Durbin-Watson statistic were slightly improved by the quadratic equation 8.2 but, notably, the negative coefficient on the time-square variable suggests that incremental yield gains have declined over time.

The time variable accounts for relatively less of the variation in root and tuber yields (equation 9.1) and pulse (bean, food legume) yields (equation 10.1) than in yields of other crop groups in annex table 2. Roots and tubers (potatoes, cassava, yams, etc.) account for 5 percent of diets and pulses for 2 percent of diets around the world but are especially of importance to developing countries. It is of concern that yields are increasing slowly, 0.078 metric tons per year for roots and tubers and only 0.0055 metric tons per year for pulses based on linear equation 9.1 and 10.1 respectively. Furthermore, annual yield increments of the two crop groups are getting smaller as evidenced by the negative coefficients of the time-square variable in quadratic equations 9.2 and 10.2.

The concept of area and yield in crop production has counterparts in animals and yield per animal in livestock production. But similarities go only so far. Crop output depends heavily on yield of crops because global expansion at the extensive margin of land area is severely constrained by natural resource and environmental limits.

Most food comes directly from crops or from livestock that are fed crops. As such livestock are less of a constraint than crops in providing food in the future. With time for biological processes to work, livestock can be expanded almost without limit if crop feed is available. Still, ability to produce more food per animal and hence improved technology and management have played a key role in reducing the real cost of dairy and poultry products, for example.

Annex table 3. Statistical equations of global livestock yields using annual data, 1961 to 2007

Dependent variable and equation	Coefficients[a]				Adjusted R-square	Durbin-Watson
	Intercept	Time T	Time square	Animal no.		
Pig meat (hg/pig)						
11.1 Linear	390.500	3.879 (0.1405) [27.60]			0.943	0.529
11.2 Quadratic	353.753	4.777 (1.970) [2.43]	-0.00535 0.0117 [-0.46]		0.942	0.535
Cattle meat (tons/head)						
12.1 Linear	1.161	0.00778 (0.00911) [12.04]			0.758	0.097
12.2 Quadratic	-1.450	0.0729 (0.00447) [16.30]	-0.000380 (0.0000266) [-14.30]		0.956	0.488
Chicken meat yield (hg/chicken)						
13.1 Linear	6,879	71.195 (1.735) [41.04]			0.973	0.771
13.2 Quadratic	12,134	-57.284 (14.730) [-3.89]	0.765 (0.0874) [8.74]		0.990	2.066
Egg yield (kg/hen)						
14.1 Linear	2.503	0.0790 (0.00273) [28.98]			0.948	0.252
14.2 Lin.+	0.6320	0.1236 (0.00909) [13.60]		-.000539[a] (0.00011) [-5.06]	0.966	0.307
Milk yield (hg/cow)						
15.1 Linear	8,925	7.843 (3.836) [2.04]			0.065	0.232
15.2 Lin.+	8,289	148.931 (16.700) [8.92]		-.0000220[a] (0.00000258) [-8.54]	0.640	0.441

Source: FAOSTAT, 2008

[a] Time variable is year less 1900, i.e. 1961=61, 1962=62, etc. Animal numbers in 10.2 are in million hens and in 11.2 are in number of cows. Numbers in parenthesis are standard errors and in brackets are t-ratios of the coefficient to the standard error.

Livestock yield per animal is one measure, albeit imperfect, of livestock productivity. The livestock yield model is that of annex equation (c) except that yield is output per animal and "area" is number of animals. Statistical results of the simplified model, presented in annex table 3, are on the whole less satisfactory than crop results in annex table 2 because livestock data are less reliable. As shown in graphs in the text, livestock data in several cases show erratic movements and periodic trends that are difficult to explain except as shortcomings of the data.

Output per pig has been rising on average by nearly four hectograms (hg) or 0.4 kilograms annually based on annex equation 11.1. Quadratic equation 11.2 with yield a function of time and time-square offered little advantage over linear equation 11.1. The negative coefficient implies diminishing yield improvement over the 1961-2007 study period, but the statistically insignificant time-square coefficient indicates the trend was essentially linear.

Statistical parameters of quadratic equation 12.2 for cattle yield are superior to those of linear equation 12.1. Beef output per animal increased on average about 8 kilograms per year from 1961 to 2007, but the increments have been getting smaller over time according to equation 12.2. Yield gains per chicken also are slowing based on statistical results in equation 13.2.

Statistical results of equations depicting egg and dairy yield are improved by including number of animals as independent variables. Improvements in technology and management that have increased egg yield per hen (equation 14) and milk per cow (equation 15) also have restrained chicken and cow numbers—given the limited demand for eggs and dairy products.

The annual percentage rates of growth and total supply of farm output derived from equations in annex tables 2 and 3 are shown in the text for selected within-sample and projected future years.

Annex table 4. Calculation of annual per capita increase in global food demand

Country Classification	Population	Income per capita		World income share	Income elasticity of demand	Per capita food increase from income	
	(Million)	*Total ($)*	*Increase (% incr/yr)*			*(%/yr.)* Unweighted	Weighted
		1994					
Low income	3,185	380	3.0	0.048	0.6	1.80	0.0869
Middle income	1,570	2,520	1.8	0.158	0.3	0.54	0.0853
High income	850	23,420	1.2	0.794	0.1	0.10	0.0953
				1.000			0.2675
		2050					
Low income	6,206	1,989	2.1	0.189	0.5	1.05	0.1985
Middle income	2,075	6,843	1.3	0.217	0.2	0.26	0.0564
High income	850	45,677	0.8	0.594	0.05	0.040	0.0238
				1.000			0.2787

Source: Tweeten (2007, annex table 9.1); see Mellor (1996) for income elasticities.