# Biofuels, Food Security, and Ecological Intensification of Agricultural Systems

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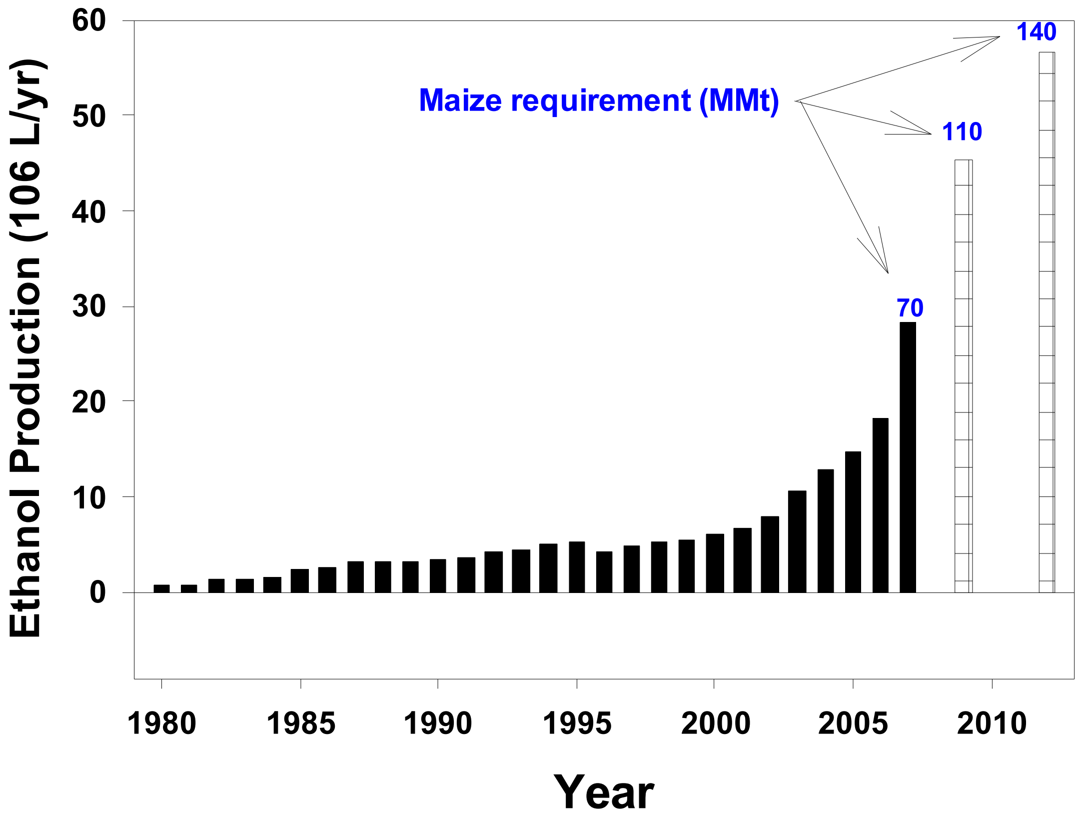
## Introduction

Agriculture is undergoing a biofuel revolution that no one predicted even two years ago. Rapid economic growth in the world's most populous countries, political instability in regions with greatest petroleum reserves, and a massive hurricane that damaged much of the USA petroleum producing and refining infrastructure combined to cause an abrupt rise in fossil fuel energy prices. In response, the USA Congress passed the 2005 Energy Security Act that mandated a two-fold increase in annual biofuel production capacity to about 30 billion L by 2012 and provided a generous federal excise tax incentive to the ethanol industry. At the local level states and rural communities are also providing incentives to attract investment in new biofuel plants—especially in the USA Corn Belt. In addition to these incentives, the high price of petroleum-derived gasoline makes ethanol production from maize grain (hereafter called maize-ethanol) highly profitable, which also helped to attract a large amount of new investment capital to support a rapid growth of biofuel production capacity. As a result, USA ethanol production capacity greatly exceeds projections and will reach more than 46 billion L per year by early 2009, and is likely to reach 58 billion L by 2012 (Fig. 1).

**Figure 1.** USA ethanol production and the maize grain required to produce it. Values for 2009 are based on existing capacity and capacity under construction. Values for 2012 assume federal ethanol subsidies continue and petroleum prices > US$50/bbl.



High petroleum prices and favorable government policies are also encouraging the expansion of biofuel in other countries with adequate land and water resources to support this growth. Significant examples are ethanol from sugarcane in Brazil and biodiesel from palm oil in Indonesia and Malaysia. In each of these cases, biofuel production utilizes feedstock crops that can be used for human food. As a result, commodity prices for maize, sugarcane, and vegetable oil have risen dramatically. Farmers have responded to high prices by increasing area planted to biofuel crops. In the USA where there is little scope for increasing total crop area, there has been a dramatic shift out of soybean and cotton to maize. The recent June 29, 2007 USDA crop report estimates that 2007 planted maize area increased by 19% (+5.9 Mha) compared to 2006, while soybean and cotton area decreased by 15% (4.6 Mha) and 28% (1.71 Mha), respectively (http://www.nass.usda.gov/index.asp). Sugarcane area in Brasil and oil palm area in Indonesia and Malaysia are also expected to rise substantially.

These responses mark the first phase of a biofuel revolution that will likely continue into the foreseeable future if petroleum prices remain high or go even higher. The most notable feature of this revolution is that the price of food crops that can also be used to produce biofuel will be determined by their energy conversion content rather than by their value as a human food or livestock feed (CAST, 2006). This marked change in the valuation of agriculture raises a number of critical issues concerning the impact on global food security—especially for the urban and rural poor in low-income countries—and the ripple effects on environmental quality, protection of natural resources, and climate change. These issues will be considered in the following sections, followed by a discussion about the need to refocus national and international agricultural research portfolios to ensure that the biofuel revolution does not compromise food security or environmental services.

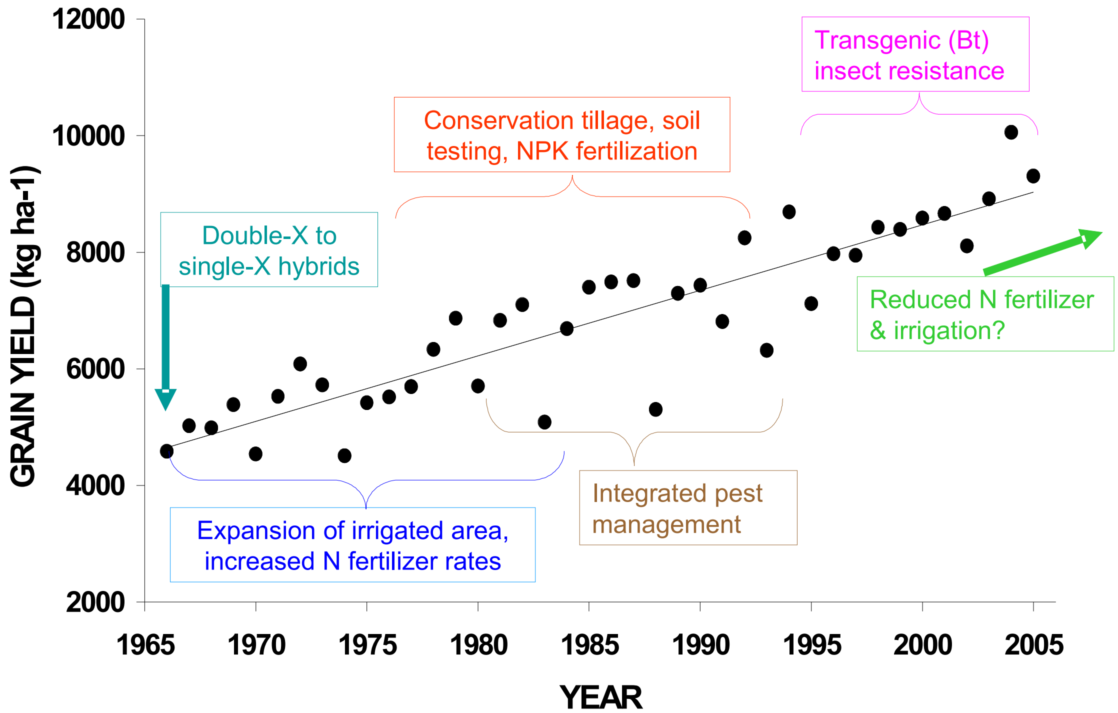
**Food versus Fuel**

There is considerable debate about the potential to meet ambitious goals for biofuel production without causing an excessive rise in consumer food prices—both in the USA and globally. These concerns are heightened by the fact that the USA accounts for 40% of global maize production and nearly 60% of global maize exports. Likewise, Indonesia and Malaysia produce 88% of global palm oil, which is the lowest cost vegetable oil on global markets. Despite these concerns, crop commodity groups and the seed industry maintain an optimistic view that farmers can easily meet this challenge. For example, the USA National Corn Growers Association (NCGA) believes it will be possible to produce sufficient maize to meet demand for annual ethanol production of 58 billion L by 2015 while also meeting non-ethanol maize demand in both the USA and export markets (NCGA, 2006). The NCGA support their projection by assuming a large expansion of maize area and a doubling in the rate of maize yield growth above the 40-year historical trend line. Indeed, USA maize area increased by nearly 6.0 Mha in the 2007 planting season, but it will be difficult for further maize area increases without driving up prices of other commodities such as soybean and cotton or converting marginal land in the Conservation Reserve Program (CRP) to maize production. In fact, soybean prices have risen markedly in recent months making it unlikely there will be a further significant shift from soybean to maize.

In making their optimistic forecast of future trends in maize yields, the NCGA relies on projections from seed industry executives. For example, Dr. Robert Fraley, Chief Technology Officer for Monsanto, suggests that maize yield growth is on an accelerated track due to the impact of biotechnology and molecular breeding on maize hybrid improvement, especially with regard to maintaining yields under drought conditions. He is cited by the NCGA as predicting the rate of yield gain will double or triple and that USA average maize yields will reach 16-19 t/ha within a generation (http://www.ncga.com/news/OurView/pdf/2006/FoodANDFuel.pdf), which would require a 2.3% exponential annual rate of gain in maize yields. At issue is whether these optimistic projections are reasonable and what it would take to achieve them.

In fact, the 40-year time trend for USA maize yields is markedly linear, not exponential, and has proceeded at a steady annual rate of 112 kg per $ha^{-1}$ since the 1960s (Fig. 2). This rate of increase represents only a 1.2% relative rate of gain when compared to the 2005 trend-line yield of 9.2 metric tons $ha^{-1}$. And, because yield gains are increasing in a linear fashion, the relative rate of gain decreases over time as average yields rise. Hence, Fraley's prediction of a 2.3% exponential rate of increase would require both an abrupt jump in the rate of yield gain and a steady acceleration of yield growth over time.

**Figure 2.** USA maize yield trends from 1966-2005 and the technological innovations that contributed to this yield advance. Rate of gain is 112 kg ha-1 yr-1 ($R^2$ = 0.80). Modified from CAST, 2006.




A powerful set of scientific and technological innovations underpin the linear rate of gain in USA maize yields since the mid-1960s (Fig. 2). New breeding methods, expansion of irrigated area, soil testing and balanced fertilization—including both macro- and micro-nutrients, conservation tillage, and integrated pest management were the driving forces of innovation in the first thirty years of this time series. Insect resistant "*Bt*" maize, a transgenic crop variety produced by genetic engineering (often called a GMO), was introduced in the mid-1990s. However, despite investment of hundreds of millions of dollars in genomics and crop genetic engineering by both the public and private sectors since then, biotechnology has had little additional impact on maize hybrids. Moreover, some scientists argue that it is unlikely genetic engineering will have substantial future impact on complex traits such as yield potential or drought resistance based on the premise that evolution has already optimized such traits and that conventional breeding can access these traits in existing crop germplasm (Denison et al., 2003).

Although commodity groups and executives of large seed companies like Monsanto make claims that maize yield growth is accelerating, there is no evidence published in peer reviewed scientific journals to substantiate these claims and the reasons for such acceleration. Equally disturbing is the fact that these optimistic projections have a strong influence on setting research priorities of the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE), as well as funding priorities of the World Bank and the CGIAR International Agricultural Research Centers like CIMMYT. For example, while the USDA and DOE are increasing research funding substantially for genomics and chemical engineering to improve conversion of cellulosic biomass to ethanol, there is no research funding to accelerate the rate of gain in crop yields and to do so in an ecologically sustainable manner. Without an acceleration in yield growth rate, it will be difficult to achieve annual USA ethanol production of 58 billion L by 2012 (Fig. 1) without a large increase in maize prices and the associated impact on food prices more generally—especially for meat and livestock products. Despite the optimism of policy makers and seed industry executives, it is more likely that crop yields will remain on their current linear trajectory over the next 10 years without a substantial increase in research funding tightly focused on identifying factors limiting crop yields and innovative crop and soil management practices to overcome them using environmentally sustainable methods.

Although a transition to ethanol production from cellulosic biomass crops not used for food is a promising option to reduce the intensity of food versus fuel competition, profitable technologies for large-scale cellulosic biomass production, harvesting, transport, storage, and conversion to ethanol are at least 7-10 years away from commercialization on a large scale. In the meantime, global biofuel production capacity from food crops will build out rapidly. Hence, a key issue is whether crop productivity can grow fast enough to meet global demand for food, feed, and fuel during this build-out phase without negative environmental impact.

**Environmental Sustainability of Biofuel Systems**

The primary environmental concerns about the rapid global growth of biofuel production include: (i) pressure to expand crop area into marginal land or native ecosystems such as rainforests and wetlands, (ii) the net impact on greenhouse gas emissions (GHG), and (iii) the low energy efficiency of some biofuel systems, and in the case of maize-ethanol, the assertion that it requires greater energy input than energy output. If these concerns cannot be addressed effectively, public support for the biofuel industry is likely to decrease markedly and favorable government policies in support of expanding the biofuel industry could be eliminated.

*Expansion of crop production*

The key to avoiding pressure on land resources is to accelerate crop yield growth rate and to focus the area expansion of biofuel crops like maize, soybean, and sugarcane in regions that have adequate land reserves with suitable soils and climate to support such expansion without negative environmental impact. In one possible scenario, the USA would focus on maize production at the expense of soybean area, which would protect against conversion of marginal CRP land, while Brasil and Argentina would make up the reduction in soybean output by expanding their soybean production area. This option recognizes the fact that current USA average maize yields are about 3-fold greater than average maize yields in Brasil and 26% greater than average maize yields in Argentina (Table 1). In contrast, soybean yields are more comparable. It is also notable that the amount of maize required for anticipated USA ethanol production in 2012 (140 MMt, Fig 1) is 2.5 times larger than the current total combined maize production of Brasil and Argentina.

**Table 1.** Maize and soybean yield and total production in Argentina, Brasil, the USA and world in 1966 and 2005, and the rate of yield gain during this period.

| | 1966 | | 2005 | | | |
|---|---|---|---|---|---|---|
| | Maize | Soybean | Maize | Soybean | Maize | Soybean |
| | Yield (kg $ha^{-1}$) | | | | % increase/(rate of gain)¶ | |
| Argentina | 2150 | 1160 | 7359 | 2729 | 242/(128) | 135/(52) |
| Brasil | 1307 | 1213 | 3040 | 2230 | 133/(43) | 84/(25) |
| USA | 4589 | 1709 | 9287 | 2839 | 102/(112) | 66/(28) |
| World | 2210 | 1372 | 4929 | 2300 | 123/(68) | 68/(23) |
| | Total Production (MMt) | | | | % increase | |
| Argentina | 7.04 | 0.018 | 20.45 | 38.30 | 190 | 212700 |
| Brasil | 11.37 | 0.595 | 35.11 | 51.18 | 209 | 8500 |
| USA | 105.86 | 25.270 | 282.31 | 85.04 | 167 | 237 |
| World | 245.61 | 36.418 | 703.41 | 214.47 | 186 | 489 |

¶Rate of yield gain, 1966 to 2005, in kg $ha^{-1}$ $yr^{-1}$.

Such a strategy would require increased reliance on continuous maize systems in the USA, which would be prone to disease and insect problems and would require much higher rates of nitrogen (N) fertilizer to sustain yields. Even with higher N rates, there is a yield penalty of about 600 kg/ha in continuous maize compared to the traditional annual rotation of maize following soybean, which would decrease average USA maize yields. And while Brasil is blessed with a large reserve of uncultivated land suitable for soybean production, large-scale expansion would come at the expense of native rainforest with associated concerns about deforestation in the Amazon basin and the negative impact on biodiversity and climate change (Soares-Filho et al., 2006; Zhang et al., 2001). Effective policies are required to ensure adequate native forest buffer zones along rivers and tributaries to intercept nutrient-rich agricultural runoff, as well as conservation policies to protect large tracts of native rainforest as biodiversity reserves. Another concern is that the variable costs of Brasil soybean production are very high compared to the USA and Argentina due to the acid-infertile soils and tropical climate in areas where Brasilian soybean expansion is occurring, which require large inputs of fertilizer, lime, and pesticides.

*Net impact on GHG emissions and energy efficiency*

There is a large body of research that supports the view that the net effects of replacing petroleum-derived gasoline or diesel fuel with biofuel results in reduction of GHG emissions and a net energy surplus based on “farm to fuel” life-cycle assessment (Farrell et al. 2006; Hill et al., 2006). A minority of researchers conclude otherwise (Patzek and Pimentel, 2005; Patzak, 2004). Scientists who report a net negative energy balance, however, utilize data on efficiencies and energy input values for crop production and ethanol conversion that are outdated. Likewise, in the case of maize-ethanol, these scientists also set the boundaries of the life-cycle assessment to exclude an energy credit for use of distiller’s grains co-product as a replacement for corn and urea in beef cattle rations. Most industrial ecologists would disagree with this exclusion because there has been little increase in USA cattle numbers despite a large increase in ethanol production so that an energy credit for replacement of corn and urea in cattle feed is justified.

On average, energy inputs for maize production account for about 30% of total energy use in the life-cycle production of maize-ethanol. The energy required to produce nitrogen fertilizer represents about 50% of total energy use in maize production. Therefore, progressive maize cropping systems that produce higher than average yields with management practices that increase nitrogen fertilizer efficiency contribute to greater total ethanol yield per unit land area and higher ethanol life-cycle energy efficiency. Of the 70% of total life-cycle energy used in the ethanol plant, about 70% is required for grain processing, fermentation, and distillation while the remaining 30% of ethanol plant energy is used to dry the distiller's grains (DDGS) co-product so that it can be more easily transported and stored for use in livestock feeding operations. While most current ethanol plants produce DDGS, a growing number of ethanol facilities are being located within 80 km of cattle feedlots where distiller's grains can be used wet, which avoids the need for drying and reduces energy use by the ethanol plant.

Recent studies of the energy input requirements for both nitrogen fertilizer and ethanol plants indicate the energy costs for maize production and ethanol conversion are smaller than previously estimated (Liska et al., 2007). Moreover, average maize yields continue to increase (Fig. 2), such that previous life-cycle assessments are based on smaller maize yields than currently achieved by USA maize producers. Using updated values for energy inputs and yield in a life-cycle assessment of USA maize-ethanol systems gives larger estimates of net energy efficiency and GHG mitigation than in previous studies (Table 2). Compared to the earlier estimates of Farrell et al (2006), for example, the net energy ratio of an average USA maize-ethanol plant that produces DDGS increases from a 1.20 to 1.47 while ethanol yield increases by 5%, and GHG mitigation increases from 13% to 51%. If an ethanol plant produces wet distiller's grains, the energy efficiency and GHG mitigation increases to 1.80 and 60%, respectively.

**Table 2.** Life-cycle energy and greenhouse gas mitigation analyses of USA maize-ethanol systems based on "old" (Farrell et al. 2006) and updated values for energy input requirements, different co-product processing methods, and corn production systems.

| | Net Energy Ratio† | Ethanol Yield† | GHG reduction† |
|---|---|---|---|
| | MJ/L | L/ha | % |
| USA average, Farrell et al., 2006 | 1.20 | 3830 | 13 |
| USA average, BESS‡ model update, dry DDGS | 1.47 | 4040 | 51 |
| USA average, BESS‡ update, wet DDGS | 1.80 | 4040 | 60 |
| Nebraska irrigated corn, BESS‡ update, progressive crop management, wet DDGS | 2.36 | 5964 | 73 |

†Net energy ratio is the ratio of energy output to energy input, including an energy credit for use of distiller's grains co-product. Ethanol yield is based on 435 L/t conversion of grain to ethanol and average USA maize yield of 8.75 t/ha for Farrell et al. (2006) versus the 2005 trend line yield of 9.29 t/ha as estimated from Figure 2. GHG reduction is relative to combustion of petroleum-derived gasoline on an energy equivalent basis.
‡Based on life-cycle assessment performed by the Biofuel Energy Systems Simulator (Liska et al., 2007; available at www.bess.unl.edu).

Higher maize yields and input use efficiencies also result in greater net energy efficiency, ethanol yield and GHG mitigation. In our Carbon Sequestration Project, for example, we achieve average maize yields of 13.7 t/ha in a production-scale field of about 65 ha with an annual maize-soybean rotation under pivot irrigation (Verma et al., 2005). We use progressive nitrogen fertilizer management practices based on yield goal, soil organic matter content, residual soil nitrate based on a soil test to 1 m depth, and a nitrogen credit for the previous soybean crop (http://soilfertility.unl.edu/). Nitrogen in applied in three split applications with two-thirds applied before planting and two equal applications at V6 and V10 through the pivot irrigation system. In this system we measure nitrogen fertilizer efficiencies that are 60% greater than achieved by average USA maize farmers at yield levels 33% lower than we achieve (Arkebauer et al., 2004). In addition, we optimize irrigation efficiency using a low-pressure pivot irrigation system and irrigation timing and amount matched precisely to replace evapo-transpiration. Because about 75% of all maize in Nebraska is produced with irrigation and assuming that all Nebraska farmers who produce irrigated maize adopt the progressive management practices used in our Carbon Sequestration Project, there would be an additional large improvement in net energy efficiency, ethanol yield, and GHG mitigation compared to the updated USA average wet DDGS (Table 2). In fact, the ethanol yield of this progressive system would be comparable to that of Brasilian sugarcane ethanol.

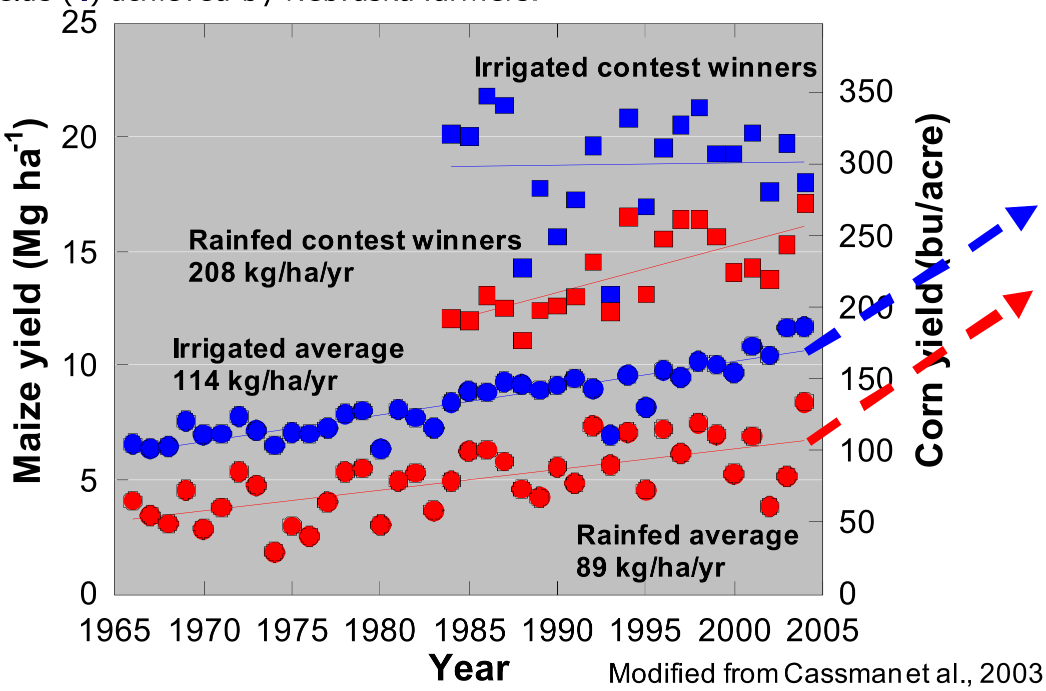
**Critical Role of Ecological Intensification**

Ecological intensification of crop production systems provides a path forward to help alleviate increasing pressures on global land and water resources to meet the abrupt rise in demand for crops that can be used for food, feed, and fuel. Ecological intensification is an approach that seeks to consistently produce crops near their genetic yield potential under irrigated conditions, and near their water-limited yield potential under rainfed conditions, while at the same time protecting environmental quality and conserving natural resources (Cassman, 1999). The characteristics and goals of an ecologically intensified cropping system include:

- Yields that consistently reach 85-90% of the genetic yield potential in irrigated systems, or the water-limited yield potential in rainfed systems;
- Nitrogen fertilizer uptake efficiency >70% of applied nitrogen;
- Soil and residue management practices that improve soil quality with regard to the physical, chemical, and biological properties that support plant growth;
- Use of integrated pest management to minimize use of pesticides;
- Contribution to a net reduction in greenhouse gases based on life-cycle analysis;
- In irrigated systems: 90-95% water use efficiency.

Yield potential is defined as the yield that can be achieved with an adapted hybrid or cultivar when all forms of growth-reducing abiotic and biotic stresses have been alleviated. Achieving yield potential requires perfect crop and soil management with regard to selection of the most appropriate hybrid or cultivar for the particular field and soil type, optimal planting date and plant population, adequate supply and balance of all essential nutrients, adequate moisture availability throughout crop growth (typically provided by irrigation), and elimination of yield loss from all insect pests, diseases, and weeds. Rainfed yield potential also has perfect crop and soil management except for moisture availability, which is determined by rainfall amount and distribution such that maximum attainable yield is typically limited by water deficit. For example, while the 2005 trend-line average irrigated maize yield obtained by Nebraska farmers was about 11.2 t/ha, contest-winning irrigated yields average about 20.0 t/ha (Fig. 3), which means that average yield are only 56% of the average genetic yield potential. There is also a large yield gap between average rainfed yields and rainfed yield potential as estimated by the trend-line contest-winning rainfed yields. A robust, well validated crop simulation model also provides a useful tool for estimating yield potential and water-limited rainfed yield potential (Yang et al., 2006).

**Figure 3.** Trends in Nebraska contest winning yields under irrigated (■) and rainfed conditions (■) from annual yield contests sanctioned by the National Corn Grower's Association, and trends in average irrigated (●) and rainfed yields (●) achieved by Nebraska farmers.




But it is impossible for all farmers to achieve perfect crop and soil management. It is also not cost-effective because crop response to inputs such as fertilizer or water follows a diminishing return function as yield approaches the yield potential ceiling. Therefore, the highest average yield that a population of farmers can achieve in a country or region is about 85% of the irrigated or rainfed yield potential. As average farm yields approach this 85% threshold, average farm yields stagnate as if they have hit a yield ceiling, which has already occurred for average rice yields in Japan and most of China, and for wheat in the Indian Punjab (Cassman, 1999; Cassman et al., 2003). Using the 85% rule, Nebraska irrigated maize has an unexploited yield gap of about 5.8 t/ha between current average yields (11.2 t/ha) and 85% of the average yield potential (≈20 t/ha) that could be closed by improved crop and soil management; the rainfed yield gap is also about the same size.

## Conclusions

Quite unexpectedly we have entered a new phase of agricultural history in which the long-term trend of declining real prices for the world's major crop commodities since the 1960s has been abruptly reversed because we are in a demand-driven market. The challenge is to meet this sudden increase in demand without destroying the remaining rainforests, wetlands, and grassland savannahs and while ensuring protection of environmental services. Although ecological intensification of agriculture provides a means to achieve these goals, there is little funding to support this kind of research. Instead, public-sector research investment at national and global levels has focused on measuring and understanding the environmental impact of agriculture without regard to crop productivity, and the private sector has emphasized productivity without little scientific regard for environmental impact. These trends must change, and change quickly with a substantial increase in research investment focused tightly on accelerating the rate of gain in crop yields, as indicated in Figure 3, and doing so in a manner that decreases the environmental footprint of agriculture. Note also that the yield potential ceiling of maize (Duvick and Cassman, 1998) and rice (Peng et al., 2000) have not increased in the past 30-40 years although breeders have improved stress resistance.

The agriculture sector is in the enviable position of being in a supply-driven market for the first time in many decades. In large part this new era has resulted from the convergence of energy and agriculture. Avoiding food shortages and excessive rises in consumer food prices, ensuring that food-crop biofuel feedstock production does not lead to severe environmental degradation, and verifying that biofuel systems deliver the expected benefits of GHG mitigation and replacement of petroleum-based transport fuels are critical to sustaining this new era without provoking negative public sentiment and unfavorable government policies that could abort this revolution before it takes off.

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