Comparison of Corn and Soybean Yields in the United States: Historical Trends and Future Prospects

D. B. Egli*

ABSTRACT

Developing successful strategies to ensure future increases in crop yield depends, in part, on a better understanding of the basis for past increases. To this end, I compared historical yield trends of two dissimilar crops—corn (*Zea mays* L.), a high yielding C_4 grass, and soybean [*Glycine max* (L.) Merr.], a moderate yielding C_3 legume—in high (Iowa, Illinois, Indiana) and low (Kentucky, Missouri, Tennessee) yield environments. Average state corn yield changed very little from 1866 to 1930, an era of low-input agriculture, but it increased rapidly from 1950 to 2005 in all states as the low-input system gave way to a high-input system that utilized commercial hybrids, manufactured N fertilizer, herbicides, and higher plant populations. Soybean yield, first available in 1924, increased steadily from the beginning until 2005. Corn yield increased faster than soybean yield in the early decades of the high-input era (mean growth rates of corn were 3.3 vs. 1.5% per year for soybean with a slight advantage for both crops in high yield states) in all six states, but for the rest of the era (up to 40 yr), corn and soybean yields grew at nearly the same rate (1.8% per year for corn, 1.4% per year for soybean with a slight advantage for the low-yield states). Thus, the efforts to improve the plant (plant breeding) and production environment (better management practices) had essentially the same affect on these two very dissimilar crops.

Crop yields have increased dramatically since the founding of the American Society of Agronomy (ASA) in 1907. Corn yields in the United States averaged only 1706 kg ha^{-1} (27 bu acre^{-1}) (USDA-NASS, 2006) when our society began, but they increased roughly fivefold in the next 98 yr to almost 9300 kg ha^{-1} (148 bu acre^{-1}) in 2005. Soybean was not a major crop in 1907 with most of the approximately 20,000 ha grown for forage production, not grain (Probst and Judd, 1973). Production statistics were first reported in 1924 (USDA-NASS, 2006) when the average yield was 739 kg ha^{-1} (11.0 bu acre^{-1}) compared with 2909 kg ha^{-1} (43 bu acre^{-1}) 81 yr later in 2005 (nearly a fourfold increase).

These large increases in yield were a general worldwide phenomenon, occurring in many crops and countries. For example, Calderini and Slafer (1998) evaluated wheat (*Triticum* sp.) yield trends in 21 countries and found maximum increases of 3.0- to 4.5-fold, whereas Evans (1993) reported a 2.5-fold increase for rice (*Orzya sativa* L.) in Japan during this period.

There is now evidence, however, that yield increases may be ending in some environments, with plateaus noted for wheat (Calderini and Slafer, 1998), rice (Pingali et al., 1997; Cassman et al., 2003) and soybean (Nafziger, 2004) in some countries. These plateaus may be the result of several years of below average weather or they may represent failure of more fundamental processes driving yield improvement.

Historical increases in yield resulted from modification of the plant (plant breeding) and/or the plant's environment (crop management), and often complementary changes in both were required (Duvick and Cassman, 1999). The development of better cultivars and/or improved management practices was only the beginning of the process; state and country yields increased only after the new technology was adopted and utilized by producers, a process often determined by economic considerations (Griliches, 1957).

Changes in the corn plant associated with higher yields have been documented extensively and include the use of hybrids (Griliches, 1957; Duvick, 2005), longer seed-filling periods (Egli, 2004; Duvick, 2005), tolerance to high plant populations (Duvick, 2005), improved stay-green characteristics during seed filling (Duvick, 2005), more upright leaves (Duvick, 2005), decreases in seed protein concentration (Duvick, 2005), and increased stress tolerance (Tollenaar and Wu, 1999). Changes in the soybean plant are not as well documented, but include longer seed-filling periods (Gay et al., 1980; Boerma and Ashley, 1988; Kumudini et al., 2001), decreased lodging and often shorter plants (Specht and Williams, 1984), improved disease resistance (Hartwig, 1973) and, in some cultivars, decreases in seed protein and increases in seed oil concentration (Morrison et al., 2000). Evidence that yield increases in either crop resulted from higher levels of single leaf or canopy photosynthesis is mixed (Larson et al., 1981; Crosbie and Pearce, 1982; Morrison et al., 1999; Tollenaar and Wu, 1999).

Changes in management practices also contributed to higher yield and they include, for corn, higher plant populations (Troyer, 2004; Duvick, 2005), higher rates of fertilizer, espe-

D.B. Egli, Dep. of Plant and Soil Sciences, Univ. of Kentucky, 427 Plant Science Building, 1405 Veterans Dr., Lexington, KY 40546-0312. Published with the approval of the Kentucky Agric. Exp. Stn. as Paper 06-06-133. Received 13 Oct. 2006. *Corresponding author (degli@uky.edu).

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cially N (Evans, 1993; Troyer, 2004), introduction of herbicides and improved weed control (Pike et al., 1991; Osteen, 1993; Troyer, 2004), earlier planting (Lauer et al., 1999; Kucharik, 2006), and narrower rows (Troyer, 2004). Soybean yields also benefited from narrow rows (Johnson, 1987; Heatherly and Elmore, 2004), herbicides (Pike et al., 1991; Osteen, 1993), and better weed control, but earlier planting, adoption of conservation tillage techniques, and reductions in harvest losses are also given credit for increasing yield (Johnson, 1987; Heatherly and Elmore, 2004).

Changes in atmospheric conditions could also influence yield trends. Higher CO_2 levels (Pritchard and Amthor, 2005), gradual decreases in solar radiation (Stanhill and Cohen, 2001), and increases in O_3 are all candidates. Some have argued that changes in CO_2 levels (Amthor, 1998) or solar radiation (Stanhill and Cohen, 2001) have not yet had a major impact, but current O_3 levels may be high enough to reduce yields (Chameides et al., 1994; Morgan et al., 2003; Pritchard and Amthor, 2005).

The variation in atmospheric conditions could also cause changes in temperature and rainfall amounts or patterns that could, in turn, affect yield growth. Baker et al. (1993) described a period of "benign climate" from the 1950s to the mid-1970s in Minnesota, when the year-to-year variability in corn yield was reduced, but there was no effect on growth rates. Anderson et al. (2001) used crop models to evaluate weather effects on corn and soybean yields in Minnesota, Wisconsin, and Michigan, and found evidence that improved weather accounted for some of the increase in yield. Their analysis, however, did not account for changes in CO_2 and O_3. Lobell and Asner (2003) suggested that growth of corn and soybean yields from 1982 to 1998 at some midwestern locations was increased by declining temperatures, but the effect was the same for both crops. Their results, however, have been challenged on technical grounds (Gu, 2003).

Technological change is not always effective in increasing yield. County yields of nonirrigated soybean did not change during the last three decades of the 20th century in many counties in Arkansas and Nebraska (Egli, 2008), and in Georgia (Jagtap and Jones, 2002). Unimproved barley (*Hordeum vulgare* L.) land races produced higher yields than improved cultivars in some low-yield environments (Ceccarelli and Grando, 1999). These examples suggest that this failure of modern technology may occur only in high-stress, low-yield environments. Evaluation of yield at state or country levels includes the possible effects of these unfavorable environments.

World population is expected to increase by 1.4 billion people (~20%) in the next 20 yr (medium variant from the 2004 United Nations population division estimates; United Nations, 2004). Feeding these extra people in a sustainable manner will require significant increases in yield of all major crops, especially if significant amounts of the corn and soybean crop are diverted to fuel production (Troyer and Good, 2005). Finding the best strategy to achieve higher yields in the future often hinges on an understanding of the basis of past increases. It is always difficult to isolate and quantify individual parameters responsible for rising yields, but comparison of yield growth of two dissimilar crops—crops with different characteristics and production requirements—may make it easier to identify key changes. Consequently, my objective was to evaluate historical yield increases in corn (a high-yielding C_4 grass that produces seeds rich in starch and requires a relatively high level of production inputs) and soybean (a C_3 legume that produces modest yields of seeds with high levels of oil and protein, while requiring fewer production inputs) in high- and low-yield environments to learn more about the factors responsible for increasing yield. Corn and soybean are intermingled in many production areas in the United States, making it possible to compare yield trends of the two crops without confounding yield growth with significant differences in above- and belowground environments or economic conditions.

MATERIALS AND METHODS

Three states that produce relatively high yields (Iowa, Illinois, Indiana) and three that produce lower yields (Kentucky, Tennessee, Missouri) were chosen for analysis to evaluate potential effects of the level of productivity on yield growth rates. Selection was based on historical yield levels and the requirement that both crops represent substantial production areas in the state. This last requirement eliminated some southern states with generally low soybean yields from consideration because of their small corn areas, thereby reducing the yield differences between the high- and low-yield states selected.

Corn and soybean yield and harvested area were obtained from the website of the National Agricultural Statistics Service (USDA-NASS, 2006). Estimates for corn were available from 1866 to the present and, for soybean, from 1924 to the present. Yield was converted from bushels acre^{-1} to kg ha^{-1} and area from acres to ha before analysis.

Linear regression analysis of yield vs. time was used to estimate the absolute growth rate (kg ha^{-1} yr^{-1}). Relative growth rate (% per year, referred to hereafter as growth rate) was calculated by dividing the absolute growth rate by the mean predicted yield and was used in all analyses to provide a meaningful comparison of corn and soybean growth rates.

The ratio of corn and soybean yield for each year from 1950 through 2005 was calculated and plotted as a function of time. A linear-plateau model [segmented model in the PROC NLIN procedure in SAS (SAS for Windows, v. 9.1, SAS Inst., Cary, NC)] was used to estimate when the ratio reached a plateau.

RESULTS AND DISCUSSION

The Early Years

The dramatic increases in corn yield that occurred since the founding of ASA in 1907 occurred almost entirely in the second half of the 20th century in all six states in my sample (Fig. 1 and 2). There was almost no change in yield during the 64 yr from 1866 to 1930. The slope of the linear regression of yield vs. time was significant and positive only in the high-yield states, but the growth rates were not large [average was only 5.3 kg ha^{-1} yr^{-1} (0.25%)] (Table 1). Stagnate yields during this period were common in other crops as well; for example, wheat in the United States (USDA-NASS, 2006), Australia (Fischer, 1999), France (Brancourt-Hulmel et al., 2003), and in the Rothamsted Experiments in England (Johnston, 1994); oat (*Avena sativa* L.), rye (*Secale cereale* L.), barley, cotton (*Gossyipum hirsutum* L.), and potato (*Solanum tuberosum* spp. tuberosum) in the

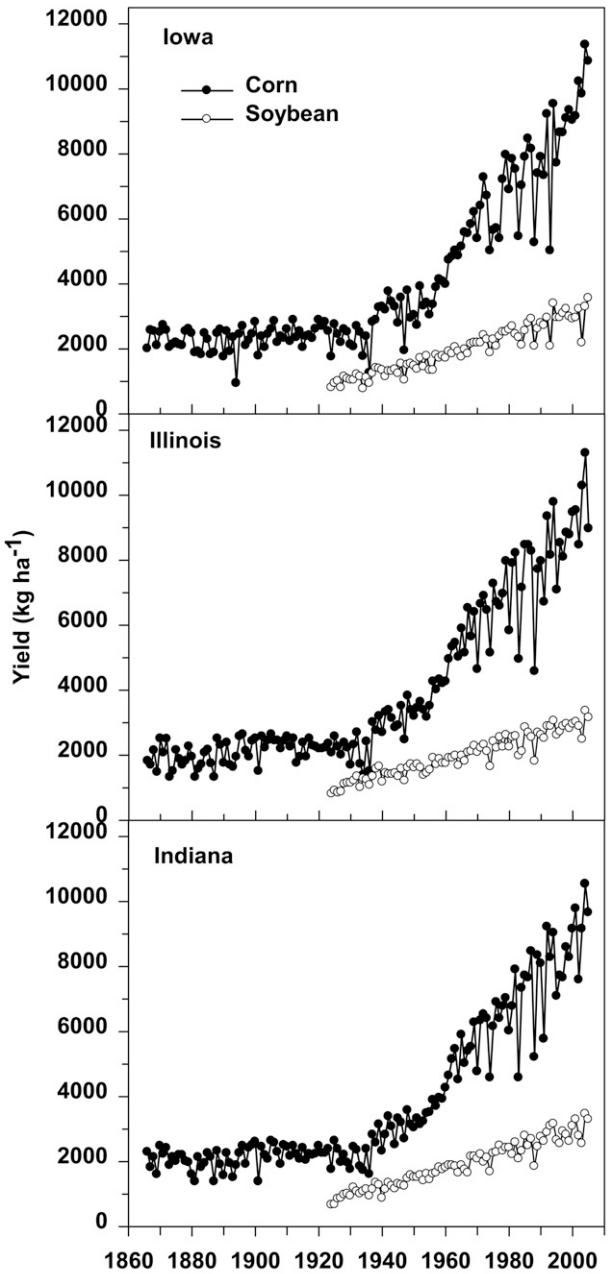

Fig. 1. Average state corn and soybean yields from 1866 to 2005 for states with relatively high-yield potential.

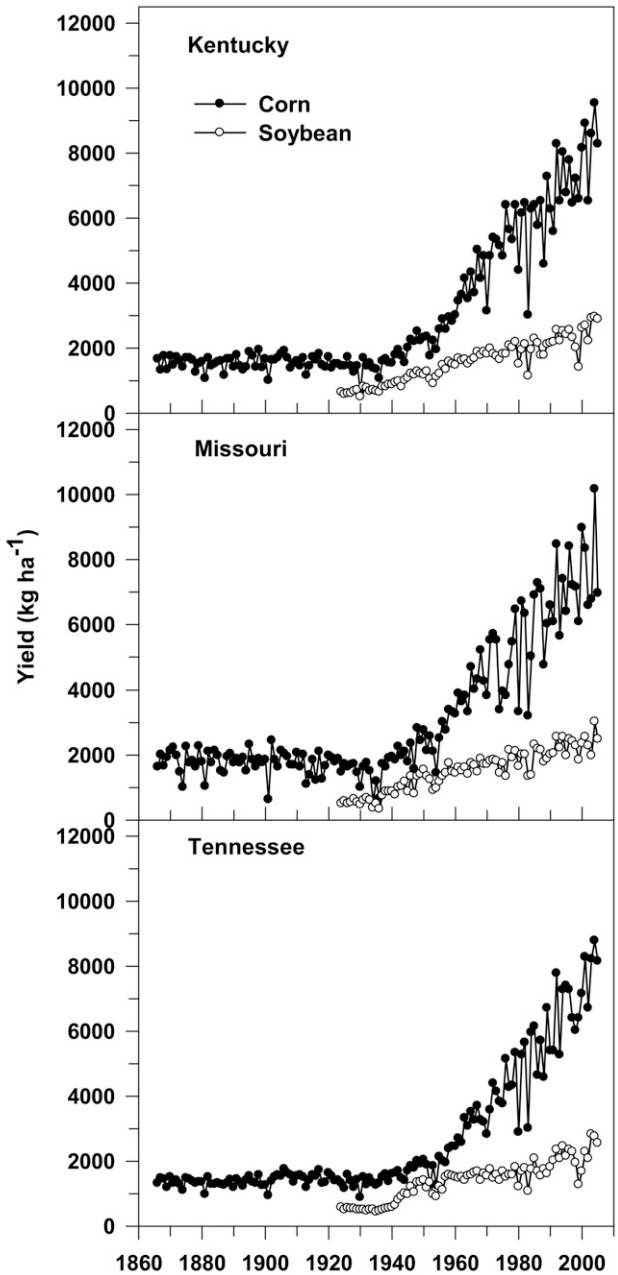

Fig. 2. Average state corn and soybean yields from 1866 to 2005 for states with relatively low-yield potential.

United States (Tracy et al., 2004); faba bean (*Vicia faba* L.) and pea (*Pisum sativum* L.) in England and Wales (Heath and Hebblethwaite, 1985); and rice in China (Ellis and Wang, 1997).

Soybean seed yields were first reported by USDA-NASS in 1924 and yield in five of the six states evaluated increased steadily through 2005 (Fig. 1 and 2); Tennessee was the exception (Fig. 2) with no yield increase until about 1940.

The period when corn yields were relatively stable includes roughly the first 25 yr of ASA's existence. Midwestern agriculture during that time would be characterized today as low-input or sustainable. Cropping systems were based on rotations involving corn, small grains (wheat and oat among others), and hay (Hudson, 1994; Nordin and Scott, 2005), and an absence of inorganic fertilizer N forced a greater dependence on organic N sources [manure and legumes in the rotation (Pieters, 1917;

Table 1. Linear regression of corn yield vs. time for three high- and three low-yield states, 1866 to 1930.

State	Slope	r^2
	kg ha^{-1}yr^{-1}	
High yield		
Illinois	7.6	0.15**
Indiana	4.2	0.06*
Iowa	4.1	0.05†
Low yield		
Kentucky	–1.7	0.02 ns‡
Missouri	–3.8	0.04†
Tennessee	1.4	0.02 ns

* Significant at $p = 0.05$, $n = 65$. † Significant at $p = 0.10$, $n = 65$.
** Significant at $p = 0.01$, $n = 65$. ‡ Not significant at $p = 0.10$.

Solbrig and Solbrig, 1994)]. There was no chemical weed control (Gardner, 2002) and farmers grew open-pollinated corn cultivars and saved their own seed (Wallace and Brown, 1988). Farm number and size [approximately 20 ha (50 acres)] were relatively constant during the first half of the 20th century, but there was a big shift from animal power (horses and mules) to mechanical power (tractors) fueled by petroleum products (Gardner, 2002). Mechanical picker–huskers replaced hand harvesting during this time (Bogue, 1983).

Midwestern corn production systems were not static between 1866 and 1930. Harvested area in all states increased dramatically until about 1900, but then there were no large changes from 1900 to 1930 in the high-yield states (Illinois, Indiana, and Iowa). Harvested area peaked about 1920 and declined steadily there after in the low-yield states (Kentucky, Tennessee, and Missouri) (USDA-NASS, 2006). To improve yield, extension workers used corn shows to help farmers learn how to identify the "perfect" ear to save for seed (Wallace and Brown, 1988). This approach, however, was completely ineffective resulting in a shift to the use of replicated yield tests to compare lines. Breeding procedures used during this era included ear-to-row selection, mass selection, and varietal hybridization (Russell, 1991). Mechanization replaced hand labor and no doubt improved the efficiency of many production operations (Bogue, 1983; Gardner, 2002). Members of ASA were active in many areas of research during this era, including soil fertility, crop physiology and management, and breeding. Papers in the *Journal of the American Society of Agronomy* during this period included "The effect of fertilizers on yield and market condition of corn" (Ellett and Wolfe, 1922), "Planting rate and spacing for corn under southern conditions" (Mooers, 1920), "Relation between yield and ear characters in corn" (Hutcheson and Wolfe, 1918), and "Breeding corn for resistance to smut (*Ustilage zeae*)" (Garber and Quisenberry, 1925). Although presumably the goal of most of these activities was to ultimately increase yield, it is clear from Fig. 1 and 2 that they had minimal affects on the average yield in the high- and low-yield states included in this analysis.

Soybean yields increased steadily from 1924 to 1930 and beyond (except in Tennessee) (Fig. 1 and 2) when corn yields were stagnant, perhaps reflecting the soybean's status as a new crop with initially low yields (yields in the six states in 1924 were less than 1000 kg ha^{-1} or 15 bu $acre^{-1}$). Yield of a new crop would probably increase quickly as farmers gained experience and management practices were refined. Cultivars were primarily plant introductions or selections from plant introductions, but the analysis of Specht and Williams (1984) suggests that continued selection within and among these lines did little to increase yield.

The High-Input Era

Corn yields in all six states began to increase rapidly (Fig. 1 and Fig. 2) approximately in the middle of the 20th century as agriculture in the U.S. Corn Belt began a dramatic shift from a low- to a high-input production system that included new cultivars produced by hybridization and selection. This transformation was not limited to corn production in the United States, it occurred at approximately at the same time in many other crops and countries with the same results [e.g., wheat in Australia (Fischer, 1999) and England (Johnston, 1994); oat, rye, barley, cotton, and potato in the United States (Tracy et al., 2004); and faba bean and pea in England (Heath and Hebblethwaite, 1985)].

The shift to a high-input system was lead by the replacement of open-pollinated corn lines with hybrids that began in the 1930s and rapidly swept across the cornbelt with 50% of the production area in hybrids by 1940 and 90% by 1950 (Russell, 1991). The replacement occurred first in high-yield states (Iowa approached 100% by 1940) followed by lower-yielding states [Kentucky had approximately 10% in 1940 and just less than 90% in 1950 (Griliches, 1957)]. The use of inorganic N fertilizer started increasing rapidly in 1945 (Thompson, 1969; Gardner, 2002) followed by increased use of herbicides (Evans, 1993) with approximately 40% of the area in Illinois treated in 1960 (Pike et al., 1991) vs. 34% of the total U.S. acreage (Osteen, 1993). Increases in plant population (Troyer, 2004) and mechanization, which often improved the timeliness of management operations, also contributed to rising yields (Evans, 1993).

The upward trend in soybean yields continued unabated between 1930 and 1950, with the exception of Tennessee, while corn yields were beginning to increase (Fig. 1 and 2). In the 1940s cultivars produced by hybridization began to replace cultivars originating as plant introductions (Hartwig, 1973), which resulted in immediate yield increases [14% average increase for grain types from maturity group 00 to IV (Specht and Williams, 1984)] that were analogous to the yield advantage of corn hybrids over open-pollinated lines (23–35%, Russell, 1991). Nitrogen fertilizer, important for corn, was not a factor for the leguminous soybean and herbicide use developed more slowly in soybean than in corn [almost none of the soybean production area in Illinois and probably other states was treated in 1960 (Pike et al., 1991) and only 68% of the United States area (50% in Illinois, Pike et al., 1991) in 1971 (Osteen, 1993)]. It seems likely that mechanization also contributed to the increasing yield, as it did in corn.

The transition from stable to increasing corn yield seemed to be complete by 1950, so I compared the yield of corn and soybean from 1950 to 2005 (55 yr), a period when the yield of both crops trended steadily upward in all six states (Fig. 1 and 2). The average yield of both crops at the beginning and end of the period was higher in states chosen to represent high-yield environments than in those representing low-yield environments (Table 2).

The area devoted to corn production increased by 25% in the high-yield states between 1950 and 2005, compared with a 39% decrease in the low-yield states (Table 2). There was a dramatic 3- to 10-fold increase, depending on the state, in soybean area. The combined corn and soybean area increased by 74 to 89% between 1950 and 2005 in the high-yield states and this increase was associated with a decline in wheat, oat, and hay production (USDA-NASS, 2006), probably partially a result of mechanization and decreased need for feed for draft animals (Gardner, 2002). The increase in soybean area in Kentucky and Tennessee (but not Missouri) was associated with a decrease in corn area, with little change in the total area. Missouri followed a pattern more like the high yield states, but the increase in combined acreage was 47% less than the high-yield states.

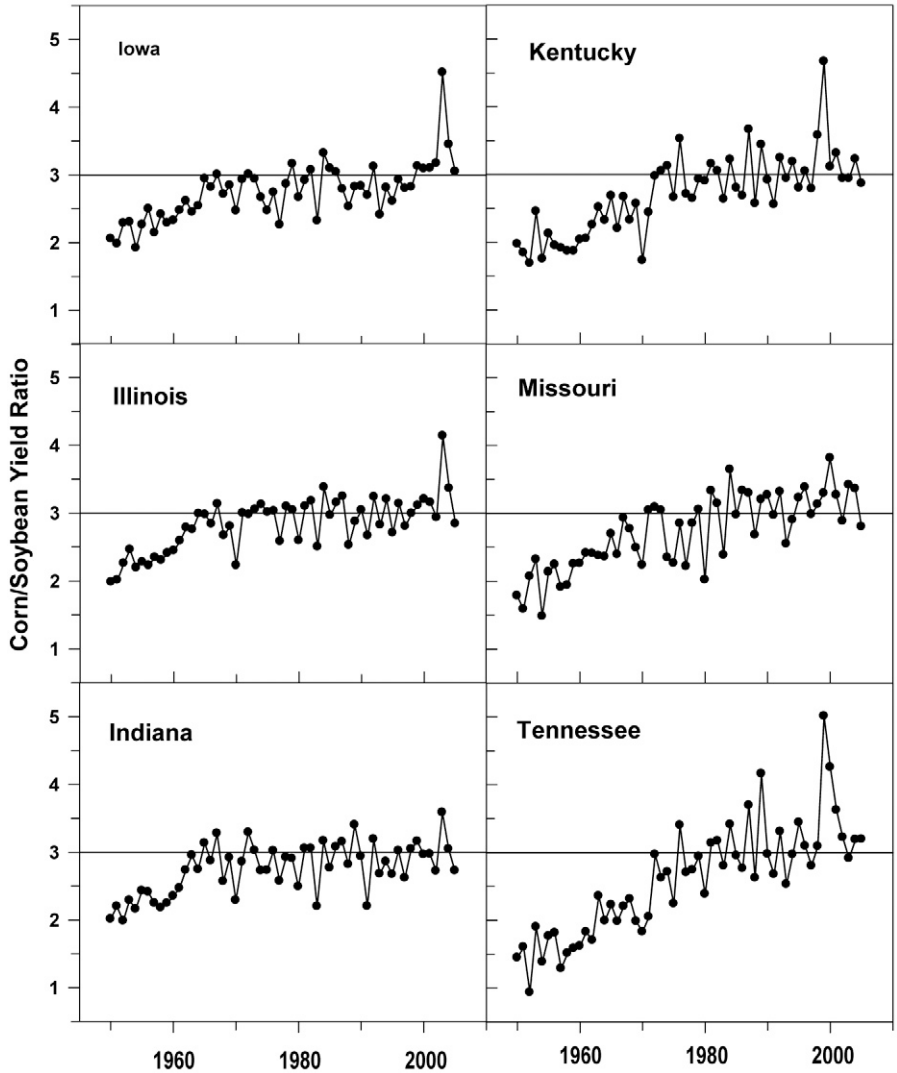

Fig. 3. The ratio of corn and soybean yield for three states with high- (Indiana, Illinois, Iowa) and three with low- (Kentucky, Missouri, Tennessee) yield potential.

Changes in production area can affect yield, if, for example, an increase in area required the use of less productive soils or vice-versa. Replacing corn with soybean or eliminating crops from a rotation may not have required the use of "new" land areas, thereby minimizing changes in soil quality. It is, however, nearly impossible to quantify the effect of these changes in production area on yield growth of the two crops.

Yield Ratios

The ratio of corn and soybean yield for each year from 1950 to 2005 was calculated to compare the changes in yield of the two crops over time (Fig. 3). The ratios varied from year-to-year, reflecting differential effects of the environment on yield of these two crops. Corn and soybean are not segregated by location in any of the states; therefore, they should be exposed, in general, to the same environmental conditions. Consequentially, much of the differential weather effect on yield is probably related to variation in environmental conditions during critical growth stages, which, because of differences in planting date (corn is usually planted first) and crop development, do not necessarily occur at the same time.

Within this year-to-year variation in the ratio, there are, however, two clear trends in all six states—a period when the ratio increased from approximately 1.5 or 2.0 to roughly 3.0 and a second phase when there was no clear tread and the ratio fluctuated around a value close to 3.0 (Fig. 3). The ratio increased for roughly two decades after 1950 in the high-yield states and nearly four decades in the low-yield states because corn yield increased faster, on a relative basis, than soybean yield (roughly a 2× advantage for corn, Table 3). Hybrid corn was probably grown on nearly all of the corn area in the six states by 1950 (Griliches, 1957),

Table 2. Production statistics from six states representing high- and low-yield environments in the United States.

	Corn				Soybean			
	Mean yield		Mean harvested area		Mean yield		Mean harvested area	
State	1950–1954	2001–2005	1950–1954	2001–2005	1950–1954	2001–2005	1950–1954	2001–2005
	kg ha^{-1}		ha†		kg ha^{-1}		ha†	
High yield								
Illinois	3368	9,708	3427	4563	1552	2983	1573	4112
Indiana	3242	9,206	1806	2233	1525	3077	712	2237
Iowa	3286	10,284	4077	4862	1559	3044	714	4216
Mean	3299	9,733	3103	3886	1545	3035	1000	3521
Low yield								
Kentucky	2120	8,366	814	451	1102	2375	49	502
Missouri	2163	7,763	1444	1130	1202	2466	646	1950
Tennessee	1320	8,027	737	247	1162	2499	81	450
Mean	1868	8,052	998	609	1155	2567	259	967

† Thousands of hectares.

Table 3. Relative growth rates of corn and soybean yield for six states representing high- and low-yield environments, 1950 to 2005.

States	Growth rate				Intersection‡	Mean ratio§
	Corn		Soybean			
	Before†	After†	Before†	After†		
	% yr^{-1}					
High yield						
Illinois	3.2 (0.29)¶	1.4 (0.27)	1.7 (0.21)	1.1 (0.20)	1973	3.0
Indiana	3.8 (0.41)	1.4 (0.19)	1.4 (0.30)	1.2 (0.15)	1966	2.9
Iowa	3.7 (0.26)	1.7 (0.20)	2.1 (0.25)	1.2 (0.20)	1972	2.9
Mean	3.6	1.5	1.7	1.2	1970	2.9
Low yield						
Kentucky	3.3 (0.24)	2.2 (0.47)	1.7 (0.19)	1.9 (0.50)	1982	3.1
Missouri	2.6 (0.32)	1.8 (0.75)	1.2 (0.22)	1.7 (0.61)	1987	3.2
Tennessee	3.0 (0.27)	1.9 (0.61)	0.8 (0.19)	1.6 (0.88)	1988	3.3
Mean	3.0	2.0	1.3	1.7	1986	3.2

† Growth rate calculated for the years before or after the intersection of the rising and plateau portions of the relationship between the corn/soybean yield ratio and time (Fig. 3). The regression analysis was always significant at $p = 0.10$ and in 19 of 24 comparisons it was significant at $p = 0.001$.

‡ The year of the intersection of the rising and plateau portions of the plot of the ratio of corn and soybean yield vs. time. The time of the intersection was estimated with a linear-plateau model.

§ Mean ratio for the years from the beginning of the plateau to 2005.

¶ Standard error.

but hybrid improvement continued and increasing N fertilizer rates (USDA-ERS, 2006; Thompson, 1969; Evans, 1993), herbicide use (Pike et al., 1991; Osteen, 1993), and plant populations (Troyer, 2004) contributed to the rapid increase in yield during this period.

Soybean yield was also influenced by many of these changes, that is, cultivar improvement by hybridization and selection (the shift to cultivars created by hybridization was probably essentially over by 1950 or soon there-after, Hartwig, 1973; Specht and Williams, 1984), increased use of herbicides (Pike et al., 1991; Osteen, 1993), and other improvements in management practices. It is difficult to evaluate the effect of each of these individual changes on the growth rate of the two crops; but soybean yield was not affected by N fertilizer and that difference may account for much of the advantage for corn.

The ratio was lower (<2.0) in the low yield states in the early 1950s (Fig. 3), but the rate of increase (Table 4) did not differ consistently between the high- and low-yield states. Consequently, the increase in the ratio continued longer in the low-yield states (an average of 16 yr longer, Table 3). Apparently the effect of the new technology on corn and soybean yield growth and the ratio was relatively independent of the level of productivity.

The corn–soybean yield ratio eventually stopped increasing and reached a plateau in all six states (Fig. 3) that was maintained for 17 to 39 yr, depending on the state (Table 3). Linear regression analysis indicated that there was no significant ($P = 0.05$) change in the ratio during this period, except for Iowa, which exhibited a small but significant increase (Table 4). Although there was considerable year-to-year variation, the mean ratios during the plateau period only varied from 2.9 to 3.3 (Table 3). The ratio of average corn and soybean yields from long-term (10–20 yr) rotation studies where corn and soybean were grown in the same environment fell between 2.9 to 3.2 (Mallarino et al., 1991; Porter et al., 1998; West et al., 1996; Karlen et al., 1995). The ratio of irrigated corn and soybean yield in Nebraska from 1972 to 1997 averaged 2.8 (Specht et al., 1999). Comparison of record yields summarized by Evans (1993) produced a mean ratio of 3.3. Corn should produce higher yields than soybean by virtue of substantially lower oil and protein concentrations in the seed (Egli, 1998) thereby requiring less carbon to synthesize a unit weight of seed tissue (Penning de Vries, 1974), the higher photosynthetic capacity of the C_4 pathway (Loomis and Amthor, 1999), and possibly a slightly longer seed-fill duration (Egli, 2004). It is, however, somewhat surprising that corn and soybean, which react differently to some environmental stimuli (Loomis and Amthor, 1999), responded so similarly to environments ranging from the relatively ideal environments producing record yields to the highly variable and obviously less than ideal environments associated with average state yields.

The development of the plateau was a result of a large decrease in the growth rate of corn yield to more nearly match

Table 4. Linear regression analysis of the ratio of corn and soybean yield from 1950 to 2005.

State	Before†			After†		
	n‡	Slope	r^2	n‡	Slope	r^2
		(kg/ha) (kg/ha)$^{-1}$ yr^{-1}			(kg/ha) (kg/ha)$^{-1}$ yr^{-1}	
Illinois	23	0.0399 (0.0068)§	0.62***	33	0.0080 (0.0050)§	0.06 ns
Indiana	16	0.0584 (0.0097)	0.72***	40	0.0037 (0.0041)	0.02 ns
Iowa	22	0.0403 (0.0058)	0.70***	34	0.0166 (0.0063)	0.18*
Kentucky	32	0.0415 (0.0057)	0.64***	24	0.0140 (0.0132)	0.05 ns
Missouri	37	0.0344 (0.0054)	0.54***	19	0.0108 (0.0127)	0.04 ns
Tennessee	38	0.0536 (0.0046)	0.79***	18	0.0249 (0.0291)	0.04 ns

* Significant at $p = 0.05$, NS = not significant.

*** Significant at $p = 0.001$.

† Separate analyses were conducted for the data before or after the intersection between the rising and plateau portions of the curve relating the ratio of corn and soybean yield to time. The time of the intersection was estimated with a linear-plateau model. Before includes all data from 1950 through the year before the intersection, after includes all of the data from the year of the intersection through 2005.

‡ Number of years included in the regression analysis.

§ Standard error.

the rate of soybean (Table 3), but there is little evidence that a lower rate of genetic improvement contributed to this decline. Evaluations of hybrids from different eras (1930 through the present using populations appropriate for the era) in the same experiment always revealed linear increases in yield (Castleberry et al., 1984; Russell, 1991; Cooper et al., 2004; Duvick, 2005) or the yield components associated with higher yield (Cavalieri and Smith, 1985). These increases are due, in some sense, to a mixture of genetic and management improvements (i.e., increased plant populations), but they mimic the contribution of improved hybrids in the production environment. Nitrogen fertilizer rates did not increase much after 1980 (USDA-ERS, 2006), so the contribution of N to the rising corn yields was probably reduced. Diminishing returns from other management inputs may also have contributed to the decline in growth rates.

Regardless of the cause, once the adjustments in growth rates, which apparently occurred rapidly (Fig. 3), were completed, the ratios fluctuated around a constant mean value until 2005, suggesting that the relative effects of plant breeding and improved management systems on corn and soybean yields have been the same for up to four decades. This consistency occurred in both high- and low-yield states although the growth rates of both corn and soybean were consistently higher in the low-yield than in the high-yield states (Table 3).

Corn vs. Soybean

Yields increase because plants are modified to make them more productive, because crop management improves the crop's environment, or because the environment changes and is more favorable. It is, however, impossible to accurately estimate the contributions of each of these three mechanisms to the increases in corn and soybean yield between 1950 and 2005. The two crops have little in common—corn is a high-yielding C_4 grass of tropical origin that produces a high starch seed whereas soybean, a C_3 legume that originated in northern China, produces moderate yields of seeds with high levels of oil and protein. The two crops, however, are grown in the same environments in each state by producers with equal skills (probably often the same producers) and probably equal access to advanced technology, eliminating some of the factors confounding yield comparisons among countries with different environments and economic conditions.

The breeding systems responsible for cultivar improvement are quite different in corn and soybean. Cultivar development in corn, by virtue of the use of hybrids, was dominated by commercial companies (but supported by inbred lines developed at agricultural experiment stations) from early in the high-input era (Kloppenburg, 2004; Troyer and Good, 2005). In contrast, cultivar development in soybean was conducted, almost entirely, by breeders at agricultural experiment stations and the USDA (Hartwig, 1973) until the passage of the Plant Variety Protection Act by the federal government in 1970 (Copeland and McDonald, 2001). This act extended proprietary protection to breeders of self-pollinated crops and caused a slow shift of soybean cultivar development from the public sector to the current domination by private industry. The corn seed industry supports a much larger breeding effort than that devoted to soybean. Surveys of the industry in 1982 and 1989 found that the involvement of trained personnel holding Ph.D., M.S., and B.S. degrees in corn breeding exceeded those in soybean breeding by a factor of 5 (641 full-time scientific year equivalents in corn vs. 138 in soybean in 1989). There were also twice as many companies involved in corn breeding than in soybean breeding at that time (Kalton et al., 1989). In spite of these substantial differences in effort, the relative rates of yield improvement from cultivar development (estimated by comparing cultivars or hybrids from different eras in the same experiment or by evaluating elite lines in cultivar tests over time) are often between 0.5 and 1% for both crops (Boerma, 1979; Russell, 1984; Wilcox, 2001; Duvick et al., 2004).

The changes in management practices responsible for the increases in corn and soybean yield are well documented (Evans, 1993; Troyer, 2004; Johnson, 1987; Heatherly and Elmore, 2004), but they are not necessarily consistent across crops. The increased use of N fertilizer and higher plant populations played a major role in increasing corn yields, but neither was important in soybean. Both crops, however, benefited from the development of herbicides and improved weed control, mechanization, and narrow rows. Except possibly for the beneficial effects of N fertilizer on corn when the corn/soybean ratio was increasing, it is impossible to quantitatively compare the affect of the changes in management practices in the two crops.

The effect of increases in atmospheric concentrations of CO_2 and O_3, and a decrease in solar radiation (Stanhill and Cohen, 2001; Pritchard and Amthor, 2005) on yield may not be the same for the two crops since, for example, soybean is more sensitive to the positive effects of CO_2 and the negative effects of O_3 than corn (Lessor et al., 1990; Nali et al., 2002; Long et al., 2006). The magnitude of the changes in CO_2 and solar radiation in the past 55 yr, however, may not be large enough to cause measurable changes in yield of either crop (Amthor, 1998; Stanhill and Cohen, 2001). Ozone levels may, however, be high enough to reduce yield (Pritchard and Amthor, 2005) and the effects could be greater on soybean than corn. There is some evidence suggesting that changes in rainfall and temperature increased corn and soybean yields during the high-input era (Baker et al., 1993; Anderson et al., 2001; Lobell and Asner, 2003), but none of these reports identify a differential affect on corn and soybean. Thus, although corn and soybean should respond differentially to some environmental stimuli, there is no evidence, beyond the O_3 effect, that environmental change had any differential effects on yield growth since 1950.

In spite of all the differences between corn and soybean production systems, including the characteristics of the plant and the inputs that supported yield growth during the high-input era, the primary feature of the second half of this era was similar growth rates for the two crops. Corn had the advantage early, in fact, growers and others (Brown, 1967) often complained that corn yield was increasing faster than soybean yield (or that soybean yield was not increasing at all); this conclusion was once correct, but for the last roughly 30 yr yields have increased at essentially the same rates in a variety of environments in the midwestern United States. The reason for this consistency in two such disparate crops is not obvious, but it is tempting to speculate that it stems from similar rates of genetic improvement in both crops, with smaller contributions from improved management practices.

The yield potential of the production environment had some affect on the rate of yield growth of both crops. The rates tended to be lower in the low-yield states in the years before the yield ratios reached the plateau (Table 3). During the plateau period, however, the growth rates of both crops were consistently higher in the low yield states, a complete reversal of the previous situation. The early disadvantage in the low yield states could simply reflect the delayed development of new technology, particularly adapted hybrids, and less economic incentive to adopt the available technology (Griliches, 1957, 1960). Eventually, however, those restrictions were apparently overcome and the growth rates in the low yield states actually exceeded those in the high yield states.

Future Yields

Corn and soybean yields have been trending steadily upward for nearly three quarters of a century; however, the long-term record for corn (Fig. 1 and 2) and many other crops (Heath and Hebblethwaite, 1985; Johnston, 1994; Ellis and Wang, 1997; Fischer, 1999; Tracy et al., 2004) clearly shows that rapidly increasing yields are a phenomenon of high-input agriculture in the 20th century. Will these increases in yield end as suddenly as they once began or will they continue for the foreseeable future? There is evidence that yield plateaus may be developing in some crops (Pingali et al., 1997; Calderini and Slafer, 1998; Cassman et al., 2003). The corn and soybean data for the six high and low-yield states presented here, however, provides no evidence of declining growth rates or the appearance of plateaus (Fig. 1 and 2), which should show clearly in Fig. 3 if the growth rate of only one crop (corn or soybean) began to decline. Incipient yield plateaus are difficult to identify given the substantial year-to-year fluctuations in yield, but in spite of past pessimism (see for example, Wennblom, 1978; Nafziger, 2004), there is no clear evidence through 2005 that increases in corn and soybean yields in the midwestern United States are ending.

Crop management made significant contributions to higher yield in the past and advanced production technologies are important in maintaining high yield levels, but it seems unlikely that management will play a major role in yield growth in the future. Improved management eventually starts to show diminishing returns as past improvements make the next increment in yield more difficult, and it may not be possible to continually identify new practices to start the cycle again. Crop management will obviously continue to make important contributions to improving crop production efficiency (e.g., precision agriculture), an important aspect of any cropping system, or in a defensive posture to maintain yields in the face of new production hazards.

Plant breeding made a consistent, steady contribution to increasing yields since 1950. Continued success depends on the availability of genetic variation, which at present seems to be adequate (Fehr, 1999; St. Martin, 1999; Duvick, 2005) for the near future. Genetic variation may also be increased by contributions from biotechnology (Van Camp, 2005). Biotechnology has the potential to help produce higher yields in the future, but a focus on quality traits over yield and the rush to develop strong proprietary positions could serve as negative influences on yield growth. The lack of funding for plant breeding programs at universities could reduce the supply of plant breeders and impede the movement of the fruits of biotechnology from the laboratory to the farmer's fields (Gepts and Hancock, 2006).

No one can say with any certainty what will happen to corn and soybean yields in the next 20, 30, or 50 yr. Some seem to be suggesting that high yields cannot be sustained and are advocating a return to the agricultural systems prevalent during the low-input era when yield was low and unchanging (Jackson, 1985; Berry, 2005; Pimentel et al., 2005; Pollan, 2006). It is not clear, however, how this approach will provide food for 6.5×10^9 people today or the nearly 8×10^9 expected in 20 yr. A more realistic approach suggests that yields will have to continue to increase as long as population increases (Borlaug, 1999). Instead of speaking pessimistically of future disasters, I prefer to take an optimistic viewpoint of future opportunities. The work of the members of ASA since its inception in 1907 provided a strong foundation that supported steadily increasing corn and soybean yields since the middle of the last century. I assume that man's ingenuity and a strong scientific effort will strengthen this foundation and continue to provide the technology to keep the yield of both crops increasing in the future, much as they have in the past, and thereby provide an adequate food supply for a growing population.

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