Chapter 9
Sustainable Agriculture and Soybean Breeding: Contribution of Soybean Yield Increase to Sustainable Agriculture

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9.1 Introduction

Continual human population growth has driven the need for increased food production worldwide. Greater food production was initially accomplished by increasing the area under cultivation. According to USDA statistical data (USDA-NASS 2011), farmland for soybean production increased almost 50-fold from 1924 to 2010 in the USA. This increase allowed for greater food and feed production, but it has also been associated with land degradation. More than 70 million cropland hectares eroded at rates higher than recommended for sustainable production (Hargrove et al. 1988). The limitation of land suitable for agricultural use, as well as farmland degradation due to misuse or overuse, made it necessary to focus on growing higher yielding crops on available crop land to lessen the demand to clear forested area for crop cultivation. Norman Borlaug estimated that if American farmers did not grow the high yielding crops available in recent decades, all the forest east of the Mississippi river would have to be cleared in order to produce the current food supply (Avery 1998). Globally, total area saved by modern agricultural systems was estimated to be almost 20 million square miles (Avery 1998). In this context, growing higher yielding crops is the most effective environmental conservation effort.

The major factors contributing to soybean yield increases in the USA have been: genetic improvement of soybean varieties, optimization of agronomic practices, market trends, and government policies. Genetic improvement was estimated to

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have contributed 45–50 % to the realized yield gain for soybean (Luedders 1977; Specht and Williams 1984). Most genetic changes contributed to improved pest resistance (Hartwig 1973; Riggs 2004; Parrott et al. 2008), alteration of plant morphology (Specht and Williams 1984; Boerma 1979), changes in plant physiology (Specht et al. 1999; Morrison et al. 2000; De Bruin and Pedersen 2009), or introduction of herbicide-tolerant varieties (Fernandez-Cornejo and Caswell 2006). These higher yielding varieties contributed to environmental protection not only via preservation of land needed for soybean production but also by reducing the need for chemical pest control (due to introduction of disease-resistance, insect-resistance or herbicide-tolerance genes).

Optimization of agronomic practices was mostly due to improvement of agricultural mechanization (Specht et al. 1999), application of chemical pesticides and fertilizers (Aldrich 1983; Luedders 1977), use of crop rotation (Luedders 1977; Riggs 2004), and improvement of tillage systems (Specht et al. 1999). The extent of erosion of USA soils in the 1930s emphasized the need for optimizing tillage systems that would ensure high yielding crops as well as preserve farm soil (Power and Doran 1988). Development of chemical herbicides and herbicide-tolerant varieties (Fernandez-Cornejo and Caswell 2006) allowed for an increase in conservation tillage because much of the tillage during soybean production is associated with weed control management (Buhler and Hartzler 2004). Conservation tillage contributed to a reduction of soil erosion by water and wind, soil degradation, and water or chemical runoff (Unger et al. 1988).

Government policies regarding intellectual property protection (Sleper and Shannon 2003; Kesan and Gallo 2005; Lesser 2005) or environmental protection (Reeder 2000) significantly influenced investment in and direction of soybean research and production, and consequently contributed to increased yield. The objective of this chapter was to identify and discuss the major factors influencing soybean production and yield increases as important contributors to sustainable agriculture.

9.2 Materials and Methods

The National Agricultural Statistical Services (USDA-NASS 2011) data were used to obtain information about soybean yield, grain production, planted area, and harvested area for the period covering 1924–2010 in the USA. The English units used in this database were converted to the SI system. For soybean yield, the conversion was from bushels per acre (bu ac^{-1}) to kilograms per hectare (kg ha^{-1}), for grain production from bushels (bu) to kilograms (kg), and the land area under soybean production was converted from acres (ac) to hectares (ha).

Linear regression analysis was performed for yield, planted area, and grain production with year as the independent variable. The slopes from the regression lines were interpreted as average rates of change for grain yield (kg ha^{-1} $year^{-1}$), planted area (ha $year^{-1}$), and grain production (kg $year^{-1}$) between 1924 and 2010.

Additionally, segmented linear regression models were applied to evaluate changes within each soybean production period (1924–1942, 1943–1977, 1978–1998, and 1999–2010). The breakpoints between segments were modeled at the three mid-points between adjacent periods. Slope coefficients and error variances were estimated separately for each of the four production periods, but only one intercept term was included so that the resulting model would be a continuous function with respect to time. The main purpose of the segmented models was to estimate an average annual rate of change during each period. The PROC REG function in SAS (SAS Institute Inc. 2002–2008) was used for the overall regression lines, and PROC NL MIXED was used to obtain estimates for the segmented linear regression models.

9.3 Results and Discussion

9.3.1 Soybean Production in the USA

According to USDA statistical records (USDA-NASS 2011), USA soybean production increased steadily from 1924 to 2010 (Fig. 9.1). Two major factors contributed to this trend: more farmland utilized for soybean production (Fig. 9.2) and greater soybean yield per unit area (Fig. 9.3). During this 87-year period, there have been four distinct eras that impacted soybean production and were based on type of varieties grown by farmers:

Soybean introductions prior to 1942
Public sector varieties from 1943 to 1977
Private sector varieties from 1978 to 1998
Biotechnology varieties from 1999 through present time

9.3.1.1 Soybean Introductions Prior to 1942

The early records of soybean introduction into North America date back to the eighteenth century (Riggs 2004) when soybean was grown mostly as a novelty plant species. By the end of the nineteenth century, soybean was used predominantly as a forage or silage crop. At the beginning of the twentieth century, exploration trips to China, Japan, and Korea resulted in several thousand soybean land races introduced to the USA (Riggs 2004). These land races were used primarily as a forage crop for hay production (Sleper and Shannon 2003). Some introductions from 1935 to 1940 were large seeded, but low yielding genotypes that were utilized as a vegetable crop (Specht and Williams 1984). Prior to 1943, most cultivars grown by farmers were plant introductions with limited or no breeding effort (Specht et al. 1999). Specht and Williams (1984) showed a nonsignificant genetic yield gain for cultivars released from 1902 to the 1940s. This indicates that breeding did not contribute

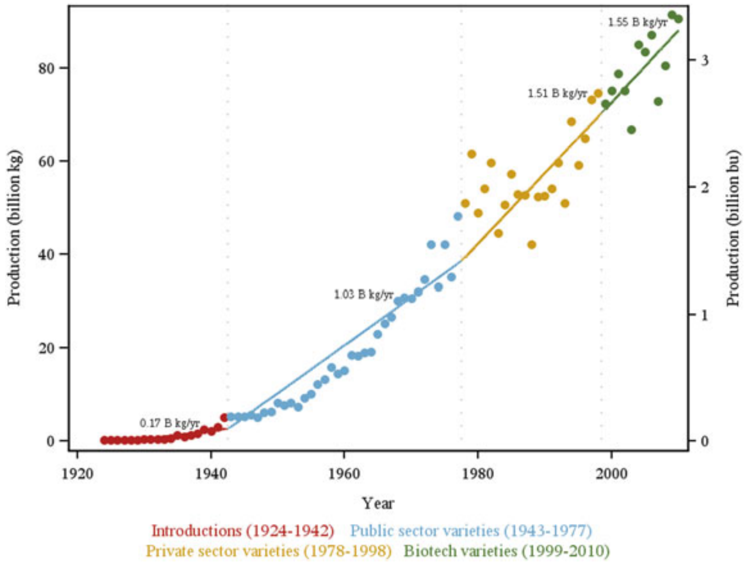

Fig. 9.1 Soybean production (billion kg and billion bu) in the USA for the four eras from 1924 to 2010

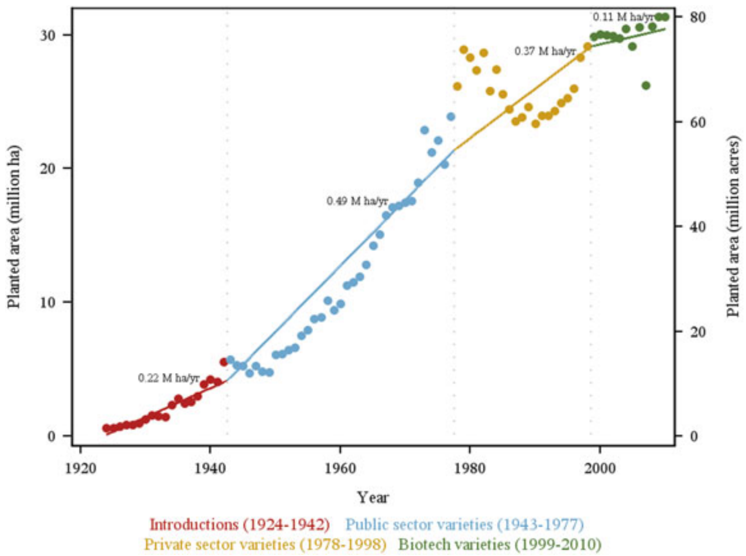

Fig. 9.2 Area under soybean production (million ha and million ac) in the USA for the four eras from 1924 to 2010

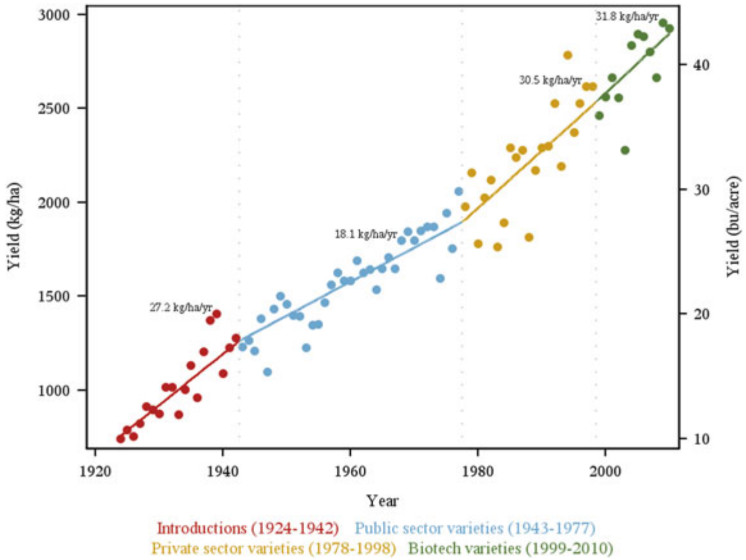

Fig. 9.3 Soybean yield (kg ha^{-1} and bu ac^{-1}) in the USA for the four eras from 1924 to 2010

to yield increase during this period, although some changes were observed, such as increase in seed weight and seed quality, or decrease in plant height and lodging (Specht and Williams 1984). The adaptation of the introduced varieties, optimization of agricultural practices, and a shift in soybean utilization in the USA contributed to the realized yield gain of 27.2 kg ha^{-1} $year^{-1}$ (Table 9.1, Fig. 9.3). The area planted with soybean increased almost ninefold from 1924 to 1942 (Fig. 9.2). Interestingly, for the same period, the harvested area increased 22-fold (USDA-NASS 2011). Only 28.6 % of planted soybeans were harvested in 1924 (probably for grain), whereas 72.2 % of planted soybeans acres were harvested in 1942. This is likely due to the change in soybean usage from a forage to a grain crop, as well as to reduced crop losses. The factors that contributed to reduced grain losses were better adaptation of introduced land races, farmers with more soybean growing experience, introduction of *Rhizobia* to the USA soils, and/or improved agronomic practices.

9.3.1.2 Public Sector Varieties from 1943 to 1977

More focused breeding of the soybean introductions started after the establishment of the USA Regional Soybean Industrial Products Laboratory in 1936 (Sleper and Shannon 2003). Breeders started making crosses between different land races from Asia and initiated selection for better yielding lines that were offered to farmers in the 1940s (Wilcox et al. 1979; Specht and Williams 1984). Soybean varieties released in this period resulted from breeding conducted in the public sector:

Table 9.1 Average annual rate of change[a] for grain production (billion kg year^{-1}), planted area (million ha year^{-1}) and yield (kg ha^{-1} year^{-1}), and the ratio of harvested (H) and planted (P) area for each production era for 1924–2010 period in the USA[b]

Years	Era	Grain production (billion kg year^{-1})	Planted area (million ha year^{-1})	Yield (kg ha^{-1} year^{-1})	H/P (%)
1924–1942	Introductions	0.17	0.22	27.2	36.7
1943–1977	Public sector varieties	1.03	0.49	18.1	93.5
1978–1998	Private sector varieties	1.51	0.37	30.5	97.9
1999–2010	Biotechnology varieties	1.55	0.11	31.8	98.5
1924–2010	Overall	1.10	0.41	23.4	82.7

[a]Regression coefficient
[b]*Source*. USDA-NASS (2011)

State Agricultural Experiment Stations (SAES) and the Agricultural Research Service, a subdivision of United States Department of Agriculture (USDA ARS) (Sleper and Shannon 2003). The average annual genetic gain for this period was estimated to be 12.5–13.7 kg ha^{-1} year^{-1} (Specht and Williams 1984; Boerma 1979), which was a major contributor to the realized yield gain (18.1 kg ha^{-1} year^{-1}) observed for this era (Table 9.1, Fig. 9.3). Estimated genetic yield increase for this period was 15–26 % greater compared to the introductions from the previous era (Luedders 1977; Wilcox et al. 1979; Specht and Williams 1984). This step change in yield increase was due to better gene combinations that resulted from hybridization followed by selection of lines with superior yield. This trend is similar to the one that occurred in corn when the hybrid production system replaced open-pollinated varieties (Specht and Williams 1984). The soybean yield increase was achieved by introducing and combining genes that contributed to better *Phytophthora* root rot resistance (Hartwig 1973), increased nitrogen content, greater nitrogen fixation (Specht et al. 1999), heavier seeds, better quality grain, shorter plants, and reduced plant lodging (Specht and Williams 1984). The area planted with soybeans expanded at the fastest rate during the 1943–1977 period (Fig. 9.2). An average of 0.49 million hectares under soybean production were added annually during this 35-year period, compared to an average increase of 0.22 million hectare per year for the previous period (Table 9.1). With this large increase in area, many soybeans were grown on farms with marginal soil conditions or inadequate management practices (Luedders 1977). However, a much greater percentage of planted acres were harvested for grain for the 1943–1977 period when compared to the average for the previous era (93.5 % vs. 36.7 %).

9.3.1.3 Private Sector Varieties from 1978 to 1998

The private sector started to invest significantly in soybean breeding after the passage of the Plant Variety Protection Act (PVP) in 1970. This act allowed for intellectual property protection of released varieties (Sleper and Shannon 2003). A total of 2,242 soybean cultivars were registered from 1970 to 2008, and 80 % of them were developed through private sector programs (Mikel et al. 2010). Almost four times as many employees devoted to soybean breeding were working in private seed companies compared to the public sector (82 vs. 22, respectively) in 1994 (Frey 1996). By the end of this era, approximately 90 % of soybean acres in the USA were planted with varieties developed in the private sector (Sleper and Shannon 2003). The estimated annual genetic gain for commercialized proprietary varieties in maturity groups 2 and 3 was 25–30 kg ha^{-1} $year^{-1}$ (Specht et al. 1999). This rate of gain is greater than the estimate by Specht and Williams (1984) for pre-1977 commercial releases (18.8 kg ha^{-1} $year^{-1}$). The genetic gain represents a major portion of the 30.5 kg ha^{-1} $year^{-1}$ realized yield gain for this era (Table 9.1, Fig. 9.3). Varieties from this period generally had a greater dry matter accumulation rate during the seed filling period (Specht et al. 1999), improved nitrogen content (Specht et al. 1999), better tolerance for higher plant density (Specht et al. 1999), and better soybean cyst nematode (SCN) resistance (Riggs 2004). The area under soybean production was variable from year to year for this period (Fig. 9.2). This fluctuation might have been influenced by factors associated with demand, market prices, and farm program policies for soybean in comparison to other crops. For example, the 1996 legislation on the ratio of soybean to corn loan rates resulted in an increase in soybean hectares (Sonka et al. 2004).

9.3.1.4 Biotechnology Varieties from 1999 Through Present Time

Herbicide-tolerant soybean varieties were introduced to farmers in 1996 and by 1999 over 50 % of the soybean acres in the USA had this biotechnology trait (Fernandez-Cornejo and Caswell 2006). Such a rapid adoption can be explained by the benefits of this new technology to farmers. Surveys have shown that 63 % of farmers preferred herbicide-tolerant soybean varieties because of higher yields, 17 % of growers liked the reduction of pesticide input cost, and 17 % indicated time saving and ease of management (Fernandez-Cornejo and Caswell 2006). The increased soybean yields that farmers observed with herbicide-tolerant soybeans can be attributed to several factors. In weed-free fields, soybean plants do not need to compete with weeds for water and nutrients (Buhler and Hartzler 2004; see Lee et al., Chap. 10). Weed control also contributes to reducing those pests that use weeds as hosts, such as root-knot nematode (*Meloidogyne* spp.) (Niblack et al. 2004) or soybean cyst nematode (*Heterodera glycines*, Ichinohe) (Riggs 2004). Furthermore, biotechnology utilization in agriculture resulted in more investment in soybean breeding and associated research and development. The realized yield gain for this era is higher (31.8 kg ha^{-1} $year^{-1}$) compared to the previous three periods (Table 9.1, Fig. 9.3). This estimate might be affected by the fact that this is also the shortest of the four eras; more years are needed to confirm this trend. Subsequent generations of traits resulting from biotechnology will continue to provide farmers with soybean varieties that have higher yield, increased pest resistance, healthier oils, and/or contribute to longer shelf life of soybean products. The area planted with soybean for this period has been relatively flat (Fig. 9.3), whereas total soybean production has increased at the greatest rate during this period compared to the previous three eras (Table 9.1, Fig. 9.1). This is a different trend compared to previous periods, as the increase in total soybean production in the USA was achieved mostly by yield increase rather than by both greater yields and land expansion (Table 9.1).

9.3.2 Factors Contributing to Soybean Yield Increase

The increase in soybean yield (23.4 kg ha^{-1} $year^{-1}$) has been a consistent contributor to greater grain production across all four eras with the highest rate estimated for the 1999–2010 era and the lowest observed for the 1943–1977 period (Table 9.1). There are several factors that influenced the increase in soybean yield per unit area over the 87-year period with three major ones being:

Genetic improvement of soybean varieties
Optimization of agronomic practices
Market trends and government policies

9.3.2.1 Genetic Improvement of Soybean Varieties

Soybean yield increases per unit area have been achieved by continual development of varieties with better agronomic performance and greater yield performance. From the beginning of the twentieth century to the 1970s, annual genetic gain has been estimated as 11.7–18.8 kg ha^{-1} $year^{-1}$ (Luedders 1977; Boerma 1979; Wilcox et al. 1979; Specht and Williams 1984) which represents 45–50 % of the realized yield gain for that period (Luedders 1977; Specht and Williams 1984). Breeding for higher yielding varieties resulted in changes associated with plant architecture, seed properties, disease resistance, and plant physiology. Average plant height of modern soybean cultivars decreased compared to the soybean introductions grown at the beginning of the twentieth century (Specht and Williams 1984; Boerma 1979). This was achieved mostly by shortening of the internodes rather than reducing their number. Several studies reported improved lodging resistance (Luedders 1977; Wilcox et al. 1979; Voldeng et al. 1997), which made harvesting easier and contributed to reduced harvest losses (Luedders 1977). Some researchers observed that the yield increase was associated with more pods per plant (Boerma 1979), others that it is due to more seeds per plant (Morrison et al. 2000; De Bruin and Pedersen 2009). Increased dry matter accumulation during the seed filing period (Specht et al. 1999; De Bruin and Pedersen 2009; Kumudini et al. 2001) resulted in heavier seeds (Specht and Williams 1984; Kumudini et al. 2001). Seed quality generally improved across maturity groups (Specht and Williams 1984). Seed shattering reduced (Mikel et al. 2010) and integrity of the seed coat was improved. Several studies observed a reduction in protein and an increase in oil (Wilcox et al. 1979; Voldeng et al. 1997; Mikel et al. 2010). In contrast, Yaklich et al. (2002) showed a decrease in oil since 1974. De Bruin and Pedersen (2009) showed that new soybean cultivars have an increased growth rate compared to older varieties. Identification of pest-resistant cultivars and their use in breeding programs contributed to development of varieties that can more reliably realize their yield potential. Morrison et al. (2000) observed a decrease in foliar disease rating when comparing early maturing varieties that represent seven decades of soybean breeding from 1934 to 1992. Since the late 1930s, selection for pubescence practically eliminated potato leafhopper (*Empoasca fabae*, Harris) as a soybean pest (Parrott et al. 2008). Introgression of genes for *Phytophthora* root rot resistance (Hartwig 1973) greatly improved plant health. Several soybean cyst nematode varieties such as Pickett, Bedford, Forest, or Fayette were introduced since the late 1960s (Riggs 2004). It has been estimated that an average yield increase of 2–5 % can be attributed to SCN resistance (Monson and Schmitt 2004), and that the yield advantage can be much greater (18 %) under increased SCN pressure (De Bruin and Pedersen 2009). Healthier plants associated with resistant varieties contributed to increased leaf area later in the season (Specht et al. 1999; Kumudini et al. 2001) and greater photosynthetic rate (Morrison et al. 2000). Higher yielding cultivars also had greater nitrogen fixation and accumulation rates (Specht et al. 1999). In the northern regions modern varieties were bred to have more cold tolerance (Voldeng et al. 1997). Newer soybean cultivars tend to yield more under higher plant density when compared to older cultivars (Specht et al. 1999). In recent years the introduction of herbicide tolerance genes also contributed to yield increases in soybean (Fernandez-Cornejo and Caswell 2006).

9.3.2.2 Optimization of Agronomic Practices

Several agronomic and management practices contributed to the greater soybean yields. Introduction of nitrogen-fixing *Rhizobia* to USA soils resulted in better nitrogen utilization. For soybean grower, this translated into much reduced need for nitrogen fertilizers which are considered the significant contaminators of surface and groundwater in the USA (Hargrove et al. 1988). Continual improvement of agricultural machinery such as planters and combines allowed for earlier planting and reduced harvest losses (Specht et al. 1999)—both contributing to greater yields of soybean. Reduction of harvest losses can be seen when comparing the three eras during which soybeans were grown predominantly for grain (1943–2010). The percent of harvested vs. planted area for the three eras steadily increased (93.5, 97.9, and 98.5 %) over this 68-year period (Table 9.1). Growers made the transition from planting wider to planting narrower rows (Specht et al. 1999) which resulted in a greater number of plants grown per unit area. Soybean farmers started implementing crop rotation in order to manage diseases like soybean cyst nematode (Riggs 2004) or root-knot nematode (Niblack et al. 2004), as well as controlling weeds and insects that can be favored by monoculture (Hargrove et al. 1988). Studies showed yield benefits of a soybean—corn rotation system compared to continuous soybean across different tillage practices (Pierce and Rice 1988). Advances in agricultural chemicals contributed to more intensive agriculture and greater yielding crops (Luedders 1977). Use of chemical fertilizers increased over time. From 1968 to 1977 fertilizer use increased 55 % across crops grown on the USA farms (Aldrich 1983). Development of chemical herbicides and herbicide-tolerant varieties contributed to better weed control in soybean fields and facilitated tillage reduction (Duncan 1969; Specht et al. 1999; Fernandez-Cornejo and Caswell 2006). In the 1960s, Duncan (1969) noted considerable interest in a new "cultural method called no-tillage." During the 1980s, with widespread use of chemical herbicides, a reduced or no-till production system was used on 25–40 million hectares across crops in the USA (Power and Doran 1988). In the 1990s, the introduction of herbicide-tolerant soybean varieties further facilitated conservation tillage. By the late 1990s, about 60 % of the area planted with herbicide-tolerant varieties was under conservation tillage compared to 40 % of the area planted with conventional soybeans. Similarly, 40 % of hectares planted with herbicide-tolerant soybean were under no-till, compared to only 20 % of hectares planted with conventional varieties (Fernandez-Cornejo and Caswell 2006). It has been estimated that due to no-till practices facilitated by herbicide-tolerant soybean varieties, 37 million tons of soil will be saved from erosion by 2020 (Parrott and Clemente 2004). Additional benefits of reduced tillage are an increased amounts of plant debris in the field that result in greater water retention of farmland (Unger et al. 1988; Power and Doran 1988), reduction in losses of soil organic nitrogen through erosion (Power and Doran 1988), increased nitrogen uptake (Power and Doran 1988), and a decrease of SCN population density both in rotational soils (Niblack et al. 2004; Westphal et al. 2009) and under continuous soybean production (Barker et al. 2004)—all contributing to greater yields.

9.3.2.3 Market Trends and Government Policies

Market trends and governmental policies in the USA have been influencing the effort invested into soybeans from research to soybean production and utilization. In the 1920s, several Illinois farm groups guaranteed market prices for soybean grown in Illinois in order to encourage farmers to grow the new crop (Riggs 2004). The price of soybean compared to corn is another factor determining the interest of farmers to grow one or the other crop (Specht et al. 1999). Farm program policies, especially the ratio of soybean to corn loan rates in the 1996 legislation influenced an increase in soybean hectares compared to other crops (Sonka et al. 2004). Once the government subsidies for corn were phased out, investing in soybeans became more attractive for the industry (Specht et al. 1999). Increased protection of Breeder's rights has influenced crop production as it increased the seed sale prices, thereby increasing investment in research and variety development, and consequently contributing to increases in yield (Kesan and Gallo 2005). The Plant Variety Protection Act of 1970 was associated with intellectual protection of novel varieties (Kesan and Gallo 2005; Lesser 2005) and was followed by the 1980 US Supreme Court ruling on patenting of living matter (Sleper and Shannon 2003). These events gave incentives to the private sector increase investment in soybean breeding. With advances in biotechnology in the 1990s, the use of soybean patents was associated with development and commercialization of biotechnology varieties (Lesser 2005). The incentive to develop agricultural pesticides has been influenced by the regulatory approval process, namely the extent of required testing, the time from application to approval, and restrictions or bans on pesticide uses (Aldrich 1983). Generally, the number of new pesticides increased from the 1930s to the 1960s, but declined from the 1960s to the 1970s with increased regulatory requirements (Aldrich 1983).

The use of soybean has changed over time in the USA. Since the 1940s soybean has been grown for grain to be used as food (soybean oil) and feed (soybean meal). In the future, industrial and energy uses of soybean may increase, especially if mandated by legislators for political and/or environmental reasons (Sonka et al. 2004; see Redick Chap. 3). For example, the 2002 Farm Bill encouraged expansion of biodiesel (see Hughes et al. Chap. 2) use of soybean (Schmitt et al. 2004). If more of the soybean crop is grown for fuel production, then less may be available for feeding the growing human population in a sustainable manner (Egli 2008). Since 1994, federal legislation has required farmers to implement conservation management on highly erodible land (HEL) in order to receive US Department of Agriculture program benefits (Reeder 2000). This measure stimulated changes in management practices and as a result, several years later, about 55 % of soybeans were grown under conservation tillage (Reeder 2000). The 2002 Farm Bill also includes more funding for soybean farmers who use conservation practices (Schmitt et al. 2004).

9.4 Conclusions

From the beginning of the twentieth century until the present time, four distinct eras have been identified for their association with soybean production in the USA. The general trend has been a steady increase in soybean grain production. For the first two eras, this was achieved by significant expansion of land used to grow soybean and yield increases per unit area. The third era was characterized by large fluctuations of soybean hectares and steady yield increases. For the period after 1999, increases in overall soybean production have been primarily achieved by yield increases per unit area. These advancements in soybean yield were driven primarily by genetic improvements (adaptation, breeding, and advances in biotechnology), optimization of agronomic practices (mechanization, application of *Rhizobia*, disease, insect and weed control, and tillage system improvements), and by government policies (environmental and intellectual property protection). The fourfold increase in yield from 1924 to 2010 contributed to slowing the expansion in farmland usage for soybean production. With limited farmland available, new soybean varieties will need to continue to have high yield potential and perform well under reduced input. This is no small task, and if we are to be successful, continual innovations and modernization of agriculture are a priority. Considering the estimated increase in human population and its environmental impact worldwide, it is very important for the general public, environmental groups, seed industry, and policy makers to carefully evaluate the risks associated with each of their initiatives and decisions so that innovation and technology development can help to meet our future needs.

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