Chapter 14
The Importance of Herbicides for Natural Resource Conservation in the USA

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14.1 Introduction

Herbicides are used to reduce weed populations on approximately 220 million acres of US cropland (Gianessi and Reigner 2007). More than 90 % of the acreage of most field crops as well as vegetable, fruit, nut, and specialty crops are treated with herbicides annually. Herbicides were first introduced in the 1940s and by the 1970s had achieved a dominant role in managing weeds in crop fields. Prior to the introduction of herbicides, the dominant methods of weed control were cultivation and hand weeding. Although still practiced, cultivation and hand weeding have been greatly reduced in US crop production.

The use of herbicides has had major impacts on the conservation of soil, water, and energy resources in the USA. These impacts occurred largely due to the replacement of tillage with herbicides for weed control. Weed control methods used by organic growers, who do not use synthetic herbicides, also impact natural resources, which furthers our understanding of the role of herbicides in conservation.

14.2 Historical Aspects

14.2.1 Pre-1900

Many of the farming practices used by European settlers resulted in land exhaustion, erosion, declining yields, and abandonment. The kind of farming that paid best in the westward expansion of agriculture was exploitation of the soil. Land was

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cheap, labor was scarce, fields were large, and the best management was the application of a minimum amount of labor per acre. A common fault of almost every farmer was bringing more land into a farm than he could manage well (Bidwell and Falconer 1973).

By the early 1800s, northern Illinois and southern Wisconsin had become the new breadbasket of the nation as the wheat frontier pushed west. Farmers grew wheat until soil nutrients were depleted and fields became weed-choked. In the mid-nineteenth century, per-acre wheat yields in New York were just half of those from Colonial days (Montgomery 2007). Most eastern wheat farms were so overrun with weeds that a common practice became fallowing the land for 1 year while multiple cultivations were made (Bidwell and Falconer 1973).

In 1838 John Deere invented a steel plow capable of turning up the prairie's thick turf (Montgomery 2007). The steel moldboard plow became widely used throughout the country for removing weeds from fields before planting a crop in the spring. In the 1860s, the sulky cultivator put the farmer on a seat behind a pair of horses. Using three or four horses, 15 acres could be weeded in 1 day (Fussel 1992).

By the end of the 1800s, almost 11 million acres of American farmland had been abandoned due to erosion from excessive cultivation (Montgomery 2007).

14.2.2 1900–1950s

In the early 1900s, land was kept bare of vegetative cover after harvesting and plows were pulled through fields by horses or tractors to kill weeds before planting (Wimer 1946). Tillage required ten or more trips over the field (Triplett 1976). Use of the moldboard plow was followed by other equipments such as cultivators, harrows, and rotary hoes. In order to facilitate complete cultivation of cornfields, corn plants were planted far enough apart to allow for cultivation on all four sides of each plant (Pike et al. 1991).

Experiments in the late 1800s and early 1900s consistently showed that the only benefit of cultivation was weed control. In 125 experiments conducted before 1912, corn yields were equivalent between plots that had been cultivated and plots where weeds had been removed by hand (Cates and Cox 1912). Thus, in the early 1900s, agriculturalists realized that if a practical alternative method of weed control could be devised, they could dramatically reduce cultivation.

Several major problems were associated with tillage in the early 1900s, namely, bare soil was susceptible to water and wind erosion. The moldboard plow was at least partially responsible for the Dust Bowl of the 1930s (Triplett 1976). The Dust Bowl was as much about tillage as it was about drought (Lal et al. 2006). On April 14, 1935, known as Black Sunday, the most powerful of the dust storms, driven by 60 mile/h winds, struck Dodge City, Kansas, at noon, leaving the city in total darkness for 40 min (Helms 2010). A dust storm in May 1935 carried an estimated 350 million tons of soil into the air, dropping 12 million tons on Chicago (Lal et al. 2006).

After the Dust Bowl, it was estimated that because of erosion, 50 million acres of cropland in the USA had been essentially ruined for growing crops and an additional 50 million acres had been almost as severely damaged. Another 100 million acres, although still in crop production, had suffered such severe removal of fertile topsoil that they were only one-tenth to one-half as productive as they had been (Bennett and Loudermilk 1938). More than three quarters of original topsoil had been stripped from nearly 200 hundred million acres of land (Montgomery 2007). Approximately 300 million acres out of the 400 million acres of farm fields in America were eroding faster than soil was being formed. Two hundred thousand acres of abandoned Iowa farmland was eroded beyond redemption. More than three quarters of Missouri had lost at least a quarter of its original topsoil, more than 20 billion tons of dirt since the state was first cultivated (Montgomery 2007).

The Dust Bowl created a controversy about the usefulness of the moldboard plow. There were two strong but opposing schools of thought—no-till and plow tillage. The no-till movement was spearheaded by an extension worker in Ohio, Edward Faulkner, who wrote the book *Plowman's Folly*. Faulkner (1943) pointed out that weed control is the only reason for plowing and that if weeds could be controlled by some other method, erosion would be greatly reduced. It was not until the development of herbicides that an effective alternative method was available.

14.2.3 1950s–Today

Early research in the late 1940s with the first herbicide available for corn growers—2-4,D—indicated that a preemergence application could eliminate 1–3 cultivations while a postemergence application could eliminate one or more in-season cultivations (Slife et al. 1950). By the 1960s, the invention of new machines to plant through mulch combined with the widespread availability of chemical herbicides to control weeds set the stage for commercial adoption of conservation tillage (Montgomery 2008). As more effective herbicides were developed, farmers continued to reduce tillage before planting and in some cases completely eliminated postemergence cultivation (Triplett 1976).

The first sustained no-till development (see Hatfield, Chap. 4) for corn began in 1960 in Virginia and Ohio. It is not coincidental that the herbicide atrazine was introduced at about this time. Atrazine controlled many grasses common to the Midwest and was most effective when applied in the early spring. Atrazine also provided broad-spectrum residual control of many germinating weed seedlings. When combined with 2,4-D or dicamba to control perennial broadleaf species, growers could expect season-long vegetation control (Triplett and Dick 2008).

Rapid expansion in reduced tillage operations occurred in the 1990s with the introduction of efficient, high-residue seeding equipment and federal legislation requiring soil conservation on highly erodible land. Recent increases in diesel price and decreases in glyphosate price favored farmer acceptance of herbicide-intensive conservation tillage systems versus fuel-intensive traditional tillage systems (Nail

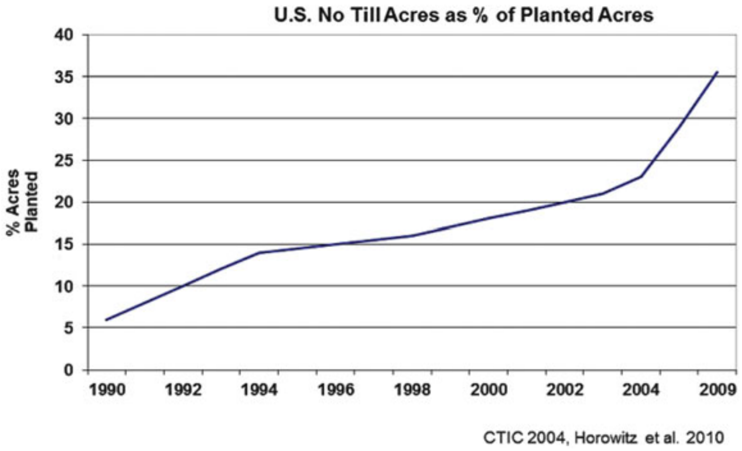

Fig. 14.1 US no-till acres as % of planted acres

et al. 2007). Between 1998 and 2005, the price of glyphosate fell by 38 % while the cost of diesel fuel went up by 160 % (Nail et al. 2007).

Approximately 36 % of US cropland planted to eight major crops—88 million acres—had no tillage operations in 2009, which represents a sixfold increase since 1990 (Fig. 14.1) (CTIC 2004; Horowitz et al. 2010). Herbicides are so crucial to conservation tillage that the National Academy of Science has concluded widespread adoption of conservation tillage would likely not have taken place without them (NRC 2000).

14.3 Soil Conservation

Herbicide use has made a significant contribution in the conservation of the nation's soil resources (see Hatfield, Chap. 4). In a no-till system, the farmer first sprays herbicides on the field to kill any growing vegetation. Seeds are planted by a machine that cuts through the plant residue on the surface, positions the seed in the soil, and covers them, all in one operation. The soil is left undisturbed except for a band made by the planter. Maintaining crop residues on the soil surface shades the soil, decreases soil water evaporation, slows surface runoff, and increases water infiltration. Thus, it simultaneously conserves soil and water (Munawar et al. 1990). Compared to the moldboard plow, no-till farming reduces soil erosion by as much as 90 % (Magleby 2003). In a 6-year experiment in North Carolina, average soil loss for no-till was 1.2 tons/acre while conventional tillage averaged 33.3 tons/acre (Raczkowski et al. 2009).

In 2007, cropland erosion in the USA averaged 5 tons/acre/year, down 44 % from the late 1930s and 32 % from 1982 (Fig. 14.2) (Magleby 2003). The total

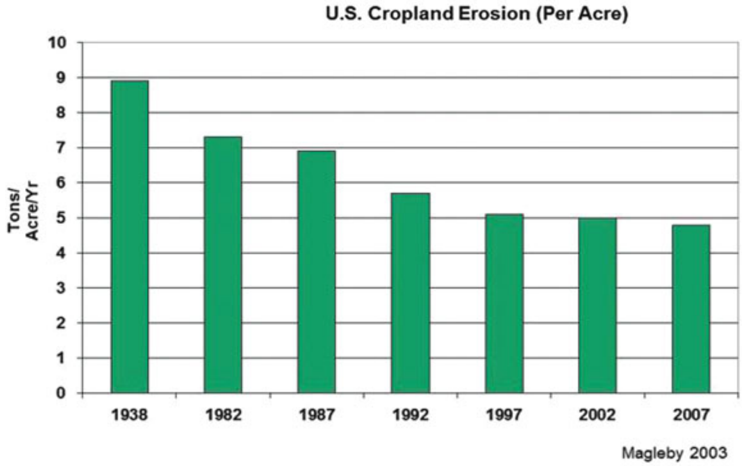

Fig. 14.2 US cropland erosion (per acre)

volume of erosion declined by 1.4 billion tons per year between 1982 and 2007 (Fig. 14.3) (USDA 2009a, b). This reduction in cropland erosion is due largely to reduction in tillage, which herbicides made possible. In the 1950s, 100 % of US corn acres were cultivated 3–4 times. In recent years only 50 % of corn acres are cultivated at all with an average of one time (USDA 1995).

14.3.1 The Pacific Northwest

The Pacific Northwest is recognized as one of the most productive, nonirrigated wheat producing areas of the world. Croplands in the Northwest are characterized by steeply rolling hills. The Northwest wheat areas have experienced some of the highest erosion rates in the USA since farming began there. By the 1970s, all of the original topsoil had been lost from 10 % of the cropland in the Palouse Basin; ¼ to ¾ had been lost from another 60 % of farmland (USDA 1979).

In the 1970s it was estimated that 110 million tons of soil were being eroded annually in the Pacific Northwest (Calvert 1990). Researchers from universities in Idaho, Oregon, and Washington and the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) launched the Solutions to Environmental and Economic Problems (STEEP) program in 1975 to develop new approaches to control erosion and water quality degradation (Kok et al. 2009). The core strategy was to shift away from conventional moldboard plow-based tillage in favor of reduced tillage and no-till methods.

Widespread use of the herbicide glyphosate for weed control has advanced conservation efforts by replacing tillage in the Pacific Northwest (Kok et al. 2009). During the 1970s, wheat required 4–8 tillage operations. Today,

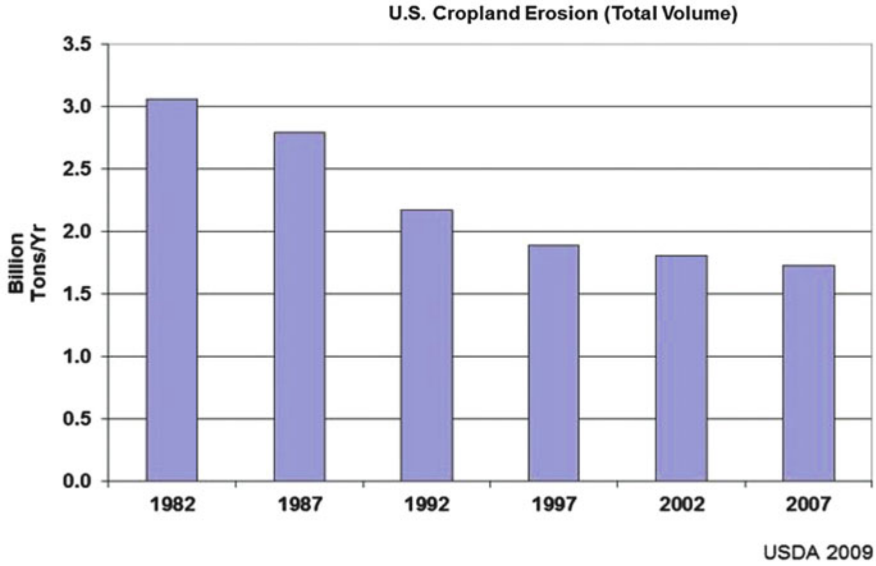

Fig. 14.3 US cropland erosion (total volume)

most growers make two glyphosate applications and two tillage passes. Prior soil loss rates of 20 tons/acre on high precipitation sites have been reduced to 5 tons/acre or less and from 12 to 6 tons/acre on intermediate precipitation sites (Kok 2007). Erosion decreased from an average of 9 tons/acre to about 4.5 tons/acre on the low precipitation sites.

14.3.2 Soil Conservation in Organic Systems

Organic farming systems mainly use tillage for weed control; therefore, soil erosion remains a concern. Organic soybean growers, for example, use up to ten tillage treatments for weeds, the same number of tillage operations used in conventional systems before the no-till era (Mutch 2008). A 2010 article (Gallagher et al. 2010) points out that organic grain production is not common to eastern Washington since a tillage-intensive organic system is not sustainable in regions with highly erodible soils (see Redick, Chap. 3).

Likewise, most crops in the Mid-Atlantic are grown on fields with steep slopes, and soil erosion is a major threat to long-term productivity (Lu et al. 1999). USDA-ARS researchers at long-term trials in Beltsville, Maryland, used the Water Erosion Prediction Model (WEPP) to compare soil erosion risks between no-till and organic corn systems (Green et al. 2005b). Chemical herbicides were applied to no-till corn while weed control for the organic system was accomplished by primary tillage, rotary hoeing, and cultivating. The WEPP model predicted greater soil loss from the organic system (43 Mg/ha/year) in comparison to the no-till system (8.5 Mg/ha/year) (Green et al. 2005a).

The soil erosion potential of no-till corn was compared to organically grown corn as part of a University of Wisconsin's Arlington Research Station research trial (WICST). Soil loss was estimated at 0.6 tons/acre in the no-till plots and at 10.0 tons/acre in the organic plots due to annual tillage and repeated cultivations (Hedtcke and Posner 2006).

14.4 Water Conservation

Agricultural operations, which account for about 90 % of freshwater consumption in the western states and over 80 % nationwide, are increasingly being asked to use less water in order to meet societal demands for other uses (Schaible and Aillery 2006). In recent years, national irrigated land has remained at about 55 million acres. However, since US farmers have adopted more water-conserving practices, the average depth of water applied has declined by one-fifth (5.4 in./acre) since 1969 (Fig. 14.4) (Gollehon and Quinby 2006).

Herbicide use has made a significant contribution in the conservation of water in US crop production. Herbicides have replaced multiple tillage operations in dry farming areas of the country, resulting in increased soil moisture content with less need for irrigation. Tillage dries out soil to the depth that the soil is disturbed; as a result, tillage causes 0.5–0.8 cm of evaporative water loss from each operation (Greb 1983). Soil moisture is lowest under conventional moldboard tillage. In a Kentucky experiment, soil moisture averaged 25 % higher in no-till versus moldboard plow tillage systems (Munawar et al. 1990). In California almond orchards, herbicides replaced the need to cultivate 16 times per season, which led to a 25 % reduced need for irrigation water (Meith and Parsons 1965).

Conservation tillage also reduces soil evaporative losses (see Alam et al., Chap. 5). Researchers have estimated that the reductions in water loss due to conservation tillage represent the equivalent of 2.6–4.3 days of water required for typical farms in Georgia. It has been estimated that the full adoption of conservation tillage on the state's crop acreage would save enough water (170.5 billion gallons/year) to meet the needs of 2.8 million people (Reeves et al. 2005). Conservation tillage has been shown to reduce runoff in Georgia by 29–46 %. This translates to a 29–46 % increase in total infiltrated rainfall (Sullivan et al. 2007).

14.4.1 The Ogallala Aquifer

The Ogallala Aquifer stretches 174,000 square miles beneath eight states from South Dakota to Texas. Ogallala groundwater is largely nonrenewable because its

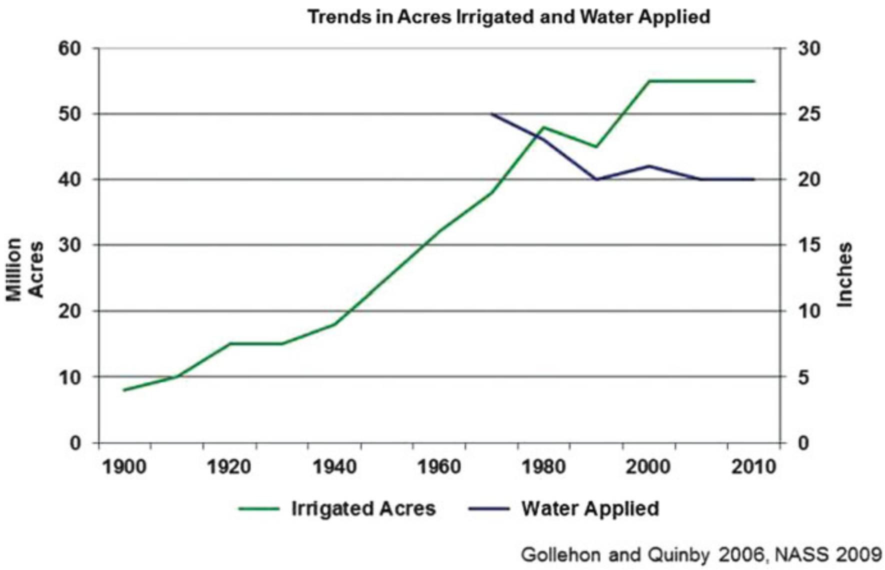

Fig. 14.4 Trends in acres irrigated and water applied

sources in the Rocky Mountains were cut off thousands of years ago. Americans are mining the Ogallala, drawing 5 trillion gallons of water from the aquifer annually (Ashworth 2006). At the current withdrawal rate, the Ogallala will be completely drained in 200 years; if completely drained, the aquifer would take more than 6,000 years to recharge. More than 90 % of the water pumped from this source is used to irrigate crops. Irrigation water from the Ogallala Aquifer supports nearly one-fifth of the wheat, corn, cotton, and cattle produced in the USA.

In Texas, conservation tillage with herbicides is 80 times less costly than making changes to irrigation equipment and has been identified as the most cost-effective method of conserving water from the Ogallala Aquifer for future generations (Amosson et al. 2005). A water savings of 1.75 in./acre/year has been estimated from shifting an acre of conventional systems to conservation tillage and substituting herbicide applications for tillage operations. On the Texas High Plains, increasing conservation tillage from 50 % of all irrigated acres in 2000 to 72 % by 2060 would lead to a cumulative water savings over the 60-year period of 2.1 million acre-feet (682 billion gallons) (Amosson et al. 2005).

Researchers in Kansas found that the use of herbicides substituted for 3–4 tillage operations and increased soil moisture content by 50 %, thereby reducing the need to irrigate (Unger et al. 1971; Jones et al. 1985). In another study, no-till corn and sorghum received from 7 to 11 in./acre less total irrigation than conventional tillage corn and sorghum (Harman et al. 1998).

14.4.2 The Great Plains

Since about 1900, researchers at state and federal experiment stations have worked to develop crop production systems better suited to the Great Plains (see Lee et al., Chap. 10). One of the practices that evolved for dryland crop production was the use of summer fallow, wherein no crop is grown during a season when a crop might normally be grown. Since most wheat is grown on soils capable of storing considerable amounts of water, fallowed soil can supply water to the crop in a subsequent season during prolonged periods without rainfall (Smika 1983). The primary reason for summer fallow is to stabilize crop production and reduce the chances of crop failure by forfeiting production in one season in anticipation that there will be at least partial compensation by increased crop production the next season (Nielsen and Vigil 2010).

To maximize the amount of stored water, a grower must control weeds throughout the fallow season. Undisturbed weeds remove 2–6 in. of soil water, with 800–2,700 lb./acre of weed biomass produced (Anderson and Smika 1984). Tillage systems, beginning in the spring with moldboard plowing and followed by shallow harrowing, were developed to remove weeds during the fallow season. Maximum tillage resulted in only 19 % of the fallow year's precipitation being stored in the soil. Experimentation with herbicides to remove weeds during the fallow period began in 1948 with contact types such as 2,4-D and accelerated after 1962 with the introduction of new contact and preemergence types such as atrazine, glyphosate, and paraquat (Greb 1979). Atrazine became the standard herbicide used in the fallow period for making the transition from wheat to sorghum or corn in Great Plains cropping systems (Regehr and Norwood 2008). The use of herbicides reduced the need for tillage operations to 2–4 per season and resulted in storage of 33 % of the fallow year's precipitation (Peterson and Westfall 2004). The extra water stored in the soil with the use of herbicides was reflected in an average 21 % increase in winter wheat grain yield over conventional spring tillage fallow (Greb and Zimdahl 1980).

In rainfed, dryland farming areas of the Central Great Plains, the substitution of herbicides for tillage has resulted in preserving enough soil moisture to make sustained annual production of crops possible without the need for a fallow year to store soil water. Fallow acreage in the USA has declined significantly in recent decades (Fig. 14.5). Improved herbicide options have eliminated the need for fallow years in all but the driest areas of the Great Plains (Derksen et al. 2002). Most data indicate that there can be as much or more stored water in no-tilled managed soils after a spring wheat harvest as there would be if fallow is continued until fall wheat planting (Peterson and Westfall 2004). As a result, there has been an expansion of summer corn and sorghum acreage in the Great Plains.

Sorghum grain yields more than tripled from 840 to 3,760 kg/ha in studies at the USDA-ARS Research Laboratory in Bushland, Texas from 1939 to 1997. Soil water content at planting was the dominant factor contributing to yield increases over time. Most increases in soil water content at planting occurred after 1970,

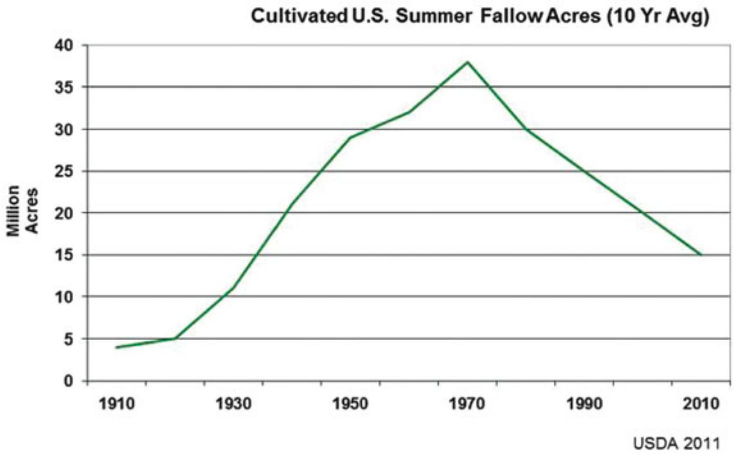

Fig. 14.5 Cultivated US summer fallow acres (10 year avg)

when improved herbicides became available and conservation tillage began receiving major emphasis (Unger and Baumhardt 1999).

14.4.3 Rice Production

During the twentieth century, the only method to suppress the weed red rice in commercial rice production was by water seeding. Rice producers were aware that if the fields could be kept flooded during the season, most of the red rice seed in the soil would not have the opportunity to germinate. Aerial application of pre-germinated rice seed was the best red rice control method available to the rice farmers at the time (Harrell 2007). After the release of Clearfield rice varieties in 2003, water seeding was no longer the only effective management practice for red rice control. Red rice could now be controlled with the use of imidazolinone herbicides; therefore, a shift toward more drill-seeded rice acres began. The Clearfield technology was used on 60 % of the southern US rice acreage in 2010 (Linscombe 2007). Drill-seeded rice fields require 0.96 acre-inches less water than water-seeded fields (Manley 2008).

Traditionally, rice production in the Southeast has involved intensive cultivation. However, new herbicides have made it possible for rice to be planted using less tillage, even no-till methods. Recently in Texas, it has been estimated that adoption of no-till rice management would save 2.5 acre-inches of water by increasing soil moisture and decreasing evaporation owing to residue cover on the soil surface (Yang and Wilson 2011).

14.4.4 Water Conservation in Organic Systems

A common practice for irrigated organic crop systems is the preplant germination of weeds. Preplant germination of weeds (pregermination) involves the use of irrigation to stimulate weed seed germination before planting the crop. The emerged seedlings are then killed by shallow cultivation, flaming, or an organic herbicide, such as vinegar. Waiting 14 days after the time of a preplant irrigation allows for weeds to emerge and for the field to dry enough to permit use of shallow tillage to control emerged weeds. This method removes up to 50 % of the weeds that would have otherwise emerged in the subsequent crop (University of California 2009). The extra irrigation application to germinate weeds before planting means that organic crop producers use more water per acre than conventional growers (Southeast Farm Press 2012). A recent survey of organic and conventional cotton farmers on the Texas High Plains showed that the organic growers used 78 % more water because of the need for additional water to maximize yield potential (Funtanilla et al. 2009).

14.5 Energy Conservation

For agricultural production, energy use is classified as either direct or indirect (embodied). Direct energy use in agriculture is primarily petroleum-based fuels used to operate tractors for preparing fields, planting, cultivating, and harvesting crops, as well as machinery for applying pesticides (Schnepf 2004). Indirect energy is consumed off the farm for manufacturing fertilizers (see Reetz, Chap. 15), pesticides, and machinery. Modern pesticides and fertilizers are almost entirely produced from crude petroleum or natural gas products. The total embodied energy input is thus both the material used as feedstock and the energy used in the manufacturing process (West and Marland 2002).

The transition from animal power (horses and mules) to machine power (tractors) occurred between 1915 and 1950 and resulted in a sixfold increase in energy use in agriculture. Energy inputs increased faster than outputs, leading to a decline in energy productivity (Cleveland 1995b). The per gallon cost of fuel for farm operations remained inexpensive and constant through the 1950s and 1960s, but increased dramatically following the energy price shocks of 1973–74 and 1980–81 and has increased again in recent years (Fig. 14.6).

Energy price increases significantly altered the pattern of energy use on US farms, resulting in a large decrease in direct energy use (Fig. 14.7). Since the late 1970s, American agriculture's direct energy use has declined by 26 %, while the energy used to produce the fertilizers and pesticides used on farms has declined by 31 % (Schnepf 2004). In the USA, the combined use of gasoline and diesel fuel in agriculture fell from its historical high of 29 billion liters in 1973 to 17 billion in

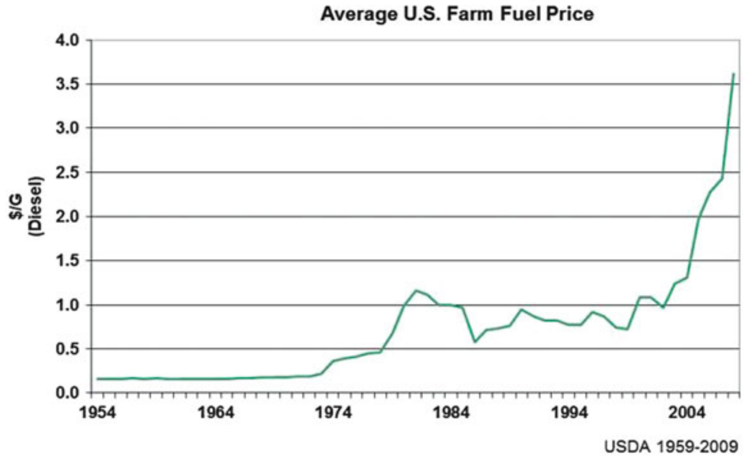

Fig. 14.6 Average US farm fuel price

2002, a decline of about 40 %. One reason for this change was a shift to minimum and no-till practices on roughly two-fifths of US cropland (Triplett and Dick 2008).

The decline in agricultural energy use resulted in a significant reduction in agriculture's share of the nation's total energy usage. In 1978, the total direct and indirect energy use in agriculture accounted for about 5 % of US energy use (Cleveland 1995b). Currently, the direct energy use in US agricultural production (encompassing both crops and livestock) represents about 1 % of total US energy consumption while the indirect energy use in the manufacture of the pesticides and fertilizers used on US farms represents about 0.5 % (Schnepf 2004).

The large declines in agricultural energy use since the late 1970s have not come at the expense of lower output. Since 1973, farm output has grown 63 % while direct energy consumption has declined 26 %. Agriculture has made dramatic efficiency gains in energy use. As a result, direct energy use per unit of agricultural output is 50 % less today than it was in the 1970s (Fig. 14.8) (USDA 2012).

A 2010 analysis of energy use in corn production in nine Midwestern states concluded that the amount of diesel used per acre has declined by 33 % since 1996 while the embodied energy in pesticides has declined 50 % since 1991 (Shapouri et al. 2010). Because of increased corn yields, the reductions in energy required to grow a bushel of corn declined even more: 48 % less diesel and 62 % less embodied energy in the form of pesticides were needed to produce a bushel of corn.

One of the main factors accounting for the decrease in energy use in agriculture has been the substitution of herbicides for tillage to control weeds (Brown et al. 2008). The energy price increases stimulated an increase in conservation tillage that reduces fuel consumption relative to conventional tillage (Cleveland 1995a). The additional energy embodied in the herbicides used in reduced-tillage systems does not nearly offset the energy conserved by reduced tillage (Frye and Phillips 1980). Reduced tillage dramatically reduces direct fuel consumption

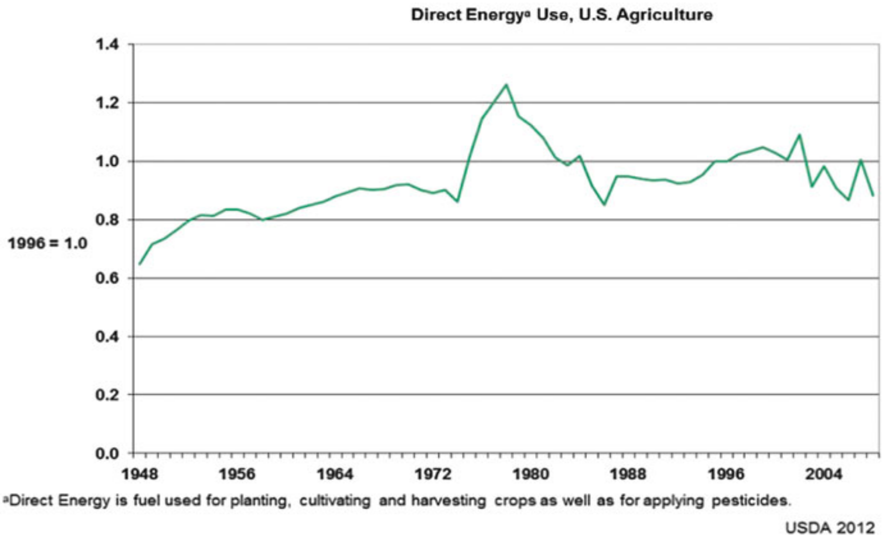

Fig. 14.7 Direct energy[a] use, US agriculture

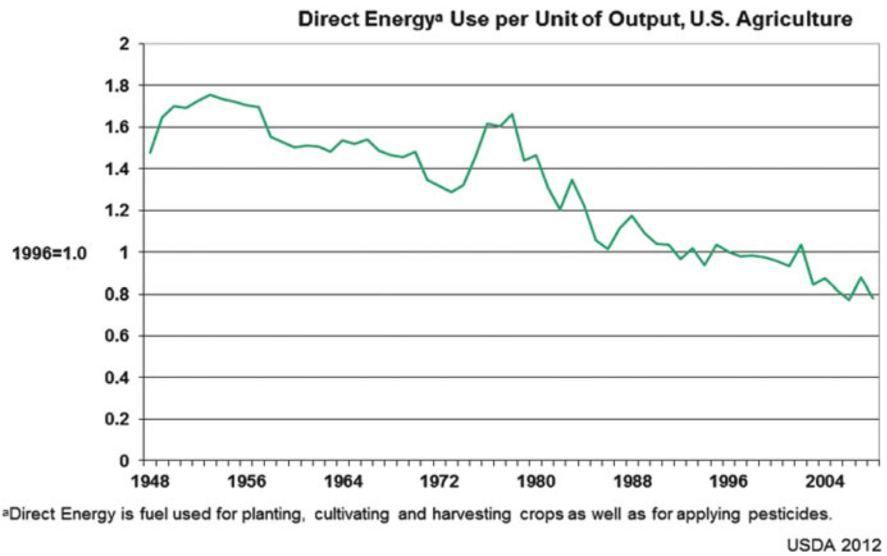

Fig. 14.8 Direct energy[a] use per unit of output, US agriculture

relative to conventional tillage with the moldboard plow. Not only does one herbicide application substitute for several tillage trips, tillage equipment is also heavier than herbicide sprayers and needs more energy to pull steel implements through the soil. A moldboard plow consumes 17 times more diesel fuel per acre than an herbicide sprayer. A row-crop cultivator requires four times more gallons per acre each trip than an herbicide sprayer (Hanna 2001).

A 2009 comparison of direct and embodied energy use between conventional tillage and no-till soybeans in Kansas indicated an overall reduction of 24 % with the no-till system (Williams et al. 2009). Direct energy consumption is 55 % lower in the no-till system, although embodied energy use is higher, primarily due to increased herbicide use.

The Conservation Technology Information Center (CTIC) has estimated a savings of 3.9 gallons of direct fuel use per acre by going from conventional tillage to no-till (USDA 2006). By 2008, the number of no-till acres reached 88 million (Horowitz et al. 2010), implying an annual fuel savings of 343 million gallons.

14.5.1 Energy Conservation in Organic Systems

Both conventional and organic agriculture depend on fossil fuels. Several long-term research trials at US locations have compared the energy inputs between growing corn and soybeans with conventional, no-till, and organic practices. These studies include comparisons of direct and embodied energy use.

In a study from 1992 to 2000 at the University of Wisconsin's WICST, no-till corn required 35 % less direct fuel for field operations than organic corn (Oosterwyk and Posner 2000). The primary difference in field operations between the no-till and organic systems was the amount of tillage needed; typically 11 tillage operations or rotary hoeings were made in organic corn versus one tillage operation in no-till corn (Oosterwyk and Posner 2000). For soybeans, the direct use fuel requirement at WICST was 68 % higher in the organic soybeans. The organic soybeans were typically cultivated 12 times in comparison to no cultivations in the no-till soybeans. The total amount of embodied energy in pesticides plus direct fuel use in no-till corn was 7 % less than the fuel use in the organic corn (Oosterwyk and Posner 2000). For soybeans, the organic system used 31 % more total energy (direct plus embodied) than the no-till system. The embodied energy requirements for the herbicides used in no-till were offset by the higher fuel use required for field operations in the organic system.

At the ARS Swan Lake Research Farm's long-term cropping systems field study in Minnesota, weed control in the organic corn and soybeans included the in-crop use of a rotary hoe two times early in the season followed by interrow cultivation 1–3 times until canopy closure. The organic treatments used 43 % more direct fuel than the conventional treatments (Archer et al. 2007).

In a study from 1989 to 2007 at Michigan State University's Long Term Ecological Research (MSU-LTER) site, direct fuel use in the MSU-LTER organic system averaged 58 %, 93 %, and 28 % more than in the no-till system for corn, soybean, and wheat, respectively (Robertson et al. 2000). The organic plots were prepared with the moldboard plow followed by 3–4 passes with cultivators and rotary hoes; weeds in the no-till plots were controlled with 2–3 herbicide applications (Davis et al. 2005).

A 2010 study in Pennsylvania modeled the energy use of a conventional no-till system and three organic crop systems (Ryan 2010). The use of diesel fuel was twice as great in the organic systems (74 l/ha) versus the no-till system (38 l/ha). The energy from direct fuel use in the organic systems averaged 67 % more than the combined total of direct fuel use and embodied energy from herbicides used in the conventional no-till system (Ryan 2010).

An organic corn system in Beltsville, Maryland, uses twice as much energy operating machinery as a no-till system uses in operating machinery and herbicide usage (Cavigelli et al. 2009).

14.6 Conclusions

Herbicide use has made a significant contribution in the conservation of natural resources in the USA. Is high-yield crop production depleting the nation's natural resources that are necessary to maintain crop production into the future? A pessimistic view is not warranted. The negative consequences of resource depletion persisted in the USA through the 1940s, with high soil loss due to tillage for weed control. Clearly, American farmers were not on a sustainable agricultural path. Since the introduction of herbicides for controlling weeds, tillage on US acres has been significantly reduced, which has resulted in more soil, water, and energy conservation and less fallow acreage.

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