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THE IMPORTANCE OF HERBICIDES FOR NATURAL RESOURCE CONSERVATION IN THE U.S.

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Introduction

Herbicides are used to reduce weed populations on approximately 220 million acres of U.S. cropland [1]. 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 U. S. crop production.

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

Historical Aspects

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 cheap, labor was scarce, fields were large, and the best management was the application of a minimum of labor per acre. A common fault of almost every farmer was bringing more land into a farm than he could manage well [2].

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 [3]. Most eastern wheat farms were so overrun with weeds that a common practice became fallowing the land for one year while multiple cultivations were made [2].

In 1838 John Deere invented a steel plow capable of turning up the prairie’s thick turf [3]. 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, fifteen acres could be weeded in a day [4].

By the end of the 1800s, almost 11 million acres of American farmland had been abandoned because of erosion damage caused by excessive cultivation [3].

1900-1950s

In the early 1900s, plows were pulled by horses or tractors through fields to kill weeds [5]. The land was kept bare of vegetative cover after harvesting. Tillage required 10 or more trips over the field [6]. Use of the moldboard plow was followed by other equipment 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 [7]. Several major problems were associated with tillage in the early 1900s. Bare soil was susceptible to water and wind erosion.

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 [8]. Thus, in the early 1900s, the realization had been made that if a practical alternative method of weed control could be devised, cultivation could be dramatically reduced.

The moldboard plow was at least partially responsible for the Dust Bowl of the 1930s [6]. The Dust Bowl was as much about tillage as it was about drought [9]. On April 14, 1935, known as Black Sunday, the most powerful of the dust storms, driven by 60 mile per hour winds, struck Dodge City, Kansas at noon, leaving the city in total darkness for 40 minutes [10]. A dust storm in May 1935 carried an estimated 350 million tons of soil into the air, of which 12 million tons were dropped on Chicago [9].

In the late 1930s, it was estimated that because of erosion, 50 million acres of cropland in the US 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 [11]. More than three-quarters of original topsoil had been stripped off nearly 200 hundred million acres of land [3]. 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 twenty billion tons of dirt since the state was first cultivated [3].

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* published in 1943 [12]. In the book Faulkner pointed out that the only reason for plowing was weed control 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.

1950s-Today

Early research in the late 1940s with the first herbicide (2,4-D) available for corn growers indicated that a preemergence application could eliminate 1-3 cultivations while a postemergence application could eliminate one or more in-season cultivations [13]. 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 [14]. As more effective herbicides were developed, farmers continued to reduce tillage before planting and in some cases completely eliminated postemergence cultivation [6].

The first sustained no-till development 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, season-long vegetation control could be expected [15].

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 [16]. Between 1998 and 2005, the price of glyphosate fell by 38% while the cost of diesel fuel went up by 160% [16].

Approximately 36% of US cropland (88 million acres) planted to eight major crops had no tillage operations in 2009, which represents a six-fold increase since 1990 (Figure 1) [17] [18]. 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 [19].

Soil Conservation

Herbicide use has made a significant contribution in the conservation of the nation’s soil resources. 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 [20]. Compared to the moldboard plow, no-till farming reduces soil erosion by as much as 90% [21]. In a six-year experiment in North Carolina, average soil loss for no-till was 1.2 ton/acre while conventional tillage averaged 33.3 ton/acre [22].

In 2007, cropland erosion in the U. S. averaged 5 tons/acre per year, down 44% from the late 1930s, and 32% from 1982 (Figure 2) [21]. The total volume of erosion declined by 1.4 billion tons per year between 1982 and 2007 (Figure 3) [23]. This reduction in erosion from cropland is due largely to reduction in tillage, which was made possible with herbicides. In the 1950s, 100% of U.S. 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 [24].

The Pacific Northwest

The Pacific Northwest is recognized as one of the most productive, non-irrigated 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 US since farming began there. By the 1970s, all of the original topsoil had been lost from 10% of the cropland in the Palouse basin; one-fourth to three-fourths had been lost from another 60% of farmland [25].

In the 1970s it was estimated that in the Pacific Northwest 110 million tons of soil were being eroded annually [26]. The STEEP program (Solutions to Environmental and Economic Problems) was launched in 1975 to develop new approaches to control erosion and water quality degradation [27]. 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 glyphosate herbicide for weed control has advanced conservation efforts by replacing tillage in the Pacific Northwest [27]. During the 1970s wheat required 4 to 8 tillage operations. Today, most growers have reduced tillage passes to two. Typically, two glyphosate applications are made. Prior soil loss rates of 20 tons/acre on high precipitation sites have been reduced to 5 tons/acre or less and from 12 tons/acre to 6 tons/acre on intermediate precipitation sites [28]. Erosion decreased from an average of 9 tons/acre to about 4.5 tons/acre on the low precipitation sites.

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 10 tillage treatments for weeds, the same number of tillage operations used in conventional systems before the no-till era [29]. A 2010 article 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 [30].

In the Mid-Atlantic, most crops are grown on fields with steep slopes and soil erosion is a major threat to long-term productivity of agricultural lands [31]. 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 [32]. 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/yr) in comparison to the no-till system (8.5 Mg/Ha/yr) [33].

The soil erosion potential of no-till corn was compared to organically-grown corn as part of a University of Wisconsin 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 [34].

Water Conservation

Agriculture, which accounts for about 90% of freshwater consumption in the Western States and over 80% nationwide, is increasingly being asked to use less water in order to meet societal demands for other uses [35]. In recent years, national irrigated land has remained at about 55 million acres (Figure 4). However, since U.S. farmers have adopted more water-conserving practices, the average depth of water applied has declined by one-fifth (5.4 inches per acre) since 1969 (Figure 4) [36].

Herbicide use has made a significant contribution in the conservation of water in U.S. crop production. Herbicides have replaced multiple tillage operations in dry farming areas of the U.S. 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 to 0.8 cm of evaporative water loss from each operation [37]. 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 [20]. In California almond orchards, herbicides replaced the need to cultivate 16 times per season, which led to a 25% reduced need for irrigation water [38]. Conservation tillage also reduces soil evaporative losses. 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 [39]. Conservation tillage has been shown to reduce runoff in Georgia by 29-46%. This translates to a 29-46% increase in total infiltrated rainfall [40].

The Ogallala Aquifer

The Ogallala Aquifer stretches across eight states from South Dakota to Texas and underlies about 174,000 square miles. Ogallala groundwater is largely non-renewable because its sources in the Rocky Mountains were cut off thousands of years ago. Americans are mining the Ogallala, drawing five trillion gallons of water from the aquifer annually [41]. If completely drained, it would take more than 6000 years to refill the Ogallala Aquifer. At the current withdrawal rate, the Ogallala aquifer will be completely drained in 200 years. More than 90% of the water pumped 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 U.S.

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 [42]. A water savings of 1.75 inches per acre per year has been estimated from shifting an acre of conventional systems to conservation tillage with herbicide applications substituting 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) [42].

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 withdraw irrigation water [43][44]. In another study, no-till corn and sorghum received from 7 to 11 inches per acre less total irrigation than conventional tillage corn and sorghum [45].

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. 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 [46]. 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 [47].

To maximize the amount of stored water, weeds must be controlled throughout the fallow season. Undisturbed weeds remove 2 to 6 inches of soil water, with 800 to 2700 pounds per acre of weed biomass produced [48]. Tillage systems, beginning in the spring with moldboard plowing and followed by shallow harrowing, were developed to remove weeds during the fallow season. The maximum tillage system resulted in 19% of the fallow year's precipitation being stored in the soil. Experimentation with herbicides to remove weeds during the fallow period began during 1948-55 with contact types such as 2,4-D and accelerated after 1962-1967 with the introduction of new contact and preemergence types such as atrazine, glyphosate and paraquat [49]. 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 [50]. The use of herbicides reduced the need for tillage operations to 2-4 per season and resulted in storage of 33% of the precipitation [51]. 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 [52].

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 possible the sustained annual production of crops without the need for a fallow year to store soil water. Fallow acreage in the U.S. has declined significantly in recent decades (Figure 5). Improved herbicide options have eliminated the need for fallow in all but the driest areas of the Great Plains [53]. Most data indicate that there can be as much or more stored water in no-tilled managed soils in the spring after wheat harvest as there would be if fallow is continued until fall wheat planting [51]. 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 3760 kg/ha in studies at the USDA-ARS Research Laboratory, Bushland, Texas from 1939-1997. 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 when improved herbicides became available and using conservation tillage received major emphasis [54].

Rice Production

During the 20th century, the only method to suppress red rice in commercial rice production was by water seeding. Most 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 [55]. After the release of Clearfield rice varieties in 2003, water seeding was no longer the only management practice that could be used for red rice control. Red rice could now be controlled with the use of imidazolinone herbicides, and a shift toward more drill-seeded rice acres began to occur. The Clearfield technology was used on 60% of the southern U.S. rice acreage in 2010 [56]. Drill-seeded rice fields require 0.96 acre-inches less water than water-seeded fields [57].

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 in rice fields would save 2.5 acre-inches of water due to increased soil moisture and decreased evaporation due to residue cover on the soil surface [58].

Water Conservation in Organic Systems

A common practice for irrigated organic crops is the preplant germination of weeds. Preplant germination of weeds (pregermination) involves the use of an 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 [59]. The extra irrigation application to germinate weeds before planting means that organic crop producers use more water per acre than do conventional growers [60]. 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 [61].

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 [62]. Indirect energy is consumed off the farm for manufacturing fertilizers, 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 [63].

The transition from animal power (horses and mules) to machine power (tractors) occurred between 1915 and 1950 and resulted in a six-fold increase in energy use in agriculture. Energy inputs increased faster than outputs, leading to a decline in energy productivity [64]. The per gallon cost of fuel for farm operations remained inexpensive and constant through the 1950s and 60s, but increased dramatically following the energy price shocks of 1973-74 and 1980-81and has increased again in recent years (Figure 6).

Energy price increases significantly altered the pattern of energy use on U.S. farms, resulting in a large decrease in direct energy use (Figure 7). Since the late 1970s, the direct use of energy by agriculture has declined by 26%, while the energy used to produce the fertilizers and pesticides used on American farms has declined by 31% [62]. In the U.S., 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 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 U.S. cropland [15].

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 U.S. energy use [64]. 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 to manufacture the pesticides and fertilizers used on U.S. farms represents about 0.5% [62].

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 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 (Figure 8) [65].

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 [66]. 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 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 [67]. The energy price increases stimulated an increase in conservation tillage that reduces fuel consumption relative to conventional tillage [68]. The additional energy embodied in the herbicides used in reduced-tillage systems does not nearly offset the energy conserved by reduced tillage [69]. Reduced tillage dramatically reduces direct fuel consumption 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 [70].

A 2009 comparison of direct and embodied energy use between conventional tillage and no-tillage soybeans in Kansas indicated an overall reduction of 24% with the no-tillage system [71]. Direct energy consumption is 55% lower in the no-tillage system, although embodied energy use is higher, primarily due to increased herbicide use.

The Conservation Tillage 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 [72]. By 2008, the number of no-till acres reached 88 million [18], implying an annual fuel savings of 343 million gallons.

Energy Conservation in Organic Systems

Both conventional and organic agriculture depend on fossil fuels. Several long-term research trials at U.S. 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 1992-2000 at the University of Wisconsin's Arlington Research Station (WICST), no-till corn required 35% less direct fuel for field operations than organic corn [73]. The primary difference in field operations between the no-till and organic systems was the number of tillage operations, with typically 11 tillage/rotary hoeings in organic corn versus one tillage operation in no-till corn [73]. 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 [73]. 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 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 inter-row cultivation 1-3 times until canopy closure. The organic treatments used 43% more direct fuel than the conventional treatments [74].

In a study from 1989-2007 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 [75]. 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 [76].

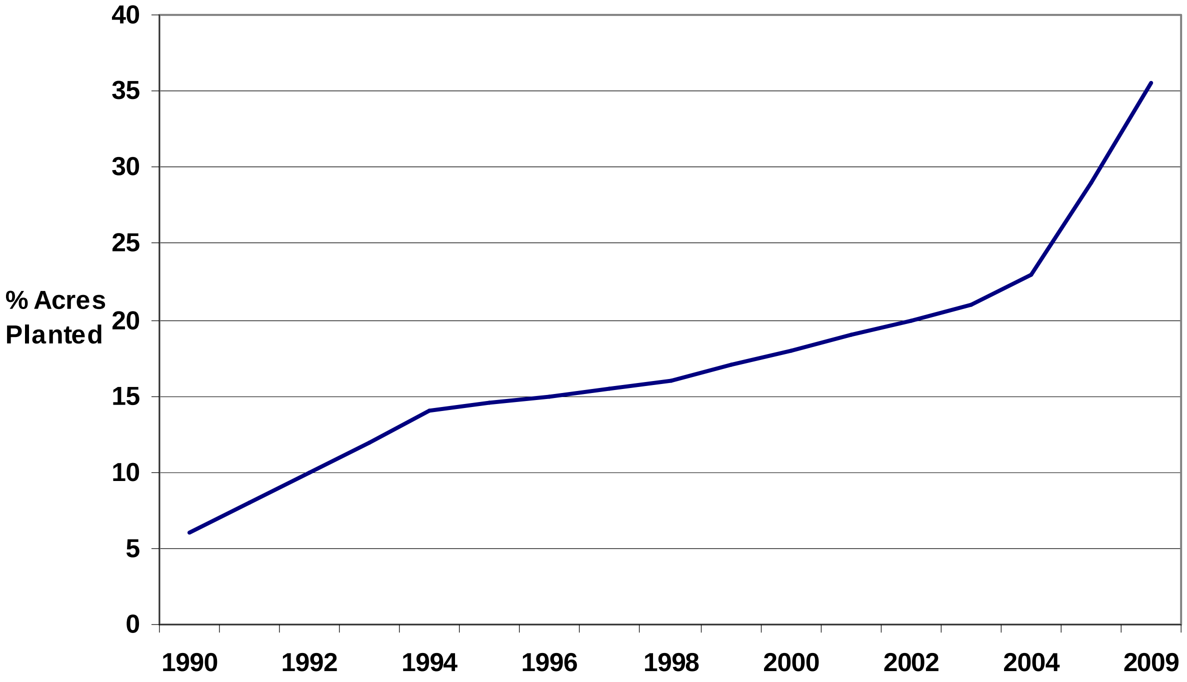
A 2010 study in Pennsylvania modeled the energy use of a conventional no-till system and three organic crop systems [77]. The use of diesel fuel was twice as great in the organic systems (74 l/ha) versus the no-till system (38 l/ha). The energy from direct fuel use in the organic systems averaged 67% greater than the combined total of direct fuel use and energy embodied in the herbicides used in the conventional no-till system [77].

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 [78].

Conclusions

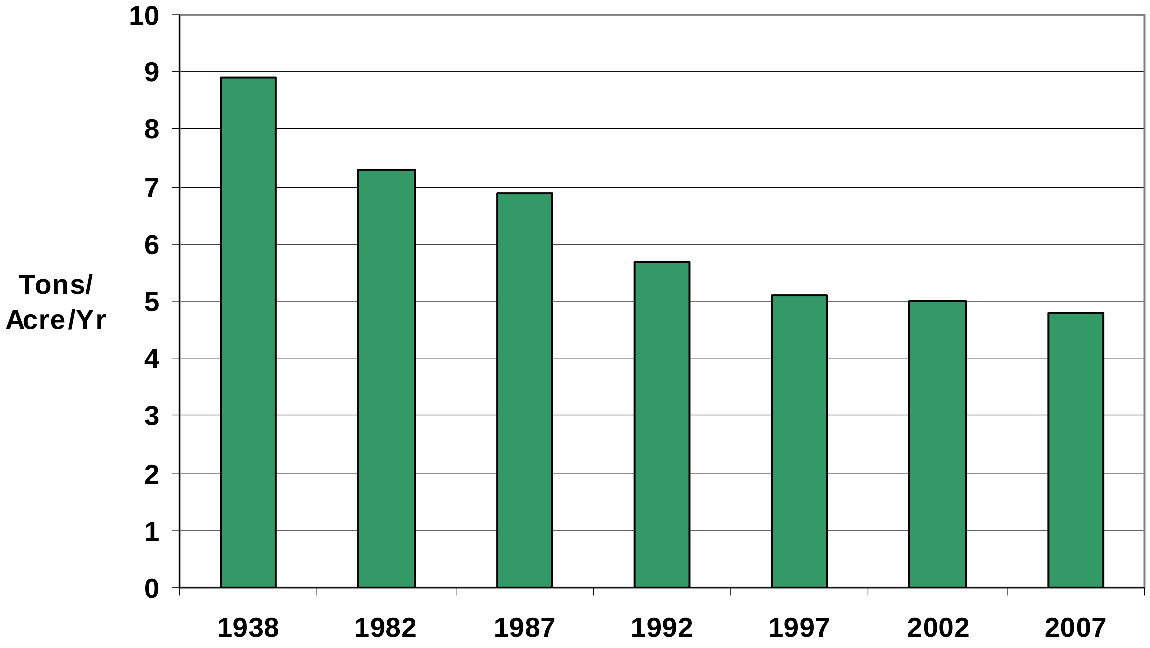
Herbicide use has made a significant contribution in the conservation of natural resources in the U.S. Is high yield crop production depleting the nation's natural resources that will be necessary to maintain crop production into the future? A pessimistic view is not warranted. The negative resource consequences resulting from farming persisted in the U.S. through the 1940s, with high soil losses due to tillage for weed control. Clearly, the U.S. was not on a sustainable agricultural path until the introduction of herbicides for controlling weeds. Since the introduction of herbicides, the amount of tillage has been significantly reduced, which has resulted in less soil erosion, less water use, less fallow acreage, and less energy use. U.S. farmers are conserving soil, water, and energy resources due to herbicide use.

Figure 1: U.S. No Till Acres as % of Planted Acres



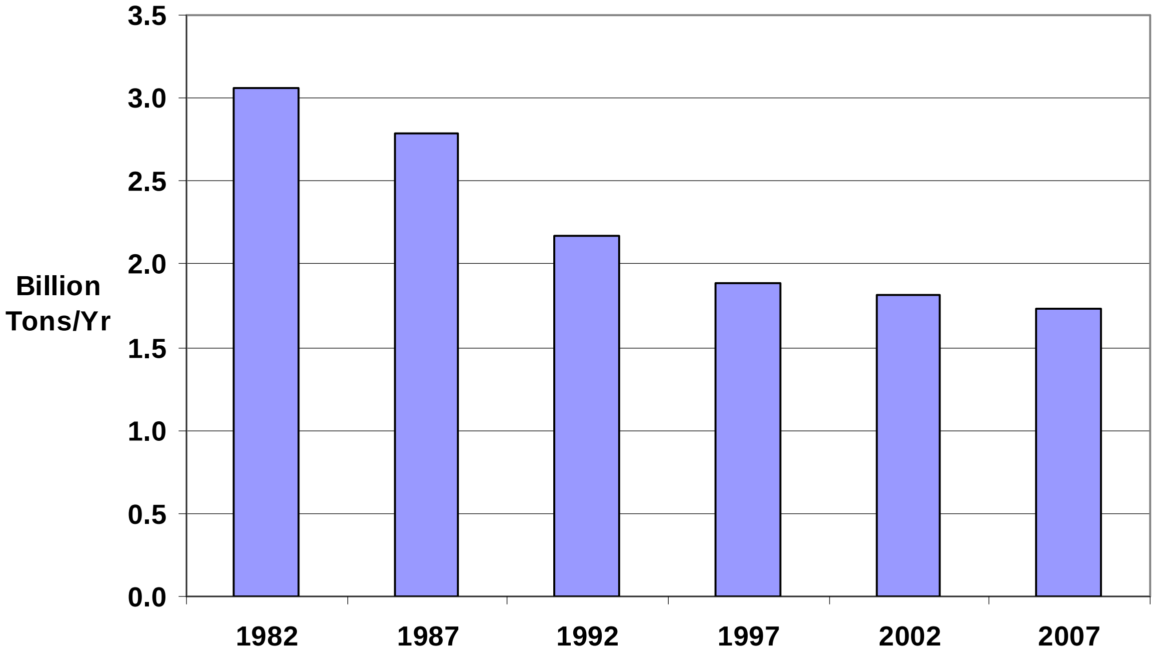
Source [17] [18]

Figure 2: U.S. Cropland Erosion (Per Acre)



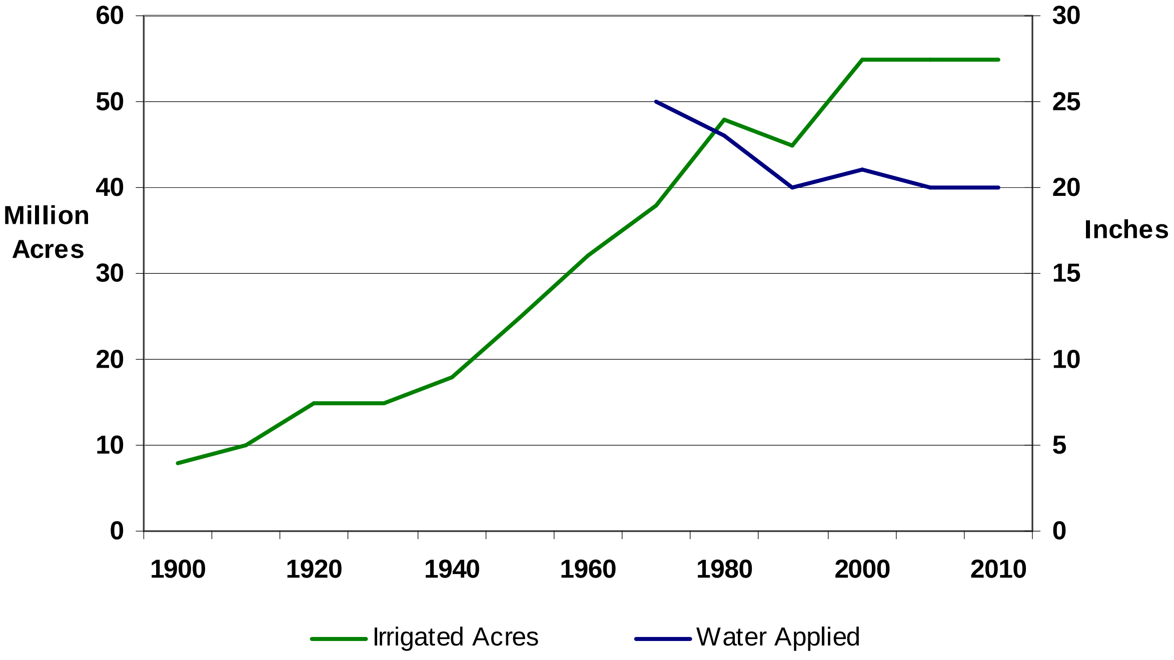
Source [21]

Figure 3: U.S. Cropland Erosion (Total Volume)



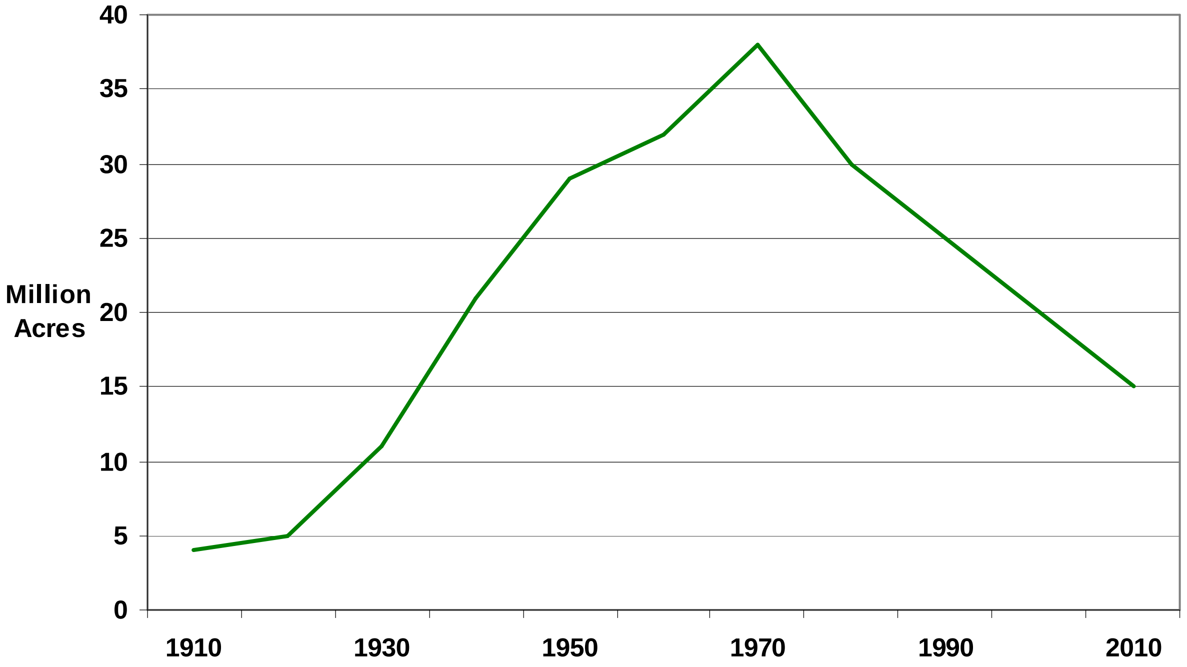
Source [23]

Figure 4: Trends in Acres Irrigated and Water Applied



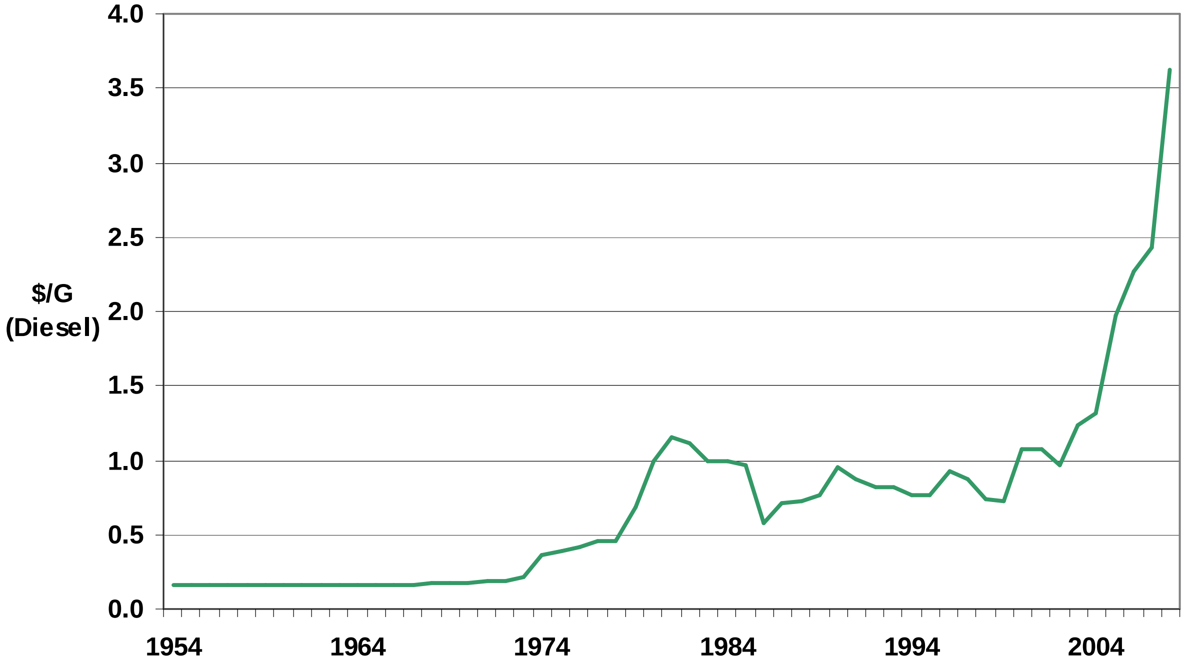
Source [36] [79]

Figure 5: Cultivated Summer Fallow Acres: U.S.



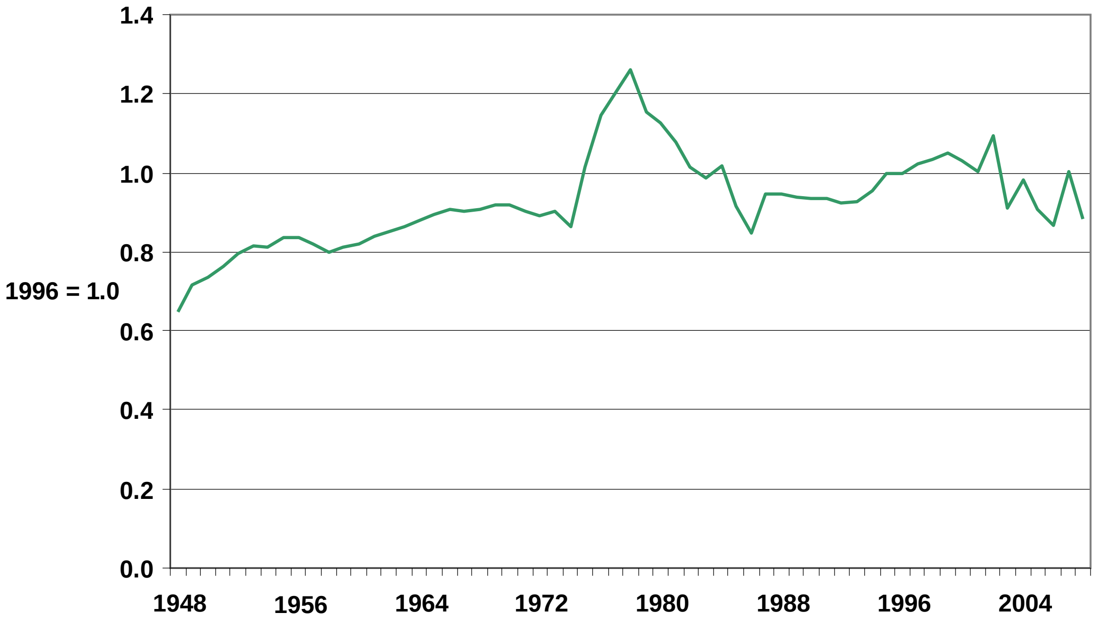
Source [80]

Figure 6: US Farm Fuel Price



Source [81]

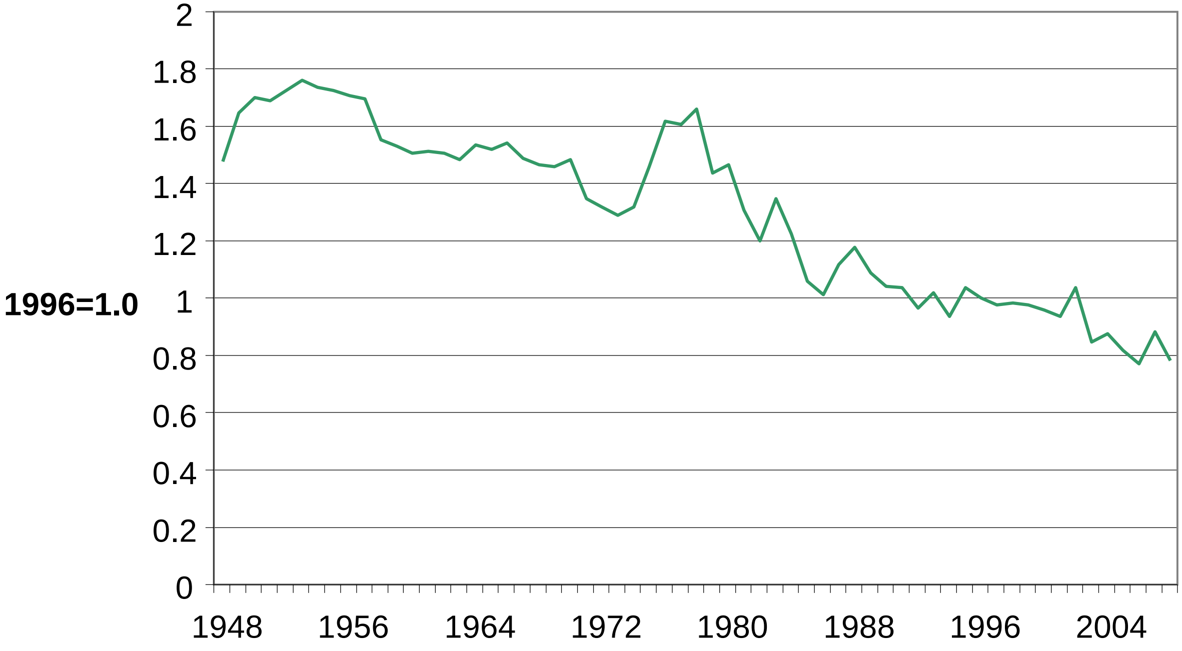
Figure 7: Direct Energy[a] Use, US Agriculture



[a] Direct Energy is fuel used for planting, cultivating and harvesting crops as well as for applying pesticides.

Source [65]

Figure 8: Direct Energy[a] Use per Unit of Output, US Agriculture



[a] Direct Energy is fuel used for planting, cultivating and harvesting crops as well as for applying pesticides.

Source [65]

References

1. Gianessi, L.P. and N.P. Reigner. 2007. The value of herbicides in U.S. crop production. *Weed Technology*. 21:559-566.
2. Bidwell, P.W. and J.I Falconer. 1973. *History of Agriculture in the Northern United States, 1620 – 1860*. Augustus M. Kelley Publishers.
3. Montgomery, D.R. 2007. *Dirt: The Erosion of Civilizations*. University of California Press.
4. Fussel, B. 1992. *The Story of Corn*. University of New Mexico Press.
5. Wimer, D.C. 1946. *Why Cultivate Corn?* University of Illinois, College of Agriculture. Circular 597.
6. Triplett, G.B. 1976. History, principles and economics of crop production with reduced tillage systems. *Annals of the Entomological Society of America.* 289-291.
7. Pike, D.R., *et al.* 1991. A case study of herbicide use. *Weed Technology*. July-September.
8. Cates, J.S. and H.R. Cox. 1912. *The Weed Factor in the Cultivation of Corn*. Bureau of Plant Industry Bulletin No. 257. U.S. Department of Agriculture.
9. Lal, R., D.C. Reicosky and J.D. Hanson. 2006. Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil and Tillage Research*. 93:1-12.
10. Helms, D. 2010. Hugh Hammond Bennett and the creation of the Soil Conservation Service. *Journal of Soil and Water Conservation*. 65(2):37A-47A.
11. Bennett, H.H. and W.C. Loudermilk. 1938. General aspects of the soil-erosion problem. *Yearbook of Agriculture*. U.S. Department of Agriculture.
12. Faulkner, E.H. 1943. *Plowman's Folly*. University of Oklahoma Press.
13. Slife, F.W., *et al.* 1950. *Controlling Weeds in Corn with 2,4-D*. University of Illinois College of Agriculture. Circular 652.
14. Montgomery, D.R. 2008. Agriculture's no-till revolution? *Journal of Soil and Water Conservation*. 63(3):64A-65A.
15. Triplett, Jr., G.B. and W.A. Dick. 2008. No-tillage crop production: a revolution in agriculture! *Celebrate the Centennial [A Supplement to Agronomy Journal]*. S:153.
16. Nail, E.L., D.L. Young and W.F. Schillinger. Diesel and glyphosate price changes benefit the economics of conservation tillage versus traditional tillage. *Soil and Tillage Research*. 94:321-327.
17. CTIC. 2004. National Crop Residue Management Survey. Available at: http://www.ctic.purdue.edu.
18. Horowitz, J., R. Ebel and K. Ueda. 2010. *"No-Till" Farming is a Growing Practice*. U.S. Department of Agriculture, Economic Research Service. Economic Information Bulletin No.70.

19. National Research Council. 2000. *The Future Role of Pesticides in US Agriculture*. National Academy Press, Washington, D.C.
20. Munawar, A., R.L. Blevins, W.W. Frye and M.R. Saul. 1990. Tillage and cover crop management for soil water conservation. *Agronomy Journal*. 82:773-777.
21. Magleby, R. 2003. Soil Management and Conservation. *Agricultural Resources and Environmental Indicators*. USDA, Economic Research Service. Agricultural Handbook No. AH722.
22. Raczkowski, C.W., M.R. Reyes, G.B. Reddy, W.J. Busscher and P.J. Bauer. 2009. Comparison of conventional and no-tillage corn and soybean production on runoff and erosion in the southeastern US Piedmont. *Journal of Soil and Water Conservation*. 64(1):53-60.
23. USDA. 2009. *Summary Report: 2007 National Resources Inventory*, Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa.
24. USDA. 1995. *1994 Pest Management on Major Field Crops*. Economic Research Service, AREI Updates No.19.
25. USDA. 1979. *Erosion in the Palouse: A Summary of the Palouse River Basin Study*. Soil Conservation Service. February.
26. Calvert, L.J. 1990. The good earth. *Oregon's Agricultural Progress*. Spring – Summer: 25-29.
27. Kok, H., R.I. Papendick and K.E. Saxton. 2009. STEEP: Impact of long-term conservation farming research and education in Pacific Northwest wheatlands. *Journal of Soil and Water Conservation*. 64(4):253-264.
28. Kok, H. 2007. Solutions to Environmental and Economic Problems (STEEP). 2007. *Impact Assessment*. October.
29. Mutch, D. 2008. Evaluation of a no-till organic soybean system in Michigan. *North Central Weed Science Society Proceedings*. 63:173.
30. Gallagher, R.S., *et al*. 2010. Alternative strategies for transitioning to organic production in direct-seeded grain systems in eastern Washington I: crop agronomy. *Journal of Sustainable Agriculture*. 34:483-503.
31. Lu, Y.-C., B. Watkins and J. Teasdale. 1999. Economic analysis of sustainable agricultural cropping systems for mid-Atlantic states. *Journal of Sustainable Agriculture*. 15(2/3):77-93.
32. Green, S., M. Cavigelli, T. Dao and D. Flanagan. 2005. Soil physical properties and aggregate-associated C, N, and P distributions in organic and conventional cropping systems. *Soil Science*. 170(10): 822-831.
33. Green, S., M. Cavigelli, T. Dao and D. Flanagan. 2005. Soil and nutrient erosion potential of organic and conventional cropping systems. USDA-ARS Chesapeake Bay Day. 05 October 2005, Beltsville, MD. Available at:

http://www.ars.usda.gov/SP2UserFiles/Place/12650400/FSP%20Research%20Summaries.pdf.

34. Hedtcke, J.L. and J.L. Posner. 2006. Increasing crop rotation diversity: a comparison of conventional grain systems on WICST (1998-2006). WICST 11th Technical Report.

35. Schaible, G. and M. Aillery. 2006. Chapter 4.6: Irrigation Water Management. In *Agricultural Resources and Environmental Indicators, 2006 Edition*. Economic Research Service, USDA.

36. Gollehon, N. and W. Quinby. 2006. Chapter 2.1: Irrigation Resources and Water Costs. In *Agricultural Resources and Environmental Indicators, 2006 Edition*. Economic Research Service, USDA.

37. Greb, B.W. 1983. Water Conservation: Central Great Plains. *Dryland Agriculture*. ASA-CSSA-SSSA. Agronomy Monograph No.23.

38. Meith, H.C. and P.S. Parsons. 1965. Nontillage and strip weed control cut almond production costs in Butte County test. *California Agriculture*. June.

39. Reeves, D.W., M.L. Norfleet, D.A. Abrahamson, H.H. Schomberg, H. Causarano and G.L. Hawkins. 2005. Conservation tillage in Georgia economics and water resources. In *Proceedings of the 2005 Georgia Water Resources Conference*, 25-27 April, 2005, ed. K.J. Hatcher. Athens, GA: University of Georgia Institute of Ecology.

40. Sullivan, D.G., C.C. Truman, H.H. Schomberg, D.M. Endale and D.H. Franklin. 2007. Potential impact of conservation tillage on conserving water resources in Georgia. *Journal of Soil and Water Conservation*. 62(3):145-152.

41. Ashworth, W. 2006. *Ogallala Blue*. Countryman Press, Woodstock, Vermont.

42. Amosson, S.H., *et al*. 2005. *Water Management Strategies for Reducing Irrigation Demands in Region A*. Report to the Panhandle Water Planning Group, Amarillo, TX. January. Available at: http://www.panhandlewater.org.

43. Unger, P.W., R.R. Allen and A.F. Wiese. 1971. Tillage and herbicides for surface residue maintenance, weed control, and water conservation. *Journal of Soil and Water Conservation.* 26:147-150.

44. Jones, O.R., P.W. Unger and D.W. Fryrear. 1985. Agricultural technology and conservation in the Southern Plains. *Journal of the Soil and Water Conservation Society.* 40(March-April).

45. Harman, W.L., G.C. Regier, A.F. Wiese and V.D. Lansford. 1998. Water conservation and economic impacts when integrating irrigation with no-tillage. *Journal of Soil and Water Conservation*. 53(4):341.

46. Smika, D.E. 1983. Cropping Practices: Introduction. *Dryland Agriculture*. ASA-CSSA-SSSA. Agronomy Monograph No.23.

47. Nielsen, D.C. and M.F. Vigil. 2010. Precipitation storage efficiency during fallow in wheat-fallow systems. *Agronomy Journal*. 102(2):537-543.

48. Anderson, R.L. and D.E. Smika. 1984. *Chemical Fallow in the Central Great Plains.* Colorado State University, Experiment Station Fort Collins Bulletin 588S.

49. Greb, B.W. 1979. *Reducing Drought Effects on Croplands in the West-Central Great Plains*. Agriculture Information Bulletin No.420. U.S. Department of Agriculture.

50. Regehr, D.L. and C.A. Norwood. 2008. Benefits of Triazine Herbicides in Ecofallow. in *The Triazine Herbicides: 50 years Revolutionizing Agriculture*. Elsevier, San Diego.

51. Peterson, G.A. and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. *Annals of Applied Biology*. 144:127-138.

52. Greb, B.W. and R. L. Zimdahl. 1980. Ecofallow comes of age in the central Great Plains. *Journal of Soil and Water Conservation*. 35(September-October):230-233.

53. Derksen, D.A., R.L. Anderson, R.E. Blackshaw and B. Maxwell. 2002. Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agronomy Journal*. 94:174-185.

54. Unger, P.W. and R.L. Baumhardt. 1999. Crop residue management increases dryland grain sorghum yields in a semiarid region. *10th Annual International Soil Conservation Organization Meeting*.

55. Harrell, D. 2007. Redefining optimum seeding rates in Clearfield varieties. *Texas Rice*. 7(3):2

56. Linscombe, S. 2007. Sustainable rice production in Louisiana. *Texas Rice*. 7(4):4.

57. Manley, S.W., ed. 2008. *Conservation in Ricelands of North America*. The Rice Foundation, Stuttgart, Arkansas. Available at: http://www.usarice.com/index.php?option=com_doclibrary&view=subcat&Itemid=220

58. Yang, Y. and L.T. Wilson. 2011. An analysis of rice water savings from on-farm conservation measures. *Texas Rice*. March.

59. University of California. 2009. UC Pest Management Guide: Weed Management for Organic Lettuce Production. UC Statewide Integrated Pest Management Program. Available at: http://www.ipm.ucdavis.edu/PMG/r441700511.html.

60. *Southeast Farm Press*. 2012. Cameron enjoys organic cotton challenge. January:26.

61. Funtanilla, M., C. Lyford and C. Wang. 2009. *An Evaluation of the Organic Cotton Marketing Opportunity*. Presented at the AAEA & ACCI Joint Annual Meeting, Milwaukee, WI, July 26-28.

62. Schnepf, R. 2004. *Energy Use in Agriculture: Background and Issues*. Congressional Research Service.

63. West, T.O. and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agriculture, Ecosystems and Environment*. 91:217-232.

64. Cleveland, C.J. 1995. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910-1990. *Agriculture, Ecosystems and Environment*. 55:111-121.

65. USDA. *Indices of Farm Output, Input, and Total Factor Productivity for the US 1948 – 2008*. ERS. Available at: http://www.ers.usda.gov.

66. Shapouri, H., *et al*. 2010. *2008 Energy Balance for the Corn-Ethanol Industry*. USDA, Agricultural Economic Report No.846.

67. Brown, D., P. Stenberg and C. McGath. 2008. Farm operators turn to energy-saving practices. *Amber Waves*. April:7-8.

68. Cleveland, C.J. 1995. Resource degradation, technical change, and the productivity of energy use in U.S. agriculture. *Ecological Economics*. 13:185-201.

69. Frye, W.W. and S.H. Phillips. 1980. How to grow crops with less energy. *Yearbook of Agriculture*. U.S. Department of Agriculture.

70. Hanna, M. 2001. *Fuel Required for Field Operations*. Iowa State University Extension, PM 709.

71. Williams, J.R., D.L. Pendell, R.V. Llewelyn, D.E. Peterson and R.G. Nelson. 2009. Returns to tillage systems under changing input and output market conditions. J*ournal of the ASFMRA*. 78-93.

72. USDA. 2006. *Energy Management*. Natural Resources Conservation Service. Conservation Resource Brief No.0608.

73. Oosterwyk, J. and J.L. Posner. 1992-2000 Energy use and output/input ratios for the Wisconsin Integrated Cropping Systems Trial. Available at: http://www.wicst.wisc.edu.

74. Archer, D.W., *et al*. 2007. Crop productivity and economics during the transition to alternative cropping systems. *Agronomy Journal*. 99:1538-1547.

75. Robertson, G.P., E.A. Paul and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science*. 289:1922-1925. Supplemental material available at: http://www.sciencemag.org/feature/data/1051816.shl.

76. Davis, A.S., K.A. Renner and K.L. Gross. 2005. Weed seedbank and community shifts in a long-term cropping systems experiment. *Weed Science*. 53:296-306.

77. Ryan, M.R. 2010. Energy Usage, Greenhouse Gases, and Multi-tactical Weed Management in Organic Rotational No-till Cropping Systems. Pennsylvania State University Dissertation, August 2010.

78. Cavigelli, M.A., M. Djurickovic, C. Rasmann, J.T. Spargo, S.B. Mirsky, and J.E. Maul. 2009. Global Warming Potential of Organic and Conventional Grain Cropping Systems in the mid-Atlantic Region of the U.S. In: *Proceedings of the Farming Systems Design Conference*, August 25, 2009, Monterey, California, p.51-52.

79. NASS. 2009. *2007 Census of Agriculture: 2008 Farm and Ranch Irrigation Survey*. USDA.

80. ERS. U.S. Cropland Used for Crops - Cropland harvested, failure, and summer fallow for the 48 states, annual, 1910-2006. Available at: http://www.ers.usda.gov/Data/MajorLandUses.

81. USDA. *Agricultural Prices Summary*. NASS. Available at: http://usda.mannlib.cornell.edu.