Conservation Tillage and Plant Biotechnology:

How New Technologies Can Improve the Environment By Reducing the Need to Plow

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RECREATING THE PRAIRIE SOIL CYCLE

Two hundred years ago, most of the lands that today make up America's row-crop farms were vast expanses of grasslands or forests. These areas supported an ecological cycle that changed radically after settlers first put plows to the soil.

In the prairies, the annual cycle of grasses created a deep layer of litter, which protected the soil from wind and water erosion and temperature extremes. Soil organisms and insects thrived in the layers of dead grasses that built up each season. As prairie plants decayed, carbon and other nutrients returned to the soil. Water, instead of running off fields, seeped back into the soil, replenishing groundwater and nearby streams.

Nearly two centuries of intensive tillage later, that cycle has been radically altered. Organic matter has been lost, and erosion has taken topsoil. Within the past decade, however, many farmers have begun to recreate the cycle that once characterized the prairie soils and forests before they were cleared for farming. Corn, cotton, soybeans, wheat and other crops have replaced the tall grasses of the 18th century, which exist only in small pockets today. Nevertheless, the life cycle of the native soils is slowly returning as farmers convert their land to soil-saving conservation tillage while continuing to produce abundant crops.

Instead of plowing and disking their fields before planting, many farmers are leaving the residue of the previous crop on the soil surface. This layer of decaying plant material provides protective litter and begins to create conditions that existed before people first began to till the soil.

CONSERVATION TILLAGE BENEFITS THE ENVIRONMENT

Conservation tillage, as defined by the Conservation Technology Information Center, (www.ctic.purdue.edu) means any minimal tillage system that leaves the soil surface at least 30 percent covered by crop residue. Farmers employ various conservation tillage systems, which leave various amounts of residue. No-till, in which the soil is left undisturbed by tillage and the residue is left on the soil surface, is the most effective soil-conserving system. Research shows that land left in continuous no-till can eventually create a soil, water and biological system that more closely resembles characteristics of native soils before the advent of agriculture. No-till systems also can provide cover for wildlife if the stubble from the previous crop is left standing. Other studies show that reducing tillage can produce many other environmental benefits, such as:

- Reduced soil erosion.
- Improved moisture content in soil.
- Healthier, more nutrient-enriched soil.
- More earthworms and beneficial soil microbes.
- Reduced consumption of fuel to operate equipment.
- The return of beneficial insects, birds and other wildlife in and around fields.
- Less sediment and chemical runoff entering streams.
- Reduced potential for flooding.
- Less dust and smoke to pollute the air.
- Less carbon dioxide released into the atmosphere.

BIOTECHNOLOGY AND THE GROWTH OF NO-TILL

The movement toward leaving more crop residue on farm fields expanded rapidly in the early 1990s. The federal government largely drove this by requiring soil conservation efforts on highly erodible acres in order to participate in farm programs. The introduction of improved high-residue seeding equipment and improved weed control technology also aided adoption.

The conversion of acreage to conservation tillage began to level off somewhat by the mid-1990s. However, since the mid-1990s, farmers have been increasing the amount of residue left on the soil surface. While reduced tillage practices such as mulch-till and ridge-till have been fairly static, farmers have been moving toward no-till farming. This agricultural practice, which has the potential to most closely approximate the native soil cycle, has expanded steadily during the time period when herbicide-tolerant crops, developed through biotechnology, have been adopted by U.S. and Canadian farmers.

There is a strong association between the use of herbicide-tolerant biotech crops and recent improvements in tillage reduction. Four trends support this conclusion:

- Weed control is a major consideration when farmers are weighing whether to implement conservation tillage, and several surveys indicate that farmers have more confidence in weed control since the introduction of herbicide-tolerant biotech crops. In some surveys, farmers say herbicide-tolerant crops enabled them to increase the amount of residue they leave on their fields.

- No-till, the tillage system that most relies on good herbicide performance, has grown more than other reduced tillage systems since 1996, and nearly all the growth has occurred in crops where herbicide-tolerance technology is available – soybeans, cotton and canola. (Herbicide-tolerant corn has not been widely adopted due to pending regulatory approval in Europe, nor has no-till corn expanded as rapidly as other crops.)
- Farmers who purchase herbicide-tolerant seeds use them disproportionately on their conservation tillage acres.
- Farmers who do not purchase herbicide-tolerant seeds are not as likely to participate in conservation tillage.

The main reason farmers till their soil is to control weeds, which compete with their crops for space, nutrients and water and can interfere with harvesting equipment. Historically, farmers have plowed under emerged weeds before planting and tilled the soil in preparation for herbicides that prevent additional weeds from emerging. If herbicides failed due to weather conditions, farmers could use additional tillage as a rescue.

With herbicide-tolerant crops, farmers allow weeds to emerge with their crops. Then they apply herbicide over the top of their crop, removing the weeds without harming the crop, which has been modified through biotechnology to withstand the herbicide. This improvement in weed control gives increased confidence that weeds can be controlled economically without relying on tillage. It partially explains why no-till farming has been increasing significantly in crops where the technology is available.

Many analyses have shown that conservation tillage provides economic benefits by saving time and reducing fuel and equipment costs. Despite these benefits, many farmers were reluctant to commit to a new system in which they saw potential risk of yield reduction due to competition from weeds. The trends since 1996, when herbicide-tolerant crops were first introduced, provide a strong indication that improved weed control made possible with the new biotech crops has given growers the confidence to increase their use of conservation tillage, especially no-till.

WHAT IS CONSERVATION TILLAGE?

Crop residues left on the soil surface protect the soil from the energy of wind and raindrops. Research shows that reductions in erosion are proportional to the degree that the soil surface is covered by crop residue.[75]

The Conservation Technology Information Center (CTIC) has defined various tillage systems according to how much crop residue is left on the soil surface and types of tillage tools used:

Conservation tillage – Any tillage and planting system that covers more than 30 percent of the soil surface with crop residue, after planting, to reduce soil erosion by water. Where soil erosion by wind is the primary concern, any system that maintains at least 1,000 pounds per acre of flat, small grain residue equivalent on the surface throughout the critical wind erosion period. No-till, ridge-till, and mulch-till are types of conservation tillage.

No-till – The soil is left undisturbed from harvest to planting except for planting and nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slots created by coulters, row cleaners, disk openers, in-row chisels or rotary tillers. Weed control is accomplished primarily by herbicides. Cultivation may be used for emergency weed control.

Ridge-till – The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters or row cleaners. Residue is left on the surface between the ridges. Weed control is accomplished with herbicides and / or mechanical cultivation. Ridges are rebuilt during cultivation.

The residue from the previous year's crop remains on the surface of this no-till soybean field, protecting the soil from wihd and rain erosion.

Mulch-till – The soil is disturbed prior to planting. Tillage tools such as chisels, field cultivators, disks, sweeps, and blades are used. Weed control is accomplished with herbicides and / or mechanical cultivation.

Conventional-tillage leaves less than 15 percent residue cover after planting, or less than 500 pounds per acre of small grain residue equivalent throughout the critical wind erosion period. It typically involves plowing or intensive tillage. Tillage types that leave 15 to 30 percent residue cover after planting or 500 to 1,000 pounds per acre of small grain residue sometimes are referred to as **reduced tillage**, but they do not qualify as **conservation tillage.**

As a significant percentage of agriculture is left untilled, more like the original prairies, the water and soil cycles also will begin to return to a more natural state. Continued adoption of no-till practices will bring additional environmental benefits, which include increasing the amount of topsoil that is saved each year, reducing runoff into streams and further cutting back on fuel use and emissions.

Improved weed control available through herbicide-tolerant crops will be an important factor in continued adoption of no-till.

TILLAGE WAS ONCE NECESSARY

Repeated tillage to prepare crop seedbeds and control weeds was an indispensable component of agriculture until the last half of the 20th century. However, excessive tillage causes soil erosion, thus reducing the sustainability of agriculture. For example, 100 years after Iowa was settled, nearly half the original topsoil had eroded.[1] Repeated tillage also can reduce soil quality and productivity by destroying soil structure, reducing organic matter content and harming beneficial invertebrates such as earthworms. Sediment eroded from intensively tilled fields fouls aquatic systems, and runoff of water contributes to flooding. Tillage destroys wildlife food sources and reduces surface crop residues that serve as wildlife cover.

Edward Faulkner was one of the earliest proponents of eliminating the use of the moldboard plow, the most widely used primary tillage tool until the late 20th century. In his 1943 book, "Plowman's Folly,"[2] he called the plow "the villain in the world's agricultural drama." He concluded that plowing crop residues deep into the soil, leaving the soil's surface bare, reduced the long-term productivity of the soil. Faulkner wrote: "Had we not originally gone contrary to the laws of nature by plowing the land, we would have avoided the problems … the erosion, the sour soils, the mounting floods, the lowering water table, the vanishing wildlife, the compact and impervious soil surfaces."

Although many of Faulkner's predictions of benefits from what was later to be called "conservation tillage" turned out to be true, poor weed control, experienced when tillage was reduced, prevented most farmers from adopting the systems until the introduction of herbicides. Development of effective herbicides in the 1960s allowed farmers to reduce their dependence on repeated tillage to control weeds. Some eliminated tillage altogether.

However, weed control challenges and uncertainties remain. Some problem weeds, such as perennials, remain difficult to control. A few weeds have developed resistance to some popular herbicides. Because most herbicides do not control all weed species present in fields, farmers often apply two, three or more herbicides in combination. Effective weed control with herbicides requires careful identification of weed species and precise application timing. Crop injury may occur if adverse weather conditions reduce crop tolerance, or herbicide residues in the soil injure rotational crops. Soil-applied herbicides may fail if sufficient rainfall does not occur to activate the chemical.

Biotechnology has given farmers additional weed control options by facilitating the development of crop varieties tolerant to herbicides, such as glyphosate and glufosinate. These herbicides, rather than preventing weed growth in the soil, are applied to emerged weeds and are effective against a broad spectrum of annual and perennial weeds. They are well-suited to conservation tillage systems because they do not require incorporation with tillage tools. In addition, they are applied at low rates, have low toxicity to animals and degrade rapidly. They cannot, however, be used with crops that have not been made tolerant through biotechnology, because they would have the same detrimental effect on the crop as they have on weeds.

As will be discussed later, farmers are using herbicide-tolerant crops disproportionately in reduced tillage systems, especially no-till. The majority of such crops are glyphosate-tolerant; therefore, subsequent discussion of herbicide-tolerant crops in this report will focus on glyphosate-tolerant varieties developed through biotechnology.

ENVIRONMENTAL BENEFITS OF CONSERVATION TILLAGE

As no-till acreage expands, farmers are able to recreate soil and water cycles more closely resembling characteristics of prairies and woodlands before settlers first put plows to the soil. The residue from the harvested crop is left on the soil surface. This layer of leaves and stems mimics the layer of litter that once covered native soils, protecting the soil from heat, preserving soil moisture and preventing erosion. Decaying root channels and burrows from earthworms serve as macropores, which aerate the soil and improve water infiltration. Other attendant benefits, including a return of soil organisms, birds and mammals, also are being realized.

Erosion is reduced by nearly 1 billion tons per year

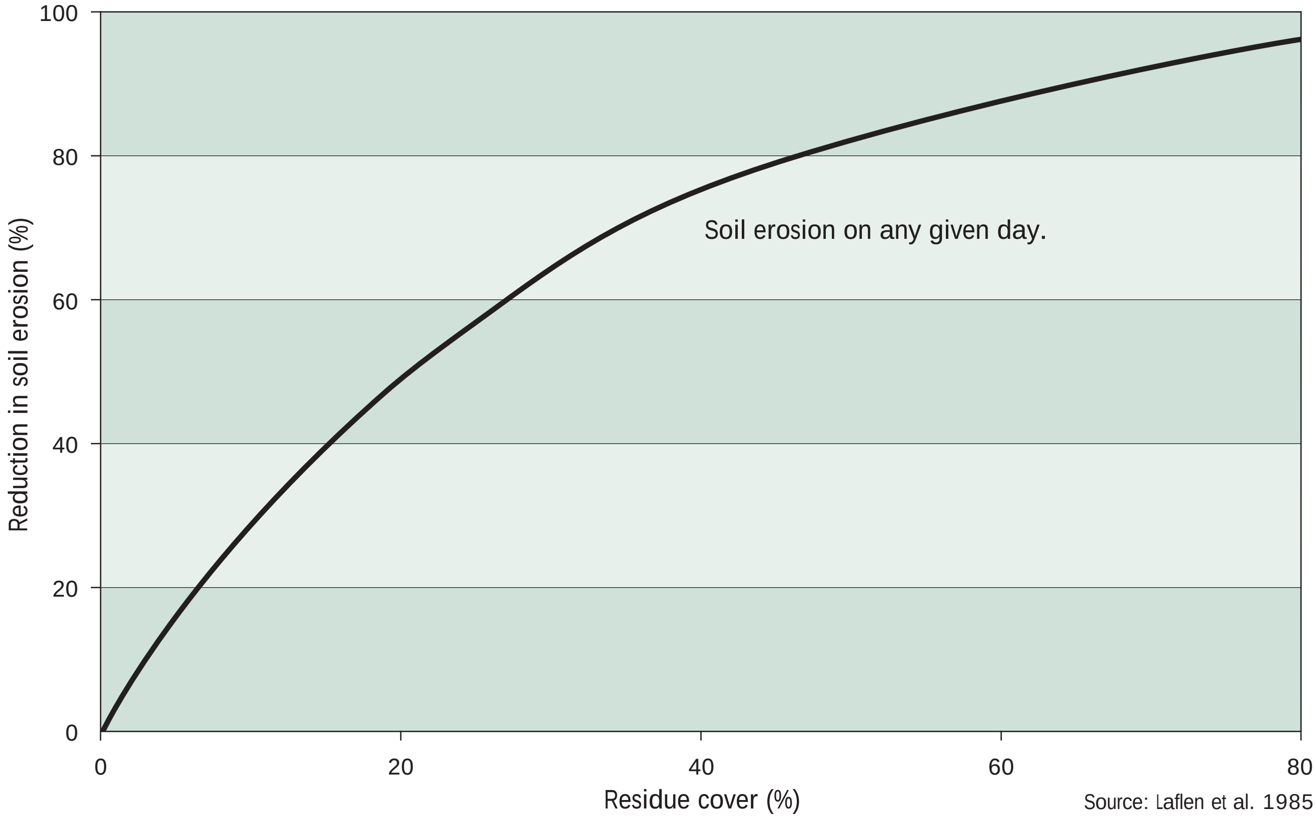
Conservation tillage is one of the most practical and economical ways to reduce soil erosion. Reducing or eliminating tillage operations leaves more crop residue on the soil surface, protecting the soil from the erosive impacts of wind and rain. Reductions in erosion are proportional to the amount of soil covered by crop residue (Figure 1).[3]

No-till systems, which leave nearly all plant surface residue in place, can reduce erosion by 90 percent or more.[4,5] The 1997 National Resources Inventory[6] showed that dramatic decreases in erosion have taken place in the United States since 1982. Much of this reduction can be credited to the adoption of conservation tillage by U.S. farmers. Sheet and rill (water) erosion on cultivated cropland fell from an average 4.4 tons per acre per year (9,856 kg/ha/year) in 1982 to 3.1 tons/acre/year (6,944 kg/ha/year) in 1997, a 30 percent decrease (Figure 2). The average wind erosion rate dropped 31 percent. Almost 1 billion tons per year of soil savings have occurred due to these changes in management. However, erosion is still occurring at a rate of 1.9 billion tons per year, and 108 million acres (29 percent of cropland) is still eroding at excessive rates.[7]

$3.5 billion in sedimentation costs saved in 2002

The 1998 National Water Quality Inventory reports that sedimentation is the most prevalent pollutant in streams that have been identified as environmentally impaired.[8] Unacceptable levels of sediment occur in 40 percent of impaired stream miles. Bacteria were the second most prevalent pollutant, present in 38 percent of impaired miles, followed by nutrients, occurring in 30 percent of impaired miles. Conservation tillage reduces the runoff of all these pollutants to surface water systems.

Figure 1. Effect of Residue Cover on Soil Erosion



Source: Laflen et al. 1985

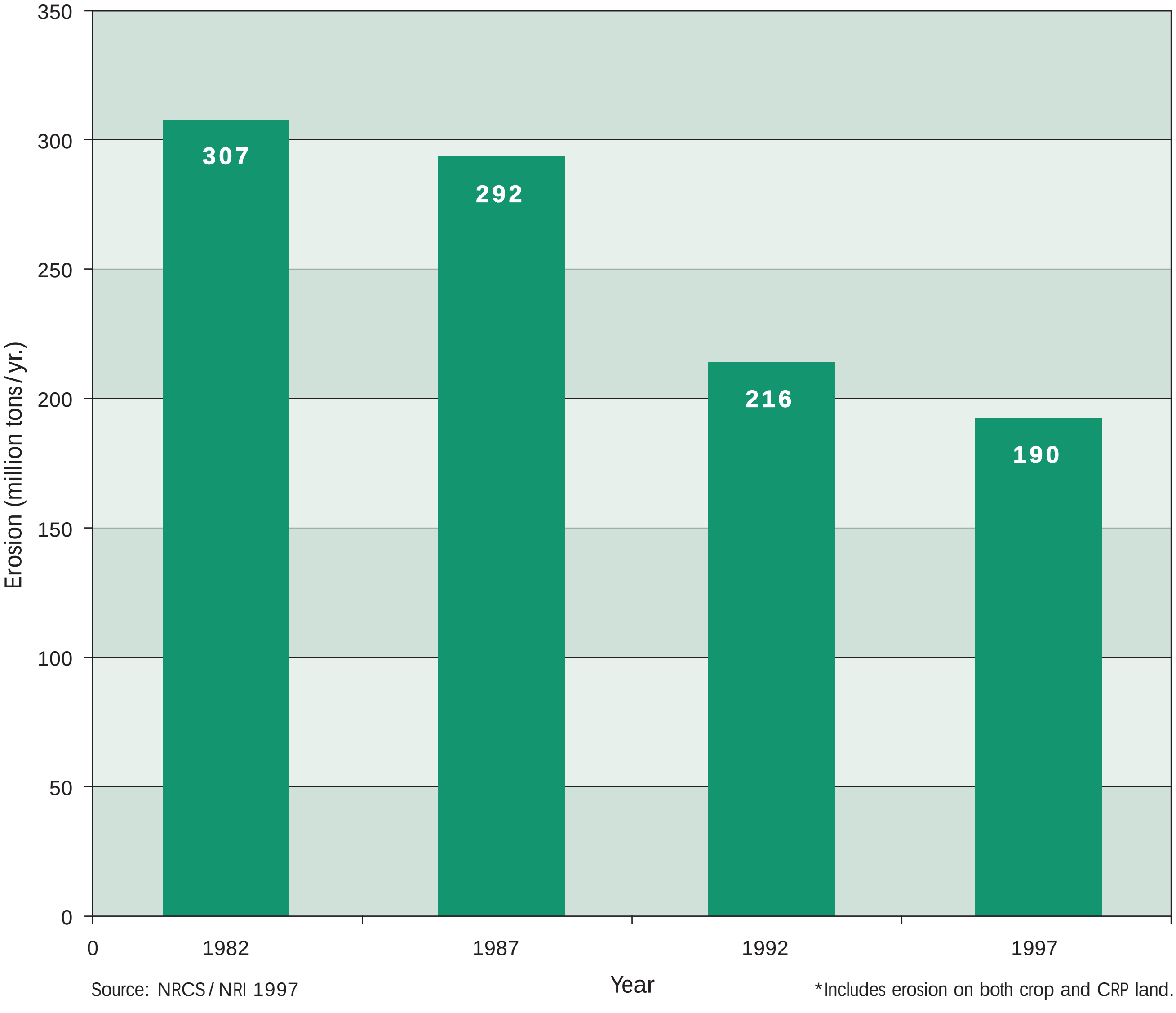
Sediment decreases the storage capacity of reservoirs and interferes with the navigational and recreational uses of water. According to a U.S. Department of Agriculture study, the annual cost of damage to water quality from sediment originating on farmers' fields was $4 billion to $5 billion in the mid-1980s.[9]

Table 1 shows USDA estimates of the annual offsite damage from water and wind erosion. These damage values were calculated considering the cost of maintenance due to erosion, such as dredging rivers, cleaning road ditches and treating drinking water, as well as economic losses. Soil erosion rates fell 30 percent between 1982 and 1997, largely due to the adoption of conservation tillage by U.S. farmers and land enrolled in the Conservation Reserve Program (CRP).[6] The offsite erosion damages ($8.78 billion) shown in Table 1 were calculated in the 1980s. If offsite damages are proportional to erosion rates, an estimated $2.6 billion annual savings has resulted due

Table 1: Annual Offsite Damage from Soil Erosion in the United States

Damage Category	Annual Offsite Damage (Millions of $)
Water recreation	2,679
Water storage	1,090
Navigation	749
Flooding	978
Ditches	978
Commercial fishing	450
Municipal water treatment	964
Municipal and industrial use	1,196
Steam power cooling	24
TOTAL	$8,783

Figure 2. Soil Erosion from Cropland*



Source: NRCS/NRI 1997

*Includes erosion on both crop and CRP land.

to the erosion reduction achieved by farmers largely through conservation tillage. If adjusted for inflation this would represent a $3.5 billion annual savings in 2002.

Sediment in water also has human health implications. Sediment and organic carbon carried on sediment cause problems for water utilities that use surface water as a drinking water source. Chlorine used to disinfect water reacts with organic carbon to produce trihalomethanes such as chloroform. Due to carcinogenicity, trihalomethanes are regulated under the Safe Drinking Water Act. Additional filtering is required to reduce sediment and organic carbon to prevent trihalomethane formation. Allowed levels of trihalomethanes are scheduled to decrease in the future, which will increase costs to water utilities.

Insects, earthworms and microbes thrive

Stinner and House[10] have reviewed studies of arthropods and invertebrates in no-till and other conservation tillage systems. They found that no-till crop fields generally have increased diversity of surface microarthropods. Many beneficial predatory arthropods, including ground beetles and spiders, are increased by no-till. For example, House and Parmalee[11] found 17.6 carabid beetles per square meter in no-till soybeans compared with 0.38 per square meter in plowed treatments. Carabid beetles are important predators of pests in many crops. Mites, which are important predators of other arthropods and nematodes, are increased in no-till.[12] Increased diversity of arthropods with no-till has been attributed to the increased structural diversity of litter.

Earthworm populations have consistently increased as tillage is reduced. House and Parmalee[11] compared a field with 17 years of no-till cropping with a conventionally tilled field and found from 3.5 to 6.3 times more earthworms in the no-till field. Earth-worms help incorporate organic residues into the soil, aerate the soil and improve water infiltration. Night crawlers (*Lumbricus terrestris* L.) are large, surface-feeding earthworms, which live in permanent, vertical burrows. Tillage harms earthworms by burying food sources and destroying burrows. As many as 81,000 burrows per acre (200,000/ha) have been reported in no-till fields.[13] Improvements in water infiltration, which often accompany conversion to no-till, have been at least partly attributed to these burrows.[14]

Tillage, which incorporates organic debris into the soil, is more suitable for microorganisms with higher turnover rates, such as bacteria and bactivorous fauna, including protozoa and nematodes.[15, 16] Decomposition processes in no-tillage systems are controlled primarily by fungi, with fungivorous microarthropods, nematodes and earthworms dominant in subsequent steps in the food web.[17] Fungal dominated microbial communities of no-till systems store more organic material for longer periods, resulting in higher steady-state levels of organic matter. Fungal hyphae aid in the formation of soil aggregates or tiny soil particles bound into larger units. These aggregates aid in improving soil structure and increasing retention of soil carbon. Extracellular polysaccharides of fungi also are important in the formation of soil aggregates. Soil aggregates allow for the most desirable mix of air and water for good plant growth.

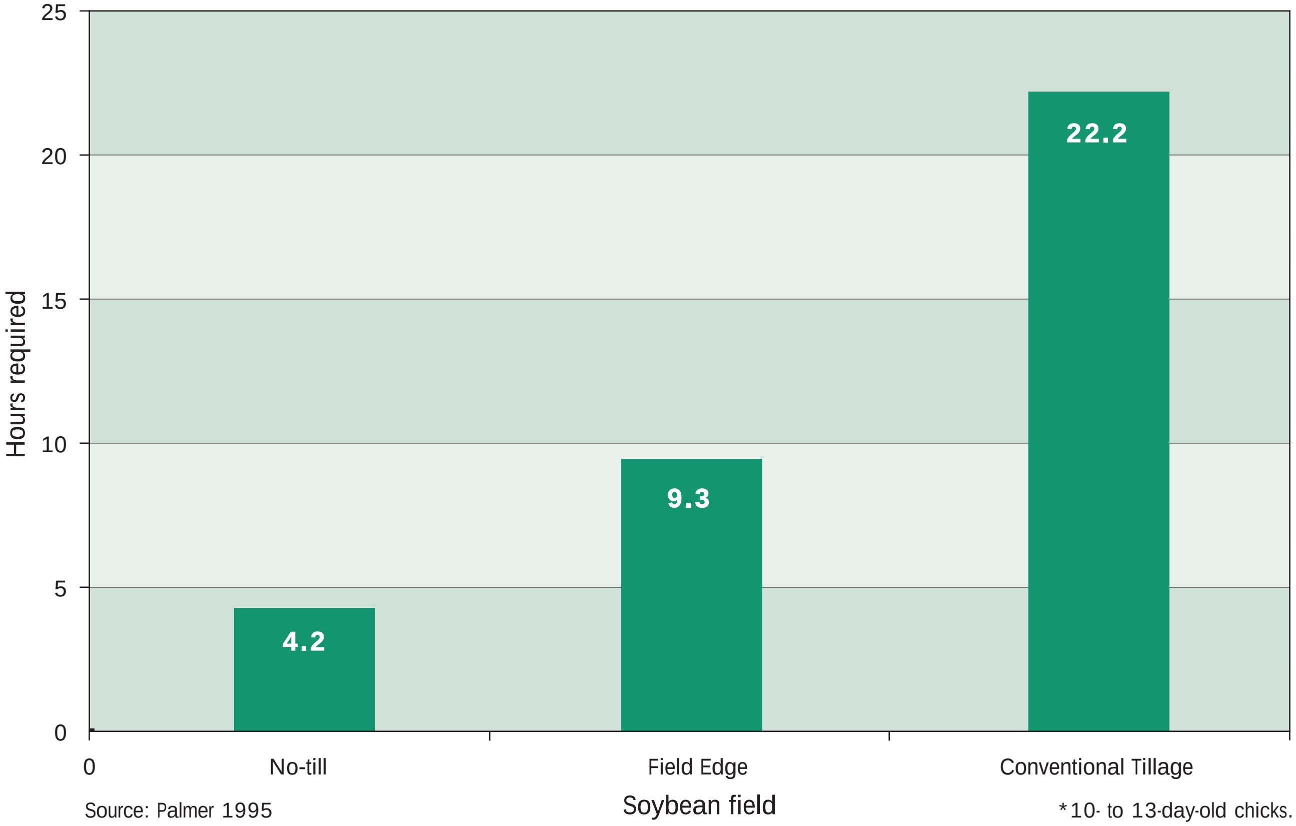
Total microbial populations are often higher in no-till soils than in tilled soils. Doran[18] found that counts of aerobic microorganisms, facultative anaerobes and denitrifiers in the surface of no-till soils were higher than in the surface of plowed soil. Phosphatase and dehydrogenase enzyme activities and contents of water and organic carbon and nitrogen in the surface of no-till soil also were significantly higher than those for conventional tillage. Such increases in microbial activity have been associated with increased rates of herbicide and insecticide degradation with no-till.[18, 19] Rapid degradation of pesticides is one of the factors that reduce their potential to enter surface or ground-water supplies.

Habitat for birds and mammals improves

Research shows that no-till fields provide food and habitat for birds and mammals. Insects and other arthropods, which thrive in the protective residue in no-till fields, are important food sources for many birds. Palmer[20] studied bobwhite quail (*Colinus virginianus*) behavior in no-till and conventional fields in North Carolina. The research showed that quail chicks needed 22 hours to obtain their minimum daily requirement of insects in conventional soybean fields. In no-till soybean fields, only 4.2 hours were required to obtain the minimum daily requirement, about the same as the 4.3 hours required in natural fallow areas believed to be ideal quail habitat (Figure 3).

Cover provided by crop residue, plus waste grain and weed seed food sources left on the soil surface, along with less disturbance from field operations, are all beneficial to wildlife. Many studies have shown that no-till row crop fields have higher densities of birds and nests and are used by a greater variety of bird species during the breeding season than tilled fields.[21, 22] Bird nesting success in conventionally tilled row-crop

Figure 3. Time Needed for Bobwhite Quail Chicks to Satisfy Daily Insect Requirements*



Source: Palmer 1995

*10- to 13-day-old chicks.

fields is usually below levels needed to sustain populations, often because field operations disrupt nests.[23] As fewer trips over the field with equipment are made with conservation tillage, nesting is favored, particularly for species that normally raise only one brood per year, such as the ringneck pheasant. Grassy nesting cover adjacent to no-till fields provides even more favorable habitat.

Small mammals also favor conservation tillage. In Illinois, no-till cornfields had more abundant and more diverse invertebrates, birds and small mammals than conventionally tilled corn.[22] Small-mammal populations, particularly deer mice, were more stable in no-till. Management changes can further improve wildlife habitat provided by no-till fields. Leaving stubble 10 to 14 inches tall when harvesting small grains provides improved habitat compared with shorter stubble heights. Additional research is needed to determine how to maximize the wildlife benefits of conservation tillage.

Preventing sediment and nutrient loss improves aquatic habitat

Sediment in rivers, streams and lakes covers gravel beds needed for habitat by fish and crustaceans. Sediment also clouds water, reducing sunlight penetration and reducing photosynthesis of submerged plants and algae, causing a cascading effect through food chains. Conservation tillage's ability to dramatically reduce erosion reduces delivery of sediment to aquatic systems, improving aquatic habitats.

Excessive loads of the nutrients phosphorus and nitrogen from agricultural land and other sources can lead to excessive growth of aquatic plants. When these plants decompose, oxygen concentrations in water can drop to levels too low to support some aquatic organisms, a condition called hypoxia. Hypoxia can occur in fresh water bodies or marine environments such as the Gulf of Mexico.[24] Because conservation tillage reduces nutrient losses, it is an important tool in reducing agriculture's impact on hypoxia.

Runoff into streams is reduced

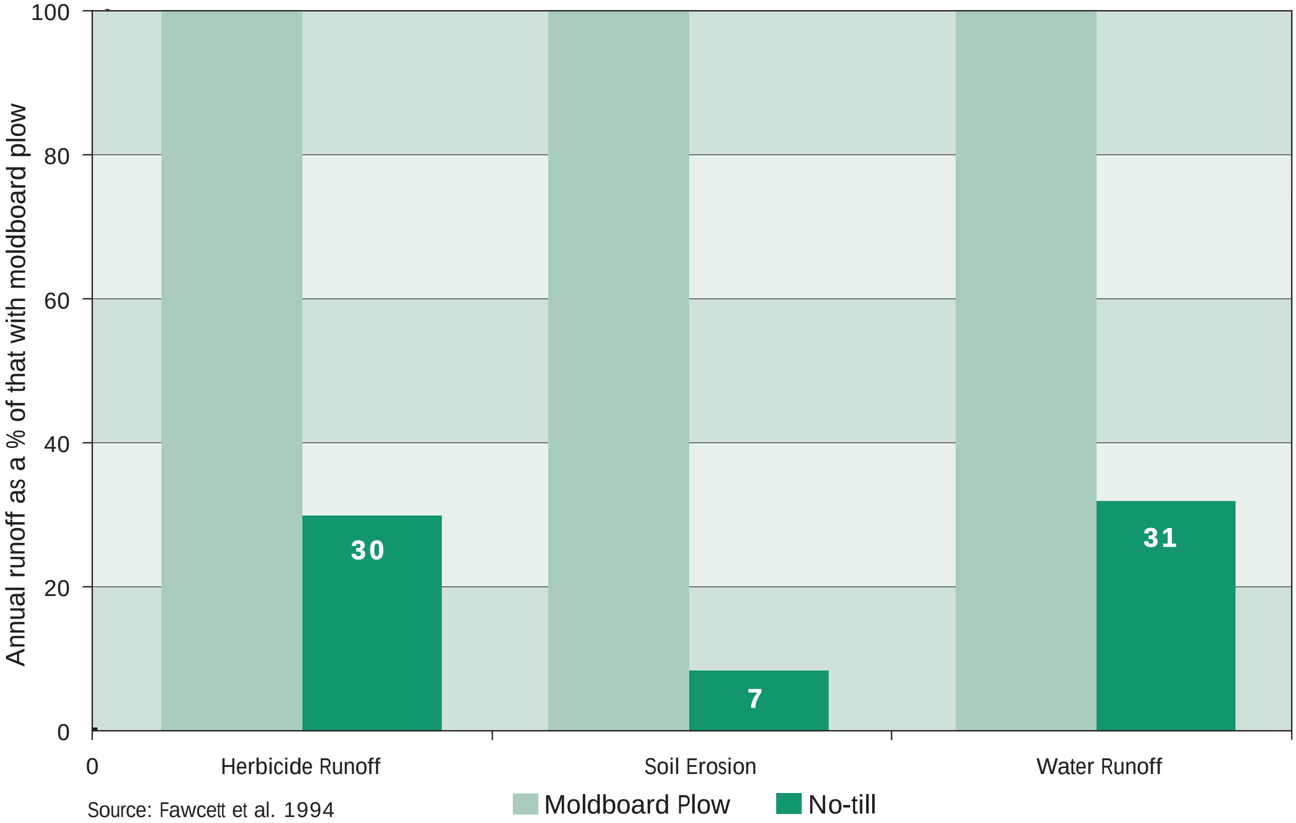
As portions of agriculture are returned to an untilled state more like the original prairies and forests, the water cycle also will return to a more natural state.[25] With less water runoff and more infiltration, streams are fed more by subsurface flow than surface runoff. This allows better use of water and nutrients by crops and allows soil clay, organic matter and biological activity to filter the water before it becomes surface water.

Decreased runoff means that fewer pollutants enter streams. Several paired watershed studies showed that no-till fields produced no seasonal runoff while conventional tillage watersheds had significant water runoff, soil erosion and pesticide runoff.[26, 27, 28] An Ohio study compared total water runoff from a 1.2-acre (0.5 ha) watershed with 9 percent slope that had been farmed for 20 years in continuous no-till corn to a similar conventionally tilled watershed. Over four years, runoff was 99 percent less under the long-term no-till. This decrease in runoff was attributed to increases in infiltration due to development of soil macropores in the absence of tillage.[29] Cracks, root channels and earthworm holes allow water to bypass upper soil layers when rainfall exceeds the capacity of soil to absorb water through capillary flow, the movement through tiny spaces between soil particles.[14]

When runoff is reduced, the flow of pollutants such as sediment, fertilizers and pesticides also is reduced. Pesticides and fertilizers enter surface waters in liquid solution or attached to sediment that washes off farm fields. Studies have demonstrated how no-till reduces chemical runoff. Baker and Laflen[30] found that a 97 percent reduction in sediment loss for no-till (relative to the moldboard plow) resulted in a 75 to 90 percent reduction in total nitrogen loss for soybeans planted following corn and 50 to 73 percent reduction in nitrogen loss for corn following soybeans. Studies show reduction in phosphorus fertilizer runoff if the fertilizers are subsurface band-applied instead of surface-applied. Andraski *et al.*[31] compared runoff losses of phosphate from four tillage systems when fertilizer was subsurface banded in all systems. Three reduced tillage systems — no-till, mulch-till and strip-till — reduced total phosphate losses by 81, 70 and 59 percent respectively, compared with the moldboard plow. Soluble phosphorus losses also were reduced by no-till and mulch-till, which employs a chisel plow. When total phosphorus losses were compared in no-till and conventional tillage, a 97 percent reduction in soil erosion with no-till resulted in an 80 to 91 percent reduction in phosphorus loss[30] for soybeans following corn. For corn following soybeans, an 86 percent reduction in soil loss led to a 66 to 77 percent reduction in phosphorus lost.[30]

Runoff of pesticides, both soil-attached and dissolved, usually is reduced in conservation tillage. No-till sometimes has resulted in complete elimination of pesticide runoff.[26, 27, 28] A summary of published natural rainfall studies comparing no-till with moldboard plowing showed that, on the average (over 32 treatment-site-years of data), no-till resulted in 70 percent less herbicide runoff, 93 percent less erosion and 69 percent less water runoff than moldboard plowing (Figure 4).[32]

Figure 4. Runoff and Erosion in No-till Watersheds Compared to Conventional Tillage Watersheds



Source: Fawcett et al. 1994

Other conservation tillage systems also have reduced herbicide runoff. In a Kentucky natural rainfall study, both no-till and chisel plowing (mulch-tillage) reduced runoff of atrazine, simazine and cyanazine by more than 90 percent, compared with moldboard plowing.[33] Ridge-till has reduced herbicide runoff by an average 42 percent in natural rainfall studies.[32]

Because no-till often increases water infiltration, some feared that this tillage system might also increase leaching of chemicals through the soil profile to groundwater. Several studies have shown, however, that no-till either had little impact on nitrate leaching or decreased leaching slightly.[34, 35, 36] A few studies have shown increased leaching of certain pesticides to shallow depths in no-till compared with tilled soil,[37, 38] while others have documented less leaching of pesticides with no-till.[39, 40, 41, 42, 43, 44] As crops genetically modified to tolerate the herbicide glyphosate are increasingly planted in no-till systems, leaching potential should be lessened, because this compound binds tightly to the soil and is highly unlikely to move to groundwater. Reductions in leaching of other herbicides used in no-till may be due to greater microbial activity degrading the pesticide, greater organic matter adsorbing the pesticide or to water bypassing upper layers of soil containing the pesticide, due to flow down macropores. The mucous lining of earthworm burrows has also been shown to adsorb pesticides.[45] When the herbicide atrazine was poured down night crawler burrows, concentrations exiting at the bottom were reduced tenfold. Although conservation tillage has not always reduced pesticide leaching, because of favorable results in many studies, no-till is recommended as a practice to reduce pesticide leaching by some water quality specialists.[42, 44]

Decreased flooding, increased soil moisture

Reduced runoff due to conservation tillage also is associated with decreased flooding. Such a decrease was documented on the Pecatonica River in Wisconsin. A decrease in flood peaks and winter/spring flood volumes accompanied by an increase in base flow (due to infiltration) was documented. The changes were not correlated to climatic variations, reservoir construction or major land use changes but appeared "to have resulted from the adoption of various soil conservation practices, particularly those involving the treatment of gullies and the adoption of conservation tillage."[46]

Conservation tillage not only reduces water loss through runoff, it also reduces evaporation losses so that more soil moisture is preserved for crop production. In one study, cumulative water losses for the first five hours after tillage were 0.113 in. (0.29 cm) with conventional tillage vs. 0.052 in. (0.13 cm) for no-till.[47] In Kentucky, annual evaporation was reduced by 5.9 inches (15.0 cm) with no-till.[48] In areas where rainfall is limited, such as the Great Plains of the United States, grain production is made possible by fallowing land. No crop is planted for a year or part of a year so that soil moisture can be stored for use by the next planted crop. Weeds must be controlled during the fallow period to prevent them from drawing moisture out of the soil. Traditionally, weeds in fallow land were controlled by repeated tillage operations. However, tillage increases evaporation losses, causes wind and water erosion and disturbs wildlife habitat. Chemical fallow or ecofallow systems, which use herbicides to control weeds, have been developed for crops planted no-till following the fallow period.[49, 50] In Kansas, Norwood[51] found that water use efficiency was increased by 28 percent in no-till corn grown in a wheat-corn-fallow rotation, compared with conventional tillage. Corn yields were 31 percent higher with no-till. Widespread adoption of these conservation systems across the Great Plains has improved the economic welfare of farmers, as well as reduced erosion and improved wildlife habitat.

Irrigation efficiency also is improved by conservation tillage. More moisture from rainfall is stored, and more of applied irrigation water infiltrates to be used by crops. The residue on the soil surface also reduces crop evapotranspiration. Improved irrigation efficiency benefits farmers by increasing yields and decreasing pumping and irrigation water costs while protecting aquifers from depletion.

Reducing "greenhouse gases" while enriching the soil

Soil organic matter is considered to be the largest terrestrial carbon pool[52] and influences the atmospheric content of CO_2, CH_4 and other greenhouse gases.[53] Soil organic matter can serve as a source or a sink for atmospheric carbon.[54] Conservation tillage, especially no-till, increases the ability of soil to store or sequester carbon, simultaneously enriching the soil and protecting the atmosphere.

Tillage increases the availability of oxygen, thus speeding the microbial decomposition of soil organic matter. Decomposition releases large quantities of CO_2, a "greenhouse" gas linked to global climate change. A 10-year analysis of common cropping systems in the United States showed that no-till farming had far less global warming potential than conventional tillage or organic systems.[55] The researchers calculated the types and amounts of greenhouse gases that were emitted or stored by each cropping activity and calculated a numerical value called the gross warming potential (GWP) for each. Conventionally plowed fields had the highest net GWP (114), compared with 41 for organic farming and 14 for no-till (Figure 5).

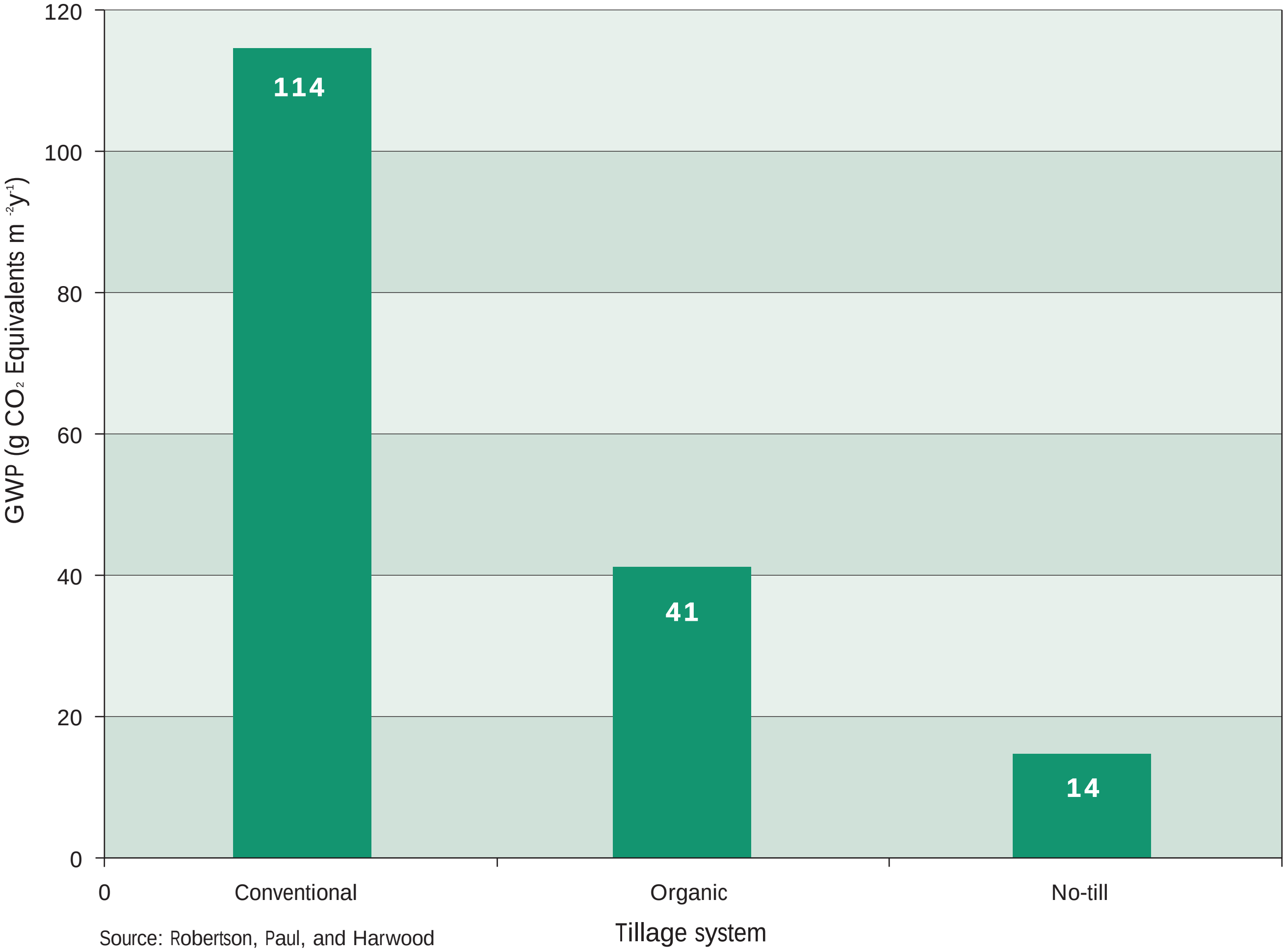
By converting land to no-till production, rather than depleting soil organic matter, organic matter can be increased, sequestering CO_2 from the atmosphere. Soil organic matter content has increased by 1,000 lb/acre/year (1120 kg/ha/year) in some no-till studies.[5, 56] That is equivalent to 590 lb/acre (661 kg/ha) carbon stored per year, compared with the 15-20 lb/acre (17-22 kg/ha) carbon that was burned as fuel to produce the crop.

Kern and Johnson[57] projected changes in atmospheric carbon due to several scenarios involving adoption of conservation tillage in the United States until the year 2020. Converting from conventional tillage to no-till on 57 percent of crop acres would result in a gain in soil organic matter of 80 trillion to 129 trillion grams (Tg) (Tg = 1012g = 1 million metric tons = 1.102 million tons) and would remove a like amount of carbon from the atmosphere.

Lal *et al.*[58] have reviewed the importance of cropland as a source and sink for atmospheric carbon. The estimated 55,000 million metric tons (MMT) of historic soil-C loss from cultivated soils worldwide accounts for about 7 percent of the current atmospheric inventory. They conclude that cropland soils potentially can sequester a considerable part of this lost carbon with adoption of practices such as conservation tillage. Considering U.S. cropland, about 5,000 MMT of soil organic carbon has been lost from its pre-agricultural levels. The authors conclude: “One reasonably can assume that cropland potentially can sequester 4,000 to 6,000 MMT, with an average of 5,000 MMT in cropland soils – potentially more, with new technologies and proper management.”

Reicosky *et al.*[56] measured CO_2 released from soil after tilling wheat stubble with various implements in the fall. Over a 19-day period, one pass of a moldboard plow caused five times as much CO_2 to be lost from the soil, compared with untilled plots. More organic matter was oxidized in 19 days than was produced all year in wheat straw and roots, helping explain why organic matter content has steadily declined in tilled

Figure 5. Gross Warming Potential (GWP) of Various Tillage Systems



Source: Robertson, Paul, and Harwood

soils until equilibrium is reached. Organic matter contents of agricultural soils in the United States have declined by as much as 50 percent or more due to this phenomenon. In effect, organic matter has been “mined” by agriculture. For example, the Morrow Plots at the University of Illinois were first established in 1876 and have been maintained in constant cropping systems to date.[59] Soil organic matter was first measured in 1903, when levels were about 40 tons per acre (44,800 kg/ha). By 1973, under continuous corn production, organic matter content had dropped to about 20 tons per acre (22,400 kg/ha). Conservation tillage systems, especially no-till systems, do not simply stop organic matter loss; they can cause soil organic matter content to increase. Reicosky *et al.* and Reeves found that organic matter has increased by as much as 1,800 pounds/acre/year (2000 kg/ha/year) in long-term no-till studies.[56, 60]

Improved air quality

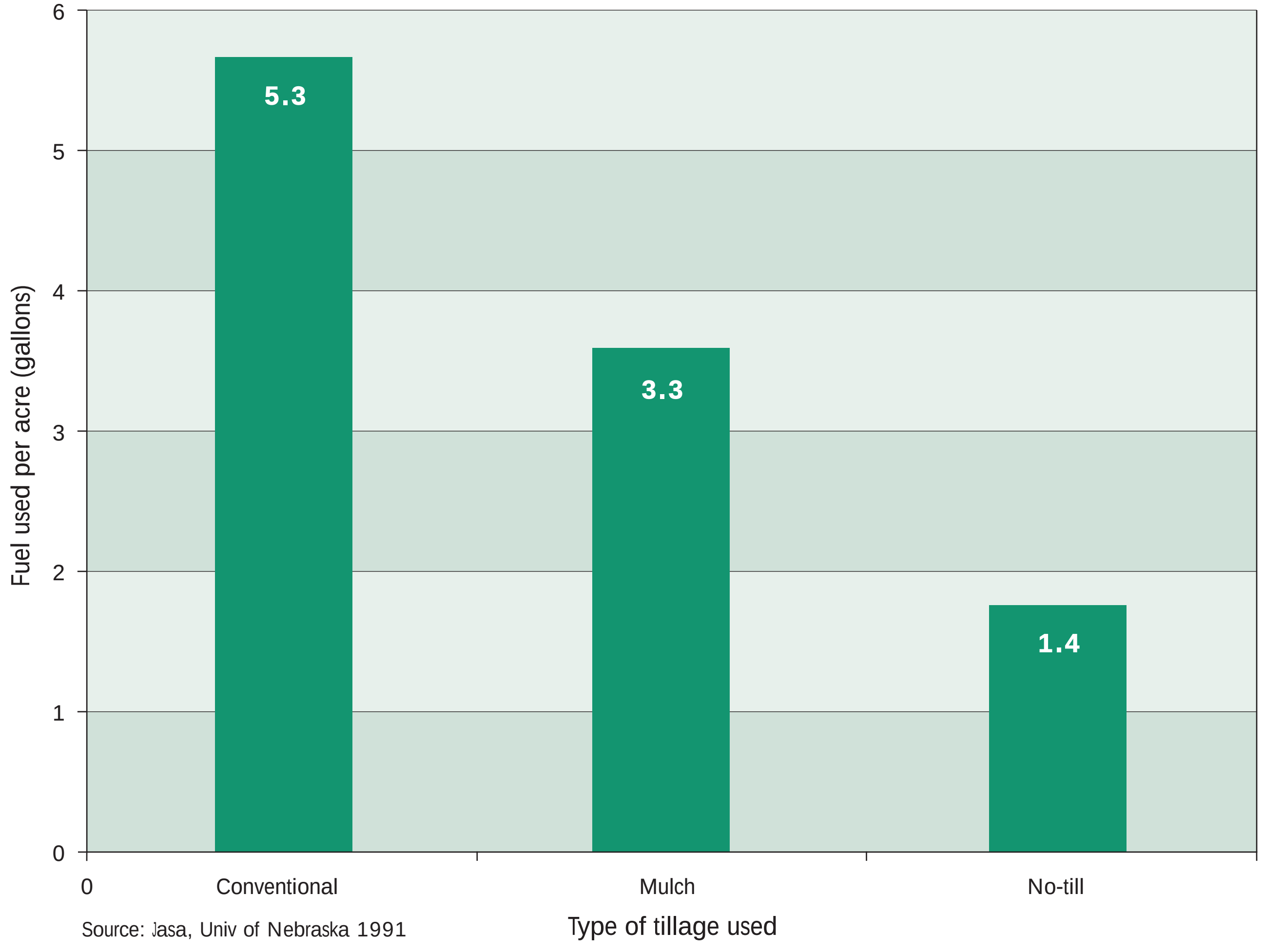
Conservation tillage, by reducing wind erosion, also reduces the amount of dust that can enter the atmosphere. In some regions, dust from agricultural fields is a major air quality concern. Wind-eroded dust also carries other contaminants such as pesticides and nutrients into the atmosphere where they are later deposited by rainfall into aquatic systems.[61, 62]

Conservation tillage is also an alternative to the practice of burning residue left on fields. In some regions of the United States, crop residue is burned to facilitate planting of rotational crops. This practice not only causes air pollution with smoke but also releases CO_2 into the atmosphere and reduces soil quality by destroying organic matter. Adoption of conservation tillage systems has significantly reduced the practice of burning crop residues.

No-till saves 3.9 gallons of fuel per acre

As tillage operations in crop fields are reduced or eliminated with the adoption of conservation tillage, fuel consumption declines. Fuel usage for no-till may decrease from 3.5 gal/acre (32.7 L per ha) to 5.7 gal/acre (53.3 L per ha) depending on the number of tillage trips reduced, clay and moisture content of the soil, and type of tillage operations eliminated.[57] Moldboard plowing typically uses 5.3 gal/acre, chisel

Figure 6. Tillage System vs. Fuel Consumption per Acre



Source: Jasa, Univ of Nebraska 1991

plowing 3.3 gal/acre, and no-till 1.4 gal/acre.[63] For every gallon of diesel fuel saved, 3.72 lbs of CO_2 are not released.

In 2002, 15 million acres (6.1 million hectares) of corn and 26 million acres (10.5 million hectares) of soybeans were grown in no-till systems in the United States, amounting to 41 million no-till acres (16.6 million hectares). Using the 3.9 gallons per acre estimated savings from no-till,[62] a net savings of 160 million gallons (605 million liters) of fuel per year is being realized in the no-till production of just these two crops. The 55.3 million no-till acres (22.4 million hectares) planted from all crops in the U.S. in 2002 would account for a savings of 216 million gallons (817 liters) of fuel that year. Mulch-tillage saves two gallons per acre of fuel compared with conventional tillage, accounting for a fuel savings of 90 million gallons on the 45 million acres (18.2 million hectares) of mulch-till systems. The combined fuel reduction from no-till and mulch-till systems therefore accounted for a savings of 306 million gallons of fuel.

Significant reductions in tillage have occurred as herbicide-tolerant crop varieties have facilitated conversions to conservation tillage. A 2001 American Soybean Association survey[64] asked soybean growers if and how much tillage had been reduced between 1996 and 2001 (the period of time glyphosate-tolerant soybeans had been available). Soybean growers responded that they had reduced tillage by an average 1.8 passes per growing season. One tillage pass consumes about 0.7 gallons of diesel fuel per acre.[65] Thus, soybean growers have reduced fuel consumption by 1.26 gallons per acre since the introduction of glyphosate-tolerant soybeans. With more than 56 million acres of biotech soybeans planted in 2001, a savings of 70 million gallons of fuel occurred just from this crop. In 2002, 75 percent of all soybeans planted were biotech soybeans. (USDA/NASS)

TRENDS LINK BIOTECH, CONSERVATION TILLAGE

Many factors determine whether a farmer will practice conservation tillage. Cultural factors, climate, soil type, equipment availability, moisture content, tradition and other considerations all can be at play in making tillage decisions. Weed control is among the most important factors, at least in commonly grown row crops. The development of herbicide-tolerant crops has given farmers a new, versatile technology for controlling weeds. It has removed much of the uncertainty in weed control that prevented farmers from abandoning tillage. Since the development of herbicide-tolerant soybeans and cotton, there have been marked increases in conversion to no-till, the system most dependent on herbicide performance. In other crops, where the herbicide-tolerant technology is not available, there have not been large increases in conservation tillage.

Farmers who use herbicide-tolerant seeds are more likely to engage in conservation tillage practices than in conventional tillage practices. Furthermore, farmers who use herbicide-tolerant seeds practice conservation tillage to a greater degree than farmers who do not use the new technology.

These facts and trends indicate that the advent of herbicide-tolerant crops, developed through biotechnology, has solidified the acreage converted to conservation tillage during the early 1990s and has contributed to the steady growth of no-till acreage since 1996, when the crops were introduced. Biotechnology may well have the potential to facilitate even more no-till.

An analysis of governmental, independent and industry data, as well as grower surveys, shows a strong association between herbicide-tolerant crops and growers' decisions to increase their level of crop residue. The following four findings emerge:

1. **Improvements in weed control, including the adoption of biotech herbicide-tolerant crops, are important reasons for initial adoption and continuance of no-till.**

Because the primary reason for tillage is weed control, many farmers, assured of weed control without disturbing the seedbed, will choose to reduce tillage. Herbicide-tolerant crops provide farmers with an important advancement in weed control capability.

Past surveys of farmers, assessing reasons for not adopting conservation tillage, consistently found that weed control was one of the greatest deterrents.[66] In 1991, Iowa farmers were surveyed on their attitudes about tillage. Weed control was most important to farmers considering tillage changes. Farmers who had tried no-till were asked to identify advantages or disadvantages to the system. Sixty-eight percent responded that weed control was a disadvantage. Only chemical costs (70 percent responding) ranked higher as a disadvantage.[67]

If farmers had greater confidence in no-till weed control systems, more farmers could be expected to convert to no-till. Conclusions from these surveys indicate that improvements in weed control, including the adoption of biotech herbicide-tolerant crops, are important reasons for initial adoption and continuance in no-till systems.

In 1999, corn and soybean producers in Iowa were surveyed to determine their tillage practices, yields and attitudes about tillage.[68] Among no-till farmers, 68 percent felt that herbicide effectiveness had increased in the last five years; 56 percent of farmers who had tried but quit no-till felt effectiveness had increased; and 34 percent of farmers who had never tried no-till felt herbicides were more effective. Thus, it is apparent that no-till adopters have more confidence in their weed control systems. Consistent weed control offered by herbicide-tolerant crop systems could increase the confidence of all farmers, resulting in the increased adoption of no-till by farmers who have never tried it and reducing the number of first time no-tillers who revert back to conventional tillage.

An American Soybean Association random survey of soybean growers planting 200 acres or more in the 19 major soybean-producing states documents the importance of glyphosate-tolerant soybeans in facilitating conversion from conventional tillage to no-till and reduced tillage. Soybean growers reported having reduced tillage by an average 1.8 passes from 1996 to 2001, during the period of time that glyphosate-tolerant soybeans were available. Average crop residue cover increased from 28 percent to 49 percent. During the same period, no-till soybean acres in the American Soybean Association survey more than doubled to 49 percent, and reduced tillage acres increased by more than one-fourth, to account for 83 percent of soybean acres. During this time, 53 percent of growers reported making fewer tillage passes, 73 percent left more crop residue on the soil surface, and 48 percent had increased their no-till acres.[64]

To what can these increases be attributed? Sixty-three percent of soybean growers who increased their crop residue between 1996 and 2001 cited glyphosate-tolerant technology as the key factor that made it possible for them to reduce tillage or increase residue.[64] That was an unaided response to the question: “In the past five years, what changes in technology such as equipment, chemicals or seed have made it possible for you to reduce tillage or increase crop residue in soybeans?”

When asked which of six factors had the greatest impact toward the adoption of reduced tillage or no-till during the past five years, growers indicated:

- The introduction of glyphosate-tolerant soybeans 54 percent.
- Availability of over-the-top or in-crop herbicides 12 percent.
- The cost of burndown herbicides 6 percent.
- The availability of burndown herbicides 3 percent.

A total of 75 percent of surveyed farmers felt some aspect of weed control was the greatest factor in adopting reduced tillage or no-till. Availability of and improvements in no-till drills garnered responses of 9 and 15 percent respectively.[64]

In a Canadian survey, 26 percent of canola growers said they had increased their conservation tillage practices because of herbicide-tolerant technology.[69] Their average increase was 69 percent, which translates into 2.6 million acres or 1.05 million hectares in western Canada having been positively impacted by increased conservation tillage practices since the introduction of the technology.

Weed control is similarly important to cotton producers. A USDA survey showed that 76.3 percent of herbicide-tolerant cotton growers said they planted herbicide-tolerant varieties because of increased yields through better weed control, and 18.9 percent cited decreased herbicide input costs.[70]

Competition brought on by herbicide-tolerant technology has resulted in an overall lowering of weed control costs, thus addressing another concern about moving to no-till. Gianessi and Carpenter calculated that U.S. soybean growers spent $220 million less on weed control in 1998 compared with 1995, after the added costs of glyphosate-tolerant seed were factored in.[71] These benefits are supported by the rapid adoption of the technology since its introduction in 1996. Glyphosate-tolerant soybeans were planted on 75 percent of soybean acres in 2002, and glyphosate-tolerant cotton was planted on 58 percent of cotton acres.[72] In Canada, herbicide-tolerant varieties were planted on an estimated 55 percent of the 12 million acres (4.9 million hectares) of canola produced in 2000.[68]

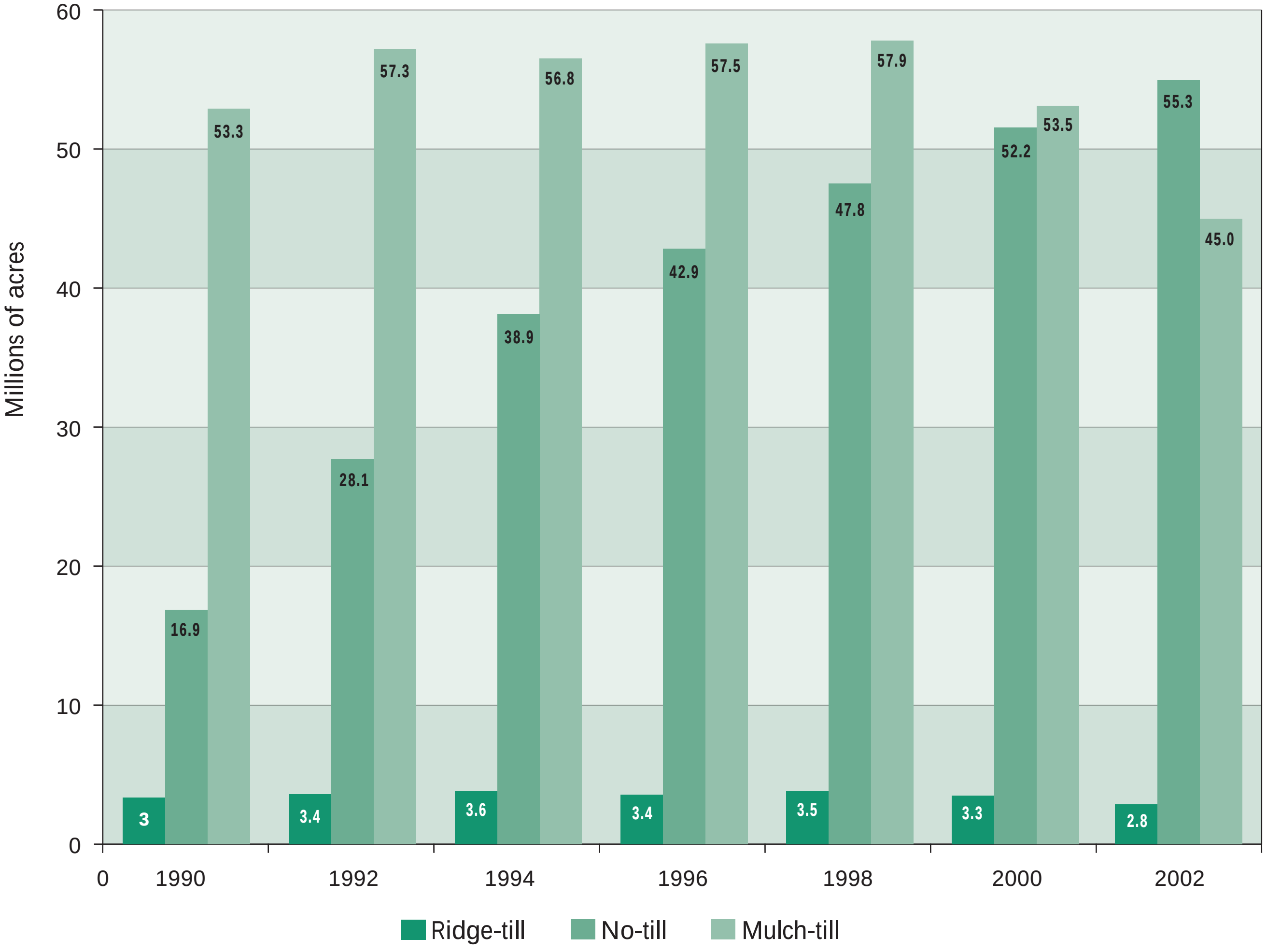
Biotech crops have given farmers a new weed management tool, allowing the post-emergence use of highly effective broad-spectrum herbicides. Perennial weeds are often prevalent in conservation tillage, especially in no-till systems. Many perennials have been noted to increase with conservation tillage.[73] The ability to apply glyphosate over tolerant crops, made possible by biotechnology, now allows control of tough perennials that escape most other herbicides. The risk of suffering poor weed control has been reduced significantly. Biotech crops are not required for the practice of conservation tillage or no-till, but the herbicide-tolerant crops developed through biotechnology have provided farmers with an additional weed management tool, solving some weed control problems faced by conservation tillage farmers.

2. No-till, the system that most depends on herbicide performance, has grown steadily since 1994. Nearly all of this growth occurred in crops where herbicide-tolerant technology is available.

CTIC tillage surveys are based on criteria it developed to define conservation tillage (at least 30 percent residue cover after planting). Mulch-till, ridge-till and no-till are the various forms of conservation tillage. Figure 7 shows national adoption trends for these systems from 1990 through 2002. Since 1996, conservation tillage adoption in the United States has remained fairly constant – about 36 percent of all annually planted cropland or between 103 million and 109 million acres. Thus, total conservation tillage acres appear to have temporarily reached a plateau. However, adoption of no-till, the most soil-conserving form of conservation tillage, continues to increase, rising from 40.9 million acres (14.7 percent of all cropland) in 1995 to 55.3 million acres (19.6 percent of all cropland) in 2002. This represents a growth of 35 percent in no-till since biotech crops were introduced in 1996, according to CTIC's National Crop Residue Management Survey.

The fact that no-till acreage increased while overall conservation tillage has remained steady indicates that growers who earlier made a commitment to some form of reduced tillage decided to leave even more residue on their fields. The 2001 American Soybean Association survey found that 73 percent of soybean growers were leaving more crop residue than five years earlier, and 48 percent of them had increased their no-till acreage from 1996 levels. As stated earlier, 75 percent of soybeans planted in 2002 were glyphosate-tolerant varieties.

Figure 7. Conservation Tillage Adoption in the U.S. (1990–2002)

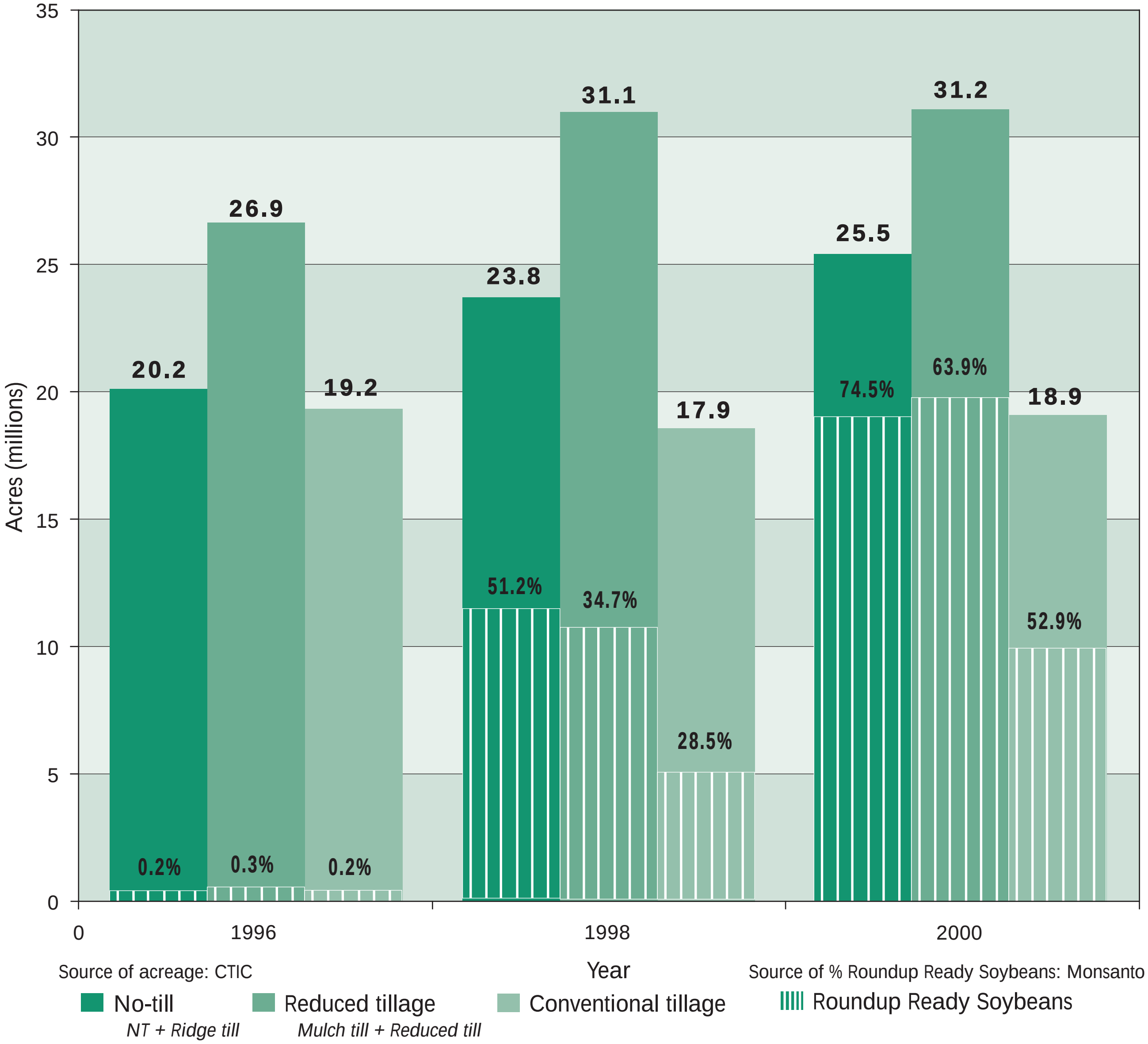


Soybeans and cotton have the highest percentage of biotech crops and account for half of the total no-till acres planted in the U.S. in 2002, according to CTIC figures. It is also significant that the two crops for which glyphosate-tolerant (Roundup Ready®) varieties have been rapidly adopted continue to show increases in adoption of no-till. No-till soybean acres increased from 19.3 million acres (7.8 million hectares) in 1995 (before glyphosate-tolerant crops) to 26 million acres (10.5 million hectares) in 2002. No-till cotton acres increased from 0.5 million (0.2 million hectares) in 1996 (before glyphosate-tolerant crops) to 2 million acres (0.82 million hectares) in 2002. Glyphosate-tolerant soybean varieties have been available since 1996, and cotton varieties since 1997. Glyphosate-tolerant corn was first marketed in 1998. Herbicide-tolerant canola became available in Canada in 1996 and the United States in 1999. Only about 1.5 million acres of canola were planted in the United States in 2000.

3. There is a clear association between sustainable tillage practices and biotech crops.

Table 2 shows national percentages of tillage categories planted to glyphosate-tolerant soybeans, cotton and corn for 1998-2000. While farmers using all tillage systems have adopted the glyphosate-tolerant crops, conservation tillage farmers are much more likely to use the biotechnology crops. For example, in 1998, no-till soybeans were nearly twice as likely to be planted to glyphosate-tolerant varieties compared with conventional varieties, while no-till cotton was more than twice as likely to be planted to glyphosate-tolerant varieties. Adoption of glyphosate-tolerant crops by conservation tillage farmers continues to grow. In 2000, 52.9 percent of conventional tillage, 63.9 percent of reduced tillage, and 74.5 percent of no-till soybean acres were planted to glyphosate-tolerant varieties. Cotton acres planted to glyphosate-tolerant varieties for

Figure 8. Comparison of Soybeans vs. Roundup Ready Soybeans (Planted 1998-2000)



Source of acreage: CTIC

Source of % Roundup Ready Soybeans: Monsanto

2000 were 46.8 percent of conventional tillage, 63.2 percent of reduced tillage and 86.2 percent of no-till. In 2000, 4.3 percent of conventional tillage, 4 percent of reduced tillage and 7 percent of no-till corn was planted to glyphosate-tolerant varieties.

No-till cotton is constrained by the predominance of furrow irrigation and boll-weevil eradication programs in some regions, such as California and Arizona, which restricts conversion to no-till. In other cotton-growing regions, producers who tried the relatively new no-till system for cotton used herbicide-tolerant varieties to facilitate the change. In Arkansas in 1998, only 6.7 percent of conventionally tilled cotton was planted to glyphosate-tolerant varieties, while 97.8 percent of no-till cotton acres were planted to the biotech varieties.[74]

In 2000, glyphosate-tolerant cotton was planted on 97, 96, 95 and 94 percent of no-till cotton in Georgia, Tennessee, Alabama and North Carolina, respectively.[73] The high adoption rate of glyphosate-tolerant cotton by no-till producers illustrates the utility of this technology in conservation tillage. In 2000, glyphosate-tolerant corn was planted on only 5 percent of corn acres in the United States, due in large part to a concern about export restrictions. About 7 percent of all no-till corn acres planted in 2000 were glyphosate-tolerant.

The American Soybean Association survey of grower practices confirms the greater usage of glyphosate-tolerant soybeans in no-till and reduced tillage systems. In the 19-state area represented by the survey, glyphosate-tolerant soybeans were planted on 36.8 million conservation tillage acres and only on 5.3 million conventionally tilled acres.[63] Clearly, with the glyphosate-tolerant seeds going disproportionately to the soybean acres in conservation tillage, farmers understand the value of the technology to reduced tillage systems.

4. Farmers who don’t use herbicide-tolerant seeds are not as likely to engage in conservation tillage.

While it is clear that many farmers who use traditional weed control systems also participate in conservation tillage, there is significantly greater participation among those soybean and cotton farmers who use herbicide-tolerant varieties developed through biotechnology. Table 3 shows results of the American Soybean Association survey[63] comparing practices of glyphosate-tolerant soybean adopters to non-adopters. Glyphosate-tolerant soybean growers planted more no-till and reduced till acres than non-adopters. For the period 1996 to 2001, 52 percent of glyphosate-tolerant soybean adopters had increased no-till acres, compared with 21 percent of non-adopters. Fifty-eight percent of adopters reported reducing tillage passes, with 20 percent of non-adopters reducing tillage passes.

Likewise, in Canada, 50 percent of canola growers who used herbicide-tolerant varieties participated in conservation tillage practices, while only 35 percent of non-adopters practiced conservation tillage.[68]

Table 2: Adoption of glyphosate-tolerant (Roundup Ready) crop technology by tillage system for U.S. soybeans, corn and cotton 1998–2000

	Percent of Acres Planted to Glyphosate-Tolerant Crop		
Year	Conventional Tillage	Reduced Tillage	No-till
Soybeans			
1998	28.5	34.7	51.2
1999	47.0	55.9	70.7
2000	52.9	63.9	74.5
Cotton			
1998	21.3	37.7	57.2
1999	35.0	51.4	65.8
2000	46.8	63.2	86.2
Corn			
1998	1.2	1.1	1.8
1999	3.2	2.9	4.4
2000	4.3	4.0	7.0

Source: Monsanto Company

Table 3: **American Soybean Association 2001 survey of U.S. soybean grower practices of glyphosate-tolerant soybean adopters and non-adopters, 1996 to 2001**

Characteristics	Glyphosate-tolerant soybean growers	Non-glyphosate-tolerant soybean growers
Percent of 2001 soybean acres in no-till or reduced till	84	72
Percent of growers having more no-till soybeans vs. five years ago	52	21
Percent of growers making fewer tillage passes vs. five years ago	58	20
Percent of growers leaving more crop residue vs. five years ago	76	57
Sample size-unweighted base	393	59

Source: American Soybean Association 2001

SUMMARY STATEMENT

Herbicide-tolerant crops developed through biotechnology have provided farmers with an additional weed management tool. They have solved some weed control problems faced by conservation tillage farmers and simplified weed control. An analysis of surveys conducted since the introduction of herbicide-tolerant crops strongly supports the conclusion that these crops developed through plant biotechnology are facilitating the continued expansion of conservation tillage, especially no-till. As more acres are converted to conservation tillage, and especially no-till, significant environmental benefits will be derived.

REFERENCES CITED

1. U.S. Department of Agriculture. 1986. Losing ground. Iowa's soil erosion menace and efforts to combat it. Soil Conservation Service, Des Moines, IA.

2. Faulkner, E.H. 1943. Plowman's Folly. University of Oklahoma Press, Norman, OK. 161 pp.

3. Laflen, J.M., G.R. Foster, and C.A. Onstad. 1985. Simulation of individual-storm soil loss for modeling the impact of soil erosion on crop productivity. *In* S.A. El-Swaify, W.C. Moldenhauer, and A. Lo, ed., Soil Erosion and Conservation, pp. 285-295. Soil and Water Conservation Society, Ankeny, IA.

4. Hebblethwaite, J.F. 1995. The Contribution of No-Till to Sustainable and Environmentally Beneficial Crop Production: A Global Perspective. Conservation Technology Information Center. West Lafayette, Indiana.

5. Fawcett, R.S. 1994. Can agriculture cool global warming? Farm Journal. 118(6):12.

6. NRCS. 2000. Summary Report 1997 National Resources Inventory. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, D.C. 99 pp.

7. USDA- ARS. 1997. Predicting Soil Erosion by Water: a Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE), Ag Handbook 703, 383 pp.

8. U.S. Environmental Protection Agency. 2000. The Quality of Our Nation's Water, 2000. EPA 841-S-00-001 http://www.epa.gov/305b/98report/98brochure.pdf USDA/NASS, 2001. Acreage report. National Agricultural Statistics Service USDA, Washington, D.C.

9. Ribaudo, M.O. 1989. Water quality benefits of the Conservation Reserve Program. Agricultural Economic Report 606, USDA Economic Research Service, Washington, D.C.

10. Stinner, B.R. and G.J. House. 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Annual Reviews of Entomology 35:299-318.

11. House, G.J. and R.W. Parmalee. 1985. Comparisons of soil arthropods and earthworms from conventional and no-tillage agroecosystems. Soil Tillage Research 5:351-360.

12. Brust, G.E. and G.J. House. 1988. A study of *Tyrophagus putrescentiae* (Acari: Acaridae) as a facultative predator of southern corn rootworm eggs. Experimental and Applied Acarology 4:335-344.

13. Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119:242-249.EPA. 2000. The quality of our nation’s waters. A summary of the National Water Quality Inventory: 1998 Report to Congress Office of Water, Washington, D.C. June 2000.

14. Edwards, W.M., M.J. Shipitalo, L.B. Owens, and L.D. Norton. 1989. Water and nitrate movement in earthworm burrows within long-term no-till cornfields. J. Soil and Water Cons. 44:240-243.

15. Hendrix, P.F., R.W. Parmalee, D.A. Crossley, Jr., D.C. Coleman, E.P. Odum, and P.M. Goffman. 1986. Nutrient mobility and detritus food webs in conventional tillage and no-tillage agroecocystems. Bioscience 36:403-407.

16. Beare, M.H., R.W. Parmalee, P.F. Hendrix, W. Cheng, D.C. Coleman, and D.A. Crossley, Jr. 1992. Microbial and fauna interactions and effects on litter nitrogen and decomposition in agroecosystems. Ecology Monographs 62:569-591.

17. Hu, S., D.C. Coleman, M.H. Beare, and P.F. Hendrix. 1995. Soil carbohydrates in aggrading and degrading agroecosystems, influences of fungi and aggregates. Agricultural Ecosystems and Environment. 54:77-88.

18. Doran, G.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Amer. J. 44:765-771.

19. Locke, M.A. and S.S. Harper. 1988. Tillage and soybean residue effects on metribuzin degradation. Agron. Abst. p. 42.

20. Palmer, W. 1995. Effects of modern pesticides and farming systems on northern bobwhite quail brood ecology. Ph.D. Dissertation, North Carolina State University. 131 pp.

21. Basore, N.S., L.B. Best, and J.B. Wooley. 1986. Bird nesting in Iowa no-tillage and tilled cropland. J. Wildlife Man. 50:19-28.

22. Warburton, D.B. and W.D. Klimstra. 1984. Wildlife use of no-till and conventionally tilled corn fields. J. Soil and Water Cons. 39:327-330.

23. Rodenhouse, N.L. and L.B. Best. 1983. Breeding ecology of vesper sparrows in corn and soybean fields. Amer. Midl. Nat. 100:265-275.

24. Rabalais, N.N., R.E. Turner, D. Justic, Q. Dortch, and W.J. Wiseman, Jr. 1999. Characterization of hypoxia. NOAA Decision Analysis Series. No. 15. 167. pp.

25. Fawcett, R.S. 1991. Scratching the surface. Agricultural Engineering. May. pp. 16-17.

26. Foy, C.L. and H. Hiranpradit. 1989. Movement of atrazine by water from application sites in conventional and no-tillage corn productions. In D.L. Weigman, ed. Pesticides in Terrestrial and Aquatic Environments. VA Water Resources Res. Center and VA Polytechnic Inst. and State Univ., Blacksburg. pp. 355-373.

27. Glenn, S. and J.S. Angle. 1987. Atrazine and simazine runoff from conventional and no-till corn watersheds. Agric. Ecosystems and Environ. 18:273-280.

28. Hall, J.K., R.O. Mumma, and D.W. Watts. 1991. Leaching and runoff losses of herbicides in a tilled and untilled field. Agric. Ecosystems and Environ. 37:303-304.

29. Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizing macropores that affect infiltration into no-tilled soil. Soil Sci. Soc. Am. J. 52:483-487.

30. Baker, J.L. and J.M. Laflen. 1983. Water quality consequences of conservation tillage. J. Soil and Water Cons. 38:186-193.

31. Andraski, B.J., D.H. Mueller, and T.C. Daniel. 1985. Phosphorus losses in runoff as affected by tillage. Soil Sci. Soc. Am. J. 49:1523-1527.

32. Fawcett, R.S., B.R. Christensen, and D.P. Tierney. 1994. The impact of conservation tillage on pesticide runoff into surface water: a review and analysis. F. Soil and Water Cons. 49(2):126-135.

33. Sander, K.W., W.W. Witt, and M. Barrett. 1989. Movement of triazine herbicides in conventional and conservation tillage systems. In D.L. Weigman (ed). Pesticides in Terrestrial and Aquatic Environments. VA Water Resources Res. Center and VA Polytechnic Inst. and State Univ., Blacksburg. pp. 378-382.

34. Kanwar, R.S., J.L. Baker, and D.G. Shires. 1988. Tillage and split N-fertilization effects on subsurface drainage water quality and crop yields. Trans. Amer. Soc. Ag. Eng. 31:453-461.

35. Kanwar, R.S. and J.L. Baker. 1993. Tillage and chemical management effects on groundwater quality. Agricultural Research to Protect Water Quality. Soil and Water Cons. Soc., Ankeny, IA. pp. 455-456.

36. Randall, G.W. and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. J. Environ. Qual. 24:360-366.

37. Hall, J.K., M.R. Murray, and N.L. Hartwig. 1989. Herbicide leaching and distribution in tilled and untilled soil. J. Environ. Qual. 18:439-445.

38. Isensee, A.R. R.G. Nash, and C.S. Helling. 1990. Effect of conventional vs. no-tillage on pesticide leaching to shallow groundwater. J. Environ. Qual. 19:434-440.

39. Fermanich, K.J. and T.C. Daniel. 1991. Pesticide mobility and persistence in microlysimeter soil columns from a tilled and no-tilled plot. J. Environ. Qual. 20:195-202.

40. Levanon, D., E.E. Codling, J.J. Mesinger, and J.L. Starr. 1993. Mobility of agrochemicals through soil from two tillage systems. J. Environ. Qual. 22:155-161

41. Isensee, A.R. and A.M. Sadeghi. 1996. Effect of tillage reversal on herbicide leaching to groundwater. Soil Sci. 161:382-389.

42. Gish, T.J., A. Shirmohammadi, R. Vyrahpillai, and B.J. Weinhold. 1995. Herbicide leaching under tilled and no-tillage fields. Soil Sci. Soc. Am. J. 59:895-901.

43. Stoltenberg, D.E., M. Soloman, J.E. Hanson, K.J. Fermanich, B.Lowery, and K. McSweeney. 1997. Effect of tillage, irrigation scheduling, and ASE-108 acrylate polymer on atrazine movement and degradation in coarse-textured soil. North Cent. Weed Sci. Soc. Proc. 47:12.

44. Novak, I.M. 1997. Conservation tillage reduces pesticide leaching. CTIC Partners 15:12.

45. Stehouwer, R.C., W.A. Dick, and S.J. Traina. 1994. Sorption and retention of herbicides in vertically oriented earthworm and artificial burrows. J. Environ. Qual. 22:286-292.

46. Potter, K.W. 1991. Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. Water Resources Research 27(5):845-855.

47. Reicosky, D.C., M.J. Lindstrom, and S. Masielewicz. 1994. Conservation Tillage Too Demonstration Barnes-Aastad Swan Lake Research Farm. U.S. Department of Agriculture. Agricultural Research Service. Soil Conservation Laboratory. Morris, Minnesota. Aug. 24, 1994.

48. Siemans, J.C. 1998. Water quality. *In* Picklesmer, P. (ed.) Illinois Agronomy Handbook 1999-2000; University of Illinois Extension. pp 117-128.

49. Wicks, G.A. 1976. Ecofallow: a reduced tillage system for the Great Plains. Weeds Today 7(2):20-23.

50. Wicks, G.A. 1986. Herbicide applications on wheat and stubble for no-tillage corn. Agron. J. 78:843-848.

51. Norwood, C.A. 1999. Water use and yield of dryland row crops as affected by tillage. Agron. J. 91:108-115.

52. Post, W.M., T.H. Peng, W.R. Emanuel, A.W. King, V.H. Dale, and D.L. DeAngelis. 1990. The global carbon cycle. American Scientist 48:310-326.

53. Bouwman, A.F. 1989. Background: Part II. *In* A.F. Bouwman (ed.) Soils and the Greenhouse Effect. New York. John Wiley and Sons.

54. Johnson, M.G. and J.S. Kern. 1991. Sequestering carbon in soils: A workshop to explore the potential for mitigating global climate change. USEPA Rep. 600/3-91-031. USEPA Environ. Res. Lab, Corvallis, OR.

55. Robertson, G.P., E.A. Paul, R.R. Harwood. 2000. Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere. Science. 15 Sept. 2000, Vol. 289, pp. 1922-1925.

56. Reicosky, D.C. and M.J. Lindstrom. 1995. Impact of fall tillage on short-term carbon dioxide flux. In Soils and Global Change. R. Lal, J. Kimble, E. Levine, and B.A. Steward, eds. Lewis Publishers, Chelsea. Pp. 177-187.Ribaudo, M.O. 1989. Water Quality Benefits from Conservation Reserve Program. Agricultural Economic Report 606, USDA Economic Research Service, Washington, D.C.

57. Kern, J.S. and M.G. Johnson. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Amer. J. 57:200-210.

58. Lal, R., J.M. Kimble, R.F. Follet, and C.V. Cole. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press, Chelsea, MI.

59. Odell, R.T., W.M. Walker, L.V. Boone, and M.G. Oldham. 1984. The Morrow Plots, a century of learning. University of Illinois Bulletin 775. Champaign, IL.

60. Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil & Tillage Res. 43:131-167.

61. Fawcett, R.S. 1992. Herbicides in the rain. Farm Journal. 116(3):A-8

62. Richards, R.P., J.K. Kramer, D.B. Baker, and K.A. Krieger. 1987. Pesticides in rainwater in the northeastern United States. Nature 327(6118):129-131.

63. Jasa, P.A., D. Shelton, A. Jones and E. Dickey. 1991. Conservation Tillage and Planting Systems. Cooperative Extension Service, University of Nebraska-Lincoln, Lincoln, Nebraska.

64. American Soybean Association. 2001. Conservation Tillage Study. St. Louis, Missouri. www.soygrowers.com.

65. Ayres, G.E. 1989. Fuel Required for Field Operations. Extension Publication Pm-709. Iowa State University, Ames, Iowa.

66. Fawcett, R.S. 1985. Weed control in conservation tillage. Cooperative Extension Service, Iowa State University. 12 pp.

67. Iowa State University Department of Sociology, 1991. Conservation Survey 1991. 4 pp.

68. USDA-NRCS. 2001. IRMP tillage survey summary, 1999-2000. Des Moines, IA. 4 pp.

69. Canola Council of Canada, 2000. Impact of Transgenic Canola on Growers, Industry and Environment, 2000. www.canola-council.org.

70. Fernandez-Cornejo, J., W.D. McBride, C. Klotz-Ingram, S. Jans, and N. Brooks. 2000. Genetically engineered crops for pest management in U.S. agri-culture: farm-level impacts. Economic Research Service, U.S. Department of Agriculture. Agricultural Economic Report No. 786. 20 pp.

71. Gianessi, L.P. and J.E. Carpenter. 2000. Agricultural biotechnology: benefits of transgenic soybeans. National Center for Food and Agricultural Policy, Washington, D.C. 103 pp.

72. USDA/Agricultural Statistics Board. 2002. Annual planting intentions survey. USDA, Washington, D.C. http://usda.mannlib.cornell.edu.

73. Becker, R.L. 1982. Perennial weed response to tillage. Ph.D. Thesis. Iowa State University. 120 pp.

74. Monsanto, 2001 personal correspondence.

75. Laflen, J.M., J.L. Baker, R.O. Hartwig, W.F. Buchele, and H.P. Johnson. 1978. Soil and water loss from conservation tillage. Trans. Am. Soc. Agr. Eng. 21(5):881-885.

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