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NEW MEXICO AGRONOMY TECHNICAL NOTE NO.64

SUBJECT: ECS – "BETTER SOIL BETTER YIELDS"

Purpose: To distribute Agronomy Technical Note No. 64.

Effective Date: When contents have been noted.

Filing Instructions: File in the Agronomy Technical Note binder.

Attached is a guidebook to improving soil organic matter and infiltration with continuous no-till. For additional copies of this publication, information on other publications, survey of tillage practices, visit CTIC on the internet at http://www.ctic.purdue.edu or www.Core4.org

KENNETH B. LEITING
State Resource Conservationist

Attachment

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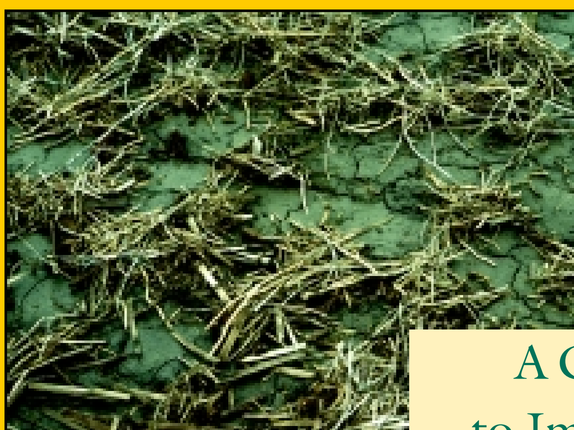
Better Soil Better Yields



A Guidebook
to Improving Soil
Organic Matter
and
Infiltration With
Continuous
No-Till

Conservation Technology Information Center 2001

Better Soil Better Yields

A Guidebook to Improving Soil Organic Matter and Infiltration

The first step to improve water quality is to improve soil quality.

♦ Written by Richard Fawcett, Fawcett Consulting and Steve Caruana, Agronomic Analytics.

♦ Early direction and comment was provided by Dave Schertz, NRCS; Don Reicosky, ARS; Ed Frye, CTIC; John Doran, ARS; Dean Wesley, Key Ag; Jim Poterfield, American Farm Bureau; Jerry Hatfield, ARS; Bill Richards, farmer; Maurice Mausbach, NRCS; George Langdale, and Doral Kemper, ARS.

♦ Produced by the Conservation Technology Information Center

♦ Edited by Dan Towery, NRCS/CTIC, and Ed Frye, CTIC. ♦ Layout by Angie Fletcher.

♦ Mention of product, trade names, or equipment photos does not constitute an endorsement by the Conservation Technology Information Center.

About the Conservation Technology Information Center…

The Conservation Technology Information Center (CTIC) is a nonprofit information data transfer network. The center promotes environmentally responsible and economically viable crop production decision-making.

For additional copies of this publication, information on other publications, survey of tillage practices, CTIC membership, etc.:

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INTRODUCTION

Our nation's soils are laregely taken for granted. Most people do not recognize the important role soils have. Soils are the fuel – the raw materials- of farming. Without high quality soils, production agriculture as we know it cannot exist. No-till production systems can improve the soil by increasing organic matter and improving infiltration. Changing these qualities can result in more moisture being available for crop development and result in higher yields in years with less than normal rainfall.

Historically, conventional row-crop production has included, by design, significant amounts of tillage for reasons ranging from weed control to simple tradition. Intensive tillages results in the soil being readily transported from the farm field by water and wind and thereby transformed from a valuable agricultural input into a pollutant with effects extending far beyond the farms.

While there are any number of activities and practices that farmers may employ in an attempt to keep their topsoil in place, one method in particular stands out among others as the most cost-effective manner of both reducing tillage trips while protecting and enhancing the environment. Conservation tillage, particularly in the form of long-term or continuous no-till, minimizes the soil leaving the field by maintaining a cover on the soil's surface. A significant added benefit of this practice is the actual rebuilding of soils by the slow decomposition of previous crop's residue, roots and macropore development. Long-term no-till minimizes fuel inputs and soil compaction by minimizing the number of tillage trips. There are a number of other production and environmental benefits of no-till, and these will be addressed later, but there can be no benefit greater than the conservation and actual improvement of these raw materials of agriculture – soils.

Agriculture Research Services

The top 1-2" of the soil determines many soil quality properties that impact production and the environment.

...there is little disagreement that organic matter content gives soils many of their desirable properties.

Organic Matter

While there is not yet a consensus on exactly how to measure soil quality, there is little disagreement that organic matter content gives soils many of their desirable properties. In an early study of soil organic matter function (71), organic matter is defined as the soil fraction derived from materials of plant and animal origin. It includes these residues in various stages of decomposition, soil organisms, and their synthesized by-products. There are long-term, stable organic compounds in the soil that persist for decades, collectively referred to as humus. Other compounds are more quickly recycled and designated as the changeable or transient portion.

Organic matter is important to soil structure and tilth. It provides energy for soil microorganisms, improves water infiltration and water holding capacity, reduces erosion potential and is an important element in the nutrient and carbon cycles. Organic matter is the adhesive of the soil, binding together the soil components into stable aggregates. The National Research Council's report, *Soil and Water Quality an Agenda for Agriculture* states: "Soil organic carbon or soil organic matter is perhaps the single most important indicator of soil quality and productivity" (57). According to a 1995 Journal of Soil and Water Conservation article, when farmers were asked how they recognized "healthy soils", organic matter was ranked as most important (64).

Although moldboard plowing is not common, almost 43% of the cropland in the US employs tillage systems which after repeated tillage trips results in low residue levels (<15% after planting).

No-till

Increases in the use of no-till systems by American farmers have led to many benefits, both direct and indirect. These include reductions in erosion, and savings of time, labor, fuel and machinery. Between 1990 and 2000, no-till farming acreage rose from 16 million acres to 52 million acres, an increase of 225 percent. Many of the soil benefits from no-till are realized primarily after having been employed for several years. These no-till fields display additional benefits to farmers and researchers - changes in soil physical, chemical and biological properties. The most notable of these benefits include increases in organic matter and improved water infiltration which results in a greater soil moisture reservoir available to crops. All other things equal, this will result in increased yields during periods when rainfall is in short supply.

John Bradley, Milan Experimental Station

Runoff from no-till field on the left and conventional tilled field on the right from plots at Milan Experimental Station, Milan, Tennessee. The clear water from the no-till side of the field is transporting significantly less topsoil, nutrient, and pesticides.

Potential Benefits

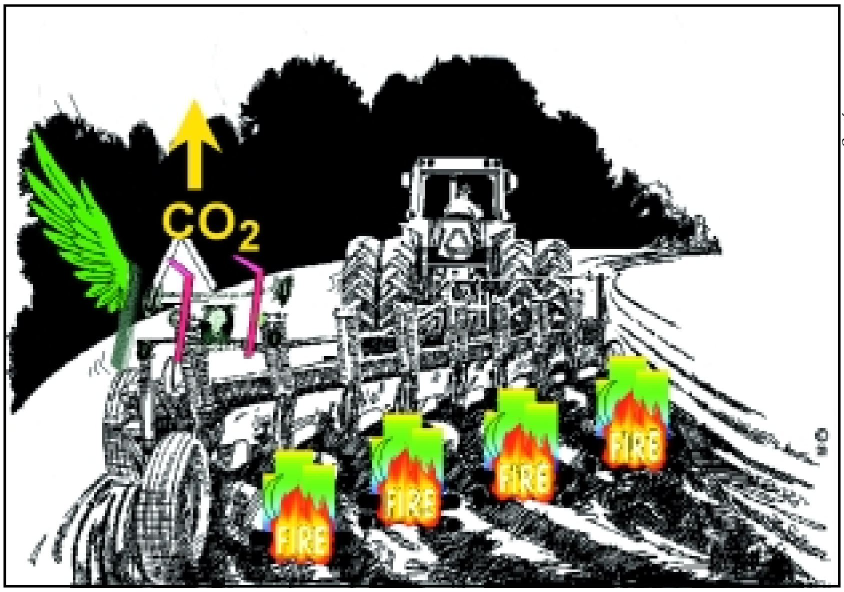
Surface Organic Matter

Tillage introduces oxygen to the soil and stimulates the natural oxidation or "burning" of soil organic matter by soil microorganisms. This process produces carbon dioxide and releases nutrients needed for crop growth. However, the long-term use of tillage has resulted in depleted organic matter contents of our soils. Long-term cropping studies have documented steady declines in organic matter (60).

Carbon Dioxide Loss

Increasing soil organic matter through additions of manure and growing green manure crops may increase organic matter levels significantly. However, increases in organic matter have almost never occurred as long as soils were tilled. New research tells us why. Reicosky and Lindstrom (61) measured carbon dioxide released from soil in the fall after tilling wheat stubble with various implements. Over a 19-day period, they discovered five times as much carbon dioxide was lost from soil that had been moldboard plowed than was lost from untilled soils.

These results suggest more organic matter was oxidized in that 19-day period than was produced all year by the wheat crop in straw and roots (62). This helps us understand why organic matter levels have declined with tillage even when crop residues are plowed into the soil.



Don Reicosky, Agriculture Researc Services

Intensive tillage either by moldboard plowing or by numerous tillage trips results in the oxidation of organic matter and the release of carbon dioxide.

Moldboard Effects

Reicosky et al (63) have summarized studies investigating long-term changes in soil organic matter with different tillage and crop production systems. In 20 long-term studies using the moldboard plow, organic matter was reduced by an average of 256 lbs/ac/yr in Illinois, Oregon, and Missouri with rotations of continuous corn, continuous wheat, and corn with soybeans and oats. Reicosky and associates concluded, "In general it is practically impossible to increase organic matter where moldboard plowing is taking place. Massive additions (6 to 10 tons/ac/yr) of manures in addition to crop residues plowed into the soil are able to cause small increases for a few years, but leveling off or slight decreases follow."

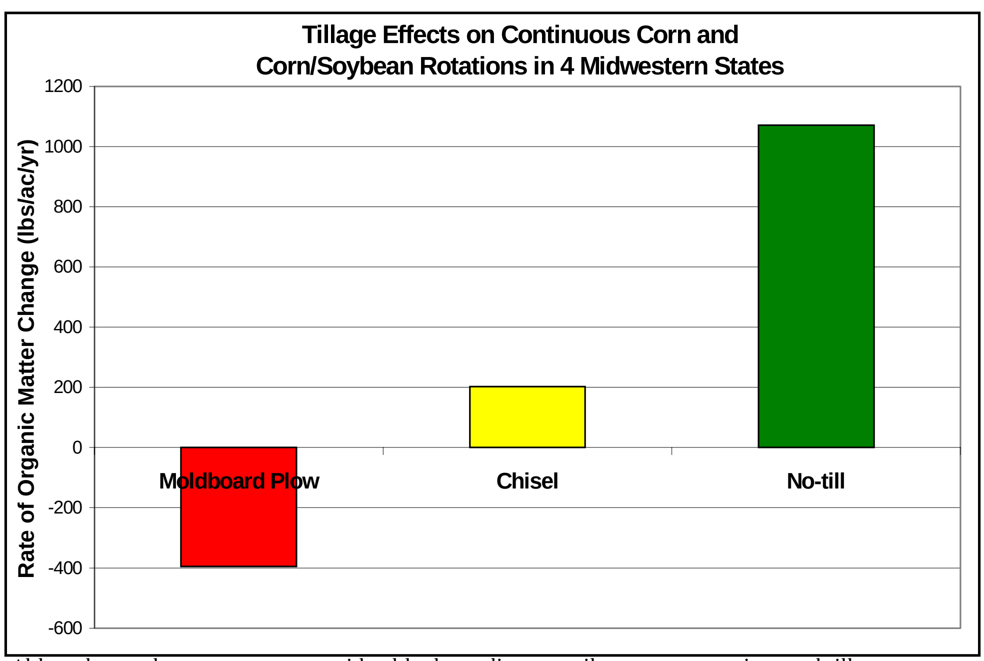
Efforts to understand the dynamics of tillage on soil organic matter through modeling have indicated that the less stable portion of the soil's organic matter is the first to be lost with cultivation (65).

No-till Increases

However, by eliminating tillage, soil organic matter can be increased. The Reicosky summary (63) listed 10 long-term no-till studies where organic matter changes were documented. Organic matter increased in all 10 of the studies, with an average increase of 953 lbs/ac/yr. Increases as high as 2000 lbs/ac/yr occurred in some studies. That would translate into an increase of about 0.1% soil organic matter by weight per year. The studies were conducted in Ohio, Alabama, Georgia, Kentucky, Illinois, Minnesota, and Nebraska with rotations of continuous corn, continuous soybeans and corn in rotation with soybeans. Analyzing the results from 15 studies measuring the effect on soil organic matter following a conversion from conventional tillage to no-till, Kern and Johnson (39) developed a relationship to predict the increase in organic matter. As crop residues were retained on the surface with the adoption of no-till, soil organic matter typically increased up to 180 percent.

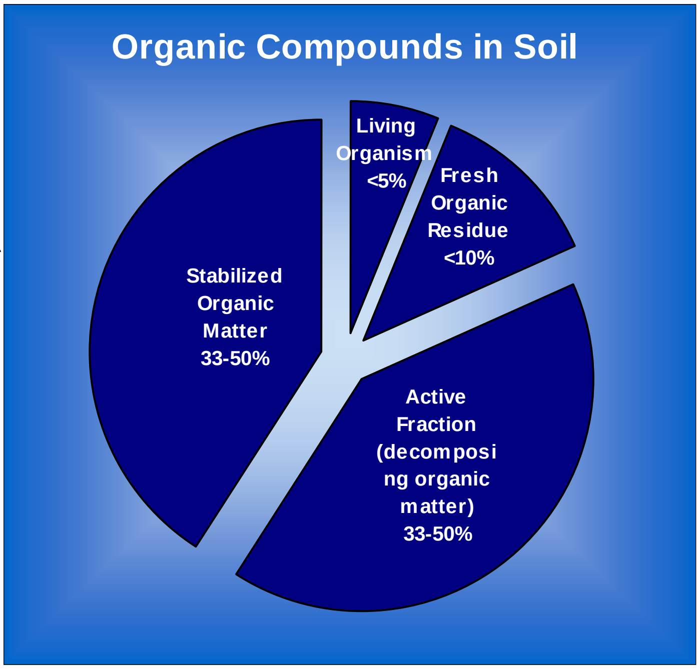
Climate & Crop Residue

Potential for increased soil organic matter is greatest in the north where growing seasons are shorter and less natural oxidation of organic



Although actual rates may vary considerably depending on soil type, crop rotation, and tillage systems, fewer tillage trips and crops with more biomass results in higher levels of organic matter or carbon sequestration.

University of Minnesota Extension



Stabilized organic matter can absorb 6 times its weight in water; a silt loam soil can increase its water holding capacity 7% and CEC by 4% by increasing organic matter levels 0.5%. Tillage causes younger organic matter to oxidize.

matter occurs. Crops differ in amounts of residues returned to the soil and the stability of those residues. For example, corn residues return more biomass to the soil than do soybean residues. Soybeans also decompose faster because of their lower Carbon:Nitrogen ratio. As plant residues are added to the soil and decay, their carbon is assimilated into the microbial biomass of the soil (29). Under arid and semiarid conditions prevalent in the western U.S., annual increases of organic matter under no-till can be expected to be slightly less.

Rotations & Cover Crops

In a long-term study comparing corn-wheat, soybeans-wheat, and corn-wheat-soybeans-wheat rotations in no-till, soil organic matter increases were greatest for the corn-wheat rotation and least for soybeans-wheat (16). Growing cover crops following row crops and leaving the cover crop residues in the field can increase organic matter beyond what is possible by simply returning row crop residues (42).

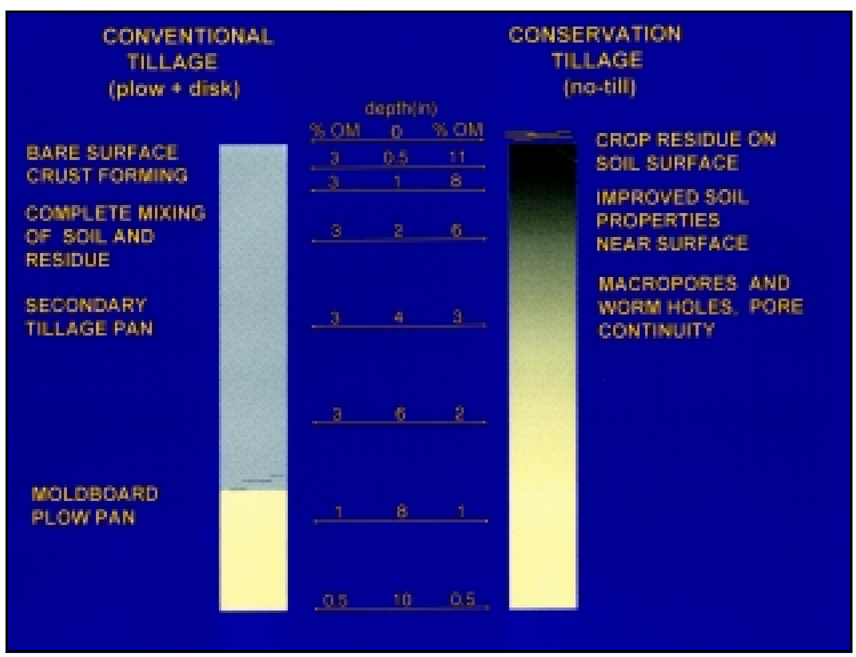
Cover crops are especially beneficial in southern states where the long growing season increases natural oxidation of organic matter.

Nitrogen fertilization also increases the rate of organic matter formation (44). The use of no-till contributes significantly to the stability of organic matter pools. No-till can increase the time organic matter resides in the soil by 10 to 15 years over conventional tillage (10).

Besides increasing total amounts of organic matter in the soil, no-till also changes the distribution of organic matter in the soil. With conventional tillage, organic matter is mixed throughout the tilled depth. With no-till, higher organic matter levels are concentrated at the soil surface and the first few inches of depth. The figure below compares organic matter distribution in a long-term no-till soil to a tilled soil. This change in organic matter distribution may cause confusion in interpreting organic matter tests.

Soil Sampling

It is important to pay attention to sampling depth when trying to measure organic matter changes over time. Standard soil tests for nutrients, pH, and organic matter are usually taken to a 6 or 7 inch depth. With the increased popularity of no-till, many fields are now sampled at the 3 inch depth to check for possible stratification of nutrients and pH and to monitor Cation Exchange Capacity (CEC).



Comparing conventional tillage to no-till in regards to organic matter changes and depth of change.

Consistency in depth of soil samples and lab procedure used is important in monitoring long-term changes in soil organic matter levels.

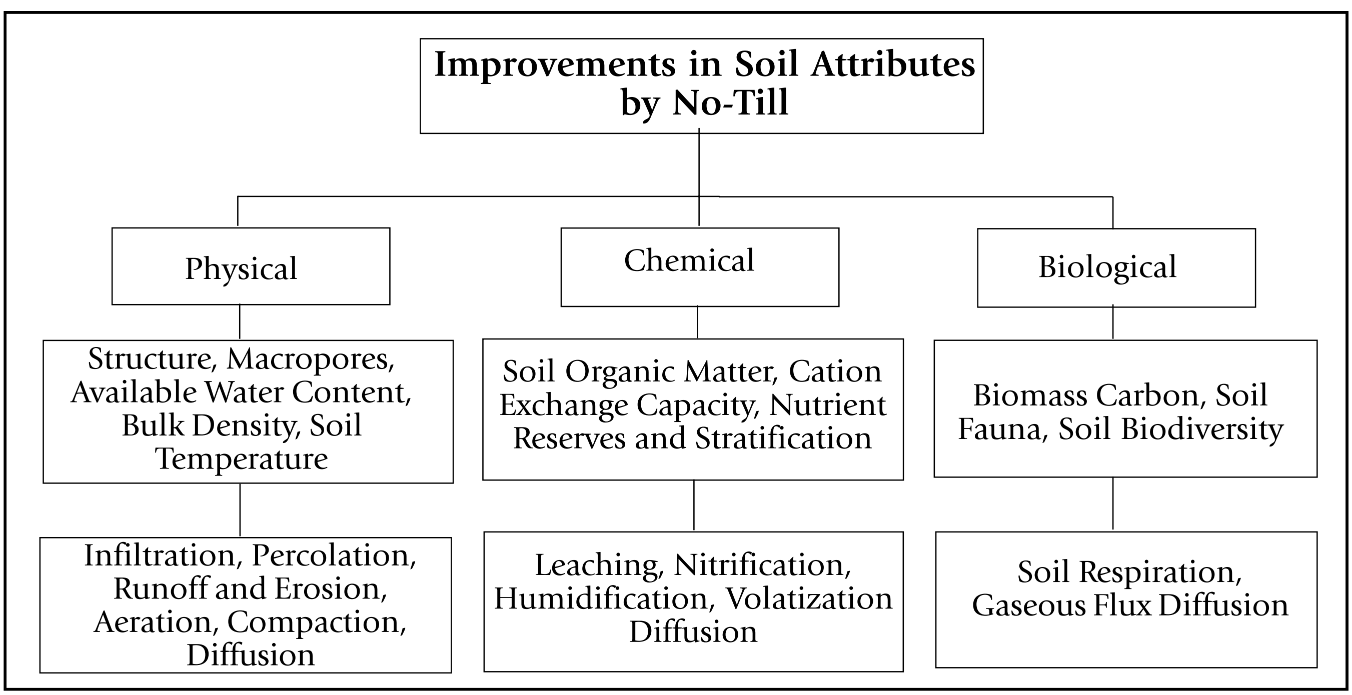
The major practical reason for determining organic matter content of soils has been to calculate herbicide rates. Because soil-applied herbicides are active in the top few inches of soil, a 3-inch sample provides a more useful reading than a 6-inch sample in conservation tillage or no-till fields.

It is critical that sampling depths are consistent over time to insure that any changes are real and not just a result of different sampling depths. Sampling to depths as shallow as 1/2 inch may be useful to document organic matter changes. Soil organic matter tests are not intended to measure undecomposed crop residue. It is best to use sampling procedures that avoid including crop residue in samples, such as removing the top 1/4 inch of soil surface. Passing the sample through a 2 mm (5/64 inch) sieve will also remove undecomposed crop residue.

Because the various laboratory testing procedures (such as dry combustion or wet Walkley-Black oxidation) can produce different results, it is also important that consistent lab methods are used to document changes in organic matter with time and tillage practice.

Bulk Density

Changes in bulk density complicate comparisons of soil tests between no-till and tilled fields. Bulk density, the weight of soil per unit of volume, usually increases with no-till. Bulk density decreases as aggregation and clay content increases. Higher bulk densities observed with no-till are tied to the proportion of macropores being lower (35). Bulk density also decreases as the organic matter content of a soil increases. If organic matter content were determined as a percentage of dry weight without considering bulk density, comparing amounts of organic matter in equal volumes of no-till vs. tilled soil would underestimate organic matter in the no-till soil. Organic matter analyses may have to be adjusted for bulk



Conservation tillage effects on properties and processes that affect soil quality (from Blevins et al. 1998)

John Doran, ARS

Roots are a major contributor to soil organic matter especially in a no-till. Corn may produce .5 to 2 tons/acres of root mass in a growing season; soybeans may produce .3 tons/acres; and prairie makes over 2 tons/acre. Finely branched roots enhance soil aggregation more than tap-rooted plants.

density to correctly track changes with no-till relative to tillage.

Soil Structure/Aggregates

Crop residue on the soil surface absorbs the energy of falling raindrops, thereby reducing erosion, and aiding the development of crop roots, enabling crops to better utilize moisture and nutrients. Soil organic matter and the microbial growth it promotes results in desirable soil structure. The fungal communities that dominate in no-till soils (rather than bacteria which predominate in tilled soils) increase soil aggregation and retention of soil carbon. Fungal hyphae contribute to the formation of larger aggregates by physically enmeshing smaller aggregates (34). Soil aggregates in no-till soils are more stable than those in tilled soils. Soil organic carbon, aggregate size and stability, and infiltration can all be significantly greater with no-till (17).

Soil aggregates enhance conditions for a desirable mix of air and water for good plant growth. Good shallow root development allows crops to fully utilize nutrients near the soil surface. Aggregation, soil carbon and nitrogen are closer to the soil surface with no-till (21). The mulching effect of surface residue in no-till also reduces surface drying, allowing shallow roots to function in moist soil and reducing temperature extremes. Aggregates resist the sealing of soil surfaces, which can cause crusting and water runoff. Surface crop residue also dams runoff, holding rainfall on fields longer and at least potentially increasing water infiltration. While no-till has sometimes dramatically increased water infiltration, it has not always produced this benefit.

WATER INFILTRATION

Many long-term no-till farmers have noted improvements in water infiltration. There are times when no runoff occurs in no-till fields when adjacent tilled fields produce runoff from the same storm.

Reducing Water Runoff

Researchers have also documented the reduction of surface runoff in no-till fields. Edwards and associates (14) compared season-long water runoff from a watershed with a 9% 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% less under the long-term no-till. No-till has performed well even under extreme conditions. For example, a no-till watershed on a 21% slope had almost no soil erosion and held water runoff to levels similar to a conventional tillage watershed of only 6% slope during a once-in-100 year storm of 5 inches in 7 hours (32). Comparison of no-till with ridge-till on a fine sandy loam in Maryland found that no-till

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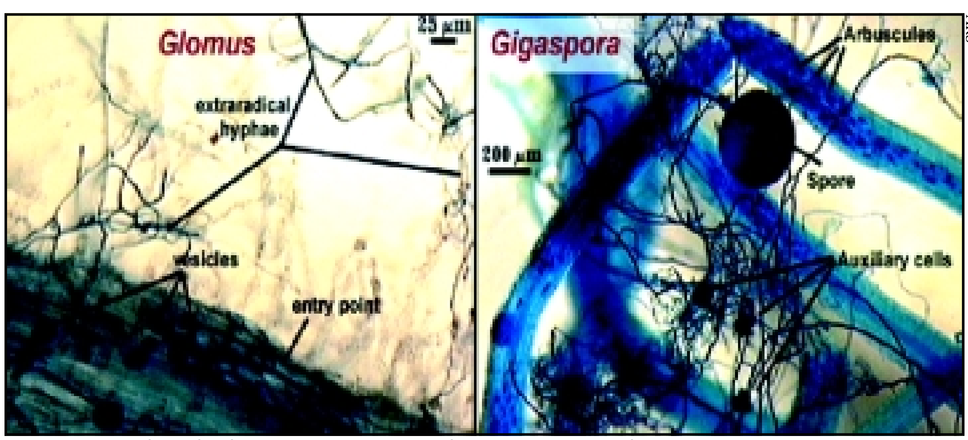

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Residue is the food for fungi and bacteria. The fungal hyphae and fine roots surround and stabilize soil aggregates (like glue holding the clay particles together). These aggregates or peds resist breakage when hit by rain or wind.

NRCS

This table top rainfall simulator shows the dramatic differences in quantity and quality of runoff associated with high residue farming versus clean tillage. All jars received the same amount of simulated rainfall.

retained more water in the soil than ridge-till through increased infiltration and macropore flow resulting in decreased runoff (73). Under the low rainfall conditions of Sidney, Montana, no-till increased precipitation storage efficiency by 16 percent during drier than average fallow seasons (70).

Infiltration Factors

Increases in infiltration with no-till are due primarily to two factors: reduction of surface sealing and development of macropores. Surface crop residue protects soil from the energy of raindrops, preventing the breakdown of aggregates. As discussed previously, increases in organic matter in surface soils also lead to more stable soil aggregates. Macropores consisting of worm holes, soil insect holes, cracks and root channels are also left intact in absence of tillage. These pores provide a kind of overflow system when rainfall exceeds the capillary flow capacity of the soil. Water can run down these macropores to increase subsoil water storage rather than running off the field, conserving water for the crop and protecting surface waters from contaminated runoff. Long-term studies of no-till fields identify undisturbed soil pore structure in no-till as significantly improving hydraulic conductivity and infiltration rates (3).

Controlling Runoff from Herbicides and Soil Particles

Some soil-applied herbicides which are detected in surface water (such as the triazines and acetanilides) are carried off treated fields primarily in runoff water. Herbicide concentrations are higher in sediment, but because so much more water leaves fields than sediment, the water carries more chemical. For that reason, soil erosion control alone will not prevent contamination of surface water by these chemicals. Because no-till not only reduces erosion, but usually also reduces runoff, it has been effective in reducing herbicide runoff. A summary of numerous published studies comparing no-till to conventional tillage under natural rainfall conditions showed that, on average, no-till reduced soil erosion, water runoff and herbicide runoff by 92%, 69% and 70% respectively (18). However, plot studies conducted on a silt loam claypan soil in Missouri found an increase in runoff with no-till compared to tilled plots (25). The claypan restricts water infiltration into the subsoil and prevents an improvement in reducing runoff. When herbicide loss is of concern, careful management is required when applying no-till to claypan soils.

Earthworm Burrows

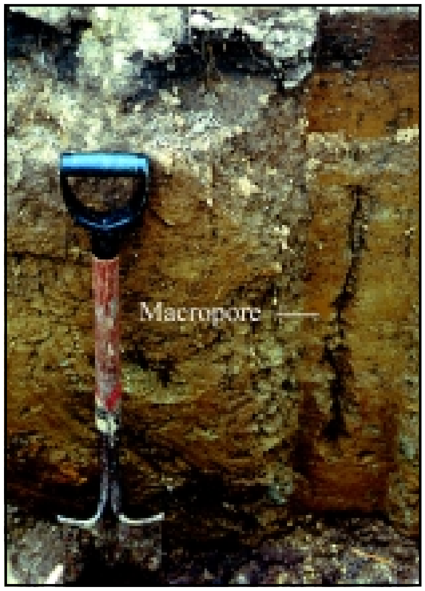
Burrows from earthworms and soil insects have been discovered to be particularly important in improving water infiltration. Nightcrawlers (*Lumbricus terrestris L.*) are surface feeders and construct permanent vertical burrows. Edwards and associates (15) found that although earthworm holes greater than 0.22 inches in diameter accounted for only 0.3 % of the horizontal area of a no-tilled field, flow into the holes during 12 rainfall events accounted for 1.2 to 10.3 % of the rainfall for each storm. Tillage


Eileen Kladivko, Purdue University

A high population of nightcrawlers can turn over the top 6 inches of soil in 10-20 years. They are more common in the north and east than in the west and south.

destroys the tops of these burrows and also buries crop residue used as a food source by nightcrawlers. Earthworm counts under no-till and conventional tilled corn and soybean rotations in Indiana and Illinois found twice as many earthworms under no-till than the conventional (40). In Missouri, earthworm numbers under no-till were close to eight times as many as under conventional tillage with well fertilized continuous corn (38).

Eileen Kladivko, Purdue University



This macropore occurred when a nightcrawler followed the old root channel. Earthworms consume soil, digest the bacteria, and excrete the soil as fecal pellets which lines the channel. Nightcrawlers are vertical feeders and channels may be 4-6 feet deep.

Eileen Kladivko, Purdue University

Nightcrawlers feed on surface litter and actually pull residue into their burrows. They will leave their tails in their burrows, extend their body and pull the surrounding residue into their burrow. A high nightcrawler population can significantly lower residue levels resulting in warmer soil at planting time and improved soil aeration.

Short-term vs. Long-term Infiltration

Tillage can sometimes increase water infiltration, especially over the short-run, because it increases surface roughness, ponding more water than a flatter surface found with no-till. This can result in increased water infiltration for a time until the roughness declines and the soil surface seals. Studies of the effect of no-till versus conventional tillage on infiltration indicate that although bulk density is higher and total porosity is lower with no-till, infiltration is greater with the no-till (41). Two factors that contribute to this are the greater effectiveness of pore space under no-till at transmitting water and that the pores are better connected in no-till soils, due to decreased tillage disturbance. Water storage created by tillage-induced roughness may be important in some dry land cropping systems (59). Tillage may also alleviate existing compaction. Unrestricted wheel traffic on no-till fields may prevent improvements in infiltration that might otherwise be achieved.

Conflicting Studies Simulated Rainfall

Controlled studies comparing water infiltration with various tillage systems have produced very conflicting results. The United States Department of Agriculture National Sedimentation Laboratory at Oxford, MS collected data from 45 different published studies which compared no-till to conventional tillage. On the average, water runoff with no-till was 86% of runoff with conventional tillage, a slight improvement. Included in the summary were studies which showed increases in runoff or no change with no-till, along with some studies with large reductions in runoff.

The majority of these studies investigated water runoff with tillage systems using simulated rainfall. Simulating rainfall, rather than waiting for natural rains, allows scientists to control conditions, is easier to coordinate than waiting for rains, and guarantees that data will be obtained (There are years when no runoff occurs from natural rains). However, because of how these studies are nearly always conducted, results must be interpreted carefully. Rainfall simulators are constructed to apply heavy rain events (such as once-in-50-years natural occurrence rates). Usually rainfall is simulated very soon after tillage and planting, prior to any natural rainfall. Under these conditions, the roughness created by tillage will often result in less runoff from tilled plots than for no-till for at least the first rainfall event until roughness is reduced and surface sealing occurs. If only one rainfall event is simulated (as is often the case),


ARS

A rainfall simulator can provide quick runoff data at a lower cost than collecting natural storm events. However, if a very intense storm event is simulated after tillage the results can be misleading. This rainfall simulator and test plot at Cottonwood, South Dakota, enabled technicians to measure water runoff rates and collect soil samples in a WEPP cropland field study.

tilled plots will most likely produce less total runoff than no-till. Studies which have simulated several rainfall events through the season have usually shown that while runoff may be greater with the first event with no-till, as the season progresses, runoff with no-till is similar or less than with tillage (23,33,44,56).

Because infiltration benefits with no-till may take several years to become evident as macropores form and surface organic matter increases, the length of time experimental plots have been under no-till is important. Very often rainfall simulation studies have been conducted on plots which have only that year been converted to no-till, reducing chances for showing benefit.

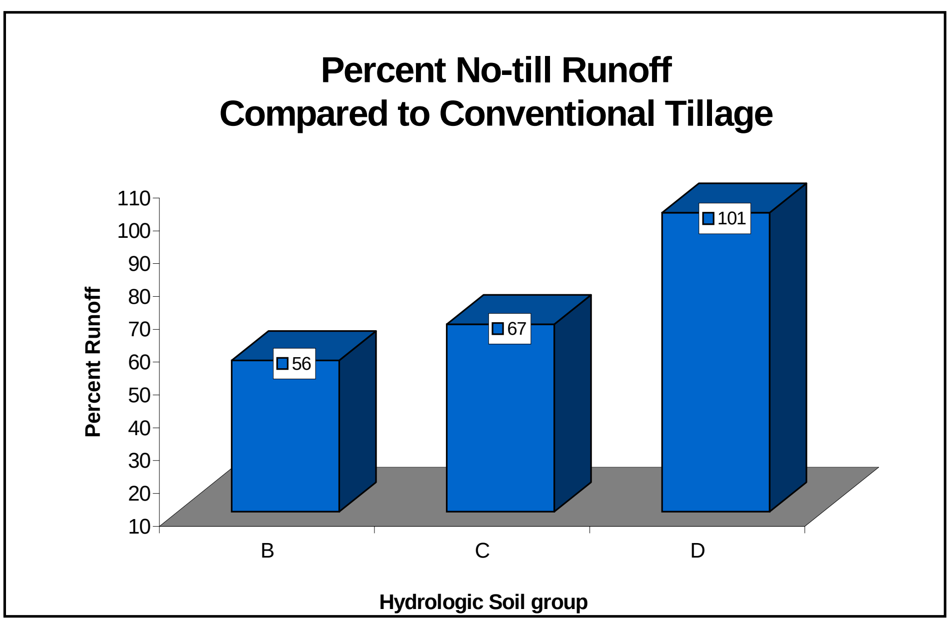
Natural Rainfall

Natural rainfall studies are more expensive to conduct, but are easier to interpret, as they usually monitor runoff for the entire growing season or year and are more often conducted on plots or small watersheds that have maintained constant tillage and cropping practices for several years. Data from published natural rainfall studies are summarized in the table found in the appendix. These studies compared water runoff with no-till to conventional tillage. In most studies conventional tillage was the moldboard plow followed by secondary tillage. In a few studies conventional tillage consisted of use of a chisel plow or disc.

Soil Types and Hydrologic Groups

Even when concentrating on natural rain studies, results are still highly variable. Runoff is totally eliminated in some studies with no-till (28) while in others, no-till increased runoff (45). In many cases soil type and years in no-till explain the differences in runoff.

If soils have restricting subsurface layers or are poorly drained, increased crop residue and organic matter at the surface cannot overcome a profile that is already full of water or restricted. These soils are also not a good habitat for nightcrawlers and other worms. Fields consisting of these soils will not realize the benefits worms produce in better-drained fields. One system of grouping soils is based on rates of water infiltration called the hydrologic soil grouping. Soil textural class is the principal determinant of hydrologic soil group. Hydrologic soil groups should be useful, though not perfect, in predicting which soils have the greatest potential for infiltration improvements with no-till.



Increased infiltration win no-till may vary depending on soil type. Soils with good internal drainage show the greatest response to no-till

Soil Texture and Infiltration

Soil texture greatly influences the impact the adoption of no-till will have on improvements to runoff through increased infiltration. The greater the clay content in the soil, the harder it will be to quickly induce infiltration changes. A good guide to predicting the likely response of a soil to the initiation of no-till is the texture class of the soil. Soils are classified for their infiltration tendency into four broad hydrologic groups.

Sandy soils exhibit the highest natural rates of infiltration and water transmission. These coarse textured soils are well suited to no-till and benefit from the increase in organic matter which usually accompanies no-till. They have the lowest runoff potential and are classified as Group A.

As the clay and silt content increases in the soil, infiltration and water transmission rates begin to decrease. This second group of soils, Group B, consists of mostly silt loams, silty clay loams (<30 percent clay content), and loamy textured soils and have good natural internal drainage. Water does not naturally infiltrate into these soils as rapidly as the first group. As a whole these Group B soils respond well to no-till and water infiltration may dramatically increase as compared to conventional tillage systems on these soils.

Soils in group C have a higher clay content or somewhat restricted layer and have an increased runoff hazard because of their slower infiltration rates and are grouped into the C classification. The soils in this Group C exhibit improved runoff and infiltration with the application of no-till, but do not usually show as great an improvement as the Group B soils.

A high content of swelling clays, the presence of a high water table and impermeable claypans near the surface significantly reduce the infiltration rate and greatly increase the runoff hazard of the Group D soils. The infiltration rates on these soils show little response to the application of no-till unless accompanied by drainage and management practices to break up the restrictive layers (if possible).

Soils also may be classified with a split designation if drainage is improved with tile. For example, a B/D soil would have the characteristics of Group D soils in absence of tile, but would be improved to a B with drainage tile.

Effects of No-till on Runoff

Analyzing data from natural rainfall events for each year in each study in Table 1 (see Appendix), Group B soils experience 56 percent of the runoff with no-till compared to conventional tillage. Group C soils showed 67 percent of the runoff compared to conventional tillage. Group D soils with a restricted layer shows no difference in no-till compared to conventional tillage.

Edwards and Amerman (13) studied two watersheds, one with well-drained subsoil, and the other with restricted drainage. When both watersheds were in conventional tillage for 7 years, runoff in summer was high and similar for both, but during non-cropping periods runoff was much higher for the watershed with restricted drainage. Both watersheds were then converted to no-till corn production for 5 years. Summer runoff was eliminated in both watersheds, but the watershed with restricted drainage still had non-cropping period season runoff. The presence of restrictive layers should be highly predictive of the potential infiltration benefits of no-till on specific soils. The closer restrictive layers are to the soil surface, the less likely no-till will benefit infiltration.


Larry Brown, Ohio State University

Adequate subsurface drainage may be an important practice in some parts of the country. Lowering the water table helps warm the soil in the spring and allows water to infiltrate into the soil rather than running off the field. Without tile the soil may be saturated, additional rainfall will runoff carrying topsoil, phosphorus and pesticides with it.

There are many types of "vertical" tillage tools which when properly operated cause minimal soil surface or residue disturbance. All tend to "heave the soil up and set it back down." These tools may aid in the transition to no-till as macropores develop or may be needed every 2-3 years on certain soil types.

Length of Time in No-till

The importance of long-term no-till is also evident from the summary. Infiltration often improved over time in long-term studies. For example in the first year of a Maryland study (28), water runoff with no-till was nearly identical to conventional tillage. In the third and fourth years in no-till, water runoff was totally eliminated. Other researchers have noted that the benefits of improved water infiltration with no-till took several years to develop (11,58).

Scientists have tried to separate the effects of surface crop residue from differences in soil structure and porosity by removing surface residues. In some studies where crop residue has been removed, water infiltration has been similar or less with no-till than with conventional tillage (47), indicating that crop residue was more important than changes in structure or macroporosity. This is due to the surface protection effect caused by the crop residue.

In some studies, soil structure improvements with no-till have been more important in increasing water infiltration. In Georgia (8), water infiltration was twice as fast into no-till sorghum as it was into sorghum planted into a disked seedbed, even when all surface crop residue was removed. A rainfall simulation study on a 15 year-history no-till field in Illinois indicated that both residue and structure were important (7). Removing surface crop residue from the soil surface reduced water infiltration by over 25%. Tilling the soil surface with a hoe caused a further 33% reduction in infiltration, compared to the untilled, no residue plots.

Utilizing No-till with Cover Crops and Sods

Planting no-till row crops into established grass sods may be a way to benefit immediately from better infiltration, since macropores are already established and organic matter and residues are already high at the soil surface. Using rainfall simulation, Foy and Hiranpradit (19) compared no-till planting into established sod to conventionally tilled plots and found that no water runoff occurred from no-till plots, even when four times as much water (5.3 inches) was applied to the no-till plots as produced runoff in tilled plots. Similarly, in Kentucky, planting into long-term bluegrass sod resulted in 83% less water runoff with no-till than occurred with plowing, even though 5.2 inches of rain were applied over a 24 hour period soon after tillage when the tilled soil would be most favorable for infiltration (67).

Cover crops are increasingly recommended for use in no-till systems to provide additional residue, suppress weed competition, remove excess nitrogen from the soil, and further decrease soil erosion. When cover crops are used to supplement the available residue cover of typically low residue producing crops such as soybeans, soil loss, runoff and nutrient losses were significantly reduced on a claypan soil in Missouri (77). Use of no-till in combination with cover crops on the Atlantic Coastal Plain significantly reduced nitrate-N storage in the lower rooting zone beyond just the use of cover crops and conventional tillage alone (69).

Wheel Track Compaction

Compaction caused by random wheel traffic may explain why some studies show little infiltration benefit from no-till and why some farmers notice little benefit. In one rainfall simulation study, planter wheel tracks did not affect infiltration rates in no-till plots soon after planting, but reduced infiltration in plowed plots to a level similar to no-till plots (43). It is possible that past random wheel traffic was reducing infiltration in the no-till plots. In another study where wheel traffic was controlled for four years prior to measurements, wheel traffic reduced infiltration in both no-till and chisel plowed plots (2). On a study of a corn and soybean rotation in Iowa the no-till soil was less dense than the chiseled plots at the surface when traffic was controlled (48).

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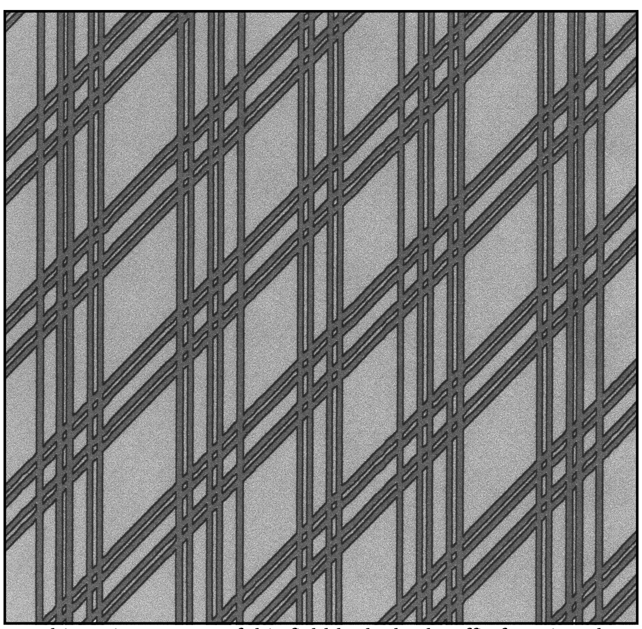
Bulk density increases with no-till. Many producers can combine their no-till fields when ruts (as deep as tillage) are cut in worked fields. However, every pass, especially under moist soil conditions, can cause compaction and seal off macropores. Too many trips under these conditions may result in less infiltration and more runoff than expected.

Long-term No-till Field

The impact of wheel tracks was studied on a long-term no-till field by determining infiltration times for one inch of applied water. The first inch of applied water took 2 minutes 15 seconds to infiltrate in a non-wheel track area, and a second inch of applied water took 31 minutes. Using the same procedure on a wheel track area, the first inch infiltrated in 7 minutes, but the second inch took more than 3 hours. These results confirm farmers' observations that runoff in no-till fields often occurs only in the wheel tracks.

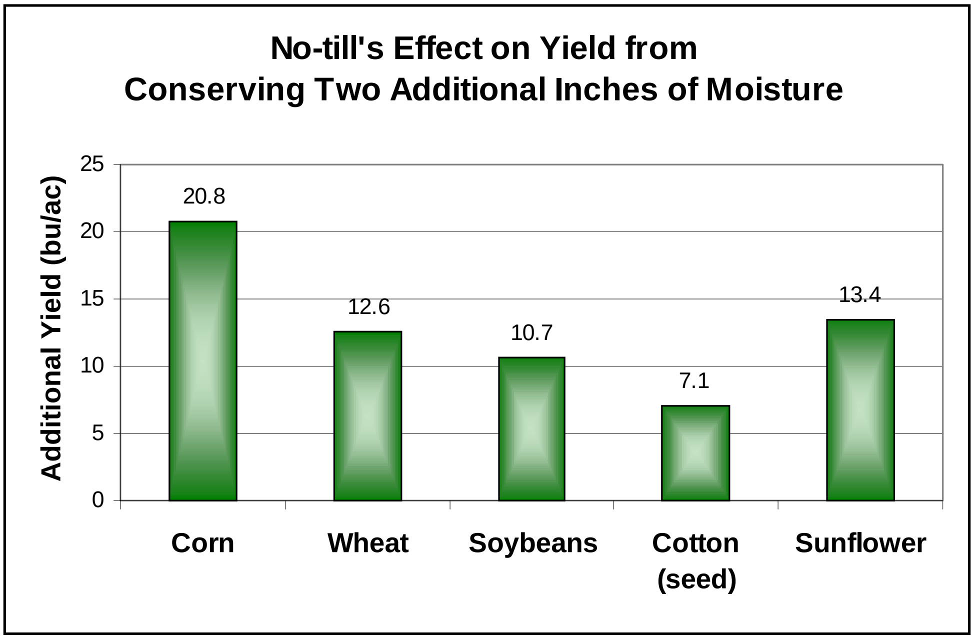
Compaction caused by wheel traffic in no-till fields is not corrected by tillage, as it is at least to some extent in tilled fields. The negative effects of compaction in no-till fields may be offset by the positive influence of earthworm activity (47). However, even better improvements in water infiltration should be possible if wheel traffic were to be controlled. No-till fields receive wheel traffic from fertilizer and lime applicators, sprayers, planters, combines and grain carts. While planter and combine traffic are usually in relatively the same locations, other traffic may be more random. Grain carts and trucks may be especially harmful if they are driven beside combines in moist soil conditions, greatly increasing the wheel coverage and compaction. When possible, farmers should control and reduce these compaction-causing activities when the soil is wet.



Thirty-nine percent of this field had wheel traffic from just three trips. This computer model show wheel traffic from a 30' field cultivator pulled by a dual wheeled tractor, a 30' planter pulled with a dual wheeled tractor and a 45' sprayer pulled by a tractor with single wheels. Graphic is courtesy of Key Ag, Macomb, Ill.

SUMMARY

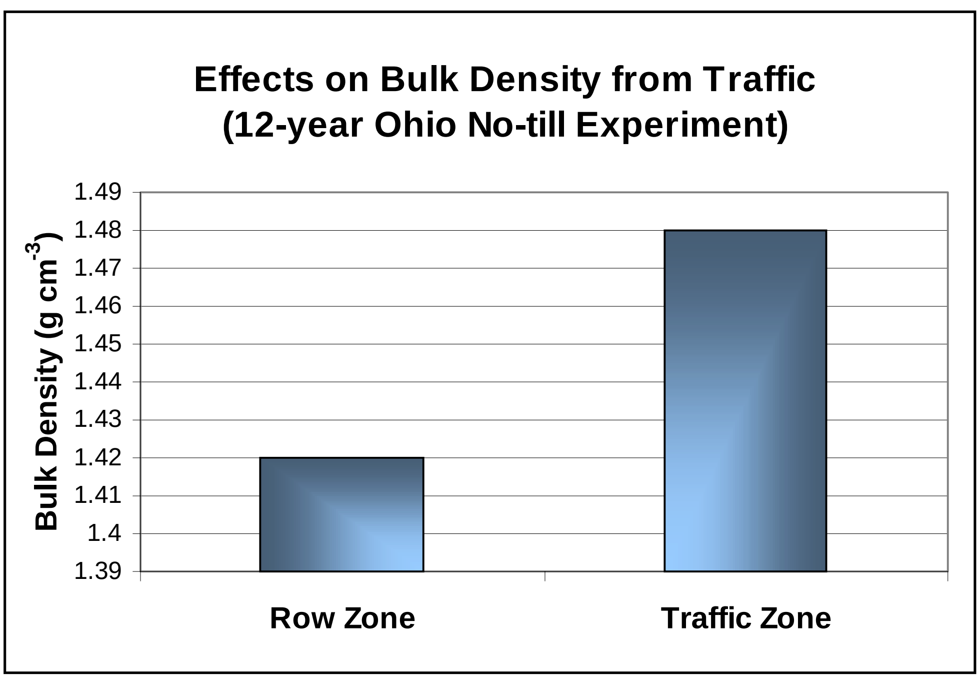
The organic matter and water infiltration benefits of no-till will benefit farmers with higher yields and higher profits due to increased water use efficiency and improved crop growth. Each additional inch of soil moisture conserved in the soil by no-till can be worth up to 6 extra bushels of wheat per acre in many regions of the country. Similarly, during critical dry periods in the Corn Belt, an additional inch of moisture can increase corn yields by 10 bushels per acre. The environment and society also benefit. As more acres are converted to no-till, crop fields will become a significant trap for carbon dioxide, reducing the possibilities of global warming. As more fields are converted to no-till, the water cycle will return to a more natural state, more closely resembling the way it was in the days of the prairies and forests. Rather than running off the land, carrying sediment, contaminants, and pathogens into surface water, more water will infiltrate into the soil and move to streams by tile drainage and natural subsurface flow. This will allow better use of water and nutrients by crops and allow soil colloids and biological activity to filter the water before it becomes stream water. Quality of surface water in streams will more closely resemble shallow ground water than it does today. Moving more water through the soil will also reduce fluctuation and impacts of flooding and low stream flow.



This graph shows how different crops respond if 2 inches of additional moisture are available during the growing season. Cotton and soybean data from Lyon, etal; Water Use Efficiency Equations. Corn, wheat, and sunflower data from ARS, Central Great Plains Research Station, Akron, Colorado.

The benefits farmers achieve from adopting no-till will depend on soil type, climate, cropping systems, and management. Greater organic matter increases can be achieved over time through leaving more crop residue in fields, growing cover crops, and fertilizing for optimum yields. Water infiltration benefits may be dependent on soil type, with high clay content soils and the presence of restrictive layers somewhat limiting the response unless internal drainage can be improved. Avoiding wheel track compaction as much as possible is important, as random wheel traffic can wipe out infiltration benefits of no-till. It may take several years for water infiltration to improve.

Ultimately, it the profitability of a farming system that governs its adoption. A recent analysis (49) of 144 no-till versus conventional research plot and farm scale comparisons indicated that no-till averaged a higher profitability than conventionally managed corn, oilseeds, and grain sorghum systems.



Traffic from tractor tires can increase the bulk density of the soil significantly compared to areas that do not receive a traffic imprint. Soil moisture conditions at the time of traffic can greatly influence actual results.

APPENDIX

Table 1. Summary of natural rainfall studies comparing water runoff with no-till to conventional tillage. Conventional tillage included the moldboard plow in most studies. Water runoff with no-till is expressed as a percent of total seasonal runoff occurring with conventional tillage. First year no-till plots were not inculded.

Hydrologic Soil Group	Average Water Runoff as a Percent of Conventional Tillage	Crops	Average Years in No-till	States	References
B	56%	Corn, Soybeans, Cotton, Rye, Tobacco	5	IA, KY, MO, MD, NC, Al	4, 5, 20, 28, 66, 68, 75, 76
C	67%	Corn, Soybean, Sorghum, Cotton, Tobacco, Rye	6	OH, MS, NC	11, 50, 51, 53, 54, 55, 75
D	101%	Corn, Soybean	4	MO, MS, MD	1, 31, 36, 72

HIGHLIGHTS

♦ Improving soil quality is the first step to improve water quality.

♦ Tillage mixes oxygen into the soil and increases the oxidization of organic matter resulting in the release of carbon dioxide (a gas linked to global warming).

♦ No-till can increase organic matter in the soil's surface by 1,000 lbs/ac/yr.

♦ Consistent soil sampling depth, bulk density adjustment, and lab procedure are important in monitoring changes in OM levels accurately.

♦ Fungal hyphae forms aggregates, which are the glue that holds soil particles together making them more resistant to erosion.

♦ Soils, which have good natural internal drainage, see the most dramatic results in runoff reduction in no-till fields.

♦ Soils with a high clay content or restricted layers "may" require vertical tillage to improve infiltration.

♦ Soil benefits are greater with continuous no-till than with rotational tillage, no-till one year and tillage the following year.

♦ Although no-till fields will better support traffic due to the increased bulk density, random traffic under moist conditions my result in surface compaction and increased runoff.

♦ Increasing organic matter and improving infiltration results in additional moisture being available for higher yields.

LITERATURE CITED

1. Alberts, E.E., R.C. Wendt, and R.E. Burwell. 1985. Corn and soybean cropping effects on soil losses and C factors. Soil Sci. Soc. Am. J. 49:721-728.
2. Ankeny, M.D., T.C. Kaspar, and R. Horton. 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J. 54:837-840.
3. Azooz, R.H. and M.A. Arshad. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can. J. Soil Sci. 76:143-152.
4. Baker, J.L. and H.P. Johnson. 1979. The effect of tillage system on pesticides in runoff from small watersheds. Trans. ASAE 22:554-559.
5. Blevins, R.L., W.W. Frye, P.L. Baldwin, and S.D. Robertson. 1990. Tillage effects on sediment and soluble nutrient losses from a Maury silt loam soil. J. Environ. Qual. 19:683-686.
6. Blevins, R.L., R. Lal, J.W. Doran, G.W. Langdale, and W.W. Frye. 1998. Conservation tillage for erosion control and soil quality. In: F.J. Pierce and W.W. Frye (ed.) *Advances in Soil and Water Conservation*. Ann Arbor Press. Chelsea, MI. pp. 51-67.
7. Bradford, J.M. and C. Huang. 1994. Interrill soil erosion as affected by tillage and residue cover. Soil and Tillage Res. 31:353-361.
8. Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1992. Soil surface modification by biomass inputs affecting rainfall infiltration. Soil Sci. Soc. Am. J. 56:1614-1620.
9. Carter, M.R., D.A. Angers, and G.C. Topp. 1999. Characterizing equilibrium physical condition near the surface of a fine sandy loam under conservation tillage in a humid climate. Soil Science. 164(2): 101-110.
10. Collins, H.P., E.T. Elliot, K.Paustian, L.G. Bundy, W.A. Dick, D.R. Huggins, A.J.M. Smucker, and E.A. Paul. 2000. Soil carbon pools and fluxes in long-term corn belt agroecosystems. Soil Biology & Biochemistry. 32:157-168.
11. Dick, W.A., R.J. Roseberg, E.L. McCoy, W.M. Edwards, and F. Haghiri. 1989. Surface hydrologic response of soils to no-tillage. Soil Sci. Soc. Am. J. 53:1520-1526.
12. Eckert, D.J. 1991. Chemical attributes of soils subjected to no-till cropping with rye cover crops. Soil Sci. Soc. Am. J. 55:405-409.
13. Edwards, W.M. and C.R. Amerman. 1984. Subsoil characteristics influence hydrologic response to no-tillage. Trans. ASAE 27:1055-1058.
14. Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizing macropores that affect infiltration into nontilled soil. Soil Sci. Soc. Am. J. 52:483-487.
15. 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.
16. Edwards, J.H., C.W. Wood, D.L. Thurlow, and M.F. Ruf. 1992. Tillage and crop rotation effects on fertility status of a Hapludult soil. Soil Sci. Soc. Am. J. 56:1577-1582.
17. Elliot, J.A. and A.A. Efetha. 1999. Influence of tillage and cropping system on soil organic matter, structure and infiltration in a rolling landscape. Can. J. Soil. Sci. 79:457-463.
18. 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. J. Soil and Water Cons. 49:126-135.
19. Foy, C.L. and H. Hiranpradit. 1989. Movement of atrazine by water from application sites in conventional and no-tillage corn production. In: D.L. Weigmann (ed.) *Pesticides in Terrestrial and Aquatic Environments*. VA Water Resources Res. Center. VA Polytechnic Inst. and State Univ. Press. Blacksburg, VA. pp. 355-377.
20. Franti, T.G., C.J. Peter, D.P. Tierney, R.S. Fawcett, and S.A. Myers. 1995. Best management practices to reduce herbicide losses from tile-outlet terraces. Paper 952713. Am. Soc. Agr. Eng., St. Joseph, MI.
21. Franzluebbers, A.J. and M.A. Arshad. 1996. Water-stable aggregation and organic matter in four soils under conventional and zero tillage. Can. J. Soil Sci. 76: 387-393.
22. Franzluebbers, A.J., G.W. Langdale, and H.H. Schomberg. 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63:349-355.
23. Freebairn, D.M. and S.C. Gupta. 1990. Microrelief, rainfall, and cover effects on infiltration. Soil & Tillage Res. 16:307-327.
24. Gaynor, J.D., D.C. MacTavish, and W.I. Findlay. 1995. Atrazine and metolachlor loss in surface and subsurface runoff from three tillage treatments in corn. J. Environ. Qual. 24:246-256.
25. Ghidey, F. and E.E. Alberts. 1998. Runoff and soil losses as affected by corn and soybean tillage systems. J. Soil and Water Cons. 53(1):64-70.
26. Gilley, J.E., J.W. Doran, D.L. Karlen, and T.C. Kaspar. 1997. Runoff, erosion, and soil quality characteristics of a former Conservation Reserve Program site. J. Soil and Water Cons. 52(3):189-193.
27. Glantz, J. 1995. *Saving Our Soil*. Johnson Books, Boulder, CO.
28. Glenn, S. and J.S. Angl e. 1987. Atrazine and simazine in runoff from conventional and no-till corn watersheds. Agric. Ecosys. and Environ. 18:273-280.
29. Gregorich, E.G., B.C. Liang, C.F. Drury, A.F. Mackenzie, and W.B. McGill. 2000. Elucidation of the source and turnover of water soluble and microbial biomass carbon in agricultural soils. Soil Biology & Biochemistry. 32:581-587.

LITERATURE CITED

30. Hall, J.K., N.L. Hartwig, and L.D. Hoffman. 1984. Cyanazine losses in runoff from no-tillage corn in "living" and dead mulches vs. unmulched, conventional tillage. J. Environ. Qual. 13:105-110.

31. Hairston, J.E., J.O. Sanford, J.C. Hayes, and L.L. Reinschmiedt. 1984. Crop yield, soil erosion, and net returns from five tillage systems in the Mississippi Blackland Prairie. J. Soil and Water Cons. 39(6):391-395.

32. Harrold, L.L. and W.M. Edwards. 1972. A severe rainstorm test of no-till corn. J. Soil and Water Cons. 27(1):30.

33. Hill, R.L. 1993. Tillage and wheel traffic effects on runoff and sediment losses from crop interrows. Soil Sci. Soc. Am. J. 57:476-480.

34. 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. Agric. Ecosys. and Environ. 54:77-88.

35. Hussain, I., K.R. Olson, and J.C. Siemens. 1998. Long-term tillage effects on physical properties of eroded soil. Soil Science. 163(12):970-981.

36. Isensee, A.R. and A.M. Sadeghi. 1993. Impact of tillage practice on runoff and pesticide transport. J. Soil and Water Cons. 48(6):523-527.

37. Ismail, I., R.L. Blevins, and W.W. Frye. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58:193-198.

38. Jordan, D., J.A. Stecker, V.N. Cacnio-Hubbard, F. Li, C.J. Gantzer, and J.R. Brown. 1997. Earthworm activity in no-tillage and conventional tillage systems in Missouri soils: A preliminary study. Soil Biol. Biochem. 29(3/4):489-491.

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

40. Kladivko, E.J., N.M. Akhouri, and G. Weesies. 1997. Earthworm populations and species distributions under no-till and conventional tillage. Soil Biology & Biochemistry. 29(3,4):613-615.

41. Lal, R., T.J. Logan, D.J. Eckert, and W.A. Dick. 1994. Conservation tillage in the Corn Belt of the United States. In: *Conservation Tillage in Temperate Agroecosystems.* Ed. M.R. Carter. Lewis Publishers. Boca Raton, FL. pp. 73-114.

42. Langdale, G.W., L.T. West, R.R. Bruce, W.P. Miller, and A.W. Thomas. 1992. Restoration of eroded soil with conservation tillage. Soil Tech. 5:81-90.

43. Lindstrom, M.J., W.B. Voorhees, and G.W. Randall. 1981. Long-term tillage effects on interrow runoff and infiltration. Soil Sci. Soc. Am. J. 45:945-948.

44. Lindstrom, M.J. and C.A. Onsted. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. J. Soil and Water Cons. 39:149-152.

45. Lindstrom, M.J., T.E. Schumacher, G.D. Lemme, and W.B. Voorhees. 1994. Corn production and soil erosion after sod on an eroded landscape as affected by tillage. Proc. Int. Soil Tillage Res. Org. pp. 43-48.

46. Logan, T.J., D.J. Eckert, B. Harrison, D. Beak, and J. Adewumni. 1989. The effects of no-till and fall plowing on pesticide movement in runoff and tile drainage. EPA-R-005970-01. Environmental Protection Agency, Washington, D.C.

47. Logsdon, S.D. and T.C. Kaspar. 1995. Tillage influences as measured by ponded and tension infiltration. J. Soil and Water Cons. 50(5):571-575.

48. Lodgsdon, S.D., T.C. Kaspar, and C.A. Cambardella. 1999. Depth-incremental soil properties under no-till or chisel management. Soil Sci. Soc. Am. J. 63:197-200.

49. Marra, M.C. and P. Kaval. 2000. The relative profitability of sustainable grain cropping systems: A meta-analytic comparison. Journal of Sustainable Agriculture. 16(4):19-32.

50. McGregor, K.C. and J.D. Greer. 1982. Erosion control with no-till and reduced till corn for silage and grain. Trans. ASAE 25(1):154-159.

51. McGregor, K.C. and C.K. Mutchler. 1992. Soil loss from conservation tillage for sorghum. Trans. ASAE 35(6):1841-1845.

52. Mielke, L.N., J.W. Doran, and K.A. Richards. 1986. Physical environment near the surface of plowed and no-till soils. Soil Tillage Res. 7:355-366.

53. Mutchler, C.K. and J.D. Greer. 1984. Reduced tillage for soybeans. Trans. ASAE 27(5):1364-1369.

54. Mutchler, C.K., L.L. McDowell, and J.D. Greer. 1985. Soil loss from cotton with conservation tillage. Trans. ASAE 28(1):160-163, 168.

55. Mutchler, C.K. and L.L. McDowell. 1990. Soil loss from cotton with winter cover crops. Trans. ASAE 33(2):432-436.

56. Mueller, D.H., R.C. Wendt, and T.C. Daniel. 1984. Soil and water losses as affected by tillage and manure application. Soil Sci. Soc. Am. J. 48:896-900.

57. National Research Council. 1993. *Soil and Water Ouality an Agenda for Agriculture.* National Academy Press, Washington, D.C.

58. Packer, I.J. and G.J. Hamilton. 1993. Soil physical and chemical changes due to tillage and their implications for erosion and productivity. Soil & Tillage Res. 27:327-339.

59. Pikul Jr., J.L., J.F. Zuzel, and R.E. Ramig. 1990. Effect of tillage-induced soil macroporosity on water infiltration. Soil & Tillage Res. 17:153-165.

60. Rasmussen, P.E. and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matters. Soil Sci. Soc. Am. J. 58:523-530.

LITERATURE CITED

61. Reicosky, D.C. and M.J. Lindstrom. 1993. Fall tillage method: effect on short-term carbon dioxide flux from soil. Agron. J. 85:1237-1243.

62. Reicosky, D.C. and M.J. Lindstrom. 1995. Impact of fall tillage on short-term carbon dioxide flux. In: R. Lal, J. Kimble, E. Levine, and B.A. Stewart. (ed.) *Soils and Global Change*. Lewis Publishers, Chelsea, MI. pp. 177-187.

63. Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas, Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil and Water Cons. 50:253-261.

64. Romig, D.E., M.J. Garlynd, R.F. Harris, and K. McSweeney. 1995. How farmers assess soil health and quality. J. Soil and Water Cons. 50:229-236.

65. Ròhlmann, J. 1999. A new approach to estimating the pool of stable organic matter in soil using data from long-term field experiments. Plant and soil. 213: 149-160.

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

67. Seta, A.K., R.L. Blevins, W.W. Frye, and B.J. Barfield. 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. J. Environ. Qual. 22:661-665.

68. Shelton, C.H., F.D. Tompkins, and D.D. Tylor. 1983. Soil erosion from five soybean tillage systems. J. Soil and Water Cons. 38(5):425-428.

69. Staver, K.W. and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. Soil and Water Cons. 53(3):230-240.

70. Tanaka, D.L. and R.L. Anderson. 1997. Soil water storage and precipitation storage efficiency of conservation tillage systems. J. Soil and Water Cons 52(5): 363-367.

71. Thorne, C.E. 1926. The function of organic matter in the soil. Agronomy Journal. 18(9):767-793.

72. Triplett Jr., G.B., B.J. Conner, and W.M. Edwards. 1978. Transport of atrazine and simazine in runoff from conventional and no-tillage corn. J. Environ. Qual. 7:77-83.

73. Waddell, J.T. and R.R. Weil. 1996. Water distribution in soil under ridge-till and no-till corn. Soil Sci. Soc. Am. J. 60:230-237.

74. Wendt, R.C. and R.E. Burwell. 1985. Runoff and soil losses for conventional, reduced, and no-till corn. J. Soil and Water Cons. 40(5):450-454.

75. Wood, S. D. and A. D. Worsham. 1986. Reducing soil erosion in tobacco fields with no-till transplanting. J. Soil and Water Cons. 41(3):193-196.

76. Yoo, K. H., J.T. Touchton, and R.H. Walker. 1987. Effect of tillage on surface runoff and soil loss from cotton. Trans. ASAE 30(1):166-168.

77. Zhu, J.C., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and P.R. Beuselinck. 1989. Runoff, soil, and dissolved nutrient losses from no-till soybean with cover crops. Soil Sci. Soc. Am. J. 53:1210-1214.

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