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No-till Farming: The Way of the Future for a Sustainable Dryland Agriculture

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Abstract: Most dryland farming systems depend on tillage to grow crops. There is overwhelming evidence that repeated tillage is destroying the soil resource base and causing adverse environmental impacts. Tillage degrades the fertility of soils, causes air and water pollution, intensifies drought stress, destroys wildlife habitat, wastes fuel energy, and contributes to global warming. Consequently, most tillage-based systems in a dryland environment are not sustainable in the long-term. Today, dryland farmers are expected to produce food in ever greater quantities. This is becoming more difficult to do in view of declining soil quality, most of which is caused by soil tillage. It is becoming well documented scientifically that continuous no-till is the most effective, and practical approach for restoring and improving soil quality which is vital for sustained food production and a healthy environment. With this way of farming crop, residues or other organic amendments are retained on the soil surface and sowing/fertilizing is done with minimal soil disturbance. Research and farmers' experience indicate that with continuous no-till soil organic matter increases, soil structure improves, soil erosion is controlled, and in time crop yields increase substantially from what they were under tillage management, due to improved water relations and nutrient availability. These changes help to promote a cleaner and healthier environment and a more sustainable agriculture. A major obstacle that farmers often face with change to continuous no-till is overcoming yield-limiting factors during the transition years, that is, the first years of no-till following a history of intensive conventional tillage. These factors are often poorly understood and may be biologically-driven. Some of the problems involve residue management and increased weed and disease infestations. Farmer experience seems to indicate that many problems during the transition are temporary and become less important as the no-till system matures and equilibrates. The judicious use of crop rotations, cover crops and some soil disturbance may help reduce agronomic risks during the transition years. Farmers switching to continuous no-till must often seek new knowledge and develop new skills and techniques in order to achieve success with this new and different way of farming. Answers to their questions are urgently needed to provide strategies for promoting no-till as a way to enhance agricultural sustainability for future generations.

Key words: Tillage, farming systems, rainfed, semi-arid, soil conservation, soil quality, organic matter, zero-till.

Dryland agriculture in many areas of the world is coming to a cross-roads. To continue as in the past with tillage-based farming systems raises some serious questions about the sustainability of future agriculture on these lands. For centuries tillage has been the main tool used to grow crops. Native ecosystems, like many of those well known in the Americas, produced some of the most fertile soils which enhanced growth and prosperity in the absence of major technological inputs in the early years when these lands were first farmed. Tillage as advocated by Jethro Tull in the mid-1800s, and his followers in the later part of the 19th and early part of the 20th centuries became widely promoted by dryland farmers as the way to conserve moisture and increase the fertility and productivity of the croplands. Tillage helped to "mine" naturally rich soils of their abundant nutrients stored in the soil organic matter and in this way for decades or longer provided food with low input for growing populations, and income for farmers. However, at the same time, tillage was insidiously destroying soil organic matter and soil structure, and in this way, accelerating soil erosion and breaking the web of the soil life itself.

This led to the loss of soil quality on which the capability to sustain food production and a healthy environment depends. Today, farmers are under growing pressure to produce food in ever-increasing quantities. With tillage-based systems crop production can be maintained or increased only through escalating use of expensive technological inputs, which can also create environmental and economic risks to farmers and society as a whole.

Effects of Tillage on Soil Quality and Environment

Soils that are routinely tilled lose their structure and cohesiveness along with their surface cover. This reduces the soil's infiltration capacity and gives rise to wind and water erosion. Soil erosion selectively removes the finer soil particulates which hold most of the plant nutrients. Along with the mass of eroded soil, these are washed into rivers and lakes and not only is the soil fertility reduced from loss of topsoil, but the nutrients feed algae which kill plants and fish, and the sediments fill water bodies causing pollution and destroying their usefulness for navigation, power generation and recreation.

The loss of the Pacific Ocean salmon (genera *Oncorhynchus* and *Salmo*) industry in the Pacific Northwest, U.S.A., can be traced in part to erosion from agricultural lands due to tillage-based farming practices. Soil quality in the region has deteriorated as evidenced by massive losses of topsoil, decreases in organic matter to one-half or below of original levels, increasing need for chemical inputs to maintain crop yields, soils that are increasingly more difficult to till, and tendency for high runoff during rain and melting snow. Similarly, the cause of wind erosion is the intensive tillage to prepare seed beds, control weeds and conserve moisture during the long fallow. The tillage destroys residue cover, and leaves the soil powdery and exposed to high winds during the spring and early fall. Soil erosion is not the only degradative process caused by tillage that is undermining the quality and productivity of soils. Intensive cultivation through oxidation of organic matter has further accelerated the loss of soil structure and plant nutrients. Tillage can also cause hard pans to develop below the depth of tillage, and compaction from equipment operating in wet soils. Soil crusting resulting from the loss of soil structure is a common problem with tillage on many soils that have been depleted of organic matter and lack surface cover.

Effects of Tillage on Soil Organic Matter

There is overwhelming evidence which indicates the devastating effects of tillage on loss of soil organic matter. At Pendleton, Oregon, U.S.A., where average annual precipitation is 430 mm, plowing under 22 Mg ha^{-1} of manure each year was only able to maintain organic matter at a slightly higher level than when the experiment was started in 1929, some 40 years after the land was first farmed out of native grassland (Fig. 1). The gains from manure addition were being offset by accelerated oxidation caused by tillage. Organic matter declined with all other of these cereal-based treatments, including addition of pea (*Pisum sativum*) vines, and was most severe where cereal stubble was burned. All treatments were tilled in this long-term experiment.

Research in the north-central U.S.A. showed that carbon dioxide evolution was by far the greatest for the first 19 days after wheat (*Triticum aestivum*) stubble was mold board plowed and least with stubble left standing with no-tillage (Fig. 2). In 19 days as much carbon was oxidized as had been photosynthesized and incorporated in residue and roots of the wheat crop

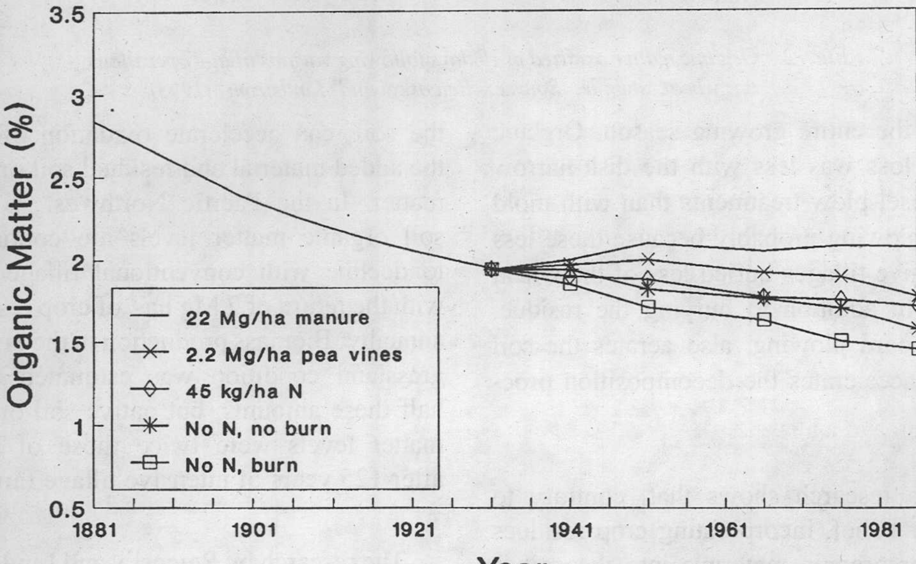

Fig. 1. The effect of management practices on long-term changes in soil organic matter in a semi-arid area of eastern Oregon. Source: Rasmussen et al. (1989).

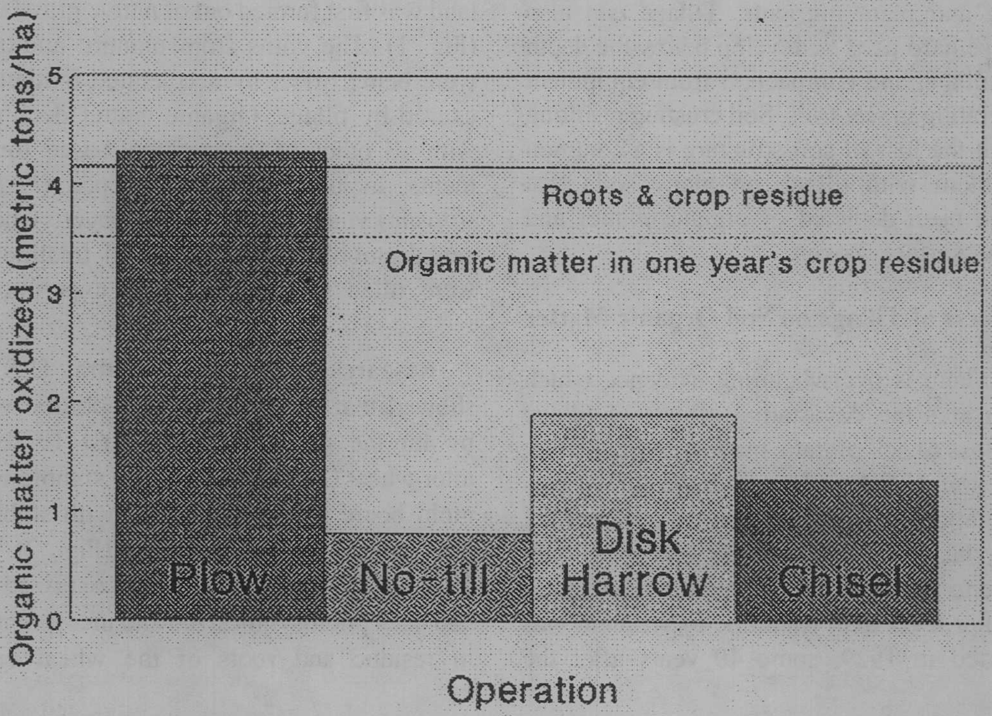

Fig. 2. Organic matter oxidized in 19 days following various tillage operations on wheat stubble. Source: Reicosky and Lindstrom (1993).

during the entire growing season. Organic matter loss was less with the disk-harrow and chisel plow treatments than with mold board plowing probably because these less aggressive tillages buried less of the wheat straw. In addition to burying the residue, mold board plowing, also aerates the soil which accelerates the decomposition process.

This research shows that, contrary to popular belief, incorporating crop residues or other organic materials into the soil is not an effective way to build soil organic matter. Aggressive tillage like mold board plowing, or with other equipment that inverts and mixes the organic amendments into the soil, can accelerate oxidation of both the added material and residual soil organic matter. In the Pacific Northwest, U.S.A., soil organic matter levels are continuing to decline with conventional tillage even with the return of 7 Mg ha^{-1} of crop residues annually. Biomass production in the original grassland condition was estimated to be half these amounts; but native soil organic matter levels were twice those of today after 125 years of intensive tillage farming.

The research by Reicosky and Lindstrom (1993) also indicates that less aggressive tillage will reduce the rate and amount of organic matter oxidation. It is important to note that any tillage that leaves most of the crop residues on the surface, such as chisel and undercutter tools, will help control soil erosion. This in itself will help reduce organic matter loss because soil erosion results in the loss of topsoil where the organic matter is the highest, and selectively removes organic matter during soil movement. However, it should be noted that reduced tillage systems, which enhance retention of surface residues, only slow the rate of organic matter decline and may result in equilibrium organic matter levels that are slightly higher than those with more aggressive tillage such as mold board plowing.

Why No-Till?

No-till is the only foreseeable practical approach for restoring the quality of dryland soils that have been severely degraded by excessive tillage and erosion, and for maintaining and improving the quality of many other soils that are less degraded and have a good production potential. Long-term gains in productivity and more stable production can only be achieved by improving soil quality, which for farmers helps ensure farm profitability and for society, a more secure and stable food supply. By improving soil quality, no-till can also protect the environment from air and water pollution, and support a greater diversity of wildlife, insects and micro-organisms, which are beneficial for a healthy ecosystem. Studies in North America showed improved habitat for ground-nesting birds in no-till fields (Domitruk and Crabtree, 1997). Moreover, these same birds survive better in no-till fields because their predators feed on insects and small mammals which are abundant in no-till environments.

Air pollution from greenhouse gases is reduced with no-till by requiring less use of fossil fuel and by sequestering CO_2 in soil organic matter. No-till-till with some residue cover essentially eliminates wind and water erosion, which means cleaner air and water in the environment. A good quality soil, which is formed under continuous no-till, acts as an environmental receptor and filter for cleansing water that percolates through it, and as an incubation chamber for the detoxification,decomposition, and humification of organic wastes, residues, manures, and for the storage and recycling of nutrients from these materials back to plants. There is some evidence that soil quality can have important effects on the nutritional quality of food but these linkages are not well understood (Hornick, 1992). The saying goes that a healthy soil will produce an abundance of safe, nutritious food which in turn promotes the health of people whose lives depend on this food. The key to food quality often relates soil organic matter, which is important for maintaining essential biological processes and a balance of available plant nutrients.

No-Till and Soil Organic Matter

Various research in the U.S.A. and abroad shows quite clearly that soil organic matter levels increase with continuous no-till. Farmers also notice that no-till soils become darker with time, which is further evidence of organic matter build-up. The increase in organic matter content is greatest in the shallow surface layers (4 to 6 cm) where it is most important for increasing infiltration, improving seedling establishment, and for increasing soil aggregation to resist erosion and reduce soil crusting. The active fraction of organic matter, which consists primarily of living plant roots, insects, earthworms, and microorganisms, and rapidly decomposing materials, greatly increases with continuous no-till.

Research in Ohio, U.S.A., showed that with continuous no-till for 20 years the residual organic carbon in the top 2 cm of soil was 2.5 times that of conventional tillage (Fig. 3). Below 8 cm, the organic carbon content of the no-till soil was slightly lower than that of the conventionally tilled soil to about 16 or 17 cm, presumably because of the soil mixing with tillage. Scientists who have studied no-till soils generally agree that with no-till the decomposed organic matter which accumulates in the top several cm is more strategically positioned to increase infiltration and reduce evaporation than when it is mixed by tillage in the top 20-25 cm of soil.

There are reports that with 10 or more years of no-till management the soil organic matter content may increase from over 200 to nearly 1700 kg ha^{-1} yr^{-1} (Moldenhauer *et al.*, 1995). The higher accumulation rates are in the cool, wetter regions with the higher rates of residues (especially where these were supplemented with cover crops), and biological oxidation of organic matter is slower. Eliminating tillage increases the amount of crop residue on the surface, decreases the biological oxidation of re-

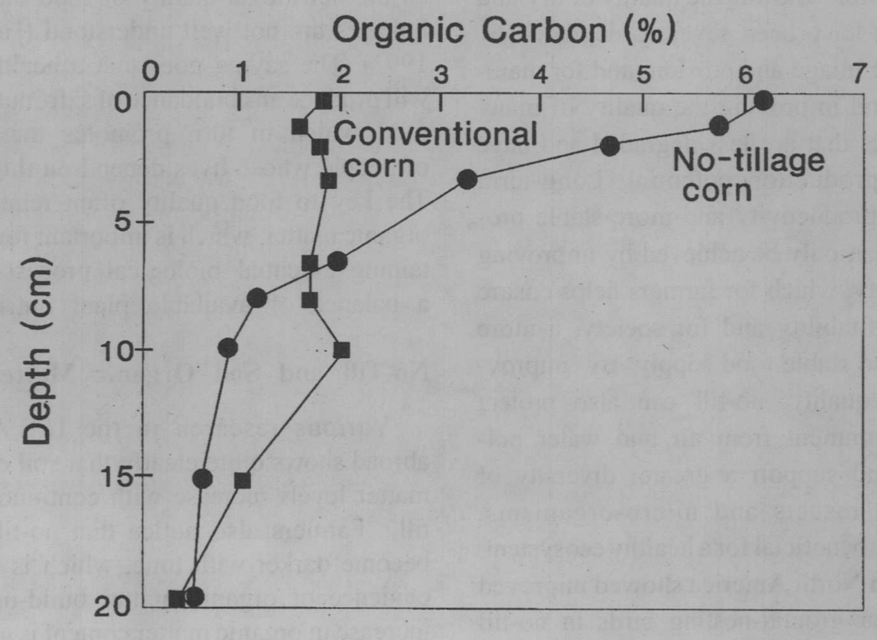

Fig. 3. Organic matter distribution with depth in no-till and conventionally tilled corn fields. Source: Edwards et al. (1988).

sidual organic matter, reduces or eliminates soil erosion, all of which tend to increase or stabilize soil organic matter levels.

Healthy Soil: A Complex, Living Medium

The soil is a living system and its capacity to perform the various productivity, environmental and health functions depends on the health of the perpetual life within it (Reganold *et al*., 1990). Life in the soil consists of larger animals such as earthworms (*Aporrectodea tuberclata* and *Lumbricus rubellus*), and insects (e.g., ants of the family Formicidae), termites (of the order Isoptera) that move about freely and mix the soil naturally, creating a structure that is favorable for moisture retention and air exchange. Rhizobium bacteria infect legume roots, produce nodules and fix nitrogen which is used by the host and other plants. Other micro-organisms including fungi, actinomycetes and bacteria decompose the readily available carbon in organic matter and regulate nutrient release for plant growth. In these processes micro-organisms also produce substances such as polysaccharides that bind soil particles into stable aggregates.

Being a living system, the soil must be fed on a continual, regular basis to stay alive and healthy, as necessary for any living creature to sustain its life. According to Lamarca (1996) the best way to feed the soil is through organic materials applied to the surface (e.g. crop residues, manures, etc.) and by leaving the soil undisturbed. This provides a more stable and uninterrupted supply of energy and nutrients for the soil life rather than by incorporating these organic materials by tillage, which causes a flush of oxidation of the readily available carbon, and leaving the organisms to starve intermittently.

Horizonation in the upper layers of a no-till soil

After tillage ceases, organic matter accumulates in the uppermost surface layers. This consists of annual residues, and older organic materials immediately below in various stages of decomposition, some humified or approaching a state of humification, and interfacing and making a continuum with what once was the original soil surface. The thickness of this new organic horizon or ''duff'' layer increases with continuous no-till. This organic mat is extremely important for sustaining infiltration, suppressing weeds and evaporation, reducing crusting, and enhancing emergence of crop seedlings. It also serves as a food source for beneficial soil animals and insects, which burrow to the surface to access plant residues and return them to deeper layers. This burrowing activity by earthworms and ants along with decomposing intact plant roots, creates a large network of interconnecting macro-pores, which provide channels for the movement of nutrients, air and water to living crop roots and soil micro-organisms. Organic matter below the surface organic horizon is conserved because the natural soil aggregates formed with no-till protects some of the soil organic matter from exposure to oxygen, while macro-pores provide adequate aeration for plant roots.

Evolution of No-till Soils

No-till soils evolve slowly and it usually takes 5 to 10 years or more to approach an equilibrium condition depending on climate, soils, cropping system and farm management. In some climates (e.g., northern U.S.A.), earthworms appear to be a good indicator of no-till-induced changes. Intensive tillage will decimate earthworm populations. In an experiment in northeastern U.S.A. with a corn and soybean cropping system, it took 6 to 7 years for earthworm population to become established with continuous no-till management, following a history of intensive cultivation (Moldenhauer *et al.*, 1995). With drier climates and lower production, it may take longer.

One tillage operation can largely destroy the soil structure that it takes years to develop with continuous no-till, and rebuilding must start all over again. The tillage of a mature no-till soil can be likened to that of a severe earthquake of a human city or other areas inhabited by people, followed by fire. All or most of what took years to build along with life is destroyed in a few moments, and then burned, and rebuilding, which can take years to complete, must start all over again. In this analogy the burning is equated to the oxidation of soil organic matter triggered by the tillage (the earthquake in the case of the city), and the life of people to that of the living soil.

Some farmers practice what is sometimes referred to as ''intermittent'' no-till, where some crops are planted without tillage and others with tillage in a cropping sequence. For example, in the Pacific Northwest, U.S.A., where fall wheat is grown in rotation with field pea, many farmers use a no-till drill to plant wheat after the pea crop (very low residue crop), but use tillage after the cereal crop to incorporate wheat stubble, control weeds, and prepare a seed bed for the pea crop. It is impossible to develop a no-till soil with this system because of the intermittent tillage.

Soil in the absence of tillage becomes more cohesive and resistant to the erosive forces of raindrop splash and runoff water. The bonding forces between soil particles decreases with tillage, but will re-establish with time after tillage ceases. With continuous no-till, the root fabric, crowns, and stalks of the previous crop remain undergo decomposition without disturbance. The residual organic matter, which accumulates in the shallow surface layers, helps stabilize soil aggregates and create a more firm but softer and spongier soil surface than in the tilled condition.

The Transition to Continuous No-Till

Converting from intensive tillage to continuous no-till usually involves major changes in the farming system, and pest and soil ecology. Success in making the transition to no-till soil depends on economic and environmental factors, management skills, and as well on a positive commitment by the farmer to make the practice work. During the first years of no-till, after a long history of tillage, the various physical, chemical and biological changes that occur may not always be beneficial for the growth of crop plants but may become favorable later on. It is during the early stages of the transition that some farmers become discouraged and return to conventional tillage. Leaving crop residues on the surface without proper management and farming equipment can interfere with fertilizer and seed placement, and in the initial years, cause inhibitory effects on crop growth. These effects appear to become less of a problem as the no-till system matures. Because of major changes in soil ecology and microenvironment near the soil surface there may be increased weed and disease infestations, and additional expenses for controlling pests while the new equilibrium is in process. Additional expenditures for different equipment to apply fertilizer and sow crops may be required. The change-over may also require farmers to gain new knowledge and skills about crop rotations, pest control, and timing of farm operations to be successful in this new way of farming.

Soil disturbance during and after the transition

The surface soil horizonation and biology, that develop with continuous no-till, depend considerably on how much the soil is disturbed by the farming operations. Some soil disturbance will occur with continuous no-till because of fertilizer and seed (and possibly pesticides) placement. Because of the benefits of leaving crop residues on the surface and the unique structure that develops with no-till, it is highly desirable to keep soil disturbance to minimum, at least as the system matures.

Different drill openers currently in use for a one-pass fertilizer/seed operation can create a range of soil disturbance. Although not scientifically proven, there are some possible benefits with using high disturbance openers during the early years of the transition to continuous no-till from an intensive cultivation system. High disturbance in the first one or two years may "soften" or make the change less abrupt as the soil ecology shifts or adjusts to the no-till environment. For example, there is reason to believe that some shifts of weeds, crop diseases, and nutrient imbalances may be less of a problem coming out of intensive tillage into no-till if the soil is disturbed around and below the seed row. As the no-till system matures and the soil ecology equilibrates, the soil disturbance should be reduced to a minimum.

Drill openers that cause high soil disturbance include those that utilize chisel shanks, sweeps or wide hoes, and heavy duty offset double discs. Low disturbance tools include slot-type openers, narrow shovels, and small diameter (less than 30 cm) discs openers. However, disc openers have a tendency to hairpin or "tuck" residue into the seed row, which can reduce seed depth control, seed-soil contact, and consequently, germination.

Sowing and Fertilizer Application

Researchers and farmers alike in many areas learned early on that for the maximum crop response fertilizer should be banded in proximity to the seed row for cereal crops. This finding is likely to apply in other crops as well. Broadcasting dry fertilizer results in lower nutrient uptake efficiency than banding and has been known to stimulate the growth of certain weeds in crops and thus, enhance their competition.

No-till drill openers vary considerably in how fertilizer is placed in relation to the seed. For example, the "Yielder" no-till opener manufactured in the U.S.A. in the 1980s placed fertilizer about 10 cm deep between a pair of cereal rows, spaced 13 cm apart with a space of 38 cm between the pairs of rows. Thus, with a seeding depth of 4 cm, the band of fertilizer is placed 6 cm below and about 6.5 cm to the side of each seed row. Some one-pass chisel planters, which cause considerable soil disturbance around the seed row, place fertilizer 2 to 3 cm directly below the seed row. The "Cross-Slot" opener, a very low disturbance slot planter, manufactured in New Zealand, places fertilizer and seed at the same depth indisposed about 3 cm apart (Baker *et al.*, 1996). Other no-till or one-pass planters provide various fertilizer-to-seed placement arrangements. However, the important underlying feature of most of these planters is simultaneous seeding, and banding of fertilizer. Studies of no-till fertilizer/seed placement methods have not identified a superior way for all conditions, but indicate that for crop response banding fertilizer in proximity to the seed row almost consistently out-performs broadcasting.

Water Conservation

In the Pacific Northwest, U.S.A., 5 to 8 cm more water is stored from that over winter precipitation in a 500 mm precipitation zone in no-till with a cover of cereal residues compared with intensively tilled bare soil (Moldenhauer *et al.*, 1995). This water, if made available to a wheat crop, will produce 900 to 1300 kg ha^{-1} of grain. Farmers practicing no-till observe little runoff from fields even on relatively steep slopes. The natural structure with macro pores formed under continuous no-till, provide a by-pass for free water flow from the surface to the subsoil, and can markedly increase infiltration during extended rains. Once broken by tillage these flow paths are destroyed and downward water movement is limited by a much slower capillary flow. They can only be re-established over time (several years or more) with continuous no-till.

In addition to increasing infiltration and reducing runoff, the extended periods of surface cover with no-till helps reduce evaporation. The partially decomposed surface organic layer tends to act as a mulch barrier, which restricts evaporation by cutting off capillary water flow to the surface. This is an added effect of a mature no-till soil to that of a surface cover of annual crop residues. Another long-term effect of continuous no-till is an increase in the water-holding capacity of the soil from the build-up of residual soil organic matter. Hudson (1994) showed that the available water-holding capacity of a loam soil was increased by almost 4% of the soil volume by each additional percent of residual soil organic matter. For topsoils with low organic matter and low water-holding capacities, e.g., in the 10 to 12% range, this gives the potential for increasing those capacities to 14-16% in 20 years. If the organic matter build-up is restricted to the top 15 cm of soil, the layer will hold an extra 6 mm of water each time the soil dries out and is refilled by rain. The feeder roots of many crops are in this 15 cm layer at critical stages of growth and thus, this increase in organic matter improves chances of plant survival during drought-stress periods. The same would be true during plant germination and seedling establishment.

No-Till in the Absence of Crop Residues

One of the major benefits of no-till is that maximum amounts of crop residues are retained on the soil surface which provide protection against soil erosion, improve soil water relations, and increase the soil organic matter content. However, in many dryland areas of the world crop residues are harvested for animal feed, fuel or building materials, leaving little or none for return to the soil. Is no-till of benefit under these conditions? The answer appears to be definitely, yes. In fact, continuous no-till is probably the only practical management alternative that can improve the soil quality of crop lands when there are little or no organic amendments available for return to the soil on a regular basis.

A study was conducted in the U.S. Department of Agriculture in Washington State comparing the effect on soil quality parameters of limited tillage or no-till where all crop residues were burned with conventional tillage and where no burning was done (D.K. McCool, personal communication, 1997). The tests were conducted on farmers' fields on relatively steep land, with hillsides ranging up to 40% in steepness. The fields were cropped annually, primarily for cereals. Water erosion on the two treatments was similar, approximately an average of 15 Mg ha^{-1} annually, and most erosion occurred on the steeper parts of the landscape. The least erosion occurred on the no-till fields where there was a burn with minimal soil disturbance. Aggregate stability and organic matter in the top 5 cm of soil were greater in the long-term (10 years or more) burn/no-till fields than on the tilled fields. Readily mineralized carbon, microbial biomass, and enzyme activity all trended higher in the top 5 cm of the burn/no-till soil compared with the conventionally tilled fields. Data collected on crown material and below ground stems of wheat indicate that this previously unmeasured material is approximately equal to the root biomass in the upper 10 cm of soil. It appears that this material, together with the plant roots, can contribute substantially to an increase in soil organic matter in the top layers of the soil with no-till.

These results indicate that even with complete residue removal, organic matter can be maintained as long as the soil is not tilled. The reason is that the roots, and in this case, the below-ground wheat crowns and stems, if left undisturbed, will help increase the soil organic matter content. In a tillage system, these materials would be readily oxidized along with some residual organic matter.

No-till Crop Rotations

Crop rotations are an important part of most tillage systems as a way to reduce agronomic and economic risks and increase farm profitability. It is only logical to assume that crop rotations will be equally important to manage risk and diversify farmers' income with continuous no-till systems. However, the best no-till rotations for dryland conditions may differ considerably from those used in tillage-based systems (Domitruk and Crabtree, 1997). The underlying reason for this is that in most dryland situations, no-till saves additional moisture, which allows crops and crop sequences to be grown that are not possible with conventional tillage. Another factor that plays an important role is the improvement in soil quality that occurs with continuous no-till.

Cropping intensity

An increase in available water allows the rotation intensity to be increased. This can be accomplished by increasing the cropping frequency, or by growing more crops with high water demand to match the water supply. For example, a crop-fallow rotation could be replaced by annual cropping (increases the cropping frequency) or mixing crops such as corn (*Zea mays*), sorghum (genus *Sorghum*), or sunflower (genus *Helianthus*) (high water use crops) with wheat, barley (*Hordeum vulgare*), pea, lentil (*Lens culinaris*) or millet (*Panicum miliaceum*). Unused water in a rotation cycle means the cropping intensity is too low, whereas, frequent appearance of water stress means the cropping intensity is too high. Ideally, the no-till rotation should have some flexibility to adjust for variations in weather cycles that can last for several or more years.

Crop diversity

Diverse crop rotations have long been part of tillage-based systems to reduce pest and environmental risks and to improve agronomic efficiency. Crops of the same type often host similar pests and have similar water and heat requirements (Domitruk and Crabtree, 1997). Mixing plant types in the cropping system will alter seeding and maturity dates, pest susceptibilities, and water use patterns. Crop diversity should do the same for no-till systems, though the rotation may be different to achieve maximum efficiency. It would appear that crop diversity and proper crop sequence would be extremely important during the first years of transition to continuous no-till because of the changing soil ecology and microenvironment. However, as the no-till soil matures diversity may become less important for controlling pests, particularly the way they occur in tillage-based systems. After 20 years of continuous no-till, Larmarca on his farm in Chile had little problem growing continuous wheat to reduce slug population that occurred with a wheat-legume rotation (Carlos Crovetto Larmarca, personal communication, 1997). John Rea, a farmer near Walla Walla, Washington, U.S.A., reports no major problems with annual monoculture cropping of spring wheat in his established continuous no-till fields (John Rea, personal communication, 1997). Average annual precipitation on the Rea farm is about 230 mm.

Crop residue management

Crop rotations can be an important approach for managing crop residues in continuous no-till systems. In some higher producing areas, growing high residue crops such as fall wheat and corn successively can lead to high rates of residue accumulation that interfere with sowing and fertilizing, or produce undesirable biological effects on subsequent plant growth. Rotating high residue crops with low residue crops with proper cropping intensity can help alleviate this problem by balancing the residue production and allowing time for decomposition. A rotation that works well for residue management with continuous no-till in some of the cereal producing areas of the Pacific Northwest, U.S.A., is fall wheat-spring barley-field pea. Fall wheat is a heavy residue producer, spring barley a moderate producer, and field pea a low producer. Sequencing these crops maintains a good supply of residue cover through the rotation cycle, but not so excessive that they interfere with cultural operations and plant growth.

Other benefits of rotations

According to many economists, crop diversity generally improves farm profitability and efficiency. Growing different crops allows farm machines and labor to be used more efficiently than with monoculture or limited rotations. With no-till, farmers spend less time working in their fields and more time planning their cropping system. Crops can be adjusted to fit current and local economic conditions and accommodate changes in the future. Rotations also can help to reduce price and weather risks, and fixed costs per acre.

Crop Yields

Long-term trends in crop yields with continuous no-till indicate that the benefits to production are substantial. For example, Ismail *et al.* (1994) showed that the yields of corn with no-till were about 90% of that with tilled corn during the first years after conversion, but gradually increased to about 110% after 20 years (Fig. 4). The cross-over point where no-till and tilled corn yields were about equal was 9 years into no-till which gives an indication of the time it takes for the no-till soil to develop and productivity changes to occur.

This yield increase is a typical experience of farmers who have maintained a continuous no-till system, especially on soils that have been degraded by tillage and erosion. Lamarca (1996) reported dramatic increases in crop yields on his farm in

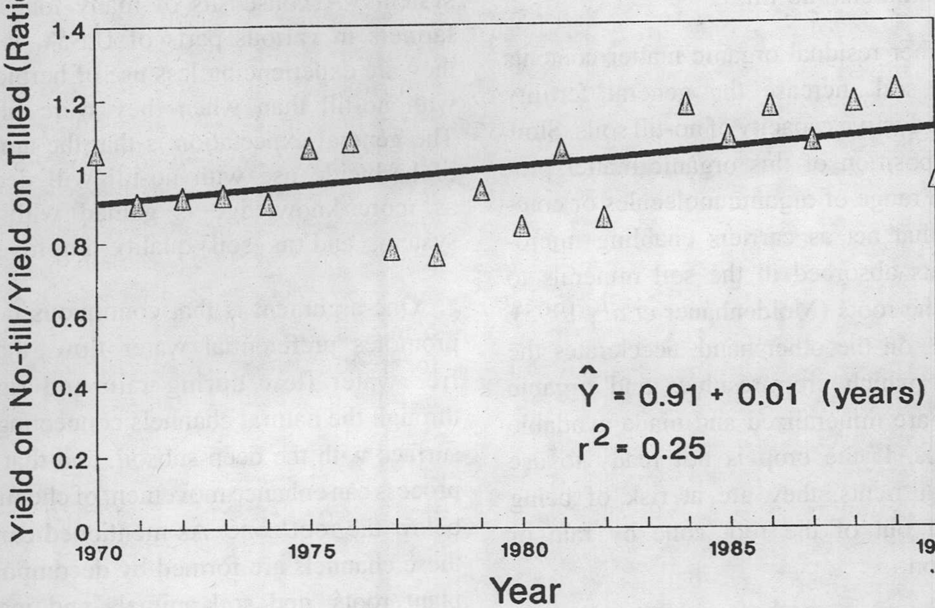

Fig. 4. Trends in corn yields comparing tilled with no-till management. Source: Ismail et al. (1994) as drawn by Moldenhauer et al. (1995).

Chile with continuous no-till on soils that were once severely eroded. Grain yields in 1978/79, when he switched to a corn/wheat rotation from conventional tillage to continuous no-till, were 4.6 Mg ha^{-1} for corn and 2.2 Mg ha^{-1} for wheat. There was a relatively steady trend of yield increase during the 14 years of no-till with a maximum of 7.5 Mg ha^{-1} for wheat in 1991 and 13.7 Mg ha^{-1} for corn in 1994. On Lamarca's farm wheat is produced under rainfed conditions and corn during the dry season with supplemental irrigation. He credits the yield increases largely to overall improved agronomic management (e.g., better pest control, improved varieties, and timeliness of farm operations) and to regenerated physical, chemical, and biological properties of the soil that are promoted by continuous no-till.

Higher residual organic matter contents in the soil increase the general fertility and productive capacity of no-till soils. Slow decomposition of this organic matter provides a range of organic molecules or comperes that act as carriers enabling micronutrients absorbed in the soil minerals to reach the roots (Moldenhauer *et al*., 1995). Tillage, on the other hand, accelerates the rate at which crop residues and organic matter are mineralized and made available to crops. If the crop is not ready to use these nutrients, they are at risk of being leached out of the root zone by rain or irrigation.

Continuous no-till also improves the soil tilth, e.g., its physical condition which improves soil water relations, and seedling establishment and early crop growth. Retention of crop residues at the soil surface moderates the extremes of drought by increasing infiltration and decreasing evaporation. All of these benefits are reflected in increased crop yields.

Environmental Effects of Continuous No-Till Systems

There has been concern in some countries that the adoption of continuous no-till will increase the use of chemical inputs, especially pesticides, which will ultimately degrade soil, water, and air quality. However, these concerns may be more of perceptions than reality. A broad survey by Bull *et al.* (1993) in the U.S.A. indicates that corn producers use about the same amount of herbicides for tillage and no-till systems. A consensus of many long-term farmers in various parts of U.S.A. is that they are experiencing less use of herbicides with no-till than when they were tilling. The general expectation is that the amount of herbicide use with no-till will decline as more knowledge is gained with this system, and as soil quality improves.

One argument is that continuous no-till promotes preferential water flow, that is free water flow during rain and runoff through the natural channels connecting the surface with the deep subsoil, and that this process can enhance movement of chemicals below the root zone. As mentioned earlier, these channels are formed by decomposing plant roots, and soil animals and insects burrowing from below to feed at the soil surface. This type of water flow occurs as long as the soil is not disturbed so that the channels remain relatively intact. It is possible for pesticides or other chemicals that are normally strongly adsorbed to soil particle surfaces, and therefore not readily moved by infiltrating water to be moved below the root zone (and ultimately to the ground water) by free flow through these interconnecting channels. These channels or macropores can also be a conduit for rapid movement of soluble chemicals such as nitrate-nitrogen below the root zone.

On the other hand, no-till management favors the use of post-emergence herbicides, which are strongly adsorbed to the soil in contrast to the more mobile pre-emergence herbicides which are the major choice with tillage systems. Since no-till has a more biologically active surface soil resulting from the accumulation of organic matter, the post-emergence chemicals that miss their target are prone to rapid degradation when they contact the soil.

There are compelling reasons to believe that well-managed, continuous no-till will, overall, improve soil, water and air quality. On the issue of water quality, no-till keeps topsoil on the land and out of stream beds, reservoirs and lakes (Moldenhauer *et al.*, 1995). Moreover, less surface runoff means less flood damage from sedimentation, more ground water recharge, more base flow, and overall, a healthier environment. Surface runoff can also carry many contaminants off the land (e.g., animal feces, disease organisms, and a host of other undesirable organic compounds) directly into surface waters which then in many cases must be treated to be usable. With no-till, the precipitation infiltrates the soil where the contaminants are filtered out and detoxified as the water percolates slowly down so that upon entering the ground water aquifers it is safe to drink.

Conclusion

Developing continuous no-till management systems should be the challenge now and for the future as the way to achieve a more sustainable dryland agriculture. This farming system surpasses all others as a way to build soil organic matter and soil structure, and to minimize soil degradation. Continuous no-till controls erosion, increases infiltration rates, decreases air and water pollution, and restores soil quality. For society this means a cleaner and healthier environment and a more secure and stable food supply.

Though good progress has been made in the U.S.A. and many other countries in developing no-till technology, many problems and questions remain which limit a more rapid adoption rate of this new and different way of farming. These include improving the efficiency and reducing the cost of seed/fertilizer no-till drills, overcoming physical and biological limitations of sowing into heavy residues, finding better methods for residue management between crops, and developing crop rotations that can help provide for crop diversity and maximize crop production. In many areas new alternative crops are needed for developing longer and more diverse crop rotations. A major research need is to learn more about soil biological and ecological changes that occur during the transition from conventional tillage to no-till, and how this information can be applied to reduce economic risks for the farmer during the early years of the conversion. A dedicated effort towards building knowledge of continuous no-till science should be the new frontier in dryland agriculture. This approach should go far in solving many environmental problems worldwide while sustaining a high level of productivity and farm profitability.

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