Reviews

Changes to the Soil Environment under Conservation Tillage

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In deciding whether a change to conservation tillage should be implemented, many site-specific factors need to be seriously considered. What may be an advantage of conservation tillage in one location can be a disadvantage in another. In certain production systems the risk of shifting to a different tillage system may not be justified. Vegetables, for example, are generally high value crops that require intensive management. A delay in plant maturation or reduction in yields represents a substantial monetary loss, causing farmers to be less willing to adopt conservation tillage practices even with the many benefits to be shown from these systems.

The advantages of conservation tillage are many. Reduced power, machinery, and labor costs are attractive to many farmers. Less time and fuel are needed to prepare fields for planting due to fewer cultivation operations. Less

evaporation and greater infiltration with conservation tillage conserves soil moisture (Blevins et al., 1984; Lal, 1976; Packer and Hamilton, 1993). Conservation tillage can reduce irrigation requirements. Crop residues associated with conservation tillage prevent the harmful effects of raindrop splash, eliminating soil crusting and increasing infiltration capacity. Several authors have shown that infiltration increases with a legume cover crop as opposed to a nonlegume cover crop, indicating that the quality of organic matter is also an important factor (McVay et al., 1989; Wilson et al., 1982). An increase in nitrogen fertilizer efficiency in nontilled soils contributes to greater water use efficiency (Frye et al., 1982; Phillips et al., 1980). This can translate into improved crop performance and increased yield. Conservation tillage protects erosion-prone soils from wind erosion and reduces surface runoff. Sloping, marginal lands that are otherwise not farmable can be put into production with less concern for soil degradation.

Soil water

Despite lower total porosity and air permeability, conservation tilled soils generally have higher surface soil water content than plowed soil during the growing season (Blevins et al., 1971, 1984; Dalal, 1989; Lal, 1976; Legg et al., 1979; Mielke et al., 1986; Thomas, 1986). More soil water enables plants to continue to grow during short-term dry periods. Blevins et al. (1971) and Lal (1976) reported that short periods of drought stress occurred in crops growing on plowed soils, whereas none occurred in crops growing on untilled soils. Thus, tillage may significantly affect crop yields during years of poor rainfall distribution.

Soil water content is generally higher with conservation tillage than with conventional tillage because of a decrease in water evaporation from the soil surface. Accumulation of crop residues on the soil surface accounts for this reduction, as much as from 1.8 to 6.0 inch (4.5 to 15.0 cm) water (Blevins et al., 1971; Phillips, 1984; Sims et al., 1994). The residue mulch reduces the amount of direct solar radiation reaching the soil surface, insulating the soil from the downward convection of heat, and decreasing the upward diffusion of water vapor to the soil surface (Larson et al., 1970; Phillips, 1984; Thomas, 1986).

Soil temperature

Soil temperature on the surface of conservation tilled soils is typically lower during the day than plowed tilled soils (Lal, 1976; Peterson et al., 1986; Power et al., 1986; Utomo et al., 1987). This is due to the insulation effect of crop residues and the tendency for the mulch to reflect solar radiation (Thomas, 1986). The opposite is true of nighttime minimum temperatures. Conservation tilled soils do not get as cold as plowed soils during the night because of the residue mulch, which retains heat in the soil for a longer period of time. This dampening of temperature extremes as compared to plowed soils is ubiquitous under conservation-tilled soils and may be aided by the higher soil moisture environment found in conservation tillage. More energy is required to heat a wet soil than a dry soil, causing conservation-tilled soils to warm more slowly.

Lower temperatures in untilled soils can slow early crop growth, potentially decreasing yields. Low temperatures can inhibit nutrient uptake, especially phosphorus and potassium, and biological activity. Generally, this does not affect crop production in the southern regions of the United States but can create yield losses in northern climates (Larson et al., 1970). In the tropics this cooling effect can be beneficial, preventing high soil temperatures from decreasing crop yields (Lal, 1976).

Effects of tillage on chemical properties

Adopting conservation tillage practices can have dramatic effects on soil nutrient status. There is concern that nutrients in a conservation tillage system may become less available to plants than under a conventional tillage system

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(Blevins et al., 1983b; Ismail et al., 1994). If this is the case, more fertilizers will be required to obtain similar yields, and farmers will be less willing to change to conservation tillage. Therefore, it is important to know how nutrients will cycle in a soil environment created by a change in tillage.

The major difference between conservation and conventional tillage is the placement of residues and fertilizer on the soil surface rather than uniform mixing of these materials into the plow layer. Residues left on the surface decompose at a slower rate than buried residue, and release nutrients for a longer time through the growing season. Continuous surface applications of fertilizer in conservation tillage without mixing leads to a stratification of some nutrients, with high concentrations at the surface and rapidly decreasing concentrations with depth (Blevins et al., 1984; Logan et al., 1991; Schomberg et al., 1994).

Another change in the soil upon implementation of conservation tillage is increased soil water content. The higher soil moisture environment created by surface residues has the potential to increase nutrient availability to plant roots due to higher rates of mass flow and diffusion. However, increased soil moisture, together with the concomitant increase in continuous pores under conservation tillage, can result in a greater leaching potential.

Soil phosphorus

The availability of phosphorus, along with nitrogen, tends to be most affected by changes in tillage. Conservation of soil moisture in reduced tillage systems allows for increased diffusion of phosphorus to plant roots (Phillips et al., 1980; Thomas and Frye, 1984; Thomas, 1986). It has often been observed that plants in dry areas suffer from phosphorus deficiency, indicating that phosphorus is very moisture sensitive. Because conservation tillage systems tend to have higher soil moisture environments, plants growing in these systems would have an advantage in accruing phosphorus, particularly during dry periods.

Another major change that occurs in conservation tillage systems affecting available phosphorus is the accumulation of organic matter at the soil surface. Organic matter constituents increase phosphorus availability by decreasing the effectiveness of phosphorus fixation

sites (Logan et al., 1991; Schomberg et al., 1994). This occurs by organic matter shielding Fe and Al particles and by organic anions replacing phosphorus on Al and Fe complexes, both of which help to maintain the solubility of phosphate in solution. Using organic sources of P fertilizer can have the same effect, as evidenced by a higher plant uptake of phosphorus in studies where poultry litter was applied (Eggert and Kahrmann, 1984; Kingery et al., 1996). Several studies have found a high positive correlation between levels of crop residue and available soil phosphorus concentrations (Black, 1973; Larson et al., 1972). Similarly, when applications of inorganic phosphorus fertilizer remain at the soil surface there is less phosphorus-soil contact, and thus, less phosphorus fixation. In addition to increases in available inorganic phosphorus at the surface, increases in organic phosphorus are likely in the higher residue environment of reduced tillage systems, providing a sustainable long-term source of phosphorus (Stewart and Sharpley, 1987).

Lower soil temperatures occurring early in the spring also may influence the behavior of phosphorus in the soil. Cool soil temperatures inhibit phosphorus uptake, therefore, conventionally tilled soils with their higher soil temperatures early in the growing season may provide more plant available soil phosphorus than conservation tillage (Thomas, 1986). The degree that soil temperature affects overall phosphorus uptake is unclear. Since conservation tillage soils generally have more available phosphorus than plowed soils, it seems likely that soils under conservation tillage can still provide adequate phosphorus.

One other factor that is well known to influence phosphorus availability is soil pH. Since pH has been shown to decrease at the surface of unlimed no-tilled soils, additional adsorption of phosphorus by Fe and Al oxides would be expected, due to the increase solubility of Fe and Al at a lower pH.

Numerous studies report greater amounts of extractable phosphorus at the surface of conservation tilled soils than conventionally tilled soils (Dick et al., 1991; Ketcheson, 1980; Stinner et al., 1983a). Studies that also examined subsurface available phosphorus report conflicting results, with some authors finding equal or greater amounts of available phosphorus in conservation tillage systems compared to conven-

tional tillage (Dick and Daniel, 1987; Franzluebbers and Hons, 1996; Moschler et al., 1972; Moschler et al., 1975; Tracy et al., 1990), while other researchers found decreased amounts of available phosphorus (Ismail et al., 1994; Karlen et al., 1991; Lal et al., 1990; Weil et al., 1988) in lower depths of conservation tillage systems. Despite inconsistencies, most of these studies showed higher surface concentrations of available phosphorus in conservation-tilled corn (*Zea mays* L.) systems (Hargrove, 1985; Ketcheson, 1980; Shear and Moschler, 1969; Singh et al., 1966; Triplett and Van Doren, 1969) and in vegetables (Ekeberg and Riley, 1996; Knavel et al., 1977).

A greater efficiency of phosphorus nutrients applied has also been shown to exist with conservation tillage compared to conventional tillage (Ekeberg and Riley, 1996; Moschler and Martens, 1975; Thomas and Frye, 1984). One reason for this may be the greater downward movement of organic P compounds than inorganic P in solution (Tisdale et al., 1993). Both Dick (1983) and Staley et al. (1988) found higher levels of organic P in no-till soils, at surface and subsurface levels. In another study, Hargrove (1985) found a greater activity of roots under no tillage by using a Rubidium tracer, indicating another probable reason why plants do not suffer from poor nutrient uptake under no tillage.

Soil pH

Numerous studies report a decrease in soil pH after adoption of conservation tillage (Dalal, 1989; Dick, 1983; Dick et al., 1988; Franzluebbers and Hons, 1996; Karlen et al., 1991; Lal et al., 1990; Stinner et al., 1983a). As with phosphorus, it is the stratification effect of not mixing the soil and the higher soil moisture content that occurs with conservation tillage which induce these changes. When crop residues are left on the soil surface and no mixing of the soil takes place, any acid-producing fertilizers added will be concentrated in the uppermost portion of the soil profile. That is, each ammonium ion oxidized to nitrite produces two hydrogen ions. This increase in acidity, which is directly related to the rate of fertilizer application, also occurs in conventional tillage but is distributed uniformly throughout the plowed horizon. This dilutes the effect rather than localizing it at the surface (Blevins et al., 1984).

To a lesser extent, the higher soil moisture in conservation tillage systems also contributes to a decrease in pH by allowing more leaching of base cations. Increased water movement through the soil profile together with an increase in continuous pore space in conservation tillage can lead to increased acidity because hydrogen ions replace leached base cations on the exchange complex. Therefore, an environment where winter and spring rainfall exceeds evapotranspiration will promote soil acidification under no till (Blevins et al., 1984). However, in areas that experience long dry periods, the tendency toward acidification under conservation tillage has not been observed (Lal, 1981). During these dry periods, salts of basic cations are brought back to the surface by plant roots rather than being flushed out by excess precipitation.

Since the acidification of conservation tillage soils is concentrated at the surface, neutralization of pH should result rather easily by a surface application of lime. Surface applications of lime appear to control low pH levels of surface soils rather well (Blevins et al., 1978). At every rate of lime application, pH of the surface 0 to 2 inch (0 to 5 cm) of a no-till soil was increased, and at the highest lime rate, pH was increased to a depth of 12 inch (30 cm). Other studies have found that with moderate lime applications the soil pH of the surface 2 inch (5 cm) was increased more when surface applied than when mixed into the plow layer, by as much as 0.7 of a unit more (Blevins et al., 1978; Hargrove, 1985; Ismail et al., 1994).

It is apparent from the literature that surface liming of no-till soil can be quite effective for controlling acidity when a highly acidic subsurface is not present. Limestone ground to an appropriate fineness will also help to increase the rate of reaction of the limestone with the soil (Thomas and Frye, 1984). In humid areas, a slightly higher application rate of lime in conservation tillage than under conventional tillage may help to ensure maximum benefits (Thomas, 1986).

Soil calcium

It is harder to generalize about the effect of conservation tillage on calcium because of variable results obtained from studies done in different soil and climatic environments. There are two principle factors in a conservation tillage environment that effect calcium avail-

ability to plants. The first is increased soil moisture under conservation tillage. More water entails greater mass flow transport of calcium to plants and, thus, potentially higher uptake of calcium. However, this is not always the case, suggesting that other factors are involved in calcium uptake (Estes, 1972; Knave et al., 1977; Stinner et al., 1983b; Stinner et al., 1988). In humid regions that receive large amounts of rainfall, there tends to be an extended period of leaching under no tillage because of excess soil water (Thomas and Frye, 1984). Also, due to the presence of a dense mulch at the surface of conservation-tilled soils, there is less evaporation, reducing cation mobility upward from the rooting zone. These factors, along with the increased frequency of undisturbed cracks and pores found under conservation tillage, increase leaching potential. Tyler and Thomas (1977) reported significantly higher concentrations of nitrate in soils under no tillage during heavy rainfall periods when compared to plow tillage under the same amount of precipitation and that the accompanying cation was, for the most part, calcium. Numerous authors have reported that calcium concentrations decreased in conservation tilled soils (Blevins et al., 1978; Blevins et al., 1983b; Karlen et al., 1991; Lal et al., 1990; Moschler et al., 1973). In the absence of lime amendments, the addition of nitrogen fertilizers, and with continued calcium loss, soil pH decreased (Thomas and Frye, 1984). In contrast, Franzluebbers and Hons (1996) reported that in a calcareous soil (pH 8.2), calcium concentration was unaffected by tillage or nitrogen fertilizers, indicating that tillage was not a factor affecting calcium concentrations in soils with high native supply of calcium. Climate generally affects calcium behavior in soil, regardless of tillage practice. In a climate having a significant dry season, Lal (1976) found higher concentrations of calcium in the surface of no-tilled soils when compared to plow tillage, suggesting that nutrients moved upward in the soil profile by evaporative water during dry periods.

The second factor affecting calcium movement in conservation tilled soils is the decrease in pH with increasing nitrogen fertilizers applied to the soil surface. This decrease in pH, discussed earlier, causes the replacement of Ca^{2+} by an abundant supply of H^{+} on soil exchange sites, leaving the Ca^{2+} suscep-

tible to leaching with the gravitational water. Therefore, the more acidic the soil surface becomes under conservation tillage, which is directly related to the amount of N fertilizer used, the more exchangeable calcium is released into the soil solution. This relationship between N fertilizer, pH and calcium loss has been shown extensively in studies by Blevins and his associates (1977, 1983a, 1983b), and by Ismail et al. (1994). When conservation tillage soils are surface limed, the results are reversed as acidity is neutralized. Equal or higher calcium concentrations were found in surface depths of no-tilled soils as compared with conventionally tilled soils, while the calcium concentrations of subsurface depths remained higher in the conventionally tilled soils (Blevins et al., 1978; Blevins et al., 1983a; Hargrove, 1985; Ismail et al., 1994; Moschler et al., 1973; Moschler et al., 1975). Although results are less predictable for calcium in conservation tilled soils, acidity, and thus calcium, can be controlled for maximum crop growth with the addition of appropriate levels of lime.

Soil potassium

The behavior of soil potassium does not appear to be significantly affected by conservation tillage (Thomas and Frye, 1984; Thomas, 1986). Numerous authors have found similar levels of potassium in conservation tilled and conventional tilled soils (Ekeberg and Riley, 1996; Moschler et al., 1975). Because potassium is a monovalent cation, it is held relatively tightly and therefore would not be leached in significant amounts except in soils which have a low cation exchange capacity. The major difference between conservation tillage and conventional tillage systems with respect to potassium is the lack of soil mixing under conservation tillage and the surface application of fertilizer. As with phosphorus, this leads to a stratification of potassium. Many studies have shown higher concentrations of exchangeable potassium in the surface layers of conservation tillage systems when compared to plowed tillage systems (Blevins et al., 1977; Blevins et al., 1983b; Franzluebbers and Hons, 1996; Hargrove, 1985; Ismail et al., 1994; Ketcheson, 1980; Lal et al., 1990; Moschler et al., 1972; Triplett and Van Doren, 1969). Below this surface layer, however, soil potassium decreases sharply with depth in conservation tillage (Frye, 1984; Thomas, 1986). This difference in potassium distribution is evi-

dently not significant to plant nutrition. Equal or greater plant recoveries of soil potassium occur under conservation tillage as evidenced by studies on corn (Estes, 1972; Ketcheson, 1980; Shear and Moschler, 1969; Triplett and Van Doren, 1969) and vegetables (Ekeberg and Riley, 1996; Knavel et al., 1977).

Some problems with potassium deficiencies in plants have been seen in studies conducted on cold, wet soils (Thomas, 1986; Thomas and Frye, 1984). This is a poorly understood phenomenon but appears to be a plant-related problem as well as a result of higher bulk density and excessive water content under conservation tillage (Thomas, 1986). This occurrence is rare in the southern US except with very early planting and should only be a concern in northern states. According to Thomas (1986), when very unusual potassium deficiency symptoms appeared in no-till corn in Kentucky, the problem disappeared within 2 weeks. This effect on cold, wet soils can be corrected by either adding more potassium fertilizer or by banding small amounts of potassium in the plant row (Thomas and Frye, 1984; Thomas, 1986).

Conservation tillage does not appear to affect soil potassium or plant uptake of potassium negatively except perhaps when planting occurs too early into soils that are cold and excessively wet. In this case, increasing the amount of potassium in the soil solution either by adding larger amounts of potassium fertilizer or banding potassium fertilizer in row appears to overcome the problem.

Soil magnesium

Most soils, with the exception of sandy soils, tend to have a continuous source of magnesium from the gradual weathering of clay minerals (Thomas, 1986). Like calcium, exchangeable magnesium losses are intensified with increasing levels of nitrogen fertilizer. The excess of H^+ tends to replace Mg^{2+} on the exchange sites as the soil environment becomes acidified due to the nitrification of NH_4^+ based fertilizers. This is indeed seen in the literature as soil magnesium concentrations under conservation tillage were lower than under conventional tillage (Blevins et al., 1977; Blevins et al., 1983b; Moschler et al., 1973). When the initial soil pH was very high, there was no difference in magnesium concentrations under the two different tillage regimes (Franzluebbers

and Hons, 1996; Lal et al., 1990). Even after 12 years of no tillage, neither of these studies showed a drop in soil pH below neutral, indicating that acidity was not a problem. This suggests that tillage will not have an effect on exchangeable magnesium concentrations in calcareous soils. However, with additions of lime, magnesium levels at the surface of conservation tilled soils tends to be higher than the surface of conventionally tilled soils and decrease with depth (Blevins et al., 1977; Blevins et al., 1983b; Hargrove, 1985; Karlen et al., 1991; Ismail et al., 1994; Moschler et al., 1973).

Another factor that can affect exchangeable magnesium levels is the amount of other cations present in the soil, especially potassium (Tisdale et al., 1993). There is evidence of increased levels of K^+ at the surface of conservation tilled soils reducing the amount of exchangeable magnesium (Estes, 1972; Hargrove, 1985). In these studies, plant uptake of magnesium was hindered in no-tillage soils when compared to conventionally tilled treatments. However, there was no indication of magnesium deficiency in either study. In a study comparing no-till and plowed vegetables, plant uptake of magnesium was no different between the two tillage systems (Knavel et al., 1977).

Magnesium, as with calcium, can be controlled with additions of lime in conservation tillage systems. Although a decrease in exchangeable magnesium may occur due to competition for exchange sites with other cations, mainly K^+ , harmfully low levels will not be likely to appear in most soils on account of the slowly available source of mineral magnesium.

Soil cation exchange capacity and base saturation

Although tillage induced changes in cation exchange capacity and base saturation are usually small, conversion to a conservation tillage system increases both (Gallaher and Ferrer, 1987; Lal, 1976; Lal et al., 1990; Moschler et al., 1973). Increases in cation exchange capacity occur exclusively in the upper 4 to 8 inch (10 to 20 cm) of the profile, are attributed to increases in organic matter.

Nutrient availability

Changes in nutrient availability that accompany the implementation of con-

servation tillage originate from the accumulation of organic matter and nutrients that occur with this practice. The nutrient stratification in the soil profile creates some uncertainty for the short term productiveness of conservation tillage. However, the higher concentration of roots and water content usually observed in the surface horizon with conservation tillage may allow for an equal or greater amount of nutrient use and productivity by crops for the longer term (Ekeberg and Riley, 1996; Estes, 1972; Hargrove, 1985; Knavel et al., 1977; Shear and Moschler, 1969; Singh et al., 1966; Triplett and Van Doren, 1969). A major problem generated by this stratification is that of acidification of the surface horizon. This in turn can lead to reduced availability of phosphorus, increased loss of calcium, as well as increased levels of aluminum. Fortunately, the addition of appropriate levels of lime to the surface of reduced tillage systems appears to adequately overcome these problems. An additional concern is the possibility of a greater leaching potential for soluble cations such as calcium, resulting from a larger number of continuous pores under conservation tillage. Which process predominates in controlling the availability of soil nutrients in a conservation tilled soil environment will change for different cropping systems, climate, etc. The slow release of nutrients from an increasing organic matter fraction from residue based conservation tillage will eventually come to equal the rapid release of the gradually decreasing pool of organic matter that occurs in plow tillage (Thomas, 1986).

Nitrogen and carbon cycling in conservation tillage systems

Microbial biomass represents an important component in the cycling of nutrients in the soil, governing the breakdown of organic matter and the availability of nutrients, particularly nitrogen. Changes in tillage that affect microbial activity and thus, nitrogen and carbon cycling, are derived from the greater amount of organic matter at the surface of conservation tillage systems and the lack of mechanical soil mixing. These differences in the soil environment will have a profound impact on the fate and availability of soil and fertilizer nitrogen.

Plowing creates favorable conditions for organic matter decomposition through a number of mechanisms

(Blevins et al., 1984). It disrupts the soil aggregates, increasing microbial access to carbon sources by exposing organic compounds that were previously protected by physical entrapment. Tillage also creates better soil aeration and physical conditions which are more favorable to microbial activity. Large pieces of residue are broken apart, increasing the surface area of residue available for microbial attack. Incorporation of residues into the soil places them in a constantly moist environment, whereas residues on the surface can become desiccated. All of these seem to favor a quicker decomposition of organic residues and release of nutrients under plowed systems.

The degree to which tillage regime will influence the overall biological activity of the plant-soil system is dependent on site- and management-specific factors. Factors that vary the effects of tillage include soil moisture, temperature, aeration, and pH. These environmental factors can potentially limit microbial growth. Placement of residues (surface vs. incorporated), quality of the residue, length of time the tillage system has been in place, previous management and even soil type all bear on the soil habitat to some degree.

Soil organic matter

A primary prerequisite for heterotrophic microbial growth is the presence of carbon substrates, and since tillage systems are inherently different in how organic residues are distributed they will also differ in how microbial populations are dispersed throughout the soil. As mentioned earlier, conservation tillage systems can accumulate large amounts of crop residue on the soil surface. The increase in soil carbon concentrations with increasing amounts of residue (Black, 1973; Larson et al., 1972) suggests that carbon will be higher at the surface of conservation tilled soils than conventional tilled soils, as shown by numerous authors (Blevins et al., 1983a; Dalal, 1989; Dick, 1983; Doran, 1980b; Gallaher and Ferrer, 1987; Lal et al., 1990; Rice and Smith, 1984; Smith and Blevins, 1987; Staley et al., 1988). At deeper levels in the soil, amounts of carbon were the same or less under conservation tillage as compared to conventional tillage.

The length of time a tillage regime is in practice also affects the distribution of carbon substrates (Dick, 1983; Dick and Daniel, 1987; Rice and Smith,

1982). Dick and Daniel (1987) found that during the first five years of implementing conservation tillage levels of organic matter increased rapidly over levels in conventional tillage. After this period, however, increases in soil organic matter of untilled soils occurred at a slower rate and similar to that of tilled systems. Staley et al. (1988) showed that after 15 years of practicing no tillage total carbon levels decreased, although levels remained higher than under plowing.

Effects of soil type on organic substrate patterns can also be significant (Dick, 1983). Soils with shrink-swell properties may allow for deeper penetration of roots and oxidation of organic matter via cracks protruding downward into the profile. In this way the properties of a no-tilled system extend deeper into the soil.

Arshad et al. (1990) found that not only was there a greater quantity of organic matter in no tillage systems, but that the quality of the organic matter was also higher. When samples were taken in September, organic matter from soils managed with conservation tillage was higher in carbohydrates, amino acids, and aliphatic carbon compounds and less in aromatic carbon compounds, suggesting that the soil organic matter in conservation tillage existed in a more easily degradable state.

Microbe populations and activity

Microbes under conservation tillage systems would be expected to concentrate at the soil surface, accompanying the distribution of organic carbon. Many studies have shown higher counts of microbes in the surface of conservation tilled soils as compared with conventional tilled soils (Blevins et al., 1984; Doran, 1980b; Doran, 1987; Follett and Schimel, 1989; Granatstein et al., 1987; Smith and Rice, 1983). Below the surface depth this trend is reversed with equal or greater amounts of microbes existing in conventional tillage at lower depths. As for the types of microbes occurring, Doran (1980b) examined seven different locations throughout the United States and found that aerobic heterotrophs, total denitrifiers and autotrophic nitrifiers all increased in the surface layer of conservation tilled systems. Denitrifier populations were much higher and remained higher than in conventionally tilled soils, even in lower depths, in five out seven of

the sites. The untilled treatments at the two remaining sites had significant moisture at lower depths as compared with plowed systems of other sites. Counts of autotrophic nitrifiers were higher in conservation tilled soils at four out of seven of the sites, with the other three sites having a lower pH in the no-till treatments. Nitrification is sensitive to pH and is a probable cause for the increased nitrifiers at these sites. Doran (1980a) concluded that nitrifiers proliferated in the higher moisture content in the surface of conservation tilled soils. In the soil profile as a whole, denitrifiers were higher in conservation tilled soils while aerobic nitrifiers were lower when compared with conventional tillage.

The surface residues of conservation tillage promote higher proportions of fungi whereas tilled systems foster more bacteria constituents (Hendrix et al., 1986; Holland and Coleman, 1987). This is probably because fungi have greater tolerance of drier, more acidic and lower nutrient environments. With their lengthening hyphal networks, fungi are able to better utilize soil N reserves and surface residue carbon. A greater ratio of fungi present promotes a higher long-term substrate use efficiency in conservation tilled soils. It also causes decomposition to proceed more slowly than bacterial-dominated soil residues. When tillage occurs and residues are incorporated throughout the plow layer, bacterial growth is promoted and decomposition and, thus mineralization, take place more rapidly.

Soil arthropods are more abundant in conservation tillage soils due to favorable moisture and temperature conditions that occur under surface applied residues (Smith and Rice, 1983). In tilled soils, arthropods' mobility is reduced due to the destruction of large channels that accompanies plowing. Many surface-feeding species are harmed as their food supply is buried during tillage.

It is clear from the preceding information that surface microbial populations are greater under conservation tillage, but does this necessarily indicate a more active population? Measuring CO₂ respiration from soils has implied greater apparent microbial activity in the surface layers of no-tilled soils (Blevins et al., 1984; Hendrix et al., 1988). However, because of the dynamic nature of soil microbial growth, numerous samples need to be taken throughout the season to get a clear

picture of general microbial activity. A few studies have attempted to approach this issue. Rice (1983) found that microbial respiration in the spring was effectively equal in no tillage and conventional tillage and suggested that the effects of higher temperatures early in the season were counteracted by lower moisture in plowed systems. When measured immediately after plowing, respiration from tilled soils were significantly greater than untilled soils as organic matter decomposition increased following residue incorporation (Rice, 1983; Blevins et al., 1984). Hendrix et al. (1988), however, found that only a gradual increase in CO₂ occurred about a month after plowing, suggesting that differences occur in soil environments from site to site. Later in the season, when differences in soil temperature between treatments becomes negligible, untilled soils showed higher respiration than plowed soils, most likely due to the more favorable moisture status under conservation tillage. This is further demonstrated by the study done by Tracy et al. (1990) in which laboratory incubation of soil gave higher respiration rates from no-tilled soils early, but that both tillage treatments were releasing similar amounts of CO₂ after 84 d. However, this experiment was carried out at a constant moisture, temperature and humidity. If this were not the case, untilled soils would be expected to have the favorable moisture status later in the season, leading to higher microbial activity.

In studies examining differences in microbial activity between different tillage regimes, similar amounts of residue are generally added. Yet soils under no tillage tend to have more organic matter present, indicating a slower decomposition of litter by soil microbes under conservation tillage (Blevins et al., 1984; Holland and Coleman, 1987; House et al., 1984b). Holland and Coleman (1987), using labeled ¹⁴C, showed that a greater amount of labeled carbon remained in surface applied residue as opposed to incorporated residues. Schimel (1986) demonstrated that, with time, the available carbon substrate is depleted in plowed soils, resulting in a slower yet longer-term activity of microbes in conservation tillage. In fact, after many years of continuous cultivation, carbon can become limiting in tilled soils (Follett and Schimel, 1989).

Another gauge of soil microbial activity is enzyme activity. Dehydroge-

nase, alkaline phosphatase, amidase and α-glucosidase have all been found to be significantly related to microbial respiration (Frankenberger and Dick, 1983). The presence of these enzymes indicates that microbial decomposition is taking place. Doran (1980a) measured higher soil phosphatase and dehydrogenase levels in both a greenhouse and field study where corn stover residues had been surface-applied as compared to bare soil. Various enzymes, including some of those mentioned above, were found to be greater in the surface layers of untilled soils from a wide range of geographic locations (Dick, 1984; Doran, 1980b). Below this surface layer, enzyme activity was generally equal to or less than conventionally tilled soils of the same depth.

Since the level of microbial activity of untilled soils appears to be directly related to the presence of a surface mulch, a review of how residue type and quality affect microbial decomposition would be appropriate. Growing roots can be considered a type of residue since microbes are known to heavily colonize these rhizoplane zones. Elliott et al. (1984) found that the levels of soil bacteria were greater on roots of no-till winter wheat (*Triticum aestivum* L.) as compared to winter wheat planted into a plowed soil. This would suggest a population of microbes either on existing residues or residing in the soil that are better able to colonize roots once a crop is planted. Whether this is due to a higher microbial population or simply a population that is better able to take advantage of all available carbon substrates is unclear. The presence of a winter cover crop is generally beneficial to microbial activity as shown by pulses of CO₂ evolution immediately following the mowing of a winter cover, regardless of tillage regime (Hendrix et al., 1988). The type of cover crop is also important, as demonstrated by greater microbial activity when crimson clover (*Trifolium incarnatum* L.) was the winter cover compared to rye (*Secale cereale* L.). It was proposed that this resulted from rye immobilizing greater amounts of nitrogen, limiting microbial decomposition. However, since the rye treatments also received inorganic N fertilizers this explanation would be questionable. The authors of the study suggested that increased activity under crimson clover occurred because clover was a more active source of carbon than rye. When legume covers were the source of

nitrogen, greater microbial populations and greater activity resulted as compared to treatments receiving only inorganic N fertilizers (Bolton et al., 1985; Harris et al., 1994). In a study comparing systems utilizing either inorganic N fertilizer, legume cover crop or animal manure as a nitrogen source, the cover cropped system had the largest and most diverse soil microbial population while the animal manure system had the least diverse but most active population (Wander et al., 1995). This may be due to differences in organic substrate composition between the legume cover and the animal manure. However, these samples were only taken in November after corn harvesting and do not reflect the dynamic nature of microbial populations in soil. Martyniuk and Wagner (1978) sampled monthly over a period of ten months and found larger bacterial and fungal populations in manure treated soils than soils treated with chemical fertilizers. The authors proposed that microbial populations were related to the long-term management effects impacting the ability of the soil to accumulate amounts of soil organic matter. It is clear, however, that soils treated with long-term organic amendments, either animal manure or legume cover crops, tend to have higher microbial populations and activities than those receiving inorganic amendments during most of the year (Dick et al., 1988; Fraser et al., 1988).

Tillage and residue effects on microbial activity can exert their influence through other factors. It has been shown that soil microbial levels are closely associated with organic carbon, but they are also affected by soil temperature and water content (Blevins et al., 1984; Doran, 1987; Hendrix et al., 1988). Temperature affects microbial activity directly, inhibiting activity in the cooler temperatures of spring that occur under a residue mulch. However, the moderation of temperature variations that occurs under surface mulch is seen as beneficial for microbial activity. Soil water indirectly affects microbial activity but is often the major reason for differences in microbial populations between different tillage regimes (Doran, 1980a; Mielke et al., 1986; Smith and Rice, 1983). Water serves as a medium for microbial activity as well as acting to solubilize organic substrates. Doran (1980a) found that at seven locations across the United States, soil moisture was the primary factor influencing the

higher microbial populations found under conservation tillage on well-drained soils. Hendrix et al. (1988), on the other hand, found no correlation between soil moisture and microbial respiration in Georgia. A water filled pore space of 60% is regarded as maximum for aerobic microbial activity (Linn and Doran, 1984b). Mielke and his colleagues (1986) compared four different soils from around the country and found that water filled pore space of no-till treatments was at or near 60% while most of the plowed soils were well below this level. On well-drained soils, this would be a major advantage of conservation tillage, but on poorly drained soils, this effect would tend to promote anaerobic conditions following rain events, creating the potential for denitrification (Smith and Rice, 1983).

Nitrogen cycling

Tillage practices influence not only crop residue decomposition but also nitrogen cycling pathways and use efficiency. Typically, nutrient transfer in any given ecosystem is accomplished through complex, biologically mediated processes. Conventional tillage essentially skips some of these steps, instead performing them in one energy-consuming, mechanically mediated event—plowing (House et al., 1984a and 1984b). Just as with organic residue decomposition, nitrogen is cycled more slowly under conservation tillage than when soils are plowed.

In the soil system there is fierce competition for nitrogen between plants and microbes, with the microbes generally being the stronger competitor. Plants depend on microbes to transform the nitrogen that is trapped in organic residues into a usable form. Whether nitrogen is immobilized by microbes or becomes available to plants depends on the same environmental factors that influence organic matter breakdown. Climate, season, and crop residue type, quality, and management practices influence the activities of microbes, which in turn affects the mineralization or immobilization properties of the soil. In examining potentially mineralizable nitrogen levels from various sites throughout the U.S., Doran (1987) found that levels of examining potentially mineralizable nitrogen were greatest in more humid climates and lowest in the driest climates, demonstrating the influence of climate in nitrogen cycling. Rice et al.

(1987) found that in well-drained soils net nitrogen mineralization was higher in plowed than in no-tilled soils. In poorly drained soils, however, differences in mineralization due to tillage became minimal or, in some cases, higher mineralization was found in no-till soils. The only explanation the authors offered was that continuous channels would have been disrupted in plowed soils, restricting aeration and reducing mineralization. What is clear from this study and the previous one is that the effect of tillage system will not always be the same, even on the same soil.

Unless crop residues consist of legume debris, the residue material that is concentrated at the surface of untilled soils generally has a high carbon: nitrogen ratio, which will favor immobilization (Fox and Bandel, 1986). Even when nitrogen fertilizer is added at low levels, it is added to the surface and is likely to become immobilized due to the accumulation of decomposable organic material (Kitur et al., 1984). At higher N fertilizer rates, there appears to be adequate nitrogen for microbes and plants and net mineralization occurs.

Crop residue management will have a major influence on the amount of nitrogen that is mineralized and the amount of nitrogen that is retained in the soil organic matter in a potentially mineralized state. Many authors have found that higher nitrate pools exist in plowed soils, while more nitrogen is retained in the organic phase in soils under conservation tillage (Blevins et al., 1983a; Carter and Rennie, 1987; Doran, 1980b; Dou et al., 1995; Franzluebbers et al., 1995; Hubbard and Jordan, 1996; House et al., 1984a; Rice and Smith, 1984; Smith and Blevins, 1987; Utomo et al., 1990). This suggests better nutrient storage capacity under conservation tillage and is apparently related to the higher microbial biomass and carbon substrate and the slower rate of mineralization when no tillage occurs. Rice and Smith (1984) found that twice as much nitrogen was immobilized in a conservation tilled soil when compared to a tilled soil in as little as 7 d after ^{15}N application. Carter and Rennie (1987) discovered that most of the immobilized nitrogen in no tillage was recovered in nonmicrobial biomass organic N, suggesting a relatively more stable source of nitrogen.

A few studies have also shown the opposite effect of tillage regime, finding

higher levels of inorganic N in the surfaces of conservation tilled soils (Follett and Schimel, 1989; Franzluebbers et al., 1995; Tracy et al., 1990). Some of the possible reasons for this outcome are ideal environmental conditions for mineralization, higher nutrient retention and cycling capacity and accumulation of recoverable organic matter at the surface of conservation tillage soils. In the study by Tracy et al. (1990), the higher inorganic nitrogen measurement for the no-till treatment did not occur until the last sampling date, 84 d after incubation was begun. This seems to make sense as higher amounts of slower-decomposing organic matter in the no-till treatment was better able to supply a continuous source of mineralizable nitrogen throughout the season. In fact, this seasonality effect is seen in other studies as well (Dou et al., 1995; Dowdell and Cannell, 1975; Groffman et al., 1987a; Smith and Blevins, 1987). These authors suggest that it is not the amounts of mineralization or immobilization that differ between tillage systems, rather it is the timing of organic residue turnover that is different. Dowdell and Cannell (1975) working in England, and Smith and Blevins (1987) working in Kentucky, found that early in the growing season nitrate was higher in tilled soils, reflecting the effects of plowing. This higher level of nitrate remained during the winter and spring in England but disappeared by summer. Depleted carbon levels lead to decreased mineralization in the tilled soils. In Kentucky, spring microbial respiration was similar among tillage systems but higher under no tillage later in the season. The authors suggest that this effect was caused by the interplay of beneficial and detrimental temperature and moisture levels. Early in the season, higher temperatures in plowed soils and higher moisture levels in untilled soils balanced each other. Toward the end of the season when temperatures were more balanced between tillage systems, a higher moisture content in the untilled soil enhanced microbial activity. Groffman et al. (1987a) examined soil organic matter mineralization in Georgia and found that immobilization reduced N availability during the summer in untilled soils but caused larger amounts of inorganic nitrogen to be released in the winter. This is most likely due to the residues under conservation tillage slowly releasing nitrogen throughout the season and could indicate a potential ni-

trate loss if no growing plants are present.

Under conservation tillage, a new steady state is eventually approached with regard to organic carbon and nitrogen, in which, mineralization continues to occur at a faster rate in tilled soils but is compensated for by a growing pool of total carbon and nitrogen in conservation tilled soils (Smith and Blevins, 1987). Inorganic nitrogen may be limiting during rapid plant uptake of nitrogen during the first years of implementing a conservation tilled system. In the long run, however, amounts of nitrogen that have been incorporated into relatively stable organic matter pools will provide a higher level of nitrogen fertility and cycling efficiency (Carter and Rennie, 1987; Gilliam and Hoyt, 1987; Peterson and Power, 1991). Smith and Blevins (1987) found that during the first 5 years of no tillage, plowed systems had more available nitrogen, but after 5 and 10 years net mineralization became similar among tillage regimes.

Aspects of cover crop usage

The planting of a winter cover crop is a practice commonly used in a conservation tillage system (Hoyt and Hargrove, 1986). The use of a nonleguminous cover crop can potentially increase the availability of nitrogen to the summer crop by capturing residual soil N that might otherwise be leached (Waggoner and Mengel, 1988). Rye for example, is capable of scavenging significantly large quantities of residual soil nitrogen (Ditsch et al., 1993; Ranells and Waggoner, 1997; Shipley et al., 1992). Ranells and Waggoner (1997), using labeled N^{15} , found that rye recovered 39% of N fertilizer while a legume cover only recovered 4%. Ditsch et al. (1993) found that little or no fertilizer-derived mineral N was measured to a depth of 35 inches (90 cm) following a rye cover crop. The rye cover was also well suited for use with no tillage, recovering the highest amount of nitrogen in this treatment. However, the cover crop also can act as a sink and compete for available nitrogen with the principle crop through immobilization. When the cover is incorporated into the soil, however, there tends to be less immobilization as compared to where the cover residue is left on the soil surface (Holland and Coleman, 1987).

Legume cover crops can supply supplemental nitrogen to the agricul-

tural system through biological fixation. Waggoner (1993) estimated that a well-established legume cover can supply 75 to 100 lb/acre nitrogen (84 to 112 kg-ha⁻¹) to the summer crop that follows. A hairy vetch (*Vicia villosa* L.) cover can accumulate nine times as much above ground nitrogen as a rye cover crop (Huntington et al., 1985). In studies comparing inorganic N fertilizer and legume N, early season mineral N concentrations in the soil were lower from legume materials (Dou et al., 1995; Groffman et al., 1987a; Varco et al., 1993). Later in the season, however, legume N became slowly available, exceeding levels of fertilizer N. The continued mineralization of the legume material past the period of plant uptake can leave accumulations of nitrate in the soil profile after crop harvest (Dou et al., 1995). In fact, with the use of a legume winter cover, approximately double the amount of legume N is retained as soil N compared to fertilizer N (Corak et al., 1992; Harris et al., 1994; Varco et al., 1987).

As with any organic source, incorporating legume residues causes faster decomposition and release of nitrogen (Dou et al., 1994; Hubbard and Jordan, 1996; Sarrantonio and Scott, 1988; Varco et al., 1987; Varco et al., 1993). Varco and his colleagues (1987) found that 15 d after vetch residues were applied, 47% of the incorporated vetch was mineralized while less than 10% of vetch N was made available from surface-applied residues. In a study from Dou et al. (1994) legume N mineralization reached 80% of its maximum within 4 weeks when residues were plowed under, but where legumes were herbicide killed it took twice as long for maximum N mineralization to be reached.

Different types of organic substrate will affect the behavior of the system. Utomo et al. (1990) showed that mineralization was greater for a vetch residue than rye or corn stover residue. Wander et al. (1994) compared two organic nitrogen sources, animal manure and a legume cover crop, with conventional inorganic N fertilizer. The animal manure treatment mineralized the most nitrogen, but the cover cropped treatment accumulated more stable soil organic matter. This would suggest a long-term sustainable source of nitrogen with the use of legume cover crops than with animal manure. It is clear that winter cover crops have the potential to

provide many benefits to a soil system, including nitrogen accrualment, decreased leaching and maintaining a more sustainable source of nitrogen. Which type of cover crop will provide the most benefits for a particular system and which benefits will be most important, is once again contingent on site specific and management factors.

Mineral nitrogen

If ammonium is not limiting, nitrification tends to be higher in conservation tilled soils due to more favorable moisture conditions (Rice and Smith, 1983). However, mineralization is usually limited in no-tilled soils, causing less nitrification to take place. If environmental conditions such as pH and moisture are controlled, no tillage and conventional tillage have the potential for similar amounts of nitrification activity (Rice and Smith, 1983). Soils under conservation tillage tend to be less oxidative, and this would create less mineralization than under tilled soils. Higher nitrification in conservation tillage represents a greater potential for leaching or denitrification losses than in tilled soils because the environment under no-tilled soils is more conducive to these losses. Nitrification is also influenced by nitrogen source, with higher activity found early in the growing season when fertilizer N was used as opposed to legume N. In August, this pattern was reversed, showing the manner in which legume N becomes more slowly available.

Nitrogen uptake by plants in different tillage systems should be influenced by amounts of available soil nitrogen, and, for the most part, would be expected to follow mineralization trends. The observation that more nitrogen was accumulated in growing crops when organic residues are tilled under as compared to surface residues seems to be easily explained by greater decomposition and faster mineralization under plowed soils (House et al., 1984a; House et al., 1984b; Hubbard and Jordan, 1996; Meisinger et al., 1985; McCracken et al., 1989; Varco et al., 1989). Studies where greater N uptake was found under conservation-tilled soils than under tilled soils, it was generally because of the greater water content of conservation-tilled soils (Ekeberg and Riley, 1996; Hargrove, 1985). Legg et al. (1979) found that plants grown under no tillage took up more nitrogen when precipitation was low. However, in years receiving ample precipitation, there was

no difference in uptake between tillage systems provided that adequate levels of nitrogen fertilizer were added. Early in the season, plant uptake has been shown to be greater from tilled soils, but the final total nitrogen accumulated by corn was not different between tillage systems (Carter and Rennie, 1987; Meisinger et al., 1985; Sullivan et al., 1991; Varco et al., 1989). Short-term tillage induced differences that occur early in the season are later compensated for by soil conditions becoming more favorable under conservation tillage. Carter and Rennie (1987) suggest that the long-term differences between tillage systems will be small or negligible. However, if soil conditions under conservation tillage favor greater nitrogen losses, then nitrogen uptake will most likely be less.

Lower plant nitrogen uptake for conservation tillage has been demonstrated by numerous studies (Fox and Bandel, 1986; Fox and Piekielek, 1987; Kitur et al., 1984; Meisinger et al., 1985; Moschler and Martens, 1975; Smith and Rice, 1983). Fertilizer uptake efficiencies tend to be higher in conventional tillage at low N fertilizer rates, but this trend is reversed and conservation tillage maintains a higher fertilizer use efficiency at higher nitrogen rates. Gilliam and Hoyt (1987) suggested that the lower efficiency of fertilizer N of no-tilled soils at low rates is most likely caused by increased immobilization occurring in conservation tillage. The higher efficiencies found for some conservation tilled soils are probably related to improved moisture conditions in these soils. Fox and Bandel (1986) proposed that greater nitrogen efficiencies under tilled soils occur mainly in poorly drained soils and in humid environments where soil water levels are not low enough to limit yield. Under these conditions, greater soil moisture in conservation tilled soils will likely lead to more denitrification, leaching and less mineralization. In drier climates where lack of soil moisture can limit yield, greater water availability under conservation tillage will increase nitrogen-use efficiency. In geographic areas where climate and soil are intermediate, nitrogen efficiency may be lower during the first few years after converting to conservation tillage, but will eventually equal or surpass that in conventional tillage (Fox and Bandel, 1986).

Greater nitrogen uptake by crops is associated with higher quantities of de-

composable residue, probably because of greater native soil nitrogen and soil moisture (Power et al., 1986). Residue type also has an effect on plant uptake of nitrogen. Abdul-Baki et al. (1996) demonstrated that tomatoes (*Lycopersicon esculentum* Mill.) growing in legume-mulched plots contained more leaf nitrogen than bare soil, black plastic mulch or Horto paper mulch. Other studies have shown that plants growing under a hairy vetch mulch accumulated more nitrogen than those growing under a rye mulch (Ebelhar et al., 1984; Huntington et al., 1985; Sullivan et al., 1991). This effect was due to a higher plant nitrogen pool in hairy vetch cover and a more rapid decomposition of vetch residue (Huntington et al., 1985).

When comparing nitrogen sources, it seems that inorganic nitrogen fertilizer is more available for uptake by plants than legume N (Corak et al., 1992; Harris et al., 1994). In an ^{15}N study, Harris et al. (1994) found that although plants initially accumulated more nitrogen from an inorganic nitrogen source, the second year crop recovered about twice as much legume N than fertilizer N. This was due to more legume residue N being left in the soil from the year before.

One way to improve the uptake of applied nitrogen sources under surface residues is by subsurface placement of N fertilizer (Blevins et al., 1983b). This will reduce immobilization as the nitrogen source is isolated from the surface concentration of organic substrates and microbial activity. This allows plants to out compete soil microbes for available nitrogen. Another solution is to delay nitrogen fertilization until a few weeks after planting (Thomas and Frye, 1984). This prevents potential early season losses of nitrogen from leaching and denitrification with conservation tillage and provides a nitrogen source nearer to the time the plant needs it most.

Nitrogen losses

Nitrogen losses in the soil system through leaching and denitrification are highly dependent on the state of the soil environment. In order for leaching to occur, there must be sufficient nitrate in the soil, and water movement through the soil must exist (Legg and Meisinger, 1982). Plowing the soil would seem to create an ideal situation for leaching to occur. Tillage creates a flush of decomposition followed by mineralization, resulting in a supply of nitrate in the soil

(Blevins et al., 1984). If the soil is left bare in the winter, as is often done in conventional tillage, leaching of residual nitrate from the previous season can occur. In early spring when temperatures rise, a significant amount of nitrate can build up via nitrification and fertilizer application. Heavy rains that occur before summer crops accumulate large amounts of biomass can cause significant amounts of nitrate to be leached (Legg and Meisinger, 1982). However, soils under conservation tillage generally have higher moisture contents than tilled soils and rainwater can move deeper into the soil profile than under conventional tillage (Phillips, 1984). Conservation tilled soils also tend to have more continuous pores, large cracks, and earthworm and root channels throughout the soil profile because they are not destroyed during tillage but rather are left to develop year after year (Douglas et al., 1980). The flow of water and potentially soluble salts through these macropores can be an important mechanism for leaching of nitrate into subsurface soil (Smith and Cassel, 1991). Also, the surface residue that is present in conservation-tilled soils reduces evaporation of water from the soil, thereby reducing the upward movement of nitrate, which creates conditions for substantial leaching from conservation tilled soils. Phillips (1984) observed greater drainage of soil water below the rooting zone under no tillage. In their work, Tyler and Thomas (1977) collected significantly greater levels of nitrate in June of two consecutive years from lysimeters in no tillage than conventional tillage soils. In August and September of the second year, more nitrate was lost from the conventionally tilled system, suggesting a residual pool of soil nitrogen which was not present under no tillage. This indicates that the timing and rate of nitrogen mineralization will play a role in the amount of nitrate lost through leaching. Although greater accumulations of soil nitrate are often found in the rooting zone of plowed soils, deeper accumulation of soil nitrate below the root zone has been found in no-till soils (Dalal, 1989; Eck and Jones, 1992). McMahon and Thomas (1976) found that leaching losses of nitrate in a silt loam soil took place throughout the summer and fall months resulting in only 57% of the applied chloride tracer being present in December, while 120% was recovered under conventional tillage. In April, 50% remained in conven-

tionally tilled soil while only 3% remained in killed sod.

House et al. (1984a, 1984b) found higher nitrate concentrations at lower soil depths 16 to 20 inch (40 to 50 cm) in conventionally tilled soils. Kanwar et al. (1985) found that significantly greater amounts of nitrate remained in the rooting zone [0 to 60 inch (0 to 150 cm)] after a heavy rain under no tillage than under conventional tillage. This presumably results from the increased occurrence of continuous macropores under conservation tillage combined with a mechanism known as bypass flow, where water percolates through the profile without displacing the initial soil water (Quisenberry and Phillips, 1976). Thus, added water will have limited exposure to ions in small pores within the structural units of the soil (Elrick and French, 1966; Kissel et al., 1973; Shuford et al., 1977; Thomas and Phillips, 1979). Because soil aggregates are broken up during tillage, water in the conventional tillage soil is exposed to more surface area of soil and solutes (Booltnik, 1995; Kanwar et al., 1985). Power and Doran (1988) also suggested that the rapid water flow with no tillage through these macropores comes into little contact with microbial microsites predominantly found in smaller diameter pores, resulting in less nutrient leaching. Thomas et al. (1973) indicated that when rainfall occurs on wet surface aggregates of no-till soils, no water or nitrate is absorbed by the aggregates as they move through the large pores. In the drier soil of conventional tillage, rain water and soluble nitrate would move into the soil aggregates instead of moving downward (Thomas et al., 1973; Tyler and Thomas, 1977). Angle et al. (1989) compared the percolate and groundwater of two separate watersheds with different tillage management. During most of the three year study, there were little or no differences in soil water nitrate between conventional tillage and no tillage. However, in one year, the conventionally tilled treatment had significantly more nitrate in both percolate and groundwater samples, perhaps due to the less than normal rainfall that occurred during that year. These conditions would create a more efficient use of nitrogen under no tillage due to the greater soil moisture. Stinner et al. (1983a) found consistently higher levels of nitrate in lysimeters throughout the fall, spring, and summer from no tillage than from

conventional tilled soils. It is clear that the amount of nitrate leached is often different for the same tillage system because many factors, including different pore size and pore continuity through which water and nitrate move are involved (Smith and Cassel, 1991).

The effect of winter cover crops on nitrate leaching has been well demonstrated (Bertilsson, 1988; Booltnik, 1995; Groffman et al., 1987a; McCracken et al., 1994; McCracken et al., 1995). A cover crop has the potential to significantly reduce the amount of nitrate that is leached through a soil profile. Bertilsson (1988) concluded that leaching losses were more dependent on conditions after harvest than on nitrogen level. The growing of a cover crop, straw incorporation and late growing crops all reduced the amount of leaching, but the presence of a cover crop was superior to all treatments.

The type of cover crop can also cause a major difference. Rye planted as a winter cover crop reduced leaching losses when compared to a legume cover such as hairy vetch or crimson clover (Groffman et al., 1987a, 1987b; McCracken et al., 1994). Groffman suggested that this was due to greater availability of nitrate in the root zone of the legume cover cropped soil than in the rye cropped soil.

Differences in denitrification due to tillage regime are usually less variable than leaching differences, with most studies finding higher levels of gaseous nitrogen losses from conservation-tilled soils than from plowed soils (Aulakh et al., 1984; Linn and Doran, 1984a; Linn and Doran, 1984b; Rice and Smith, 1982; Smith and Rice, 1983). Denitrification is favored in conservation tillage because of the greater soil water content, increased bulk density, greater water-filled pore space and more active denitrifying population that typically exist under conservation tillage (Fox and Bandel, 1986). Higher bulk densities and water contents both can cause lower rates of oxygen diffusion by acting as a barrier to oxygen movement through soil pores (Linn and Doran, 1984a). Douglas et al. (1980) suggested that the presence of more continuous channels under conservation tillage might improve aeration in lower soil depths, but this does not seem to be a strong enough influence to overcome the increased aeration of plowing. Denitrification is also greater in humid climates, and in clayey or poorly drained soils because of the wetter and less permeable environ-

ments (Power and Doran, 1988).

Studies also have shown that untilled soils produce more gaseous nitrogen losses and began evolving N_2O gas sooner than did plowed soils (Rice and Smith, 1982; Smith and Rice, 1983). This may be explained by greater numbers of denitrifiers, both obligate and facultative, that are normally found under conservation tillage management systems (Aulakh et al., 1984; Linn and Doran, 1984a). Rice and Smith (1982) found that soil nitrate content influenced the rate of denitrification very little, with higher moisture contents in no-till soils being the primary cause of greater denitrification. Conversely, Groffman et al. (1987) found that denitrification activity was tied to carbon and nitrogen availability. They showed greater N_2O evolution occurring from a fertilizer N system in the late spring, early summer period as compared to a legume N treated soil. This presumably resulted from greater soil nitrogen availability after plowing.

Increased losses from denitrification could potentially decrease the amount of nitrate available for loss by leaching. However, most authors suggest that losses of denitrification are appreciably smaller than losses due to leaching. Small microsites of denitrification can often occur but result in negligible losses of nitrogen. However, on poorly drained soils or during above normal precipitation, potential denitrification losses can be substantial.

It is clear from the foregoing discussion that nitrogen is cycled more slowly under no tillage cropping practices and is used less efficiently than for conventional tillage (House et al., 1984b). Every reaction that can cause lower N availability is favored by no tillage (Thomas and Frye, 1984). However, there is a reorganization of N storage and movement in conservation tillage, as more nitrogen is conserved and a higher nitrogen retention and recycling capacity is maintained. Conversely, continuous plowing eventually depletes organic matter and acts as a stress rather than an energy subsidy. In conservation tillage ecosystems, crop and weed residue are decomposed exclusively through the activity of soil flora and fauna, and this critical role between soil biota and organic matter maintains efficient nutrient cycling and retention in conservation tillage systems (House et al., 1984a, 1984b).

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