NITROGEN CYCLING UNDER DIFFERENT SOIL MANAGEMENT SYSTEMS

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I. INTRODUCTION

Soil tillage is one of the oldest known management techniques to mine organic nutrient reserves for enhancing crop production. The side-effects of initiating tillage are a rapid reduction of soil organic matter and soil structure resulting in increased erosion and a loss of soil nutrients, especially nitrogen (N), phosphorus (P), and potassium (K). Conservation tillage, especially no-tillage, limits loss to our soil resource base and is one of our most important options for sustaining economic food production. Yet adoption of no-tillage in the major U.S. agricultural areas, which rapidly increased in the early 1990s, has leveled for soybean and has

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decreased for corn production. My focus is to review the limitations of N cycling in conservation tillage, especially no-tillage, that has been discovered in the last 30 years of research and to evaluate scientific studies as a means to understand how residue and nutrient stratification in no-tillage impacts the N cycle.

II. MANAGEMENT SYSTEMS

The Conservation Technology Information Center (CTIC, 1998) defines tillage systems based on the amount of residue remaining on the soil surface. Conservation tillage results in >30% of the residues remaining on the surface and includes the practices of no-till, ridge-till or mulch-till. Reduced tillage results in 15–30% of the residues remaining on the surface and intensive tillage with <15% surface residue remaining. The following are commonly accepted definitions for the tillage systems discussed in this review (CTIC, 1998).

> *No-tillage* (NT). A narrow seed band is prepared during planting with the rest of the soil undisturbed from harvest to planting unless nutrients are injected. Weed control is by herbicide and/or cover crop.
>
> *Strip tillage* (ST). A form of NT management when a strip of soil is prepared generally in the fall where nutrients are knifed and then in the spring, the seed is planted in this strip.
>
> *Ridge-tillage* (RT). Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. The residue left on the surface between ridges and weed control is accomplished with herbicide and/or cultivation.
>
> *Mulch-tillage* (MT). The soil is disturbed prior to planting by tillage implement such as chisels, field cultivators, disks, sweeps, or blades with weed control by herbicide and/or cultivation.
>
> *Conventional-tillage* (CT). Generally refers to soil inversion by moldboard plowing followed by a secondary tillage operation such as discing and/or harrowing. Weed control may be accomplished by cultivation or through use of herbicides.

An additional tillage system that can be used is called *stubble-mulch* (SM) farming. This involves the mixing of the soil by undercutting the residue with stirring and mixing machine and not inverting the residue (Mannering and Fenster, 1983). Terminology such as "reduced tillage" or "minimum tillage" as used in the past may or may not qualify as conservation tillage depending on the level of residue remaining at the surface after planting.

No single tillage system, including CT, is suitable for all soils or climatic conditions due to the unique properties of individual soils that determine their limitations and suitability for utilizing conservation tillage methods. There are many advantages of conservation tillage over CT. The reduction in size and cost of machinery, fossil fuel usage, and total labor costs makes conservation tillage attractive to many producers.

Management-related distribution of crop residues across the soil surface can affect soil biological properties and may result in economic differences for tillage systems. The biological implications of residue-related changes in soil water and temperature on plant development, nutrient uptake, and microbial activity are climate and soil specific. Even though the advantages of conservation tillage are many, a perceived reduction in total yields or a need for additional N fertilizers resulting from the change in soil biological activities has resulted in farmers abandoning NT practices in recent years.

A. SOIL PROPERTIES WITH MANAGEMENT

Tillage systems affect soil productivity through influences on soil properties. Long-term NT results in physical soil properties that may or may not be different from CT, but NT typically has a large impact on the biological properties influencing the timing and amount of nutrient cycling. The lack of soil disturbance with the presence of plant residue cover are primarily responsible for the environmental benefits noted for conservation tillage. Yet, the lack of soil tillage has been responsible for most of the perceived management problems associated with reduced or NT systems. Notable improvements that occur with conservation tillage include decreased erosion, improved water quality and crop-available water, and enhanced soil quality. Soil quality has been suggested as a tool for assessing long-term sustainability of agricultural practices (Lal, 1991; Papendick and Parr, 1992). Soil properties that have been suggested to affect soil quality include aggregate stability (Arshad and Coen, 1992), bulk density (Linn and Doran, 1984), organic matter (Pajasok and Kay, 1990; Arshad and Coen, 1992), and soil water infiltration and availability. A summary of the modification of soil properties with different tillage practices is shown in Table I.

1. Erosion

Conservation tillage decreases soil erosion almost in direct proportion to the amount of soil cover left following the tillage practice (Mannering and Fenster, 1977) and other researchers have reported that NT reduces erosion compared to CT (Mueller *et al.,* 1984; Wendt and Burwell, 1985; West *et al.,* 1992; Dabney *et al.,* 1993). There also appears to be erosion benefits from the lack of disturbance aside from the strong soil cover and soil-loss relationship. Blevins and Frye (1993) reported soil losses of 426 kg ha^{-1} with NT soybeans [*Glycine max* (L.) Merr.]

Table I

Conservation and Conventional Tillage Affects on Soil Properties

Author[a]	Duration[b]	Soil type	Previous management	Results
South				
Blevins *et al.* (1977); KY, corn	5 years NT, CT	Maury silt loam	Bluegrass sod for 50 years	Organic C was decreased with NT and CT from native sod levels, but OC under NT was increased as N application rate increased. Bulk density was not different between NT or CT.
Tollner *et al.* (1984); GA, soybean	1 year NT, CT	Piedmont soil	NT 6 years after CT soybean	No difference in BD as compared with CT, organic C with soybean did not accumulate and residue resulted in cooler soil temperatures.
Bruce *et al.* (1990); GA, soybean, sorghum, wheat	8 years NT, MT, CT	Cecil sandy loam	MT, wheat, sorghum	Tillage decreased BD and increased percentage pore space. Sorghum had increased aggregate stability, air-filled pore space and lower BD than soybean with same tillage.
West *et al.* (1992); GA, soybean, sorghum	1 year NT, CT	Cecil clay loam; Pacolet sandy clay loam	5 years CT and NT	NT increased OC and aggregate stability with a 60–70% reduction in erodibility. Surface consolidation reduced rill erosion.
Edwards *et al.* (1992); AL, corn, soybean, wheat	10 years NT, CT	Hartsells fine sandy loam	CT for previous 50 years	NT increased organic C by 56% with no increase in CT and NT decreased BD as compared with CT.
Dabney *et al.* (1993); MS, soybean	2 years NT, CT	Grenada silt loam	Grass sod	Erosion rates were several fold higher with CT compared to NT. Row cultivation substantially increased sand size aggregreate erosion.
Drees *et al.* (1994); KY, corn	1 year NT, CT	Maury silt loam	CT and NT for continuous corn production established in 1970	Earthworm channels were abundant in NT, but not in present in CT. CT had smaller aggregates with more pore area and granular strucutre. NT had bigger pores and platy structure.
Ismail *et al.* (1994); KY, corn	1 year NT, CT, sod	Maury silt loam	20 years NT, CT after bluegrass sod for 50 years	Surface BD differed little between NT, CT, and bluegrass sod. Organic C increased proportionally in NT with increasing N additions, but not under CT.
Bruce *et al.* (1995); GA, sorghum, soybean	4 years CT, NT	Cecil and Pacolet clay loam	CT, NT established for 20 years with sod the previous 50 years	Erodibility decreased with NT sorghum planted into crimson clover due to threefold increase in OC compared with sorghum under CT.

Hunt *et al.* (1996); SC, corn, wheat, soybean, cotton	14 years CT and NT	Norfolk loamy sand	MT corn and soybean previous 5 years	During first 3 years, no organic C accumulated, but nearly doubled in year 9 to 14 under NT as compare with CT.
Midwest				
Gantzer and Blake (1978); MN, corn	1 year NT, CT	Minnesota clay loam	6 years NT and CT corn	NT had increased bulk density, worm burrows; and water content and decreased saturated hydraulic conductivity and air-filled porosity in surface 30 cm compared with CT with no differences below 30 cm
Dick *et al.* (1991); OH, corn, soybean	1 year NT, CT	Hoytville silty clay loam, Wooster silt loam;	25 years NT, CT	Initiation of NT caused a redistribution and increase of organic C in the soil surface and decreased soil erosion and water runoff from 12 mm water in NT as compared to > 700 mm from CT.
Mueller *et al.* (1984); WI, corn	2 years NT, MT, CT	Dresden silt loam	CT corn, NT initiated with experiment	Erosivity and erosion rates were decreased with NT compared with CT and MT with significantly reduce erosion rates for the second year of study.
Wendt and Burwell (1985); MO, corn	6 years NT, MT, CT	Mexico silt loam	CT corn, NT initiated with experiment	Average annual run off was the same for CT and NT, but annual soil loss decreased by 6.5-fold with NT.
Larney and Kladivko (1989); IN, corn	13, 8, 4 years NT, MT, RT, CT	Chalmers silty clay loam Blount silt loam; Clermont silt loam	CT corn, NT initiated with experiment	Maximum soil strength moves closer to the soil surface with less tillage and NT had decreased BD in ontraffic positions as compared with NT.
Staricka *et al.* (1991); MN, oat	2 years MT, CT	Ves loam	7 years MT	Moldboard plowing incorporated residues down to 28 cm (mostly in 10 cm). MT went down to 10 c Primary tillage buries residues without effectively dispersing in a microscopic scale.
Staricka *et al.* (1992); MN, oat	3 years MT, CT	Ves loam	7 years MT	CT incorporated tracers into aggregates slower than MT. First till incorporated <5%. Each year tillage incorporated more tracers into aggregates.
Pierce *et al.* (1994); MI, corn	6 years NT, CT	Capac loam	CT corn, NT inititated with experiment	CT decreased BD, organic C and microporosity and increased total and macroporosity as compared with NT.

(*continu*

Table I—*continued*

Author[a]	Duration[b]	Soil type	Previous management	Results
Lal *et al.* (1994); OH, corn	1 year CT, MT, NT	Wooster silt loam	28 years NT and CT corn	NT decreased BD, increased aggregate stability and organic C content compared with MT and CT plots.
Allmaras *et al.* (1996); MN, oat	1 year MT, CT	Waukegan silt loam	Oat previous crop	CT incorporated 67% of tracers in 10–20 cm. MT 90% in 1–11 cm. Secondary tillage didn't influence depth distribution.
Logsdon *et al.* (1999); IA, corn, soybean	4 years NT, MT	Muscatine soil; Tama soil; Downs soil	NT 3 and 8 years after MT corn and soybean	MT did not decrease BD compared with NT unless traffic was controlled. No significant BD differences in NT and MT in nontraffic areas.
West				
Rasmussen and Douglas (1991); OR, wheat	4 years CT	Walla Walla or Athena silt loam	CT wheat	Erosion reduced yields. Yield reduction from rill erosion in field yielding 5.2 Mg ha^{-1} is 88 kg ha^{-1} or \$13 ha^{-1} for wheat valued at \$0.147 kg^{-1} compounded each year.
East				
Angle *et al.* (1984); ML, corn	3 years CT and NT	Manor loam	MT corn	CT watershed had a 9-fold increase in runoff and a 29-fold increase in soluble solids when compared to a NT watershed.
Angers *et al.* (1993); Quebec Canada, corn	1 year MT, RT, CT	Neubois silt loam	Continuous corn silage 11 years after 20 year meadow	Corn silage removal resulted in no organic C or BD differences between tillage systems.
Vyn and Raimbault (1993); Ontario Canada, corn	15 years NT, MT, CT	Maryhill silt loam	NT, MT, CT initiated 1976 for continuous corn	NT increased aggregate size, BD and penetrometer resistance measured shortly after secondary tillage and planting compared with MT and CT.

[a] Citation, study location, and crops.

[b] NT = no-tillage, MT = minimum tillage, RT = ridge tillage, CT = conventional tillage.

without cover crop and 269 kg ha^{-1} with a winter wheat (*Triticum aestivum* L.) cover crop. A CT soybean management system had soil erosion of 9050 kg ha^{-1} without a cover crop, and 1142 kg ha^{-1} with a wheat cover crop. The decrease in soil erodibility with NT was attributed to the lack of soil disturbance (Blevins *et al.,* 1990) due to an increase in soil consolidation. The consolidation effect depends on the length of time elapsed since the tillage operation (Mutchler and Carter, 1983; Van Doren *et al.,* 1984) and results from the combined effects of raindrop impact and drying rates (Gerard, 1987). Larney and Kladivko (1989) found soil consolidation effects move closer to the surface with decrease in tillage intensity.

Soil erosion is determined largely by the erosivity of the rainfall events (runoff) and erodibility (sediment load) of the soil. Conventional and MT disrupt surface crusts and increases surface roughness and potential detention volume especially immediately after tillage, resulting in less surface runoff with the first major storm event compared to NT (Mueller *et al.,* 1984). However, surface roughness is rapidly decreased with CT and subsequent rainfall events that exceed the surface storage and infiltration capacities will result in large soil losses. Mueller *et al.* (1984) reported that first-year NT reduced erosion 18 and 4% compared to CT and MT, respectively, and the second year, NT decreased erosion 83 and 46% compared to CT and MT, respectively, even though NT had larger runoff volumes than CT or MT. Their study also found that erosion during the second year of the study from the different tillage systems was reduced 70 and 47% for NT and MT, respectively, but increased 48% for CT. No-tillage decreases the erodibility of the soil due to an increase in the surface residue, consolidation and stability of the surface soil aggregates.

The top layer of soil is the primary source of fertility for the majority of our productive soils and uncontrolled erosion can significantly reduce production capacity. Burwell *et al.* (1975) reported that sediment transport accounted for more than 95% of the N and P lost from fallow, continuous corn and rotational corn systems under CT. The economic significance of erosion was measured by Rasmussen and Douglas (1991) who found wheat yield reductions from erosion on a soil with a slope of 1–15% was due to reduced head density, dry matter yield, and N uptake, at six study sites. The yield reductions ranged from 0.84–0.94 of yield with no erosion for a single year with yield reductions continuing for each cropping year. Bauer and Black (1992) suggested that the loss of productivity from erosion was due to loss of nutrients and biological activity rather than a loss in available water capacity.

2. Aggregate Stability

Conservation tillage increases the structure of the soil surface. Drees *et al.* (1994) reported that long-term NT changed the granular, fragmented structure of CT to a platy structure with a concomitant two- to three-fold increase in soil aggregates. Vyn and Rainbault (1993) also reported that after 15 years, NT resulted in larger soil aggregates in a silt loam soil when compared to CT. Mahboubi *et al.* (1993) found after 28 years, aggregate stability at two different Ohio sites was increased 114% with NT compared to CT in the traffic zone and increased 138% in the nontraffic row zone. West *et al.* (1992) determined that aggregate stability after 5 years of NT, increased 50–76% on three soils that were converted from CT.

Staricka *et al.* (1992) found that with the first tillage pass, CT incorporated <5% of introduced tracers into soil aggregates and after 3 years, subsequent CT incorporated 33% of the tracers into soil aggregates and MT incorporated 38% suggesting that tillage-incorporated materials such as residue, fertilizers, pesticides, etc., remain in interaggregate spaces during the first year of application where they are more susceptible to decomposition and plant uptake. Crop residues decompose faster as soil to residue contact increases (Brown and Dickey, 1970), and the effect of incorporated crop residue on soil stabilization may be greatly limited by deep incorporation or enhanced by limited or no incorporation (Staricka *et al.*, 1991).

Bruce *et al.* (1990,1992,1995) reported that soil aggregate stability was increased with MT and NT compared to CT, and concluded that different crop residues have different effects on aggregate stability. In their study, NT grain sorghum (*Sorghum bicolor* L.) planted into a crimson clover winter cover crop (total stover 14.3 Mg ha^{-1} year^{-1}) was far more effective than planting soybean (total stover 11.6 Mg ha^{-1} year^{-1}) for increasing aggregate stability (Bruce *et al.*, 1992, 1995) even though approximately 12 Mg sorghum residue ha^{-1} year^{-1} was adequate for increasing aggregate stability, suggesting that quantity of the residue is not the only factor to be considered. They also found that any surface tillage could rapidly destroy the aggregate differences between the crop residues.

3. Bulk Density

No-tillage generally results in a more consolidated soil surface with greater residue cover than does CT. Often, it is the appearance of this increased consolidation that suggests that NT increased soil bulk density, because time since tillage greatly affects the apparent consolidation of soil (Mutchler and Carter, 1983; Van Doren *et al.*, 1984). Consolidation occurs from the combined effects of raindrop impact and drying rate that helps increase cohesion (Gerard, 1987) and is influenced by soil type, drainage, and climate.

The increase in consolidation is generally perceived to be an increase in bulk density. Tillage has a pronounced effect on distribution of crop residues and increases in soil organic matter with NT can offset the consolidation process. Tillage can reduce soil bulk density by movement and rearrangement of soil aggregates and the incorporated residue that may or may not be homogeneously mixed in the soil pore space. Conventional tillage incorporates at least 67% of the crop residue in the 10–20 cm depth while MT incorporates crop residue in the 1–10 cm depth (Allmaras *et al.,* 1996). Studies have found that NT results in an increase in bulk density (Miekle *et al.,* 1986; Bruce *et al.,* 1990; Vyn and Rainbault, 1993; Pierce *et al.,* 1994) or that NT does not increase bulk density (Blevins *et al.,* 1977; Tollner *et al.,* 1984; Hill and Cruse, 1985; Bauer and Black, 1992; Mahboubi *et al.,* 1993; Ismail *et al.,* 1994; Lal *et al.,* 1994; Logsdon *et al.,* 1999). The differences in findings may be explained by location and timing of the sampling. Gantzer and Blake (1978) found after CT for 6 years, bulk density was significantly lower than NT when measured shortly after spring tillage. Little differences were noted between the two systems when the bulk densities were measured in the fall after crop harvest. Blevins *et al.* (1983) reported after 10 years of management, no differences in CT and NT bulk densities were determined when measured 1 year after plowing. Mahboubi *et al.* (1993) found no significant change in bulk density in two Ohio soils under continuous corn NT and CT after 28 years. Although, it was noted that bulk density measurements taken several weeks after tillage were lower for CT compared to NT. Logsdon *et al.* (1999) found that after 3 years, uncontrolled wheel traffic slowly increased bulk density in both NT and MT, but NT was less dense than MT in the nontraffic row in a field with controlled wheel traffic.

4. Organic Matter

Soil organic matter contains plant nutrients that are mineralized as organic matter decomposes reducing the need for inorganic inputs. Intensive and often excessive tillage practices result in a decreased amount of residue remaining due to an accelerated rate of organic matter decomposition by increased microbial oxidation in the tillage zone.

No-tillage generally results in an increase in soil organic matter in the residue layer and the change in organic matter content is dependent on previous soil management, cropping sequence, and fertility levels. Studies have reported that NT increased soil organic C (OC) (Dick, 1983; Miekle *et al.,* 1986; Dick *et al.,* 1991; Wood *et al.,* 1991a; West *et al.,* 1992; Edwards *et al.,* 1992; Mahboubi *et al.,* 1993; Ismail *et al.,* 1994; Pierce *et al.,* 1994; Lal *et al.,* 1994; Franzluebbers *et al.,* 1994; Christensen *et al.,* 1994; Hunt *et al.,* 1996). Introducing agricultural practices into permanent pasture or prairies has resulted in less OC remaining with NT or CT practices. Blevins *et al.* (1977) found that continuous corn decreased OC compared to the native pasture from 19 g kg^{-1} to 15.9 g kg^{-1} with NT and to 9.8 g kg^{-1} with CT. Suboptimum N rates resulted in a further decrease in OM levels. Ismail *et al.* (1994) reported that at the same site of Blevins *et al.* (1977) after introduction of a winter rye cover crop, the OC level increased in both the CT and NT treatments with the NT returning to the level of the original sod under optimum N fertilization. Dabney *et al.* (1993) reported an OC loss in a permanent pasture converted to soybean of 22.4 and 13.3% for CT and NT, respectively, during a 2-

year study. If the surface residue is removed as in silage production systems, then OC has been reported to not increase with NT or MT compared to CT (Angers *et al.*, 1993; Hunt *et al.*, 1996).

The type of crop residue remaining may also influence soil organic matter sequestration. Bruce *et al.* (1990) found a sorghum-soybean rotation following winter wheat did not increase OC after 8 years of NT compared to CT, but Bruce *et al.* (1995) found a NT sorghum with a crimson clover winter cover crop rotation resulted in a 3.5-fold increase in OC within 4 years. Edwards *et al.* (1992) reported that after NT for 10 years, a continuous corn-wheat cover rotation increased OM faster than corn-wheat cover-soybean-wheat cover or a continuous soybean cropping system and suggested that addition of soybean to the rotation had a negative affect on OM sequestration.

The mechanism(s) by which conservation tillage, especially NT, reduce C loss or initiate C sequestration may be due to several factors. First, the reduction of C losses from the soil due to decreased erosion rates under NT limits C losses from the system as compared with C loss from CT. Second, an equal amount of rain will cause a field under NT to reach a more anaerobic state (reduced O_2 availability) faster than a field under CT (Doran, 1980a). The reduction in oxygen concentration can cause changes in the decomposition rate of the plant residues (Wershaw, 1993). Degradation of organic polymers released from decaying vegetation involves depolymerization and oxidation reactions that are catalyzed by soil enzymes. Polysaccharide (cellulose and hemicellulose) and protein polymers undergo depolymerization reactions and structural components such as polyphenols are degraded mainly by oxidation reactions (Wershaw, 1993) resulting in the carbohydrates and amino acids from fresh liter decomposed equally fast under aerobic and anaerobic conditions, while structural component mineralization under reduced O_2 tensions was hampered by inefficient and slow bacterial hydrolysis (Kristensen *et al.*, 1995). The CT decomposition rates results in buried residue decomposing 3.4-fold faster than if left as surface mulch (Beare *et al.*, 1993), which may be due to spatial separation of the residue C and the soil N (Holland and Coleman, 1987). Third, with microbial biomass increases up to sixfold by NT management, a greater amount of the residue C is cycled in biomass rather than released as CO_2 (Lynch and Panting, 1980), and maximum biomass C with conversion of CT to NT can be obtained in time as short as 1 year (Staley *et al.*, 1988). Fourth, NT results in an increase in the fungal to bacterial activity ratio, resulting in an accumulation of C in less decomposable fungal biomass and less CO_2 released as compared with low fungal to bacterial activity ratios (Holland and Coleman, 1987).

5. Soil Water

Water is the driving variable in agriculture and especially in Great Plains agriculture where sustainability depends on efficient use of incident precipitation. A summary of the effects of different tillage practices on modification of soil water availability is shown in Table II. In dryland agriculture, a fallow period has been traditionally used to conserve moisture for the next years crop, but research has found that only 16–25% of the water during the fallow period is stored by the soil (Deibert *et al.,* 1986; Peterson *et al.,* 1996). The practice of NT can increase this to 40% due to the reduction in evaporation early in the fallow when the residues still cover the surface (Peterson *et al.,* 1996). The reduction of surface water evaporation and greater infiltration with conservation tillage helps to conserve moisture (Blevins *et al.,* 1984) and allows for double cropping in areas with longer growing seasons or a reduction in the fallow time in areas with dryer climates. Although NT may increase available water-holding capacity for the organic-enriched surface (0–15 cm, Mahboubi *et al.,* 1993; 0–60 cm, Tollner *et al.,* 1984), NT may not significantly increase the total amount of water stored in the soil profile compared with CT (Merrill *et al.,* 1996). Adaption of NT and more intensive cropping rotations results in more efficient use of precipitation due to the reduction of the frequency of inefficient fallow practices and using water for transpiration that would be lost during fallow through evaporation, runoff, and deep percolation (Farahani *et al.,* 1998). The increased water-use efficiency results in increased dry matter yields (Smika, 1990; Peterson *et al.,* 1996; Merrill *et al.,* 1996).

In portions of the U.S. agricultural sector that receive more moisture, NT results in the most favorable soil water status during dry years compared to MT and CT, but may limit yields in wet years compared to MT on fine textured soils (Ghaffarzadeh *et al.,* 1997). In general, coarser-textured soils that have higher moisture stress during a growing season do better under NT than CT management (Dick, 1983; Dick and Van Doren, 1985; Dick *et al.,* 1991).

No-tillage systems also have been found to potentially improve surface runoff and ground water quality. The major consequence of not disturbing the soil surface with NT is the enhancement of porosity. Shipitalo *et al.* (1994) reported that the amount of water moving through earthworm burrows in NT established for 20 years increased from 0.25% in CT to approximately 5% in NT. Dunn and Phillips (1991) reported that in established NT, 83% of the water moved through 0.070% of the soil volume, which was increased from 73% of the water moving through 0.026% of the soil volume in CT. Waddell and Weil (1996) found that NT had greater sorptivity than RT causing NT plots to wet faster.

The improvement of groundwater quality with tillage systems has focused on nitrate leaching, because nitrate is readily leached from the soil. This fact is striking when NO_3^- concentrations under intensively managed agricultural systems (>25 mg N L^{-1}) are compared to baseline concentrations of <1 mg N L^{-1} under native forest (Weil *et al.,* 1990). Although water movement through soils is increased with NT, the load of NO_3^- may not increase compared with CT (Eck and Jones, 1992). Leaching of mineralized N from surface residue placement has been found to be less due to immobilization, whereas mineralized N from incorporated

Table II

Changes in Available and Total Soil Water with Conservation and Convention Tillage

Author[a]	Duration[b]	Soil type	Previous management	Results
East				
Dou *et al.* (1995); PA, corn	3 years NT, CT	Murrill silt loam	CT wheat	NT reduced the NO_3^- concentration in the 0–120-cm depth by half when compared CT
Mahboubi *et al.* (1993); OH, corn	1 year CT, MT, NT	Wooster and Crosby silt loam	18 years NT, MT, CT continuous corn	Porosity in NT was decreased 8% but increased hydraulic conductivity and water-holding capacity than CT and MT plots.
Waddell and Weil (1996); MD, corn, soybean	2 years NT, RT	Monmouth fine sandy loam	5 years NT, RT	NT increased sorptivity and available water compared with RT and NT increase water infiltration in the crop row. NT increased available water in dry year and had better water use efficiency in wet year.
South				
Tollner *et al.* (1984); GA, soybean	1 year NT, CT	Piedmont soil	NT for 6 years after CT soybean	NT increased cumulative water infiltration, and total water in top 60 cm.
Dunn and Phillips (1991); KY, corn, rye grass	2 years NT, CT	Maury silt loam	17 years continuous corn under NT and CT	NT increased water infiltration at all tensions, but had decreased pore-size diameter when compared with CT.
Midwest				
Mueller *et al.* (1984); WI, corn	2 years NT, MT, CT	Dresden silt loam	CT corn, NT initiated with experiment	Lower runoff values for CT and MT immediately after tillage and planting compared with NT, but lower sediment concentrations for NT.
Mielke *et al.* (1986); IL, KY, MN, NE, corn, wheat	6–13 years CT, MT, NT	Seven soil types	CT corn and wheat	Total porosity decreased 10% in NT with increased water-filled pore space in 0–150 cm depth from 6–28% higher in NT compared with CT.
Deibert *et al.* (1986); ND, wheat, sunflower	5 years NT, CT	Max loam Williams loam	CT wheat	NT continuous wheat lost 12% of precipitation received compared to 75% water loss for CT wheat-fallow. Although water storage same for CT and NT.

Bauer and Black (1992); ND, wheat	1 sampling CT, SM, grasslands	Six sandy, medium and fine textured soils	Long-term CT and grasslands	Less soil disturbance, higher water availability at field capacity in all soil types and loss of soil productivity due to nutrient loss, not change in available water.
Powers *et al.* (1992); NE, corn	1 year NT, MT	Crete silt loam	4 years NT, MT corn	MT had increased pore size and distribution after tillage, but equal porosity when compared with NT.
Shipitalo *et al.* (1994); OH, corn	1 year NT, CT	Five silt loams	20 years NT and CT	NT had increased water transport with about 5% of water transmitted in worm burrows compared to 0.25% of water transmitted in burrows in CT comparision.
Merrill *et al.* (1996); ND, wheat	12 years MT, SM, NT	Temvik-Wilton silt loam	MT wheat	Cooler soil and increased soil water conservation in the near-surface zone increased root growth in NT compared with in SM or MT.
Ghaffarzadeh *et al.* (1997); IA, corn, soybean, oat	2 years NT, MT, CT	Haig soil	MT corn-soybean	NT increased soil and plant water parameters during dry year and had excessive water during wet year when compared with MT and CT.
West				
Smika (1990); CO, wheat	12 years NT, SM	Weld silt loam	12 years NT, SM wheat	NT increased water storage efficiency by 9% with equal NO_3^- concentration in soil profile of NT and SM.
Wood *et al.* (1991b); CO, wheat, corn, sorghum, millet	4 years NT	Many soils sampled	50 years of CT wheat	More intensive cropping systems under NT had increased organic N and decreased mineral N for leaching.
Peterson *et al.* (1996); CO, wheat	74 years	North Dakota to Texas	CT, SM, and NT	Water-use efficiency increased with decreased tillage and maintance of residue cover due to better water storage storage in early fallow period.
Farahani *et al.* (1998); CO, corn, sorghum, wheat,	7 years NT	Nine soil types	Three-year rotation experiment	Gains in water use efficiency with rotation intensity due to water use that would be lost during fallow to evaporation, run-off or deep percolation.

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[a] Citation, study location, and crops.

[b] NT = no-tillage, MT = minimum tillage, RT = ridge tillage, CT = conventional tillage, SM = stubble mulch.

residue was not immobilized and the majority of N was subject to leaching loss (Cochran *et al.,* 1980). Angle *et al.* (1984, 1993) reported that amounts of NO_3^- leached below NT were significantly less than amounts of NO_3^- leached below CT in Maryland due to the larger amounts of NO_3^- immobilized with increasing soil organic matter and crop utilization. Wood *et al.* (1991b) found less profile NO_3^- and higher organic N in newly established NT systems compared to CT in a 4-year Colorado study. Dou *et al.* (1995) reported in a Pennsylvania study that NT reduced the amount of NO_3^- accumulated in the 0–120 cm soil profile to one-half of the NO_3^- levels in CT whether under legumes or commercial N fertilizer. Although, Thomas *et al.* (1973) concluded that lower NO_3^- concentrations under NT could be attributed to greater leaching losses. In CT soils converted to NT, the initial increase in infiltration rates under NT may leach from the soil NO_3^- that accumulated under CT, while the soil processes occurring under the new NT system would be acting to limit future N leaching.

In a Kentucky experiment, Blevins *et al.* (1990) found the highest levels of runoff, nitrate, P, and atrazine and sediment losses were observed for CT when compared to MT or NT systems. Angle *et al.* (1984) reported that a CT watershed lost ninefold more runoff compared to a NT watershed. This difference in runoff meant a loss of 370 and 9 kg ha^{-1} for suspended sediment from CT and NT managed watersheds, respectively, and reduction of total N lost from 1199 g ha^{-1} in the CT watershed to 87 g total N ha^{-1} for the NT watershed. Waddell and Weil (1996) reported runoff time increased from 7.2 min with RT to 26.3 min for NT allowing more water infiltration, but immediately after tillage, CT and MT may reduce surface runoff due to increased surface roughness (Mueller *et al.,* 1984). The timing of tillage before runoff measurements may explain why researchers have found reduced runoff in NT (Johnson *et al.,* 1979; Langdale *et al.,* 1979; McGregor and Greer, 1982) or no reduction or even increases in runoff from NT compared to CT (Mannering *et al.,* 1975; Siemans and Oschwald, 1976; Lindstrom *et al.,* 1981; Lingstrom and Onstad, 1984). The reduction in surface runoff with conservation tillage is important since Johnson *et al.* (1979) reported that 75–99% of the fertilizer and herbicides losses from soil surface application occurred in runoff water. The reduction of erosion with conservation tillage is important, but the lower runoff volumes from these practices reduces chemical loss because transport is proportional to the total runoff volume (Laflen *et al.,* 1978). Increased potential leaching load in CT systems may result due to incorporated fertilizers or residues in the interaggregate space where they are more susceptible to movement (Staricka *et al.,* 1992).

B. SUSTAINABILITY

In cultivation of virgin forest and grassland soils, the decline in organic C and N, and corresponding increases in plant-available N are greatest during the initial

10 years and then decreases with time (Hass *et al.,* 1957; Campbell *et al.,* 1976). The loss of organic C and N and the erosion resulting from organic matter loss has diminished productivity by deteriorating soil structure and has increased the need for inorganic fertilizers. Decreased soil structure decreases infiltration as a result of soil crusting and also limits the storage of available water and impairs root exploitation of the soil. It is evident that CT systems are not sustainable due to their destructive nature. As the world population increases, the demand for food and fiber increases, resulting in more pressure to increase our cultivation of very erosive steep, fragile soils. Conservation tillage, especially NT management has the potential reduce the problems associated with increased agricultural productivity.

The numerous benefits of NT over CT should result in NT rapidly being implemented in all of the major agricultural area in the United States, but this has not occurred as foreseen in the early 1980s.

1. Adoption

It was evident that U.S. farmers attempted to implement conservation tillage practices in the early 1990s, but these trends for corn production have decreased in recent years (CTIC, 1998). From 1990 to 1994 in Iowa, the percentage of NT corn increased from 3.7%–19.1% (5.2-fold increase), but decreased to 11.8% (1.6-fold decrease) of the corn production in 1998. The loss of conservation tillage appears to be increasing. Iowa alone lost 1 million corn and 400,000 soybean conservation tillage acres in 1 year from 1997–1998 (CTIC, 1998). At the same time, NT soybean production increased from 1.9% in 1990 to 19.0% in 1994 (10-fold increase) to 22.0% in 1998 (1.2-fold increase) (CTIC, 1998). On a nationwide basis, the trends found in Iowa agriculture are also occurring. No-tillage corn production in the United States decreased from 18% in 1994 to 16.4% in 1998 as NT soybeans increased from 24.2% in 1994 to 28.7% in 1998 (CTIC, 1998). In a personal communication with an Iowa farmer, who implemented NT for continuous corn on 285 ha from 1994–1996, reported a consistent 13% yield reduction due to poor spring performance (his evaluation) with NT compared to MT strips cost him \$126,000 at the corn value of \$0.11 kg^{-1} (1994–1996). The farmer has abandoned NT and now is returning to systems that incorporate more tillage management.

At present, there is very little information available for farmers that will help in the transition from CT to NT. One of the largest problems is that NT nutrient management plans are not very different from CT management plans even though nutrient cycling, especially N availability is dramatically changed as a soil evolves from CT to NT.

2. Productivity

Experiments conducted in all geographic areas of the United States have found NT equal or superior to CT for grain yields for all years of the studies (Estes, 1972;

Thomas *et al.*, 1973; Bandel *et al.*, 1975; Moschler and Martens, 1975; Fredrickson *et al.*, 1982; Kitur *et al.*, 1984; Wendt and Burwell, 1985; Locke and Hons, 1988; Deibert and Utter, 1989; Fortin, 1993; Knowles *et al.*, 1993; Ismail *et al.*, 1994; Young *et al.*, 1994; Kapusta *et al.*, 1996; Tsegaye and Hill, 1996). Studies have also determined that NT yielded less during the first years of initiation, but then with time, yielded better than CT for grain production (Campbell *et al.*, 1993; Phillips *et al.*, 1997). Angle *et al.* (1993) reported in a Maryland study, decreased NT corn yields the first year of NT initiation, but increased NT yields up to 32% by the fourth year over CT. Studies have also determined that NT continuous corn yielded less than CT, but equal for corn-soybean rotation (Van Doren *et al.*, 1976; Chase and Duffy, 1991; Stecker *et al.*, 1995; Kanwar *et al.*, 1997) or that different soil types yielded less with NT (Van Doren *et al.*, 1976; Dick, 1983; Wagger and Denton, 1989; Dick *et al.*, 1991) or in different years NT yielded less than CT (House *et al.*, 1984; Rao and Dao, 1992). Several studies have also found that NT resulted in a consistent decrease in Ontario Canada corn and Northern Idaho wheat yields compared with CT (Vyn and Raimbault, 1993; Hammel, 1995). A summary of the yield comparison results with CT and conservation tillage is shown in Table III. The findings that NT continuous corn reduces yield, but corn in rotation with soybeans yields comparable with CT suggests that an early spring N mineralization problem may exist with continuous NT corn.

Adopting conservation tillage practices can have a dramatic effect on soil nutrient status. It appears that nutrients in conservation tillage may become less available to plants than under CT (Blevins *et al.*, 1983; Ismail *et al.*, 1994) requiring a better understanding of how nutrients cycle in NT soil. Farmers will be less willing to switch to conservation tillage or continue using conservation tillage if the only answer to reduced N cycling is application of more fertilizers especially during times where farmers are being encouraged to use less N fertilizers.

The disadvantages of CT has been covered in the above discussion and in comprehensive reviews by Blevins and Frye (1993) and Johnson and Hoyt (1999). Several of the disadvantages associated with conservation tillage include higher herbicide costs due to increased difficulty in controlling certain weed infestations, lower spring temperatures at planting time, decreased soil pH due to stratification of acid-producing fertilizers on the soil surface, and with poorly drained soils, conservation tillage may increase the existing wetness limitation. Conservation tillage practices may increase cool temperatures problems during planting. Crop residues left at the soil surface cause slower warming of soils during the spring and may result in serious problems in the northern U.S. Corn Belt (Griffith *et al.*, 1977). The major disadvantage of NT is the slower timing in the spring of N availability resulting in slower plant development, although many studies from all geographical areas in the United States has shown that NT can yield as productively as CT.

A greater research effort must be given to address NT problems, especially understanding the N cycle with NT to allow this management system, which has such

Table III

Crop Yields with Conservation and Conventional Tillage

Author[a]	Duration[b]	Soil type	Previous management	N application[c]	Results
East					
Estes (1972); NH, corn	1 year NT, CT	Scantic silt loam	Sod	168.1 kg N ha^{-1} broadcast pre-plant with starter	Silage yield was increased for NT compared with CT despite lower plant populations.
Bandel *et al.* (1975); MD, corn	1 year NT, CT	Mattapex, Bertie Beltsville silt loam	CT, corn; NT initiated with experiment	1, Broadcast at planting	NT yielded comparable to CT at 180 kg N ha^{-} but resulted in N deficiencies at lower N rates compared with CT.
Moschler and Martens (1975); VA, corn	3 years NT, CT	Jefferson silt loam	Fallow field (25 years), NT initiated with experiment	1, Broadcast prior to planting	NT increased yields with high N rates and decreased corn yields with low N rates as compared with CT.
Wagger and Denton (1989); NC, corn, soybean, wheat	3 years NT, CT	Pacolet sandy clay, Aycock fine sandy loam	CT continuous corn, NT initiated	1, surface starter 166 kg N ha^{-1} sidedressed later	NT increased sandy clay soil yields 32% for corn and 43% for soybeans. NT equal to CT yields of sandy loam soil.
Angle *et al.* (1993); MY, corn	3 years NT, CT	Manor loam	CT corn, NT initiated with the study	1, 90, 180 and 260 kg N ha^{-1}	NT decresed yields the first year, but increased yield each successive year with NT yields in fourth year increased 32% compared to CT.
Fortin (1993); Ontario Canada, corn	2 years NT, CT	Harrow and Dalhousie sandy loam	CT continuous corn	1, broadcast or starter and broadcast	If starter included, NT increased yields as compared with CT, if starter not included, CT yielded better for continuous corn.
Vyn and Rainbault (1993); Ontario Canada, corn	15 years NT, MT, CT	Maryhill silt loam	CT corn, NT initiated with experiment	160 kg ha^{-1} pre-plant broadcast or sidedressed	NT decreased plant growth and yields as compared with MT and CT. Further NT yiel depression was noted when no N was added at planting and all sidedressed later in sprin
Tsegaye and Hill (1996); MD, corn	4 years NT, CT	Bertie silt loam	CT corn, NT initiated with experiment	2, 35 kg ha^{-1} starter and 135.6 kg ha^{-1} sidedress	Corn had higher emergence rates with NT and equal or better yields compared with C

(continue

Table III—*continued*

Author[a]	Duration[b]	Soil Type	Previous Management	N application[c]	Results
South					
Thomas *et al.* (1973); KY, corn	2 years NT, CT	Maury silt loam	Bluegrass sod NT planted into killed sod	1, broadcast 0–336 kg N ha^{-1}	In dry year, NT increased corn yields compared to CT, but in wet year, only >168 kg N rates increased NT yields compared to CT.
House *et al.* (1984); GA, soybean, sorghum	4 years NT, CT	Hiwassee loam, Cecil sandy loam	12 years of NT and CT pr	148 kg N broadcast sorghum	NT increased yields in dry year and equal yields in year with adequate moisture when compared with CT sorghum and soybean.
Kitur *et al.* (1984); KY, corn	2 years NT, CT	Maury silt loam	10 years NT and CT corn	1, sprayed solution 84 and 168 kg N ha^{-1}	CT increased yields each year at the 84 kg N rate, but NT increased yields at the 168 kg N rate as compared with CT corn yields.
Locke and Hons (1988); TX, sorghum	2 years NT, CT	Weswood silt loam	CT sorghum, NT initiated with experiment	1, broadcast and subsurface banded 150 kg N ha^{-1}	NT decreased yields the first year 1.9%, but increased yields by 5.4% the second year as compared with CT.
Rao and Dao (1992); OK, wheat	4 years NT, CT	Renfrow silt loam	CT wheat	1, starter, surface banded or broadcast	NT equal or increased yields two of three years when spring moisture was limiting. With adequate moisture CT had increased yields.
Knowles *et al.* (1993); TX, sorghum, wheat	3 years NT, CT	Austin silty clay	NT initiated with experiment	1, broadcast preplant	NT sorghum decreased yields with no yield difference for NT wheat when compared with CT at 135 kg N rate.
Christensen *et al.* (1994); NM, sorghum, wheat	4 years NT, SM	Pullman sandy clay loam	CT for 10 years	2, banded	NT and SM wheat and sorghum yields were equal with NT increasing yields in dry year.
Ismail *et al.* (1994); KY, corn	20 years NT, CT	Maury silt loam	20 year CT and NT after bluegrass sod for 50 years	1, broadcast at planting 0–336 kg N ha^{-1}	NT consistently increased corn yields at all N rates as compared with CT corn over 20 years.
Bruce *et al.* (1995); GA, soybean, sorghum	2 years NT, MT	Cecil soil, Pacolet soil	MT sorghum-soybean, NT inititated for 5 years	No information given	NT resulted in equal or increased yields for sorghum over 80 site-year as compared with MT.

Midwest					
Van Doren *et al.* (1976); OH, corn, soybean	10 years NT, MT, CT	Wooster and Crosby silt loam, Hoytville silty clay loam, Toledo clay	CT, rotation and sod for 6 years in Wooster	1, broadcast	Coarse textured soils under NT had increased continuous corn yields compared with CT but NT fine textured soils increased corn yields with corn-soybean rotation.
Wendt and Burwell (1985); MO, corn	6 years NT, MT, CT	Mexico silt loam	CT corn, NT initiated with experiment	No information given	NT was equal or increased corn yields when compared to CT for six years.
Deibert and Utter (1989); ND, sunflower	2 years NT, MT, CT	Fargo clay	CT small grains 8 years, NT initiated with experiment	1, broadcast preplant, 112 kg N ha^{-1}	NT increased sunflower production by 23 and 10% the 2 years compared with CT.
Chase and Duffy (1991); IA, corn, soybean	10 years NT, MT, RT, CT	Kenyon loam soil	NT, MT, RT, CT tillage initiated with experiment	3, 200 kg N ha^{-1} before planting	NT decreased corn yields 8% for continuous corn, 2.7% for rotation corn, and 0% for soybeans when compared with CT (10 years)
Dick *et al.* (1991); OH, corn, soybean	18 years NT, MT, CT	Wooster silt loam Hoytville silty clay loam	18 years NT, MT, CT	1, broadcast in spring before planting	Wooster NT soil increased yields but Hoytville soil decreased yields with NT and continuou corn compared with CT.
Stecker *et al.* (1995); MO, corn, soybean	5 site-year NT, MT	Mexico silt loam	MT soybean NT initiated with experiment	3, first 2 years 2, second 2 years knife-injected	NT decreased yields first year, but equal or increased yields remaining years for corn. Maximum NT yields achieved with less N.
Kapusta *et al.* (1996); IL, corn	20 years NT, MT, CT	Ebbert silt loam	20 years of tillage NT initiated with experiment	1, Broadcast within 30 days after planting	Yields were the same with NT, CT, RT with broadcast fertilizer. Continuous NT corn did not decrease yields compared with CT.
Kanwar *et al.* (1997); IA, corn, soybean	5 years NT, MT, RT, CT	Floyd and Readlyn loam, Kenyon silty clay loam	14 years of CT, NT, MT, RT	3, knifed, 200 kg N ha^{-1} before planting	Corn production in corn-soybean rotation yielded comparable, but NT continuous corn yielded 13% less than MT or CT corn.
Phillips *et al.* (1997); IL, corn, soybean	6 years NT, MT, CT	Grantsburg silt loam	CRP acreage tillage started with experiment	3, knifed 213 kg ha^{-1}	NT decreased yields the first year, was equal the second year, and increased yields years three to six as compared with CT. NT also provided the highest net income.

(*continue*

Table III—*continued*

Author[a]	Duration[b]	Soil type	Previous management	N application[c]	Results
West					
Fredrickson *et al.* (1982); WA, wheat	2 years NT, CT	Palouse silt loam	4 years NT and CT	5, broadcast 112 and 168 kg N ha^{-1}	NT decreased spring wheat yields 7.7% but increased winter wheat yields 33% as compared with CT at 168 kg N rate.
Campbell *et al.* (1993); Canada, wheat	8 years NT, CT	Swinton loam	CT spring wheat NT initiated at start of experiment	2, broadcast and subsurface banding	NT decreased wheat yields for the first 4 years (23%) regardless of the weather and increased yields (14%) during the second 4-year period as compared with CT.
Young *et al.* (1994); WA, wheat	6 years NT, CT	Palouse silt loam	NT small grains previous 9 years	2, 5, broadcast	NT increased wheat yield following cover crop but had the same yield as CT with continuous wheat.
Hammel (1995); ID, wheat	4 years NT, MT, CT	Palouse silt loam Naff silt loam	10 years NT, MT, CT	N incorporated	NT decreased wheat yields when compared with MT and CT.
Kolberg *et al.* (1996); CO, corn, sorghum, wheat	6 years NT	Keith clay loam Weld loam	CT wheat; NT initiated with experiment	2 and 4, preplant broadcast or split application	Changing from CT wheat-fallow to more NT wheat-sorghum-corn rotations required more N due to increased N uptake.

[a] Citation, study location, and crops.

[b] NT = no-tillage, MT = minimum tillage, RT = ridge tillage, CT = conventional tillage, SM = stubble mulch.

[c] 1 = NH_4NO_3, 2 = UAN, 3 = NH_3, 4 = urea, 5 = $(NH_4)2SO_4$.

great promise to reduce environmental problems related to agriculture and to improve our agricultural sustainability, to reach its full potential.

C. NUTRIENT CYCLING

Soil disturbance from tillage operations alters the microclimate variables, contact between soil and residue and is an important regulator of decomposition in agroecosystems (House *et al.,* 1984; Wilson and Hargrove, 1986; Hendrix *et al.,* 1986). Tillage practices influences not only crop residue decomposition, but also nutrient cycling and use efficiency. Nutrient transfer in ecosystems is accomplished through complex, biological mediated processes. Conventional tillage essentially eliminates some of these biological processes by using energy from mechanical plowing (House *et al.,* 1984).

Tillage has greatly accelerated organic C and N losses from the surface of native soils within the first 30–40 years (Fleige and Baemumer, 1974), suggesting that nearly all of our knowledge on nutrient cycling has been conducted on C and N degraded soils as a result of tillage for extensive time periods. Conversion of conventional managed fields to conservation tillage results in changes in nutrient availability due to the accumulation of organic matter that did not occur under CT. The major NT change that affects nutrient cycling from CT is the stratification of nutrients on the surface of the soil profile more the fashion of natural systems rather than a complete mixing that results from CT (Follett and Peterson, 1988).

Changing land use and fertilizer management practices are among the factors that most affect the decomposition of organic compounds in soils (Ajwa and Tabatabai, 1994). The degree to which NT will change nutrient cycling is dependent on factors such as soil moisture, temperature, aeration, pH, type and quality of residues, length of time the tillage system has been in place, previous management, and soil type. Before improved nutrient management plans for conservation tillage can be suggested, scientists and producers must understand what portions of the nutrient cycle that controls nutrient availability are influenced by NT. Since nutrient availability is controlled by C mineralization, understanding the C and N interactions in CT compared to NT may provide the needed information.

III. CARBON/NITROGEN INTERACTIONS WITH DIFFERENT MANAGEMENT SYSTEMS

The supply of N is one of the most decisive factors for economic crop production. It is well known that over 90–95% of the N in surface soils occurs in organic forms and can range as high as 4000 kg N ha^{-1} for temperate soils (Powlson, 1993), yet in most agricultural systems it is customary, necessary, to increase the availability of N through fertilization. Organic soil N plays a key role in terms of plant nutrition through direct and indirect effects on nutrient availability via microbial activity. A majority of our knowledge of C and N cycling has been obtained on structurally degraded CT soils (> 50 years of tillage), but a disruption of the steady-state N dynamics in CT soils occurs upon establishment of systems with less soil disturbance such as conservation tillage (Wood *et al.,* 1991b). Numerous observations have suggested that there are significant differences between NT and CT soils with regards to soil N transformations and fate of fertilizer N (Rice and Smith, 1982). It is important to understand the distribution of N forms and cycling and timing of plant-available N release under different systems and N availability interaction with crop yields.

A. Distribution of Nitrogen Forms

The importance of organic N from the standpoint of soil fertility has been long recognized. At present, our knowledge of the forms of N in soil is limited to solubility measurements of inorganic N (NH_4^+ and NO_3^-), organic N (acid hydrolyzed amino acids and amino sugars or fumigation released N), hydrolyzed NH_4^+ present as clay-fixed NH_4^+ or released by hydrolysis of certain amino acids, unidentified hydrolyzed N and nonhydrolyzed N (Stevenson, 1994). The forms of organic N in soil can be divided into two broad categories (i) organic residues consisting of undecayed and partial decayed products and (ii) soil organic matter or humus (Kelley and Stevenson, 1995).

Literature gives very limited information on the N forms present in native grassland or prairies. Ajwa *et al.* (1998) found NO_3^- concentrations to a 7.5-m depth in agricultural soil (cultivated 40–50 years) was 58.6 times the NO_3^- concentration in an adjacent Kansas prairie (within 1 km), although the NH_4^+ concentrations were the same and the prairie had a greater total N content. Follet and Schimel (1989) found total N concentrations had decreased to 73, 68, and 50% of the native Nebraska grassland for NT, SM and CT, respectively, after 16 years of cultivation. Meints and Peterson (1977) reported that cultivation caused a decrease in the total N and the concentration of amino sugars, amino acid N, hydrolyzable N, and nonhydrolyzable N, but affected the proportions of N remaining by increasing percentages of nonhydrolyzable and amino N and decreasing hydrolyzable N. Martens (2000) found that a native prairie had greater total N than a cultivated adjacent soil, but the proportion of amino N to total N remained the same in the prairie and cultivated soil after ~90 years of tillage. Arshad *et al.* (1990) reported after 10 years, a barley (*Hordeum vulgare*) NT system had more total N, amino acids and amino sugars than an adjacent CT barley field. Christensen *et al.* (1994) found a NT system had less inorganic N and more organic N than a CT system.

Parkin and Meisinger (1989) found that 4 years of continuous corn with CT had substantially higher NO_3^- concentrations than NT to a depth of 4 m in a Maryland comparison. It is evident that tillage releases N from all of the N pools present in soil (Keeney and Bremner, 1964), and this released N has a great impact on both crop yields and water quality.

Understanding the timing of organic N release for plant assimilation is of great importance due to recent findings on the implications of early season soluble N levels and resulting yields. Binford *et al.* (1992) found that a critical spring NO_3^- concentration of 23–26 mg N kg^{-1} soil in the surface 30 cm for 45 site years under MT or CT is required for optimum corn yields. A large supply of NO_3^- early in the growing season is very important for producing corn high yields, because large amounts of inorganic N are required once corn plants reach the fifth leaf stage (Dou *et al.,* 1995). Johnston and Fowler (1991a, 1991b) found that delaying N availability in winter wheat production by even three weeks prevented early spring N uptake, reduced grain yield, and grain protein yield due to lack of available N when the grain yield potential is being determined in wheat. Sweeney (1993) determined early season nutrient availability is very important for sorghum production because maximum nutrient accumulation preceded the time of maximum dry matter growth rate. The result agrees with other research that has suggested early season N availability is of extreme importance since it is at the time of growing point differentiation, the number of kernels per head are being set for sorghum (Vanderlip, 1979).

B. MICROBIAL BIOMASS

Agronomic practices such as cultivation, residue, management, and fertilization regulate microbial activities, which affect the processes of organic matter turnover and nutrient cycling (Biederbeck *et al.,* 1984; Doran and Smith, 1987). Although soil MB-C accounts for a small portion of the total organic C in soils, MB is responsible for release of nutrients for crop utilization. Angers *et al.* (1993) reported that soil MB accounted for only 1.2–1.4 % of the organic C in CT and up to 3.5–5.1% of organic C with NT. Microbial biomass (MB) is considered the transformation agent of soil organic matter, a labile reservoir of nutrients such as C, N, P, and S (Jenkinson and Ladd, 1981) and the composition of soil microbial communities may affect the decomposition of added organic residues (Sharma *et al.,* 1998). In addition, changes in microbial nutrient status during litter decomposition have been reported. Scheu and Parkinson (1995) found that during the early stages of residue decay, microbial growth is limited by N and that in later stages, microbial growth is limited by C, resulting in changes in the composition of microbial communities during the decomposition process. Additions of N fertilizers to native grasslands resulted in higher MB-N and reduced MB-C possibly due to

Table IV—*continued*

Author[a]	Duration[b]	Soil type	Previous management	Results
Schimel el al. (1985); ND, prairie, wheat	1 year	Fine-silty, coarse loamy soils	Native grassland and CT wheat for 44 years	Soil MB had a narrow C to N ratio in CT wheat compared to prairie suggesting a change in microbial community composition when prairies are cultivated.
Doran (1987); NE, MN, IL, KY, corn, wheat	1 year NT, CT, SM sod	Many soil types	NT at sites for 5–13 years, with some sites previous in prairie or CT	Soil MB and potential mineralizable N were increased 54% and 37%, respectively in the surface 0–7.5 cm in NT as compared with CT.
Broder and Wagner (1988); MO, corn, wheat, soybean	2 years CT	Mexico silt loam	CT continuous corn, wheat or soybean	Bacteria and actinomycete populations were increased on the soybean residue while fungal populations were on corn residue
Staley *et al.* (1988); OH, continuous corn	0–20 years NT, CT pasture	Westmoreland silt loam	50 years CT corn	Soil MB reached a maximum in surface soil after only 1 year of NT, nearing the equivalent to that under improved pasture, but then declined slightly with continued NT.
Garcia and Rice (1994); KS, tallgrass prairie	3 years	Irwin silty clay loam	Tallgrass Prairie	Microbial biomass is critical in natural systems by conserving N. Nitrogen additions appeared to change the composition of the microbial biomass.
Karlen *et al.* (1999); IA, MN, ND, WA	1 year CRP and CT	Many soil types	CRP acreage and CT crops	Microbial biomass C was 17–64% higher in CRP sites than at cropland or fallow. Fungal hyphal length increased 26–62% under CRP.
West				
Carter and Rennie (1982); Canada, wheat	1 year NT, CT	Lethbridge silt loam, Melfort and Elstrow clay loam, Scott loam	NT for 2, 4, 12, or 16 years CT wheat before treatments	Within 4 years, NT significantly redistributed the soil MB to the soil surface with an increase in soil MB as compared with CT wheat.
Carter and Rennie (1984); Canada, wheat	1 year NT, MT	Lethbridge silt loam, Melfort and Elstrow clay loam, Scott loam	NT for 2, 4, 12, or 16 years CT wheat before treatments	Soil MB related to crop residue distribution in tillage systems with greatest populations with surface residue. Soil MB both a sink and a source of mineral N.

Aulakh *et al.* (1984); Canada, wheat	1 year NT, CT	Elstow clay loam	2 years NT wheat after CT wheat fallow	NT increased denitrifing populations up to sixfold over CT in the surface soil, with low denitrier counts measured in the subsurface of NT or CT.
Holland and Coleman (1987); CO, wheat	1 year NT, CT	Weld silt loam, Nunn clay loam	NT initiated in 1983, CT wheat for 50 years	Soil organic matter losses may be reduced in NT because the ratio of fungal to bacteria activity increases. Fungi have greater growth efficiency and accumulate C in less decomposable biomass.
East				
Parkin and Meisinger (1989); ML, corn	1 year NT, CT	Matapeake silt loam	4 years of NT or CT continuous corn	NT soil increased denitrification enzyme activity threefold compared to CT soil, although both soils had the same counts of viable bacteria in the soil surface.
Angers *et al.* (1993); Canada, corn	1 year MT, RT, CT	Neubois silt loam	Tillage for 11 years after meadow for 20 years	Soil MB-C under CT accounted for 1.2–1.4% of organic C and MT soil MB-C accounted for 3.5–5.1% in the soil surface.
Europe				
Lynch and Panting (1980); England, wheat	2 years CT, grass	Denchworth clay, Hamble silt loam	CT, 4 or 9 year after grass sod	Soil MB in the clay soils were tenfold greater than in silt loam. Sod had threefold the biomass as cultivated soil.
Puri and Ashman (1998); England	1 year	Sandy loam	Acidic woodland soil	In a native site, soil MB changed little during year in to C additions.
Sharma *et al.* (1998); Denmark, Germany, Italy, corn	1 year	Luvisol, Andosol	CT corn	Soil MB increased twofold in surface mulch treatments with a different microbial community compared to incorporated residue treatments.

[a] Citation, study location, and crops.

[b] NT = no-tillage, MT = minimum tillage, RT = ridge tillage, CT = conventional tillage, SM = stubble mulch.

biomass because fungal C assimilation efficiency can range from 30–70%, where bacterial C assimilation efficiencies may only range from 20–40% (Holland and Coleman, 1987). Beare *et al.* (1990) reported that the plant residues have a greater MB and a higher proportion of physiologically active microorganisms dominated by fungi during the early stages of residue decay when compared to soil.

Although the size of the microbial N pool is relatively small, its rapid turnover makes a considerable contribution to mineralization (Anderson and Domsch, 1980). The microbial biomass mediates the great majority of C and N transformations and is responsible for N transformations such as ammonification, nitrification, and denitrification in soil.

C. AMMONIFICATION OR N MINERALIZATION

Mineralization has been defined as the heterotrophic microbial transformation of N from the organic state into the inorganic forms of NH_4^+ or NH_3. Mineralization of N from soil organic matter, animal and green manures, and crop residues contributes greatly to the soil N budget and to total plant N availability (Kolberg *et al.*, 1997). Tillage systems also affect the release of plant available N. Conventional tillage of native prairies releases large amounts of plant available N as NO_3^- due to fast soil OM mineralization (Rasmussen *et al.*, 1980; Balesdent *et al.*, 1988), which appear to stabilize at approximately 50% of the initial values. Most important, early season N mineralization is slower under NT when compared to CT (Doran, 1980b; Fox and Bandel, 1986; Dou *et al.*, 1995; Rasse and Smucker, 1999), even though NT soils have increased organic N content than CT soils (Christensen *et al.*, 1994). Stecker *et al.* (1995) found that continuous corn under MT contributed 54 kg N ha^{-1} $year^{-1}$ due to mineralization while a recently established NT contributed only 24 kg N ha^{-1} $year^{-1}$ for continuous corn production spanning five-site years on Missouri soils. The lower mineralization may be due to the higher moisture, lower oxygen levels and soil temperatures that have been reported for NT as compared to CT (Rice and Smith, 1982). Systems recently converted from CT to NT have shown a N deficiency at low N application rates (Bandel *et al.*, 1975; Blevins *et al.*, 1977; Bundy *et al.*, 1992) due to slower mineralization and nitrification and greater N immobilization (Doran, 1980a, 1980b). Although long-term NT can improve the efficiency of N cycling due a larger supply of organic N from higher levels of residue on the soil surface (Black, 1973; Rice *et al.*, 1986; Maskina *et al.*, 1993) and an increase in the active organic N pools (McCarty *et al.*, 1998). Franzluebbers *et al.* (1996) reported that canola mineralization during a growing season was 57% for buried residue in CT and only 30% for surface residue in NT. Beare *et al.* (1993) and Buchanan and King (1993) also reported a much faster decomposition rate (up to a 3.4-fold) for incorporated crop residues when compared to surface decomposition rates. During the initial mineralization of crop residue under anaerobic or aerobic conditions, the rate was identical for the first 14 days, yet a 3.5-fold increase in NO_3^- concentration was noted due to lower metabolic efficiencies of anaerobic microbial populations (Gale and Gilmour, 1988). Disruption of steady-state N dynamics in CT soils occurs upon establishment of systems with less soil disturbance (Wood *et al.,* 1991b). No-tillage results in greater potentially mineralized C and N and less microbial C limitation, when compared to CT systems (Follet and Schimel, 1989). Ajwa *et al.* (1998) also found that native tall grass prairies had higher C and N mineralization rates than a CT soil (<1 km away), but the prairie soil had the lowest potential mineralized organic N to total N ratio when compared to the CT soil. These trends were also found for a North Dakota study (Schimel, 1986). It is of interest that N mineralization in native prairie and NT was not proportional to soil MB as was noted for C mineralization (Follet and Schimel, 1989), suggesting increased tillage decreases the capacity to immobilize and conserve mineral N by reducing available C substrates for microbial growth (Tracy *et al.,* 1990). A summary of residue mineralization rate with CT or conservation tillage is presented in Table V.

The type of the crop residue also affects when residue N will be released for subsequent crops. Power *et al.* (1986) reported that ^{15}N-labeled soybean residue in NT was completely mineralized and the N assimilated by mid-July of the next cropping year, where essentially none of the corn residue ^{15}N was recovered by the next years crop. Broder and Wagner (1988) determined that buried soybean residue decomposed at a faster rate (68%) than buried corn (42%) or wheat (47%) residue during the first 32 days of incubation. Also, increasing cropping management intensity in dryland agriculture with NT will increase potential and net C and N mineralization (Wood *et al.,* 1990).

Tillage is clearly an important regulator or driving variable for element cycling especially N in agrosystems (Buchanan and King, 1993). Mineralized crop residue N is believed to be first assimilated into MB (Amoto and Ladd, 1980) before becoming available for plants. A Colorado study found that soil profile (6.1 m depth) NO_3^- levels in native prairie sites was about 90 kg $NO_3^- - N\ ha^{-1}$ compared to 261 kg ha^{-1} for CT dryland winter wheat/fallow fields (6.1 m depth) before wide spread nitrogen applications. Since no nitrogen fertilizer had been applied to the agricultural fields, the approximate threefold differences in NO_3^- concentration was due to the tillage operations enhancing OM mineralization (Westfall *et al.,* 1996). The study cited indicates that leaching of NO_3^- to the vadose zone and groundwater was a potential even before N fertilizer use.

Keeney and DeLuca (1993) compared water flow and NO_3^- records from 1945 and the years 1980–1990 from a U.S. Geologic Survey gaging station that was situated on the Des Moines river just south of Des Moines, Iowa. The area drained by this watershed is approximately 78% corn (*Zea mays* L.) and soybean (*Glycine max* L.) row crop production. During this time period, the growth of fertilizer applications for this watershed ranged from less than 0.2 kg N ha^{-1} in 1945 to a max-

Table V

Changes in Carbon and Nitrogen Mineralization Rates with Conservation and Conventional Tillage

Author[a]	Duration[b]	Soil Type	Previous Management	N application[c]	Results
East					
Buchanan and King (1993); NC, corn, wheat, soybean	2 years NT, CT	Piedmont soil	Long-term NT, CT	1, 140 kg N ha^{-1}	C losses were consistently increased and more rapid when residues were buried as compared to surface residue decomposition.
Dou *et al.* (1995); PA, corn, wheat	3 years NT, CT	Murrill silt loam	CT corn, wheat NT initiated with experiment	1, broadcast	Net mineralization of clover and vetch cover crops was decreased in NT soils compared to CT soils.
McCarty *et al.* (1998); MD, corn	3 years NT, CT	Mattapex silt loam	CT corn NT initiated with experiment	120 kg N ha^{-1}	Active N mineralization pools increased with increasing year of NT faster than total N as compare with CT.
South					
Gale and Gilmour (1988); AR, alfalfa	30 days	Captina silt loam	Agricultural research farm	0	Anaerobic decomposition of alfalfa increased N release 3.5-fold compared to aerobic conditions due to lower metabolic efficiencies of anaerobic system.
Eck and Jones (1992); TX, wheat, sorghum	4 years NT, SM	Pullman clay loam	30 years CT wheat or corn-sorghum rotation	1, broadcast 56 kg N ha^{-1}	NT continuous wheat decreased NO_3^- concentrations 46% compared with SM, with no differences in NO_3^- levels under sorghum.
Beare *et al.* (1993); GA, sorghum	1 year NT, CT	Hiwassee sandy clay loam	10 years NT, CT sorghum, winter rye	1, 100 kg N ha^{-1} broadcast	Decay rates were increased for buried sorghum residue 3.4-fold compared with surface residue.
Franzluebbers *et al.* (1995); TX, sorghum, wheat, soybean	2 years NT, CT	Weswood silt loam	9 years NT, CT monoculture sorghum, wheat, soybean	1, banded or broadcast	Potential soil C and N mineralization increased under NT than CT for all crops. Except the period after harvest when CT incorporated residue with soil.
Midwest					
Doran (1980b); KY, MN, WV, NE, OR	1 year NT, CT	Many soil types	3–10 years NT, CT comparison	None given	CT increased C and N mineralization in the 7.5–30 cm depth as compared with NT, but NT had increased mineralization in the 0–7.5 cm depth.

Power *et al.* (1986); NE corn, soybean	2 years NT	Crete-Butler silty-clay loam	NT for 2 years	1, broadcast	Soybean residue N was mineralized and assimilated by following July. Corn residues released no N for the following cropping year.
Broder and Wagner (1988); MO, corn, wheat, soybean	2 years CT	Mexico silt loam	2 years continuous corn, soybean or wheat	0	Soybean residue had the most rapid decomposition rate (68%) in 32 days compared with corn (42%) an wheat (47%) residues.
Follett and Schimel (1989); NE, wheat	36 days NT, SM, CT	Duroc loam	16 years NT, Sm, CT wheat following native prairie	3	Respiration rates per unit of mineralized N increased with decreased soil tillage suggesting C availability for microbial growth declined with increased tillage.
Tracy *et al.* (1990); NE wheat	1 year NT, CT	Durac loam	NT and CT for 16 years after native prairie	0	The ratio of oxidized C to net NO_3^- accumulation was increased 21% under NT compared to CT in the 0–5 cm depth.
Binford *et al.* (1992); IA corn	2 years CT	Many soil types	CT corn, soybean	1, 2, 3 broadcast	20 to 25 mg NO_3^- kg^{-1} soil at early gowth required optimum corn yields.
Maskina *et al.* (1993); NE corn	3 years NT	Crete-Butler silty-clay loam	5 years residue rate experiment	0,1, broadcast	Increasing length of NT practice increases capacity of NT soil to provide N due to increasing organic N content.
Green and Blackmer (1995); IA, corn, soybean	1 year	Many soil types	MT corn or corn-soybean rotation	4	Increased N availability in soybean soils was due to faster mineralization of soybean residue as compared with corn amended soil.
Green *et al.* (1995); IA corn	90 days	Galva silty clay loam	Nonfertilized continuous corn	4	Nitrate fertilizer stimulated the decomposition of corn stover, not soil OM, rapidly decreasing the available C source.
Stecker *et al.* (1995); MO, corn, soybean	5 site–years NT, MT	Mexico silt loam	MT soybean NT initiated with experiment	2, incorporated	Net N mineralization under MT was 54 kg N ha^{-1} $year^{-1}$ while NT released only 24 kg N ha^{-1} $year^{-1}$ despite increased organic N content with NT.
Ajwa *et al.* (1998); KS wheat, soybean	40 weeks prairie, MT	Reading silt loam	Native prairie soybean and wheat MT	2, incorporated	Carbon and N mineralization were greater in prairie than agricultural soil. Ratio of potentially mineralizable C and N to total is less in prairie.
Rasse and Smucker (1999); MI, corn, alfalfa	3 years NT, CT	Kalamazoo loam	8 years NT, CT	0, alfalfa; 1, corn 123 kg N ha^{-1}	Alfalfa decomposing in CT plots consistently increased NO_3^- soil concentrations as compared to NT suggesting decreased NT mineralization rates.
West					
Black (1973); MT, wheat	6 years MT	Dooley sandy loam	50 years wheat fallow	1, broadcast before planting	As rates of surface mulch increase over time, an increased accumulation of NO_3^- was available regardless of the N rate added.

(continue

Table V—*continued*

Author[a]	Duration[b]	Soil Type	Previous Management	N application[c]	Results
Schimel (1986); ND, wheat prairie	1 year CT	Haploboroll	45 years CT wheat native grassland	3	Prairie had increased C evolution and gross N mineralization with low net N release. CT wheat had decreased C evolution with high net N release.
Wood *et al.* (1990); CO, corn, wheat, millet	4 years NT	Many soil types	50 years CT	N source or rate not specified	Potential C and N mineralization increased as cropping intensity and residue increased under NT.
Franzluebbers *et al.* (1996); Canada, canola	1 years NT, CT	silt loam	Canola, wheat CT	0	Carbon mineralization was increased and N mineralization was decreased for buried residue as compared with surface residue.

[a] Citation, study location, and crops.

[b] NT = no-tillage, MT = minimum tillage, RT = ridge tillage, CT = conventional tillage, SM = stubble mulch.

[c] 0 = none, 1 = NH_4NO_3, 2 = UAN, 3 = $(NH_4)2SO_4$, 4 = KNO_3.

imum of 162 kg N ha^{-1} in 1985 (Keeney and DeLuca, 1993). Fertilizer use in the U.S. Corn Belt paralleled the Iowa data and increased from 100,000 metric tons in 1945 to 5.72×10^6 metric tons in 1976, representing a 57.2-fold increase in fertilizer N use (Stanford, 1982). Comparison of river flow rates and NO_3^- levels before heavy N fertilizer applications (1945) with an average flow and NO_3^- levels for the years 1980–1990 found very comparable flows and NO_3^- levels (5.0 mg and 5.6 mg^{-1} for 1945 and the average 1980–1990, respectively) for both times suggesting that other sources of NO_3^- than fertilizer applications must be considered. Mineralization of soil N was estimated to be the largest contributor of mineral N to cropland in the watershed in 1945 and should still be considered a major source today. Enhanced mineralization of soil organic matter by tillage contributed greatly to both sets of measurements and can range from 40–120 kg N ha^{-1} $year^{-1}$ (Keeney and DeLuca, 1993). Gast *et al.* (1978) also reported fertilizer applications made little difference in NO_3^- leaching from CT soils receiving 20–112 kg N ha^{-1}. The studies emphasize that tillage is one of the greatest contributors of N leaching to surface and ground water and the practice of row crop culture must be altered to maximize the use of residual and applied N. Conservation tillage, especially NT, has the greatest potential to limit nutrient pollution to water supplies because NT has slower N mineralization and greater N retention due to more efficient N cycling when compared with tilled systems. It is important to understand that a majority of this N that is conserved under NT can rapidly become available and potentially lost from the system when tillage is introduced as a modifier of perceived higher bulk density problems (Pierce *et al.,* 1994).

D. NITRIFICATION

Nitrification is controlled by a series of chemoautotrophic bacteria and consists of two distinct stages; the oxidation of NH_4^+ to NO_2^- and the subsequent oxidation of NO_2^- to NO_3^-. Soil organic N that has been mineralized to NH_4^+ will be in competition for assimilation by the growing plants, heterotrophic microorganisms and NH_4^+ oxidizing populations of the genera *Nitrosomonas* spp. The occurrence of NO_3^- and NH_4^+ or the ratio of NO_3^- to NH_4^+ in native or reestablished ecosystems has been found to be depend on the length of time the systems have been in place (Christensen and MacAller, 1985). In tilled ecosystems, NO_3^- is the dominant form of mineral N (Rice and Smith, 1983), where as NH_4^+ is more abundant in older native systems, suggesting that nitrification is repressed in native systems (Stienstra *et al.,* 1994). Rice and Smith (1983) found higher ratios of NO_3^- to NH_4^+ in NT compared to CT, but approximately the same N concentration for both CT and NT suggesting lower nitrification rates.

It has been suggested that nitrification rates are slower in NT compared to CT (Rice and Smith, 1983) due to the low NO_3^- to NH_4^+ ratio. Doran (1980a, 1980b)

Table VI

Nitrogen Immobilization with Conservation and Conventional Tillage

Author[a]	Duration[b]	Soil type	Previous management	N application[c]	Results
South					
Rice and Smith (1984); KY, corn	1 year NT, CT	Maury, Tilsit, Cavode silt loam	2 and 11 years NT and CT corn	3, broadcast 168 kg N ha^{-1}	Immobilization in NT was increased twofold compared with CT and occurred shortly after N addition
Schomberg *et al.* (1994); TX, wheat, sorghum, alfalfa	1 year NT, CT	Pullman clay loam	MT sorghum	Plant residue N	Net immobilization was longer than 1 year for surface residue and about one-third year for buried residue.
Midwest					
Balesdent *et al.* (1988); MO, wheat, corn, timothy	97 years NT, CT	Sanborn Field	Prairie	Manure before 1950, fertilizer after 1950	Decreasing soil disturbance with addition of N as manure or fertilizer increases immobilization of C and N in soil.
Green and Blackmer (1995); IA, corn	1 year NT, MT, CT	Many soil types	CT and MT corn or corn-soybean rotation experiment	2, incorporated	Addition of corn stover and $^{15}NO_3^-$ resulted in ^{15}N immobilization with subsequent mineralization from nonlabeled soil organic matter.
Green *et al.* (1995); IA corn	2 years NT, MT, CT	Galva silty, clay loam	Nonfertilized CT corn	2, broadcast	Immobilization of N by increased residue rates may increase soil C content, but high levels of N fertilizers stimulated mineralization of corn residue not soil OM.
West					
Carter and Rennie (1984); Canada, wheat	1 year NT, CT	Many soil types	NT and CT comparisons for 2–16 years	4, broadcast 100 kg N ha^{-1}	Increased NT cropping beyond 4 years resulted in increased N availability during the year compared with CT with N immobilized released during the year. N availability was decreased in early NT systems.

Broadbent (1986); CA, forest, prairie, crop	1 year	Many soil types	Prairie, forest crop	NH_4^+, broadcast	Immobilized labeled N was found to be present as amino acids that are resistant to biological attack.
Jackson *et al.* (1989); CA, grassland	1 year	Argonaut silty loam	Native grassland	2, 3, broadcast	Microbial uptake of NH_4^+ was up to fivefold higher than NO_3^-. Nitrate was assimilated by plants as fast as NO_3^- could be formed in the soil.
Europe					
Wickramasinghe *et al.* (1985); England	3 weeks	St. Coombs, Highfield	Tea plantation grassland	2, 3, 4, solutions	Ammonium forming fertilizers were immobilized at the same rate, where NO_3^-–N immobilization was negligble in both soils.
Shen *et al.* (1989); England	1 year CT	Rothamsted Station soils	Wheat since 1843	1, broadcast	Increased N remained in the soil at harvest when labeled NH_4^+ was added as compare to N remaining when supplied as labeled NO_3^-.
Recous and Mary (1990); France	18 days	Four soils	No information given	1, 2, 3, 4	No NO_3^- immobilization occuurred when KNO_3^- was applied without glucose addition. NH_4^+ present in soil suppressed immobilization of NO_3^-.
Recous *et al.* (1992); France	1 year	Three soil types	CT wheat	1, 4	Shortly after fertilizer application, immobilization was increased for NH_4^+ as compared to NO_3^-, but plant assimilation occurred preferentially at the expense of NO_3^-.

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[a] Citation, study location, and crops.
[b] NT = no-tillage, MT = minimum tillage, CT = conventional tillage.
[c] 1 = NH_4NO_3, 2 = KNO_3^-, 3 = $(NH_4)_2SO_4$, 4 = urea.

wheat-C retained soil N content and increased wheat subsequent yields (Oveson, 1966). Rasmussen *et al.* (1980) reported that when net N inputs were positive, approximately 75% of the positive N input remains in the soil. Recent work has

(NO_2^- and NO_3^-) to N_2, and NH_3 volatilization are the major pathways of N loss from soil. Nitrogen balance experiments conducted with lysimeters have suggested that N deficits are on the order of 15–20% of N applied and can reach 50% if NH_4^+ containing fertilizers are applied to the soil surface under certain conditions. Soil tillage practices influence the loss of fertilizer N due to the stratification of plant residues on the soil surface and the reduction of evaporation that results in a higher water content in native prairies and NT systems compared to CT. The higher moisture and C substrate levels present in the surface horizon of NT soils can influence the losses of N via the denitrification and NH_3 volatilization pathways.

1. Denitrification

Tillage management of soils can influence the rates of denitrification. The mulch of organic residues that normally accumulates on the surface of NT helps increase infiltration, reduces evaporation, and often results in higher soil moisture levels, resulting in greater possible denitrification rates with NT (Rice and Smith, 1982). Denitrification is strongly dependent on organic C availability and is expected to be higher in soils that contain a high level of organic C such as NT soils.

The potential for greater denitrification in NT soils was determined by Doran (1980a, 1980b) who found higher counts of denitrifying bacteria in the top 7.5 cm of NT as compared with CT, but lower counts in the 7.5–15-cm depth. The influence of the size of denitrifying populations and soluble C was confirmed by experiments showing denitrifying activity was substantially higher in the 0–7.5-cm depth for NT soils when compared with CT soils at six long-term comparison studies, but at the 7.5–15.0-cm depth, the denitrification potential for CT soils was the same or higher that the NT soils (Linn and Doran, 1984). Parkin and Meisinger (1989) found that in the surface 0–30 cm depth, laboratory measured denitrification potential was higher in NT soils treated with glucose and NO_3^- as compared with CT, but in core samples taken from the field in April, NT has significantly lower NO_3^- concentrations to a depth of 4 m as compared with CT plots. Since the samples were taken before fertilization and when soil temperatures were cool, little denitrification should have occurred before the sampling, suggesting that NO_3^- levels in NT are lower due to other N pathways and not a higher rate denitrification. Denitrification is temperature dependent with little activity reported below 10°C even in totally flooded cores (Craswell, 1978). As temperatures increase, the minimum soil water content for denitrification to occur decreases, but as temperatures increase so would the rapid plant uptake of NO_3^-, limiting the substrate need for biological reduction of NO_3^-. Jackson *et al.* (1989) determined that the half-life for NH_4^+ in a grassland was about one day, but NO_3^- was consumed by plants and microorganisms as fast as it was produced suggesting that in NT management, the higher density of plant roots in the soil surface horizon would limit the NO_3^- available for denitrification. This was confirmed by work of Parkin and Meisinger

(1989), who determined that tillage practices had little influence on denitrification below the root zone. Aulakh *et al.* (1984) reported gaseous N losses due to denitrification for NT were 12–16 kg N ha^{-1} $year^{-1}$ compared to 3–7 kg N ha^{-1} $year^{-1}$ for CT and accounted for a very small portion of the N balance. Rice and Smith (1982) concluded that NT may increase the potential for denitrification compared to CT, but supports the findings of Aulakh *et al.* (1984) that the significance of denitrification for reducing NO_3^- concentrations under NT may not be greater than the increased plant N uptake or N immobilization processes in NT.

2. Ammonia Volatilization

Volatilization of NH_3 has been attributed to the cause of low N use efficiency observed when NH_4^+ containing fertilizers are applied directly on the soil surface. A number of soil and environmental factors affect the amount of N lost through NH_3 volatilization including soil pH, cation exchange capacity, soil organic matter content, the amount and type of residue present, soil moisture content, temperature, humidity, and N source (Ernst and Massey, 1960; Fenn and Kissel, 1974; Terman, 1979). A thorough review on the different factors affecting NH_3 loss from soil was presented by Nelson (1982).

Low fertilizer N use has frequently been observed when NH_4^+ containing fertilizers such as urea or urea blends are applied directly to the surface residue in NT corn production systems (Keller and Mengel, 1986). The accumulation of residue on the surface of NT soils and increased moisture content has been attributed to increasing NH_3 volatilization from NH_4^+ containing fertilizers when compared to CT soils (Bandel *et al.,* 1980). Surface residue accumulation under MT or NT systems has been found to increase the activities of the urease enzyme three- to fourfold when compared to CT (Doran, 1980a; Dick, 1984). This enzyme is very important in soils where urea or urea containing fertilizers are applied. The low cost and high N content make urea a very attractive N source for agriculture, but large losses of surface applied urea-N from 30–50% of the N applied has been reported due to rapid hydrolysis of urea to NH_3 when compared to soil incorporation (Keller and Mengel, 1986; Fowler and Brydon, 1989). Much of this enzyme activity increase with conservation tillage practices has been reported to be due to the presence of a larger proportion of physiologically active microbial populations on the organic residue as compared to the soil with a significant difference between different residues tested (Beare *et al.,* 1990). Barreto and Westerman (1989) reported that urease activity was uniform under CT to a depth of 60 cm, where under NT or MT, urease activity was significantly increased in the top 10 cm. The activity of the undecomposed wheat straw grown at the sites was 28-fold greater than found in the soil and was reported to be the major source of the observed increase in enzymatic activity.

IV. CONCLUSIONS

Tillage systems influence soil properties. After adoption of NT practices in the early 1990s, farmers in the United States have reverted to more tillage due to perceived problems with NT. In general, as a soil is converted from CT to NT, less erosion occurs, with greater aggregate stability, water infiltration and availability, surface consolidation, and organic matter content. The stratification of surface residues results in cooler temperatures early in the season with the higher C and available water content influencing the nutrient availability. Understanding the physical changes in a NT soil that results in greater nutrient content of the soil, but overcoming reduced nutrient availability during the expression of early season yield potential is one of agriculture's greatest challenges for improving NT performance. One important finding of this review is the competition for applied and mineralized soil N between N immobilization, nitrifiers and plants that is increased when crop residue is stratified on the soil surface with NT management. Improved early season crop growth due to increased N availability under NT must be understood to change the trends in NT abandonment for corn production.

REFERENCES

Ajwa, H. A., Rice, C. W., and Sotomayor, D. (1998). Carbon and nitrogen mineralization in tallgrass prairie and agricultural soil profiles. *Soil Sci. Soc. Am. J.* **62,** 942–951.

Ajwa, H. A., and Tabatabai, M. A. (1994). Decomposition of different materials in soils. *Biol. Fertil. Soils* **18,** 175–182.

Allison, F. E. (1955). Does nitrogen applied to crop residues produce more humus? *Soil Sci. Soc. Am. Proc.* **25,** 210–211.

Allmaras, R. R., Copeland, S. M., Copeland, P. J., and Oussible, M. (1996). Spatial relations between oat residue and ceramic spheres when incorporated sequentially by tillage. *Soil Sci. Soc. Am. J.* **60:**1209–1216.

Amoto, M., and Ladd, J. N. (1980). Studies of nitrogen immobilization and mineralization in calcareous soils. V. Formation and distribution of isotope-labeled biomass during decomposition of ^{14}C- and ^{15}N-labeled plant material. *Soil Biol. Biochem.* **12,** 405–411.

Anderson, J. P. E., and Domsch, K. H. (1980). Quantities of plant nutrients in the microbial biomass of selected soils. *Soil Sci.* **130,** 211–216.

Angers, D. A., N'dayegamiye, A., and Côtè, D. (1993). Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. *Soil Sci. Soc. Am. J.* **57,** 512–516.

Angle, J. S., McClung, G., McIntosh, M. S., Thomas, P. M., and Wolf, D. C. (1984). Nutrient losses in runoff from conventional and no-till corn watersheds. *J. Environ. Qual.* **13,** 431–435.

Angle, J. S., Gross, C. M., Hill, R. L., and McIntosh, M. C. (1993). Soil nitrate concentrations under corn as affected by tillage, manure, and fertilizer applications. *J. Environ. Qual.* **22,** 141–147.

Arshad, M. A., Schnitzer, M., Angers, D. A., and Ripmeester, J. A. (1990). Effects of till vs. no-till on the quality of soil organic matter. *Soil Biol. Biochem.* **22,** 595–599.

Arshad, M. A., and Coen, G. M. (1992). Characterization of soil quality: Physical and chemical criteria. *Am. J. Altern. Agric.* **7,** 25–31.

Aulakh, M. S., Rennie, D. A., and Paul, E. A. (1984). Gaseous nitrogen losses from soils under zero-till as compared with conventional-till management systems. *J. Eviron. Qual.* **13,** 130–136.

Balesdent, J., Wagner, G. H., and Mariotti, A. (1988). Soil organic matter turnover in long-term field experiments as revealed by carbon-13 natural abundance. *Soil Sci. Soc. Am. J.* **52,** 118–124.

Bandel, V. A., Dzienia, S., Stanford, G., and Legg, J. O. (1975). N behavior under no-till vs. conventional corn culture. I. First-year results using unlabeled N fertilizer. *Agron. J.* **67,** 782–786.

Bandel, V. A., Dzienia, S., and Stanford, G. (1980). Comparison of N fertilizers for no-till corn. *Agron. J.* **72,** 337–341.

Barreto, H. J., and Westerman, R. L. (1989). Soil urease activity in winter wheat residue management systems. *Soil Sci. Soc. Am. J.* **53,** 1455–1458.

Bauer, A., and Black, A. L. (1992). Organic carbon effects on available water capacity of three soil textural groups. *Soil Sci. Soc. Am. J.* **56,** 248–254.

Beare, M. H., Neely, C. L., Coleman, D. C., and Hargrove, W. L. (1990). A substrate-induced respiration (SIR) method for measurement of fungal and bacterial biomass on plant residues. *Soil Biol. Biochem.* **22,** 585–594.

Beare, M. H., Pohland, B. R., Wright, D. H., and Coleman, D. C. (1993). Residue placement and fungicide effects on fungal communities in conventional and no-tillage soils. *Soil Sci. Soc. Am. J.* **57,** 392–399.

Biederbeck, V. O., Campbell, C. A., and Zenter, R. P. (1984). Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. *Can. J. Soil Sci.* **64,** 355–367.

Binford, G. D., Blackmer, A. M., and Cerrato, M. E. (1992). Relationships between corn yields and soil nitrate in late spring. *Agron. J.* **84,** 53–59.

Black, A. L. (1973). Soil property changes associated with crop residue management in a wheat-fallow rotation. *Soil Sci. Soc. Am. J.* **37,** 943–946.

Blevins, R. L., Thomas, G. W., and Cornelius, P. L. (1977). Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. *Agron. J.* **69,** 383–386.

Blevins, R. L., Thomas, G. W., Smith, M. S., Frye, W. W., and Cornelius, P. L. (1983). Changes in soil properties after 10 years continuous non-till and conventionally tilled corn. *Soil Tillage Res.* **3,** 135–146.

Blevins, R. L., Smith, M. S., and Thomas, G. W. (1984). Changes in soil properties under no-tillage. *In* "No-tillage Agriculture" (R. E. Phillips and S. H. Phillips, Ed.), pp. 190–230, Van Nostrand Reinhold Co., NY.

Blevins, R. L., Frye, W. W., Baldwin, P. , and Robertson, S. D. (1990). Tillage effects on sediment and soluble nutrient losses from a Maury silt loam soil. *J. Environ. Qual.* **19,** 683–686.

Blevins, R. L., and Frye, W. W. (1993). Conservation tillage: An ecological approach to soil management. *Adv. Agron.* **51,** 33–78.

Broadbent, F. E. (1986). Nitrogen immobilization in relation to N-containing fractions of soil organic matter. *In* "Isotopes and Radiation in Soil Organic Matter Studies," pp. 131–142. International Atomic Energy Agency, Vienna.

Broder, M. W., and Wagner, G. H. (1988). Microbial colonization and decomposition of corn, wheat, and soybean residue. *Soil Sci. Soc. Am. J.* **52,** 112–117.

Brown, P. L., and Dickey, D. D. (1970). Losses of wheat straw residue under simulated field conditions. *Soil Sci. Soc. Am. Proc.* **34:**118–121.

Bruce, R. R., Langdale, G. W., and Dillard, A. L. (1990). Tillage and crop rotation effect on characteristics of a sandy surface soil. *Soil Sci. Soc. Am. J.* **54,** 1744–1747.

Bruce, R. R., Langdale, G. W., West, L. T., and Miller, W. P. (1992). Soil surface modifications by biomass inputs affecting rainfall infiltration. *Soil Sci. Soc. Am. J.* **56,** 1614–1620.

Bruce, R. R., Langdale, G. W., West, L. T., and Miller, W. P. (1995). Surface soil degradation and soil productivity restoration and maintenance. *Soil Sci. Soc. Am. J.* **59,** 654–660.

Buchanan, M., and King, L. D. (1993). Carbon and phosphorus losses from decomposing crop residues in no-till and conventional till agroecosystems. *Agron. J.* **85,** 631–638.

Bundy, L. G., Andraski, T. W., and Daniel, T. C. (1992). Placement and timing of nitrogen fertilizers for conventional and conservation tillage corn production. *J. Prod. Agric.* **5,** 214–221.

Burge, W. D., and Broadbent, F. E. (1961). Fixation of ammonia by organic soils. *Soil Sci. Soc Am. Proc.* **25,** 199–204.

Burwell, R. E., Timmons, D. R. and Holt, R. F. (1975). Nutrient transport in surface runoff as influenced by soil cover and seasonal periods. *Soil Sci. Soc. Am. Proc.* **39,** 523–528.

Campbell, C. A., Paul, E. A., and McGill, W. B. (1976). Effect of cultivation and cropping on the amounts and forms of soil N. *In* "Proc. Western Canadian Nitrogen Symp." (W. A. Rice Ed.), pp. 9–101. Alberta Agriculture, Edmonton Alberta, Canada.

Campbell, C. A., Zentner, R. P., Selles, F., McConkey, B. G., and Dyck, F. B. (1993). Nitrogen management for spring wheat growth annually on zero-tillage: yields and nitrogen use efficiency. *Agron. J.* **85,** 107–114.

Carter, M. R., and Rennie, D. A. (1982). Changes in soil quality under zero tillage farming systems: distribution of microbial biomass and mineralizable C and N potentials. *Can. J. Soil Sci.* **62,** 587–597.

Carter, M. R., and Rennie, D. A. (1984). Dynamics of soil microbial biomass N under zero and shallow tillage for spring wheat, using ^{15}N urea. *Plant and Soil.* **76,** 157–164.

Chase, C. A., and Duffy, M. D. (1991). An economic analysis of the Nashua tillage study: 1978–1987. *J. Prod. Agric.* **4,** 91–98.

Christensen, N. L., and McAller, T. (1985). Soil mineral nitrogen transformations during succession in the Piedmont of North Carolina. *Soil Biol. Biochem.* **5,** 675–681.

Christensen, N. B., Lindemann, W. C., Salazar-Sosa, E., and Gill, L. R. (1994). Nitrogen and carbon dynamics in no-till and stubble mulch tillage systems. *Agron. J.* **86,** 298–303.

Cochran, V. L., Elliott, L. F., and Papendick, R. L. (1980). Carbon and nitrogen movement from surface-applied wheat straw. *Soil Sci. Soc. Am. J.* **44,** 978–982.

Conservation Technology Information Center (CTIC) (1998). "1998 National Crop Residue Management Survey." CTIC, West Lafayette, IN.

Craswell, E. T. (1978). Some factors influencing denitrification and nitrogen immobilization in a clay soil. *Soil Biol. Biochem.* **10,** 241–245.

Dabney, S. M., Murphree, C. E., and Meyer, L. D. (1993). Tillage, row spacing, and cultivation affect erosion from soybean cropland. *Trans. ASAE.* **36,** 87–94.

Deibert, E. J., French, E., and Hoag, B. (1986). Water storage and use by spring wheat under conventional tillage and no-till in continuous and alternate crop-fallow systems in the northern great plains. *J. Soil Water Conserv.* **41,** 53–58.

Deibert, E. J., and Utter, R. A. (1989). Sunflower growth and nutrient uptake: response to tillage system, hybrid maturity and weed control method. *Soil Sci. Soc. Am. J.* **53,** 133–138.

Dick, W. A. (1983). Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. *Soil Sci. Soc. Am. J.* **47,** 102–107.

Dick, W. A. (1984). Influence of long-term tillage and crop rotation combinations on soil enzyme activities. *Soil Sci. Soc. Am. J.* **48,** 569–574.

Dick, W. A., and Van Doren, D. M. Jr. (1985). Continuous tillage and rotation combinations effects on corn, soybean, and oat yields. *Agron. J.* **77,** 459–465.

Dick, W. A., McCoy, E. L., Edwards, W. M., and R. Lal. (1991). Continuous application of no-tillage to Ohio soils. *Agron. J.* **83,** 65–73.

Doran, J. W. (1980a). Soil microbial and biochemical changes associated with reduced tillage. *Soil Sci. Soc. Am. J.* **44,** 765–771.

Doran, J. W. (1980b). Microbial changes associated with residue management with reduced tillage. *Soil Sci. Soc. Am. J.* **44,** 518–524.

Doran, J. W. (1987). Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. *Biol. Fertil. Soils.* **5,** 68–75.

Doran, J. W., and Smith, M. S. (1987). Organic matter management and utilization of soil and fertilizer nutrients. *In* "Soil Fertility and organic matter as critical components of Production Systems," (R. F. Follet, Ed.) pp. 53–72. Spec. Pub. 19, Soil Sci. Soc. Am., Madison.

Dou, Z., Fox, R. H., and Toth, J. D. (1995). Seasonal soil nitrate dynamics in corn as affected by tillage and nitrogen source. *Soil Sci. Soc. Am. J.* **59,** 858–864.

Drees, L. R., Karathanasis, A. D., Wilding, L. P., and Blevins, R. L. (1994). Micromorphological characteristics of long-term no-till and conventionally tilled soils. *Soil Sci. Soc. Am. J.* **58,** 508–517.

Dunn, G. H., and Phillips, R. E. (1991). Macroporosity of a well-drained soil under no-till and conventional tillage. *Soil Sci. Soc. Am. J.* **55,** 817–823.

Eck, H. V., and Jones, O. R. (1992) Soil nitrogen status as affected by tillage, crops, and crop sequences. *Agron. J.* **84,** 660–668.

Edwards, J. H., Wood, C. W., Thurlow, D. L., and Ruf, M. E. (1992). Tillage and crop rotation effects on fertility status of a hapludult soil. *Soil Sci. Soc. Am. J.* **56,** 1577–1582.

Ernst, J. W., and Massey, H. F. (1960). The effects of several factors on volatilization of ammonia formed from urea in soils. *Soil Sci. Soc. Am. Proc.* **24,** 87–90.

Estes, G. O. (1972). Elemental composition of maize grown under no-till and conventional tillage. *Agron. J.* **64,** 733–735.

Farahani, H. J., Peterson, G. A., Westfall, D. G., Sherrod, L. A., and Ahuja, L. R. (1998). Soil water storage in dryland cropping systems: The significance of cropping intensification. *Soil Sci. Soc. Am. J.* **62,** 984–991.

Fenn, L. B., and Kissel, D. E. (1974). Ammonia volatilization from surface applications of ammonia compounds on calcareous soils. II. Effects of temperature and rate of ammonium nitrogen applications. *Soil Sci. Soc. Am. Proc.* **38,** 606–610.

Fleige, H. and Baemumer, K. (1974). Effect of zero-tillage on organic carbon and total N content, and their distribution in different N fractions in loessial soils. *Agro-ecosystems* **1,** 19–29.

Follett, R. F., and Peterson, G. A. (1988). Surface soil nutrient distribution as affected by wheat-fallow tillage systems. *Soil Sci. Soc. Am. J.* **52,** 141–147.

Follett, R. F., and Schimel, D. S. (1989). Effect of tillage practices on microbial biomass dynamics. *Soil Sci. Soc. Am. J.* **53,** 1091–1096.

Fortin, M. C. (1993). Soil temperature, soil water, and no-till corn development following in-row residue removal. *Agron. J.* **85,** 571–576.

Fowler, D. B., and Brydon, J. (1989). No-till winter wheat production on the Canadian prairies: placement of urea and ammonium nitrate fertilizers. *Agron. J.* **81,** 518–524.

Fox, R. H., and Bandel, V. A. (1986). Nitrogen utilization with no-tillage. *In* "No-tillage and Surface Tillage Agriculture, The Tillage Revolution." (M. A. Sprague and G. B. Triplett, Ed.), pp. 117–148. John Wiley & Sons, NY.

Franzluebbers, A. J., Hons, F. M., and Zuberer, D. A. (1994). Long-term changes in soil carbon and nitrogen pools in wheat management systems. *Soil Sci. Soc. Am. J.* **58,** 1639–1645.

Franzluebbers, A. J., Arshad, M. A., and Ripmeester, J. A. (1996). Alterations in canola residue composition during decomposition. *Soil Biol. Biochem.* **28,** 1289–1295.

Fredrickson, J. K., Koehler, F. E., and Cheng, H. H. (1982). Availability of ^{15}N-labeled nitrogen in fertilizer and in wheat straw to wheat in tilled and no-till soil. *Soil Sci. Soc. Am. J.* **46,** 1218–1222.

Gale, P. M., and Gilmour, J. T. (1988). Net mineralization of carbon and nitrogen under aerobic and anaerobic conditions. *Soil Sci. Soc. Am. J.* **52,** 1006–1010.

Gantzer, C. J., and Blake, G. R. (1978). Physical characteristics of le sueur clay loam soil following no-till and conventional tillage. *Agron. J.* **70,** 853–857.

Garcia, F. O., and Rice, C. W. (1994). Microbial biomass dynamics in tallgrass prairie. *Soil Sci. Soc. Am. J.* **58,** 816–823.

Gast, R. G., Nelson, W. W., and Randall, G. W. (1978). Nitrate accumulation in soils and loss in tile drain following nitrogen applications to continuous corn. *J. Environ. Qual.* **7,** 258–261.

Gerard, C. J. (1987). Methods to improve water infiltration on fragile soils. *In* "Conservation Tillage: Today and Tomorrow," (T. J. Gerik, and B. H. Harris, Ed.) pp. 72–75, Proceedings of the Southern Region No-tillage Conference, College Station TX.

Ghaffarzadeh, M., Prechac, F. G., and Cruse, R. M. (1997). Tillage effect on soil water content and corn yield in a strip intercropping system. *Agron. J.* **89,** 893–899.

Green, C. J., and Blackmer, A. M. (1995). Residue decomposition effect on nitrogen availability to corn following corn or soybean. *Soil Sci. Soc. Am. J.* **59,** 1065–1070.

Green, C. J., Blackmer, A. M., and Horton, R. (1995). Nitrogen effects on conservation of carbon during corn residue decomposition in soil. *Soil Sci. Soc. Am. J.* **59,** 453–459.

Griffin, P. M. (1972). Ecology of soil fungi. Syracuse University Press, Syracuse.

Griffith, D. R., Mannering, J. V., and Moldenhauer, W. C. (1977). Conservation tillage in the eastern cornbelt. *J. Soil Water Conserv.* **32,** 20–28.

Hammel, J. E. (1995). Long-term tillage and crop rotation effects on winter wheat production in northern Idaho. *Agron. J.* **87,** 16–22.

Hass, H. J., Evans, C. E., and Miles, E. F. (1957). Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. USDA Tech. Bull. 1164, U. S. Government Printing Office, Washington, D.C.

Hendrix, P. E., Parmalee, R. W. Crossby, Jr., D. A. Coleman, D. C., Odom, E. P., and Groffman, P. M. (1986). Detritus food webs in conventional and no-tillage agroecosystems. *BioScience* **36,** 374–380.

Hill, R. I., and Cruse, R. M. (1985). Tillage effects on bulk density and soil strength of two Mollisols. *Soil Sci. Soc. Am. J.* **49,** 1270–1273.

Holland, E. A., and Coleman, D. C. (1987). Litter placement effects on microbial and organic matter dynamics in an agroecosystem. *Ecology.* **68,** 425–433.

House, G. J., Stinner, B. R., Crossley, D. A. Jr., Odum, and Langdale, G. W. (1984). Nitrogen cycling in conventional and no-tillage agroecosystems in the Southern Piedmont. *J. Soil Water Cons.* **39,** 194–200.

Hunt, P. G., Karlen, D. L., Matheny, T. A., and Quisenberry, V. L. (1996). Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. *J. Soil Water Cons.* **51,** 255–258.

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

Jackson, L. E., Schimel, J. P., and Firestone, M. K. (1989). Short-term partitioning of ammonium and nitrate between plants and microbes in an annual grassland. *Soil Biol. Biochem.* **21,** 409–415.

Jansson, S. L. (1958). Tracer studies on nitrogen transformations in soil and special attention to mineralization-immobilization relationships. *Kungl. Lantbrukshogskolans Annaler* **24,** 101–361.

Jenkinson, D. S., and Ladd, J. N. (1981). Microbial biomass in soil: Measurement and turnover. *In* "Soil Biochemistry, Vol. 5" (E. A. Paul, and A. D. McLauren, Ed.), pp. 415–471. Marcel Dekker, New York.

Johnson, H. P., Baker, J. L., Shrader, W. D., and Laflen, J. M. (1979). Tillage system effects on sediment and nutrients in runoff from small watersheds. *Trans. ASAE* **22,** 1110–1114.

Johnson, A. M., and Hoyt, G. D. (1999). Changes to the environment under conservation tillage. *HorTechnology.* **9,** 380–393.

Johnston, A. M., and Fowler, D. B. (1991a). No-till winter wheat production: Response to spring applied nitrogen fertilizer form and placement. *Agron. J.* **83,** 722–728.

Johnston, A. M., and Fowler, D. B. (1991b). No-till wheat dry matter and tissue nitrogen response to nitrogen fertilizer form and placement. *Agron. J.* **83,** 1035–1043.

Kanwar, R. S., Colvin, T. S., and Karlen, D. L. (1997). Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. *J. Prod. Agric.* **10,** 227–234.

Kapusta, G., Krausz, R. F., and Matthews, J. L. (1996). Corn yield is equal in conventional, reduced, and no tillage after 20 years. *Agron. J.* **88,** 812–817.

Karlen, D. L., Rosek, M. J., Gardner, J. C., Allan, D. L., Alms, M. J., Bezdicek, D. F., Flock, M., Huggins. D. R., Miller, B. S., and Staben, M. L. (1999). Conservation reserve program effects on soil quality indicators. *J. Soil Water Conserv.* **54,** 439–444.

Keeney, D. R., and DeLuca, T. H. (1993). Des Moines river nitrate in relation to watershed agricultural practices: 1945 versus 1980s. *J. Eviron. Qual.* **22,** 267–272.

Keeney, D. R., and Bremner, J. M. (1964). Effect of cultivation on the nitrogen distribution in soils. *Soil Sci. Soc. Am. Proc.* **28,** 653–656.

Keller, G. D., and Mengel, D. B. (1986). Ammonia volatilization from nitrogen fertilizers surface applied to no-till corn. *Soil Sci. Soc. Am. J.* **50,** 1060–1063.

Kelley, K. R., and Stevenson, F. J. (1995). Forms and nature of organic N in soil. *Fertilizer Res.* **42,** 1–11.

Kitur, B. K., Smith, M. S., Blevins, R. L., and Frye, W. W. (1984). Fate of ^{15}N-depeleted ammonium nitrate applied to no-tillage and conventional tillage corn. *Agron. J.* **76,** 240–242.

Knowles, T. C., Hipp, B. W., Graff, P. S., and Marshall, D. S. (1993). Nitrogen nutrition of rainfed winter wheat in tilled and no-till sorghum and wheat residues. *Agron. J.* **85,** 886–893.

Kolberg, R. L., Kitchen, N. R., Westfall, D. G., and Peterson, G. A. (1996). Cropping intensity and nitrogen management impact of dryland no-till rotation in the semi-arid western Great Plains. *J. Prod. Agric.* **9,** 517–522.

Kristensen, E., Ahmed, S. I., and Devol, A. H. (1995). Aerobic and anaerobic decomposition of organic matter in marine sediemnts: Which is faster? *Limnol. Oceanogr.* **40,** 1430–1437.

Laflen, J. M., Baker, J. L., Hartwig, R. O., Buchele, W. F., and Johnson, H. (1978). Soil and water loss from conservation tillage systems. *Trans. ASAE* **21,** 881–885.

Lal, R., (1991). Soil structure and sustainability. *J. Sustainable Agric.* **1,** 67–92.

Lal, R., Mahboubi, A. A., and Fause, N. R. (1994). Long-term tillage and rotation effects on properties of a central Ohio soil. *Soil Sci. Soc. Am. J.* **58,** 517–522.

Langdale, G. W., Barnett, A. P., Leonard, R. A., and Flemming, W. G. (1979). Reduction of soil erosion by the no-till system in the southern Pediment. *Trans. ASAE* **22,** 82–86.

Larney, F. J., and Kladivko, E. J. (1989). Soil strength properties under four tillage systems at three long-term study sites in Indiana. *Soil Sci. Soc. Am. J.* **53,** 1539–1545.

Larson, W. E., Clapp, C. E., Pierre, W. H., and Morachan, Y. B. (1972). Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus, and sulfur. *Agron. J.* **64,** 204–208.

Ledgard, S. F., Brier, G. J., and Sarathchandra, S. U. (1989). Plant uptake and microbial immobilization of ^{15}N-labelled ammonium applied to grass-clover pasture: influence of simulated winter temperature and time of application. *Soil Biol. Biochem.* **21,** 667–670.

Lindstrom, J. J., and Onstad, C. A. (1984). Influence of tillage systems on soil physical parameters and infiltration after planting. *J. Soil Water Conserv.* **39,** 149–152.

Lindstrom, M. J., Voorhees, W. R., and Randall, G. W. (1981). Long-term tillage effects on interrow runoff and infiltration. *Soil Sci. Soc. Am. J.* **45,** 945–948.

Linn, D. M., and Doran, J. W. (1984). Aerobic and anaerobic microbial populations in no-till and plowed soils. *Soil Sci. Soc. Am. J.* **48,** 794–799.

Locke, M. A., and Hons, F. M. (1988). Fertilizer placement effects on seasonal nitrogen accumulation and yield of no-tillage and conventional tillage sorghum. *Agron. J.* **80,** 180–185.

Logsdon, S. D., Kaspar, T. C., and Cambardella, C. A. (1999). Depth-incremental soil properties under no-till or chisel management. *Soil Sci. Soc. Am. J.* **63,** 197–200.

Lynch, J. M., and Panting, L. M. (1980). Variations in the size of the soil biomass. *Soil Biol. Biochem.* **12,** 547–550.

Mahboubi, A. A., Lal, R., and Faussey, N. R. (1993). Twenty-eight years of tillage effects on two soils in Ohio. *Soil Sci. Soc. Am. J.* **57,** 506–512.

Mannering, J. V., and Fenster, C. R. (1977). Vegetative water erosion control for agricultural areas. *In* "Soil Erosion and Sedimentation." Am. Soc. Agric. Eng., St. Joseph, MI.

Mannering, J. V., and Fenster, C. R. (1983). What is conservation tillage? *J. Soil Water Conserv.* **38,** 141–143.

Mannering, J. V., Griffith, D. R., and Richey, C. B. (1975). "Tillage for Moisture Conservation," Pap. No. 75–2523. Am. Soc. Agric. Eng., St. Joseph, MI.

Martens, D. A. (2000). Management and crop residue influence soil aggregate stability. *J. Environ. Qual.* **29,** 723–727.

Maskina, M. S., Power, J. F., Doran, J. W., and Wilhelm, W. W. (1993). Residual effects of no-till crop residues on corn yield and nitrogen uptake. *Soil Sci. Soc. Am. J.* **57,** 1555–1560.

McCarty, G. W., Lyssenko, N. N., and Starr, J. L. (1998). Short-term changes in soil carbon and nitrogen pools during tillage management transition. *Soil Sci. Soc. Am. J.* **62,** 1564–1571

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

Meints, V. W., and Peterson, G. A., (1977). The influences of cultivation on the distribution of N in soils of the ustoll suborder. *Soil Sci.* **124,** 334–342.

Merrill, S. D., Black, A. L., and Bauer, A. (1996). Conservation tillage affects root growth of dryland spring wheat under drought. *Soil Sci. Soc. Am. J.* **60,** 575–583.

Mielke, L. N., Doran, J. W., and Richards, K. A. (1986). Physical environment near the surface of plowed and no-tilled soils. *Soil Till. Res.* **7,** 355–366.

Moschler, W. W., and Martens, D. C. (1975). Nitrogen, phosphorus, and potassium requirements in notillage and conventionally tilled corn. *Soil Sci. Soc. Am. Proc.* **39,** 886–891.

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

Mutchler, K. C., and Carter, J. D. (1983). Soil erodibility variation during the year. *Trans. ASAE.* **27,** 1364–1369.

Nelson, D. W. (1982). Gaseous losses of nitrogen other than through denitrification. *In* "Nitrogen in Agricultural Soils," (F. J. Stevenson, Ed.). pp. 327–364. Am. Soc. Agron. Madison.

Nommik, H., and Nilsson, K. O. (1963). Fixation of ammonia by the organic fraction of the soil. *Acta Agric. Scand.* **13,** 371–390.

Oveson, M. M. (1966). Conservation of soil nitrogen in a wheat summer fallow farming practice. *Agron. J.* **58,** 444–447.

Pajasok, T., and Kay, B. D. (1990). Assesment of a combination of wet sieving and turbidmetry to characterize the structural stability of moist aggregates. *Can. J. Soil Sci.* **70,** 33–42.

Papendick, R. I., and Parr, J. F., (1992). Soil quality—The key to a sustainable agriculture. *Am. J. Alter. Agric.* **7,** 2–3.

Parkin, T. B., and Meisinger, J. J. (1989). Denitrification below the crop rooting zone as influenced by surface tillage. *J. Environ. Qual.* **18,** 12–16.

Peterson, G. A., Schlegel, A. J., Tanaka, D. L., and Jones, O. R. (1996). Precipitation use efficiency as affected by cropping and tillage systems. *J. Prod. Agric.* **9,** 180–186.

Phillips, S. R., Olson, K. R., Siemens, J. C., and Ebelhar, S. A. (1997). Economics of conservation tillage systems for CRP land in Southern Illinois. *J. Prod. Agric.* **10,** 483–489.

Pierce, F. J., Fortin, M. C., and Staton, M. J. (1994). Periodic plowing effects on soil properties in a notill farming system. *Soil Sci. Soc. Am. J.* **58,** 1782–1787.

Power, J. F., Doran, J. W., and Wilhelm, W. W. (1986). Uptake nitrogen from soil, fertilizer, and crop residues by no-till corn and soybean. *Soil Sci. Soc. Am. J.* **50,** 137–142.

Powers, W. L., Baer, J. U., and Skopp, J. (1992). Alternative soil water release parameters for distinguishing tillage effects. *Soil Sci. Soc. Am. J.* **56,** 873–878.

Powlson, D. S. (1993). Understanding the soil nitrogen cycle. *Soil Use Manage.* **9,** 86–94.

Puri, G., and Ashman, M. R. (1998). Relationship between soil microbial biomass and gross N mineralization. *Soil Biol. Biochem.* **30,** 251–256.

Puri, G., and Ashman, M. R. (1999). Microbial immobilization of ^{15}N-labelled ammonium and nitrate in the temperate woodland soil. *Soil Biol. Biochem.* **31,** 929–931.

Rao, S. C., and Dao T. H. (1992). Fertilizer placement and tillage effects of nitrogen assimilation by wheat. *Agron. J.* **84,** 1028–1032.

Rasmussen, P. E., Allmaras, R. R., Rohde, C. R., and Roager, N. C., Jr. (1980). Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. *Soil Sci. Soc. Am. J.* **44,** 596–600.

Rasmussen, P. E., and Douglas, Jr., C. L. (1991). Effect of rill erosion during early vegetative growth on winter wheat yield. *Agron. J.* **83,** 729–732.

Rasse, D. P., and Smucker, A. J. M. (1999). Tillage effects on soil nitrogen and plant biomass in a corn-alfalfa rotation. *J. Environ. Qual.* **28,** 873–880.

Recous, S., and Mary, B. (1990). Microbial immobilization of ammonium and nitrate in cultivated soils. *Soil Biol. Biochem.* **22,** 913–922.

Recous, S., Machet, J. M., and Mary, B. (1992). The partitioning of fertilizer-N between soil and crop: Comparison of ammonium and ntirate applications. *Plant Soil.* **144,** 101–111.

Rice, C. W., and Smith, S. M. (1982). Denitrification in no-till and plowed soils. *Soil Sci. Soc. Am. J.* **46,** 1168–1173.

Rice, C. W., and Smith, M. S. (1983). Nitrification of fertilizer and mineralized ammonium in no-till and plowed soil. *Soil Sci. Soc. Am. J.* **47,** 1125–1129.

Rice, C. W., and Smith, M. S. (1984). Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. *Soil Sci. Soc. Am. J.* **48,** 295–297.

Rice, C. W., Smith, M. S., and Blevins, R. L. (1986) Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production. *Soil Sci. Soc. Am. J.* **50,** 1206–1210.

Rice, C. W., and Tiedje, J. M. (1989). Regulation of nitrate assimilation by ammonium in soils and in isolated soil microorganisms. *Soil Biol. Biochem.* **21,** 597–602.

Riha, S. J., Campbell, G. S., and Wolfe, J. (1986). A model of competition for ammonium among heterotrophs, nitrifiers and roots. *Soil Sci. Soc. Am. J.* **50,** 1463–1466.

Scheu, S., and Parkinson, D. (1995). Successional changes in microbial biomass, respiration and nutrient status during litter decomposition I an aspen and pine forest. *Biol. Fertil. Soils* **19,** 327–332.

Schimel, D. S., Coleman, D. C., and Horton, K. A. (1985). Soil organic matter dynamics in paired rangeland and cropland toposequences in North Dakota. *Geoderma.* **36,** 201–214.

Schimel, D. S. (1986). Carbon and nitrogen turnover in adjacent grassland and cropland ecosystems. *Biogeochemistry* **2,** 345–357.

Schomberg, H. H., Steiner, J. L., and Unger, P. W. (1994). Decomposition and nitrogen dynamics of crop residues: Residue quality and water effects. *Soil Sci. Soc. Am. J.* **58,** 372–381.

Sharma, S., Rangger, A., and Insam, H. (1998). Effects of decomposing maize litter on community level physiological profiles of soil bacteria. *Microb. Ecol.* **35,** 301–310.

Shen, S. M., Hart, P. B. S., Powlson, D. S., and Jenkinson, D. S. (1989). The nitrogen cycle in the Broadbalk wheat experiment: ^{15}N-labelled fertilizer residues in the soil and in the soil microbial biomass. *Soil Biol. Biochem.* **21,** 529–533.

Shipitalo, M. J., Edwards, W. M., and Redmond, C. E. (1994). Comparison of water movement and quality in earthworm burrows and pan lysimeters. *J. Environ. Qual.* **23,** 1345–1351.

Siemans, J. C., and Oschwald, W. R. (1976). Erosion for corn tillage systems. *Trans. ASAE* **19,** 69–72.

Smika, D. E. (1990). Fallow management practices for wheat production in the central Great Plains. *Agron. J.* **82,** 319–323.

Staley, T. E., Edwards, W. M., Scott, C. L., and Owens, L. B. (1988). Soil microbial biomass and organic component alterations in a no-tillage chronosequence. *Soil Sci. Soc. Am. J.* **52,** 998–1005.

Stanford, G. (1982). Assessment of soil nitrogen availability. *In* "Nitrogen in Agricultural Soils," (F. J. Stevenson, ed.). p. 651. American Society of Agronomy, Madison.

Staricka, J. A., Allmaras, R. R., and Nelson, W. W. (1991). Spatial variation of crop residue incorporated by tillage. *Soil Sci. Soc. Am. J.* **55,** 1668–1674.

Staricka, J. A., Allmaras, R. R., Nelson, W. W., and Larson, W. E. (1992). Soil aggregate longevity as determined by incorporation of ceramic spheres. *Soil Sci. Soc. Am. J.* **56,** 1591–1597.

Stecker, J. A., Buchholz, D. D., Hanson, R. G., Wollenhaupt, N. C., and McVay, K. A. (1995). Tillage and rotation effects on corn yield response to fertilizer nitrogen on aqualf soils. *Agron. J.* **87,** 409–415.

Stevenson, F. J. (1994). Organic forms of soil nitrogen. *In* "Humus Chemistry." pp. 59–95. John Wiley & Sons, NY.

Stienstra, A. W., Gunnewiek, K. P., and Laanbroek, H. J. (1994). Repression of nitrification in soils under a climax grassland vegetation. *FEMS Microbiol. Ecol.* **14,** 45–52.

Sweeney, D. W. (1993). Fertilizer placement and tillage effects on grain sorghum growth and nutrient uptake. *Soil Sci. Soc. Am. J.* **57,** 532–537.

Terman, G. L. (1979). Volatilization losses of nitrogen as ammonia from surface-applied fertilizers, organic amendments, and crop residues. *Adv. Agron.* **31,** 189–223.

Thomas, G. W., Blevins, R. L., Phillips, R. E., and McMahon, M. A. (1973). Effect of killed sod mulch on nitrate movement and corn yield. *Agron. J.* **65,** 736–739.

Tollner, E. W., Hargrove, W. L., and Langdale, G. W. (1984). Influence of conventional and no-till practices on soil physical properties in the Southern Piedmont. *J. Soil Water Conserv.* **39,** 73–76.

Tracy, P. W., Westfall, D. G., Elliott, E. T., Peterson, G. A., and Cole, C. V. (1990). Carbon, nitrogen, phosphorus, and sulfur mineralization in plow and no-till cultivation. *Soil Sci. Soc. Am. J.* **54,** 457–461.

Tsegaye, T., and Hill, R. L. (1996). Wheel traffic placement effects on corn response under no-tillage and conventional tillage. *J. Prod. Agric.* **9,** 95–101.

Vanderlip, R. L. (1979). How a sorghum plant develops. Coop. Ext. Serv. Bull. KS-3. Kansas State Univ., Manhattan.

Van Doren, D. M., Jr., Triplett, G. B., Jr., and Henry, J. E. (1976). Influence of long term tillage, crop rotation, and soil type combinations on corn yield. *Soil Sci. Soc. Am. J.* **40,** 100–105.

Van Doren, D. M., Jr., Moldenhauer, W. C., and Triplett, G. B. (1984). Influence of long-term tillage and crop rotation on water erosion. *Soil Sci. Soc. Am. J.* **48,** 636–640.

Verhagen, F. J. M., Hageman, P. E. J. Woldendorp, J. W., and Laanbroek, H. J. (1994) Competition for ammonium between nitrifying bacteria and plant roots in soil in pots; effects of grazing by flagellates and fertilization. *Soil Biol. Biochem.* **26,** 89–96.

Vyn, T. J., and Raimbault, B. A. (1993). Long-term effect of five tillage systems on corn response and soil structure. *Agron. J.* **85,** 1074–1079.

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

Wagger, M. G., and Denton, H. P. (1989). Tillage effects on grain yields in a wheat, double-crop soybean, and corn rotation. *Agron. J.* **81,** 493–498.

Weil, R. R. Weismill, R. A., and Turner, R. S. (1990). Nitrate contamination of groundwater under irrigated Coastal Plain soils. *J. Environ. Qual.* **19,** 441–448.

Wendt, R. C., and Burwell, R. E. (1985). Runoff and soil losses for conventional, reduced, and no-till corn. *J. Soil Water Conserv.* **40,** 450–454.

Wershaw, R. L. (1993). Model for humus in soils and sediments. *Environ. Sci. Technol.* **27,** 814–816.

West, L. T., Miller, W. P., Bruce, R. R., Langdale, G. W., Laflen, J. M., and Thomas, A. W. (1992). Cropping system and consolidation effects on rill erosion in the Georgia Piedmont. *Soil Sci. Soc. Am. J.* **56,** 1238–1243.

Westfall, D. G., Havlin, J. L., Hergert, G. W., and Raun, W. R. (1996). Nitrogen management in dryland cropping systems. *J. Prod. Agric.* **9,** 192–199.

Wickramasinghe, K. N., Rodgers, G. A., and Jenkinson, D. S. (1985). Transformations of nitrogen fertilizers in soil. *Soil Biol. Biochem.* **17,** 625–630.

Wilson, D. O., and Hargrove, W. L. (1986). Release of nitrogen from crimson clover residue under two tillage systems. *Soil Sci. Soc. Am. J.* **50,** 1251–1254.