SEASONAL AVAILABILITY AND MINERALIZATION OF NITROGEN IN COTTON AND SOYBEAN CROPPING SYSTEMS IN MISSISSIPPI

by

Lisa Sanae Sumi

A thesis submitted in conformity with the requirements for the degree of Master of Science
Graduate Department of Geography
University of Toronto

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Abstract

In order to minimize losses of nitrogen (N) from agroecosystems, the availability of inorganic forms of N should be synchronized with crop N requirements. In this study, net N mineralization rates were measured throughout the growing season for conventional-till (CT) and no-till (NT) cotton and soybean cropping systems in northern Mississippi to determine if the soils were supplying enough N to meet crop demands in a timely manner. On a seasonal basis, the two NT systems mineralized more N than the CT systems, although neither the cotton nor the soybean soils mineralized enough N to fully satisfy crop N demands. The cotton crops did, however, receive sufficient N to meet demands via the addition of 100 kg ha\textsuperscript{-1} N fertilizer. The accumulation of inorganic N during the growing season suggests that the fertilizer N additions were excessive, and could result in N losses via leaching and denitrification.
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# Table of Contents

Abstract ........................................................................................................................................... ii
Acknowledgments .......................................................................................................................... iii
Table of Contents ......................................................................................................................... iv
List of Tables ..................................................................................................................................... vi
List of Figures .................................................................................................................................... vii
List of Appendices ........................................................................................................................... viii

1.0 INTRODUCTION ......................................................................................................................... 1
  1.1 Objectives ................................................................................................................................... 2

2.0 LITERATURE REVIEW ................................................................................................................... 3
  2.1 Nitrogen contributions from indigenous soil organic matter .................................................... 3
  2.2 Nitrogen contributions from organic additions ........................................................................... 8
  2.3 Nitrogen contributions from synthetic fertilizers ....................................................................... 12

3.0 SITE DESCRIPTION ....................................................................................................................... 17

4.0 METHODS ...................................................................................................................................... 18
  3.1 Field Procedures ....................................................................................................................... 18
  3.2 Laboratory Analyses ................................................................................................................. 19
  3.3 Statistical Analyses ................................................................................................................... 20

5.0 RESULTS AND DISCUSSION ......................................................................................................... 21
  5.1 Total Carbon and Nitrogen ......................................................................................................... 21
  5.2 Nitrogen Mineralization and Immobilization ............................................................................. 28
    5.2.1 Divergences from the Expected ............................................................................................ 33
      5.2.1.1 Early Net Mineralization .............................................................................................. 33
      5.2.1.2 High Net Immobilization ............................................................................................. 42
      5.2.2 Cumulative Net Mineralized N ($N_m$) ............................................................................. 47
5.3 Soil Inorganic N

5.3.1 Ammonium
5.3.2 Nitrate
5.3.3 Synchrony

5.4 Anomalies and Artefacts

5.4.1 Soil water content: covered core versus bulk soil
5.3.2 Soil water content and nitrogen losses
5.4.3 Priming revisited

6.0 CONCLUSIONS AND RECOMMENDATIONS

Bibliography
Appendix 1
Appendix 2
Table 1. Distribution of total C and total N in no-till and conventional-till cotton and soybean plots .......................................................... 22

Table 2. Estimated annual N inputs in the cotton and soybean cropping systems .... 23

Table 3. Summary of some published reports of crop residue C and N characteristics .................................................................................................. 36

Table 4. Cumulative N mineralized between April and December, 1996, in CT and NT cotton and soybeans .......................................................... 47

Table 5. Chemical composition of cotton and soybean residues .......................................................... 49

Table 6. Cotton plant C and N concentrations ................................................................................. 70

Table 7. Soil water contents (% dry weight) in bulk soil versus covered cores in CT (CO1) and NT (CO3)cotton plots......................................................... 79
Figure 1. Soil total carbon contents as affected by cropping system and sampling date ... 26
Figure 2. Net mineralization rates in cotton and soybean plots (0-2.5 cm depth) ............... 30
Figure 3. Net mineralization rates in cotton and soybean plots (2.5-7.5 cm depth) ........... 31
Figure 4. Soil water content in covered incubation cores in CO1 and CO3 plots ............... 35
Figure 5. Net mineralization rates in CT and NT cotton, all positions (0-2.5 cm depth) ... 41
Figure 6. Changes in NH$_4^+$ and NO$_3^-$ during 14 soil incubations in CT and NT cotton .... 44
Figure 7. Net mineralization rates and soil water contents in wheeltrack and no-track .... 45
Figure 8. Cumulative mineralized N (3 positions, 2 depths) in cotton and soybean ....... 47
Figure 9. Seasonal soil NH$_4^+$ and NO$_3^-$ levels in CT and NT cotton and soybean ........ 54
Figure 10. Soil NH$_4^+$ content in CT and NT cotton (0-2.5 and 2.5-7.5 cm depths)........... 56
Figure 11. Comparison of soil inorganic N in CT and NT cotton following fertilization .. 57
Figure 12. Seasonal variation in NH$_4^+$ and NO$_3^-$ for CT and NT cotton (0-2.5 cm) ....... 59
Figure 13. Seasonal variation in NH$_4^+$ and NO$_3^-$ for CT and NT cotton (2.5-7.5 cm ) .... 60
Figure 14. Soil NO$_3^-$ content in CT and NT cotton (0-2.5 and 2.5-7.5 cm depths) ........... 62
Figure 15. Comparison of NO$_3^-$ in wheeltrack, row and no-track for CT and NT cotton .. 63
Figure 16. Nitrate and soil water content by plot position in CT and NT cotton ............... 66
Figure 17. Soil inorganic N and N mineralization rates in relation to cotton phenology ... 69
Figure 18. NO$_3^-$ and soil water content in bulk soil vs. covered cores in CT cotton ....... 76
Figure 19. NO$_3^-$ and soil water content in bulk soil vs. covered cores in NT cotton ....... 77
Figure 20. NH$_4^+$ in bulk soil vs. covered cores in NT and CT cotton .............................. 78
Appendix 1. Crop treatments and sampling schedules ............................................. 101
Appendix 2. Calculations of estimated N released from crop residues .................... 105
In the past couple of decades, concerns about the environmental impacts of modern agriculture and a growing interest in alternative crop management techniques have intensified the need for quantifying nitrogen (N) behaviour in soil (Frissel, 1977). These concerns have spurred research into nitrogen cycling in cropping systems receiving different organic matter and nitrogen inputs (Paustian et al., 1990; van Faassen and Lebbink, 1994; Franzluebbers et al., 1995), as well as systems utilizing different tillage practices (Rice et al., 1986; Lee et al., 1996; Dou et al., 1995).

In natural ecosystems there is a direct, short-term supply of nutrients from decomposing plant materials, as well as an indirect supply from the mineralization of soil organic matter (SOM) that is formed from the continued application of organic inputs (Palm, 1995). Nutrient release from litter tends to be synchronized with plant uptake of nutrients under natural conditions, resulting in efficient use of nutrients; whereas, in agroecosystems, the two processes are often separated in time, resulting in low nutrient-use efficiency (Sanchez et al., 1989). Unmanaged ecosystems also show a tight synchrony of plant and microbial activity. During periods of plant inactivity, plant residues having high C/N ratios are often present, which results in microbial immobilization of the nutrients during decomposition, and hence, fewer losses to the environment. The retention of nutrients within the live components of native systems (plants and animals), together with greater diversity in plant rooting structures allows for rapid growth and efficient use of nutrients (Paul and Robertson, 1989).

Agroecosystems are far less efficient in their recycling of nutrients. Unlike natural ecosystems, the energy fluxes, nutrient cycles and hydrologic characteristics in agricultural systems are regulated by physical manipulation of the soil and external inputs of water, nutrients and energy. Agricultural management practices like tillage accelerate the release of nutrients bound in SOM to the soil abiotic environment where they can either be taken up by plants or lost through leaching or volatilization (Fox and Bandel, 1986).

In agricultural systems, high crop demand for nutrients occurs during defined time intervals, often during the crop's vegetative growth stages. Ideally, a nitrogen-containing material (fertilizer, plant residues or animal manure) should produce a large pool of mineral N before the period of rapid N uptake by the crop. If the mineral N pool in soil is produced when plants are absent or crop demand is low, mineralized nitrogen will accumulate in soil and, together with residual fertilizer, may be lost from the soil via leaching, denitrification or volatilization (Duxbury et al., 1989). Poorly timed nitrogen availability will not benefit the crop, and, if leaching losses are high, poses a potential threat to groundwater quality (Stute and Posner, 1995). The concept of supplying nutrients when demanded by the crop is commonly referred to as synchrony (Swift, 1987).
residues or synthetic fertilizers is a way to better understand N availability, so that closer synchrony between N release and uptake can be achieved. In agroecosystems, the activities of microorganisms responsible for the mineralization and immobilization are profoundly affected by tillage practices, crop residue management and fertilizer inputs (Lampkin, 1990). Direct relationships between management practices and N availability should not be expected, however, for these relationships vary depending on soil, climate and time (Doran and Smith, 1987).

Crop demands for nutrients also vary depending on climate, crop type and cultivar (Wagger, 1989). Therefore, results from studies on synchrony between nutrient release and crop demand may only be applicable in a limited geographic area.

1.1 Objectives

The overall objective of this project is to determine the short-term and long-term effects of the management of organic matter inputs, inorganic N sources, and tillage on nitrogen availability in four cropping systems (conventional and no-till cotton, and conventional and no-till soybeans).

To accomplish this overall objective, three specific objectives have been defined:

1. Quantify the long-term effect of tillage and crop type on soil organic C and soil N reserves under four cropping systems.

One of the attractive aspects of the Oxford, Mississippi plots are that they have been under operation for nearly a decade. The literature suggests that many of the differences in soil nutrient levels are only detectable after a number of cropping seasons (Rice et al, 1986). Measurements of total C and N in soil under the four tillage systems should reflect the influence that tillage systems have had on maintaining or depleting total C and N over the eight-year cropping period, and accentuate any differences between legume and non-legume systems.

2. Compare changes in seasonal nutrient availability (soil mineral N) and nutrient release (N mineralization rate) between the cropping systems.

Measurement of total N, as outlined above, does not provide a reliable index of plant-available nitrogen. Availability is better related by measuring mineralization, which is the transformation of organic forms of N into inorganic, plant-available forms, over discrete periods of time (Rhoades, 1995). Nutrient availability is affected by quantity, quality, placement and timing of
affected by a variety of soil and climatic processes that can fluctuate rapidly. The microbial processes that enzymatically convert N from organic to inorganic forms are controlled by temperature and soil moisture, as well as by the chemical composition of organic inputs (Parton et al., 1987). Thus, measurements of net mineralization will be evaluated with respect to crop residues, tillage practices and fertilizer amendment regimes.

3. Compare N availability and release with N uptake by crops (synchrony) during the growing season for the different cropping systems.

Synchronization of residue N release and fertilizer N amendments with crop N demand is important for maximum, efficient utilization of N, and minimum losses from the plant-soil system (Wilson and Hargrove, 1986). Therefore, the levels of inorganic N will be determined at various crop development stages to determine if the cropping systems are supplying N in a timely fashion.

2.0 LITERATURE REVIEW

In agroecosystems there are four main sources of nitrogen potentially available to a crop: indigenous soil nitrogen, N derived from added organic materials (e.g., crop residues or livestock manure), inorganic N from synthetic fertilizers and inputs via biological nitrogen fixation. Crop management strategies employed at the Nelson Farm experimental plots involve various combinations of crop residues, crop rotations, cover crops, legumes, inorganic fertilizers and tillage regimes. The differences in these crop management practices, as well as differences in the soil characteristics and physiological differences between the cotton and soybean plants, are expected to affect nitrogen cycling and hence, availability of N to plants in the four cropping systems. The following review summarizes the effects of crop management practices on the availability of inorganic N (i.e., plant-available N) from indigenous soil organic matter, organic inputs and synthetic N sources.

2.1 Nitrogen contributions from indigenous soil organic matter

In the absence of inorganic fertilizers, N availability depends on the nitrogen cycling capacity of the plant-soil system. Because most reactions involved in the N cycle are microbially
conversion of organic N to inorganic forms is known as mineralization. Nitrogen mineralization involves several steps: the decay of N-containing plant and animal tissue constituents by microbial enzyme action; the synthesis of proteins, polysaccharides and nucleic acids into new microbial cells; and the excretion of metabolic waste products (e.g., NH₄⁺). If these waste products accumulate, "net" N mineralization has occurred.

Net mineralization will occur if the C/N ratio of the decomposing substrate meets the energy and nutrient requirements of the decomposers, i.e., the microorganisms. In general, substrates with a C/N ratio of 20 or less will result in the mineralization of N (Stevenson, 1986). If the substrate has a wider C/N ratio, then the microorganisms will require an exogenous source of N, because the plant or animal substrate cannot provide all of the N required for microbial cell synthesis. The microorganisms derive this N from the soil inorganic N supply. This phenomenon is known as "immobilization," because the inorganic N has been converted into organic form and is no longer available for plant uptake. As decomposition of the high C/N ratio substrate continues, some of the C is liberated as CO₂, and eventually the C/N ratio of the substrate will be lowered to where the C and N remaining are in the proportions required to build microbial cells. From this point on, the microorganisms no longer require the exogenous N source, and net N mineralization occurs.

Soil organic matter (SOM) is composed of a plethora of substrates of differing C/N ratios, as well as a legion of microorganisms, including bacteria, fungi, and actinomycetes that simultaneously carry out the decomposition process. Net mineralization or net immobilization of N in soils thus represents the net effect of all heterotrophic microbial activity (Jansson and Persson, 1982).

Almost all of the nitrogen found in surface soil horizons is in organic combinations, and is unavailable to plants (Alexander, 1977). Soil organic matter contains about 5% N, and the nitrogenous compounds present in the soil organic fraction persist for long periods in nature. The resistance to attack is so appreciable that only a small proportion (1-4%) of the nitrogen reservoir of the soil is converted to inorganic, plant-available forms during a growing season (Tinsley, 1964). Despite this seemingly small contribution, there is universal acknowledgement that SOM is the major indigenous source of soil available N (Bauer and Black, 1994), therefore, any management practices that deplete SOM will also limit the capacity of the soil to supply nitrogen to the crop.

In the past two decades, United States federal farm bills imposing limitations on soil loss have sparked interest in finding alternatives to conventional tillage (CT) systems (Ismail et al., 1994; Triplett et al., 1996). This research is especially relevant in Mississippi, where cotton is one of the more profitable crops, yet is also considered to create a greater erosion hazard than other widely
grew annual crops (Tripepi et al., 1990). Conventional tillage not only increases susceptibility of the soils to erosion, thereby increasing SOM losses (Troeh et al., 1991), it also decreases levels of SOM levels through the accelerated decomposition of organic matter (Giddens, 1957). Tillage disrupts the physical arrangement of soil particles such that substrates previously inaccessible to microorganisms are exposed (van Veen and Paul, 1981; Ross, 1989). Consequently, after soil disturbance microbial activity often increases, leading to the stimulation of nitrogen mineralization (Balesdent et al., 1990; Fox and Bandel, 1986).

Many studies of SOM have shown that no-till (NT) systems have higher surface soil levels of organic matter, larger microbial populations and a greater reserve of N in potentially mineralizable forms compared to CT soils (Doran et al., 1985; Carter and Rennie, 1982; Lynch and Panting, 1980). Despite the fact that NT systems have higher levels of SOM and organic N contents than CT systems, the literature is replete with studies showing higher inorganic N levels in CT than NT soils (Dou et al. 1995; Doran and Power, 1983; Dowdell and Cannell, 1975; Powlson, 1980; House et al., 1984). Accordingly, NT systems often require higher rates of fertilizer N than CT systems in order to achieve maximum grain yields (Blevins et al., 1977; Meisinger et al., 1985). This has been attributed to a variety of factors, including the potential for greater N losses by denitrification and leaching in NT soils (Doran, 1980; Rice and Smith, 1982); greater immobilization of surface-applied N in NT systems (Kitur et al., 1984; Rice and Smith, 1984); and greater mineralization rates of organic N in CT soils (Blevins et al., 1977).

Rice et al. (1986), however, have pointed out that the majority of the aforementioned studies have investigated only the short-term impacts of tillage on N mineralization and availability of soil inorganic N. Rice et al. (1986) have suggested that the lower N availability often observed in NT systems may be a transient effect. During the first nine years of a long-term study, they found that corn yields with no N fertilizer were consistently greater in CT than NT. Soil inorganic N levels were also consistently lower in the NT than CT systems during this time. After nine years, however, there were no consistent differences between yields in the two tillage systems without N fertilizer, and inorganic soil N was consistently and significantly greater in the surface 5 cm of the NT soils; at the 5-15 cm depth mineral N was significantly greater in NT soils on four occasions and in CT soils on two.

The authors suggested that during the first few years of the study, the plowing of the soil resulted in more rapid net N mineralization in the CT plots, which resulted in initially higher inorganic N contents in these soils. However, with continuous cropping and tillage there was a

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1 Site: Kentucky; Soils: Maury silt loam (fine-silty, mixed, mesic, Typic Paleudalfs) -deep, well-drained
decline in the ability of the CT soil to mineralize more nitrogen than the NT soil.

Similarly, in another long-term study investigating tillage effects on soil organic matter dynamics, Salinas-Garcia et al. (1997) found that after 20 years, mineralizable C and N\(^2\) were both greater in NT than CT soils. They also reported that more corn residue C was retained as soil organic C and soil microbial biomass carbon in NT than CT. They postulated that the greater amount of crop residues remaining in NT soils provided available substrate for the maintenance of a larger soil microbial biomass pool, which led to the higher C and N mineralization observed throughout the entire growing season.

As mentioned above, several studies have found that fertilizer requirements in soils recently converted to NT exceed the amount of fertilizer required to attain similar yields in a CT system. However, after a number of years of NT cropping fertilizer requirements have also been shown to decrease and eventually the requirements are comparable to CT (Rice et al., 1986). What these long-term tillage comparison studies reveal is that relatively greater N availability in CT may be observed initially but not persist, and with time, NT soils might begin to supply as much or more N to the crop.

High soil bulk density has long been known to inhibit N mineralization (Whisler et al., 1965; van der Linden et al., 1989). There is a strong inverse relationship between SOM content and soil bulk density (Bauer, 1974), consequently, cultivation of virgin soils usually results in increased bulk densities as organic matter levels decline over time (Cameron et al., 1981). In soils naturally low in organic matter, bulk density is generally less in NT than CT soils (Griffith et al., 1977; Russell et al., 1975). Since the 1970s, however, there has been particular concern that NT crop management practices cause more compaction than CT plowing techniques, with higher bulk densities consistently found in the surface 25 cm of NT soils (Pidgeon and Soane, 1977; Tollner, Hargrove and Langdale, 1984).

Soil compaction affects nitrogen transformations in two ways: reduction of the total soil pore volume after compaction promotes anaerobic conditions (Breland and Hansen, 1996), which can enhance losses of N via denitrification (Doran and Smith, 1987), and organic matter decomposition is decreased due to the physical separation of microorganisms and mineralizable substrate (Breland and Hansen, 1996).

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\(^2\) Mineralizable C and N were estimated from the quantities of CO\(_2\)-C and NH\(_4^+\)-N + NO\(_3^-\)-N that were mineralized from unfumigated samples during a 30-day incubation at 25°C and a soil water potential of -30 J kg\(^{-1}\).

\(^3\) Site: Texas; Soils: Orelia sandy clay loam (fine-loamy, mixed, hyperthermic, Typic Ochraqualf)
content and reduced air-filled porosity led to higher denitrification rates, and gaseous losses were greater in NT compared to CT soils (Rice and Smith, 1982; Linn and Doran, 1984; Aulakh et al., 1982). These results were attributed to wetter, more compact conditions with reduced tillage. It should be noted, however, that the potential for less aerobic conditions with reduced or no-till systems is site specific and depends on climate, soil, porosity and drainage characteristics, as well as quantity of crop residues maintained on the soil surface (Mielke et al., 1986). Furthermore, anaerobic conditions will not always result in large losses of N, as research by Gale and Gilmour (1988) has shown. They observed an initial stimulation of net N mineralization from plant residues under anaerobic conditions, however, residue decomposition and N mineralization ceased when mainly recalcitrant residues remained.

Variation in N mineralization rates is also often observed within cropped plots due to the influence of wheel traffic. This occurs because wheel-induced compaction changes pore size distribution towards a higher percentage of smaller pores. In these pores, organic materials may often be physically protected against microbial attack, and microorganisms may be inaccessible to predating protozoa and nematodes (Elliot and Coleman, 1988).

Recently, a number of researchers have investigated the effects of wheel traffic, and the concomitant soil compaction, on N mineralization/immobilization (Jensen et al., 1996; Lee et al., 1996; Dick et al., 1988). Jensen et al. (1996) studied the impacts of soil compaction on N mineralization and microbial biomass dynamics in a well-structured permanent pasture with high organic C content (46 mg g⁻¹) and a site continuously cropped with cereals for 28 years with low organic C content (21 mg g⁻¹). They found that N mineralization was less in compacted than non-compacted pasture soils, but did not differ at the cropped site. They used the in situ covered core technique of Raison et al. (1987) to measure N mineralization. Because leaching losses are supposedly decreased with this technique (Subler et al., 1995), Jensen et al. suggested that denitrification rates might have been a factor in the low rates of mineralization measured. They recorded average N mineralization rates of 0.15 mg kg⁻¹ day⁻¹ in the cropped soils, and 0.27 and 0.38 mg kg⁻¹ day⁻¹ in the compacted and non-compacted pasture soils, respectively.

Breland and Hansen (1996) found that after 98 days soil compaction (1.4 g cm⁻³) had reduced net N mineralization of clover by 18% compared to uncompacted soil. In the Breland and Hansen study, no anaerobic metabolism was measured, therefore, increased gaseous N losses or retarded decomposition due to O₂ deficiency could not account for differences in mineralization. They
Conversely, Lee et al. (1996) observed that nitrogen mineralization was higher in CT soils receiving wheel traffic than in CT soils not receiving wheel traffic, NT soils with traffic and NT soils not receiving wheel traffic. They suggested that the combination of tillage plus wheel traffic promoted N mineralization, i.e., plowing exposed new organic substrates, and the wheel traffic induced contact between the soil microorganisms and the substrates. It is also possible that wheel traffic did not have a negative impact on N mineralization because the Lee et al. (1996) study was conducted on a coarse textured soil, and available pore space was not greatly reduced by wheel traffic. Hassink et al. (1993) found that soil N mineralization is negatively correlated to the fraction of small pores (<1.2 µm diameter).

2.2 Nitrogen contributions from organic additions

Pollution concerns, public criticism and the desire to cut input costs have prompted some farmers to reduce N fertilizer applications and make more efficient use of organic N sources produced on-farm (Fauci and Dick, 1994; Wilson and Hargrove, 1986). Residues from cover crops in the southeastern United States can be an important source of organic matter and nitrogen to the highly weathered soils found in the region (Entry et al., 1996). In Mississippi soils, cover crops have been found to increase organic matter content, improve soil physical and chemical characteristics, reduce erosion of topsoil during high-rainfall winter months, supply soil with additional N and reduce the loss of residual soil N from the previous crop (Boquet and Dabney, 1991).

Differences in N mineralization have been related more closely to the amount of young organic matter than to total N contents in soil (Janssen, 1984), with young SOM being that accumulated by additions of crop residues and manure, while old organic matter is the remaining amount of total SOM. The benefits of long-term additions of organic materials include increased SOM, crop productivity and soil biological activity (Collins et al., 1992; McGill et al., 1986), as well as improvements to soil physical structure (Sanchez, 1989).

Theoretically, larger and more frequent inputs of crop residues provide a more continual supply of C substrate, leading to higher microbial activity and greater mineralization-immobilization turnover (MIT) of N than in soils with low or no organic additions (Jansson and

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4 Mineralization-immobilization turnover has been defined as the continuous transfer of mineralized N into organic products of synthesis and of immobilized N back into inorganic decay products -- underlying the
This large pool of active soil C and N probably leads to a more continual supply of mineralized N available for crop uptake. Soils with greater MIT might also present less opportunity for loss of N through leaching and denitrification because only moderate levels of inorganic N are present at any point in time (Franzluebbers et al., 1995).

As with mineralization/immobilization of indigenous soil N, the decomposition of organic materials results in the conversion of residue C and N into microbial tissues. In the process, part of the C is liberated as CO₂. Litter decomposition and subsequent N release is therefore controlled by the size, activity, efficiency and nutritional status of the microbial biomass (Scott et al., 1996). The microbial community involved in the decomposition process is, in turn, directly affected by crop residue type, placement and degree of incorporation in soil, and soil temperature and water/aeration regimes (Aulakh et al., 1991).

Other cropping practices affect residue decomposition indirectly, through their impact on microbial activity. Tillage and cultivations affect soil structure, porosity, aeration, moisture status and accessibility of microorganisms to added crop residues (Doran and Smith, 1987; Alexander, 1977); the presence of growing plants alters the composition of the microbial community; microflora are affected by the application of inorganic fertilizers; and, of course, specific soil and climate factors will also influence the decomposition process and the release of N from added organic materials.

In order to effectively manage N from organic additions, it is necessary to know the pattern of N release from residues or other materials. This can only be accomplished by gaining an understanding of the N release patterns for specific residues under a particular set of environmental and crop-soil management conditions (Wilson and Hargrove, 1986).

Smith and Sharpley (1990) noted that most studies comparing soil N availability under NT and CT soils have only included either a single crop residue or soil type. Therefore, they conducted a laboratory study to examine the effects of crop residue type (legumes versus non-legumes) and tillage effects on soil N availability for a range of soils⁵. No particular trends of soil type on N mineralization were evident in their study. However, they did find that N availability was influenced by crop residue type, C/N ratio and tillage regime. During the first 14 days of a soil incubation, net immobilization of indigenous soil N occurred with all non-legume residues⁶ (C/N ratios ranging from building up and dying away of the heterotrophic biomass (Jansson, 1958; Campbell, 1978; Ladd and Paul, 1973).

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⁵ The eight soils used comprised a broad range of chemical, physical and biological properties, and soil types ranged from sandy loams to clays.

⁶ Non-legume crops species included corn, Zea mays L. (C/N 64.3); oat, Avena sativa, L. (C/N 39.8); Sorghum, Sorghum sudanense (Piper Stapf) (C/N 36); and wheat, Triticum aestivum (C/N 57.7)
residues (C/N 15-54), however, mineralization ensued within 2 weeks of residue application. Others have reported similar N immobilization with non-legume residues and mineralization with legume residues (Janzen and Kucey, 1988). However, Nicolardot et al. (1995) did not observe net N immobilization with three non-legume species. In their study, N mineralization was observed within the first month for all residues. The authors attributed the mineralization to the fact that only young plants with a narrow range of C/N ratios (8.7-11.2) were used. Conversely, in the Smith and Sharpley study the residues were at a much more mature stage, and had a wide range of C/N ratios.

Clearly, crop type alone is not enough to predict the pattern of N immobilization and mineralization. Many researchers have concluded that it is the availability of C and N in plant residues that is the major rate-controlling factor in decomposition. Ford et al. (1989) have found C/N ratio to be the best residue characteristic for predicting decay rates in CT and NT systems. It has been suggested that net mineralization will occur when residues have a C/N ratio between 20 to 30 (Alexander, 1977).

C/N ratio, however, is not the only determinant of whether net mineralization or immobilization of N from crop residues will result. Young, succulent plant tissues are metabolized by microorganisms much more readily than residues from mature plants (Alexander, 1977). As the plants age, the content of nitrogen, proteins and water-soluble substances fall, and the proportion of cellulose, lignin and hemicellulose rise. Reinertsen et al. (1984) have suggested that the level of water-soluble components determines the initial rates of decomposition. The results of a study conducted by Broder and Wagner (1988) support this idea. Broder and Wagner compared the decomposition rates of soybean, corn and wheat, and found that corn and wheat, which had similar levels of soluble components had comparable rates of decay. Soybean residues, which had higher levels of soluble constituents, also had the highest rate of decomposition in the initial 32 days of the study.

Others have found relationships between proportion of lignin/carbohydrate ratio (Herman, 1977) and cellulose and hemicellulose fractions (Wagger, 1989) and rates of decomposition. The proportions of the various organic compounds change with plant age (Waksman, 1929; Wagger, 1989), thus, time of desiccation of cover crops can mean the difference between initial net immobilization or net mineralization, which ultimately affects the amount of plant available N.

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7 Legume crops species were soybean, *Glycine max* L. (C/N 53.6); peanut, *Arachis hypogaea* L. (C/N 26.6); and alfalfa, *Medicago sativa* (C/N 15.6)

8 The three crop species were rape, *Brassica napus*; radish, *Raphanus sativus*; and rye, *Secale cereale*
Most studies conducted in the southeastern United States have shown that, regardless of the crop system, decomposing legumes release a pulse of available mineral N at two to five weeks after killing of the cover crop in the spring, followed by a decline over the growing season (Sarrantino and Scott, 1988; Groffman et al., 1987; Ebelhar et al., 1984). Moreover, irrespective of C/N ratio, all crop residues can be expected to eventually increase net soil mineralization (Black, 1968), and this mineralization usually occurs within about 4-12 weeks of residue application (Wilson and Hargrove, 1986; Smith and Sharpley, 1990; Stute and Posner, 1995; Nicolardot et al., 1995; Ebelhar et al., 1984).

In addition to residue composition, residue placement and soil moisture have also been shown to greatly impact decomposition patterns and N availability. Crop residues left on the soil surface reflect light and insulate the soil, thus reducing soil temperatures and evaporative losses of water (Bond and Willis, 1969). This buffering effect can increase or decrease N availability depending on climate and time of year. When soils are warming in the spring, cooler temperatures with surface applied residues often reduce biological activity (Doran and Smith, 1987), thus decreasing the rate of residue decomposition and slowing the mineralization of N. However, crop residues can increase soil water storage and decrease soil temperatures during stressful summer periods, creating a more habitable environment for microorganisms.

In a study conducted in the subhumid environment of the western Corn Belt, Wilhelm et al. (1986) found that for every Mg ha⁻¹ of crop residue applied to the soil surface, grain yields of NT maize and soybean increased by 10%. Availability and N uptake from SOM, crop residues and N fertilizer increased with increasing surface crop residues, presumably by creating a soil environment more favourable for microbial activity and N mineralization (Power et al., 1986).

In general, high C/N ratio residues decompose more rapidly when incorporated rather than left on the surface (Smith and Sharpley, 1990). For example, cornstalk residue placed on the soil surface required 8 weeks to decompose, compared to 5 weeks for incorporated residue (Parker, 1962). Wilson and Hargrove (1986) also found that when crimson clover residues were applied at the same rate, N release was more rapid in CT. After two weeks in the field, the clover contained only 48% of the original N under CT, while in the NT system the residues still contained 78% of the original N.

In contrast to most field studies, Scott et al. (1996) found greater decomposition of surface litter compared with incorporated residues during the first 0-10 days of a laboratory incubation when the residue and soil moisture conditions were kept at an optimum. They concluded that the lack of contact between litter and soil particles will not retard decomposition of surface litter as long as litter
The results from the Scott et al. study highlight the modifying effect of environmental conditions in the decomposition process.

There are many field studies that demonstrate that decomposition rates of surface applied residues, as found in NT systems, are more sensitive to environmental factors than are incorporated residues. Wilson and Hargrove (1986) found that year-to-year variation of N release from residues was much lower in CT than NT systems. Stute and Posner (1995) also found that the patterns of N release from incorporated legume residues did not differ greatly, despite very different growing season conditions. In the first year of their study there was near normal precipitation, coupled with extremely warm temperatures, while in the second year low rainfall resulted in drought conditions for 2 1/2 months and temperatures were below normal. These studies reflect the greater ability of the soil environment to buffer the effect of variable climatic conditions compared to when the residues are left on the surface where they are more sensitive to microclimate fluctuations.

The distribution of residues across the soil surface can also greatly affect soil biological activities and chemical properties. Doran (1980) found that with stubble mulch management, where residues were concentrated between the rows, soil microbial populations were 2 to 40 times greater between than within the rows. Nitrate levels as high as 145 kg ha$^{-1}$ accumulated in the between-row position, which the authors concluded was due to soil water contents, substrate supply and soil pH being more optimum for microbial activity.

The addition of crop residues has been found to stimulate mineralization of indigenous SOM. Scott et al. (1996) found that wheat residue additions stimulated mineralization of native soil C, the greatest effect occurring when litter was incorporated into the fine-texture soil as opposed to sandy soils. Maximum mineralization of indigenous C occurred between 0 and 10 days after residue application, which is when microbial activity was highest. This so-called “priming effect” has caused some controversy over the years. Some experiments have shown substantial increases in SOM mineralization following substrate addition (Broadbent, 1947; Sorenson, 1974; Azam et al., 1989). However, reports of soil priming are often disputed, and attributed to faulty methods such as the use of nonuniformly labeled plant litter (Jansson and Persson, 1982).

2.3 Nitrogen contributions from synthetic fertilizers

Historically, cover crops and crop rotations have been used to augment soil organic matter levels and supply N and other nutrients for crop production. However, these management
approaches have largely been displaced by the increased use of crop monocultures and more intensive cropping practices that deplete the soil resources. Consequently, in order to maintain high yields and protect against losses of soil N, farmers have come to rely on high applications of chemical fertilizers. Between 1950 and 1989, fertilizer use went from 14 million to 146 million tons (Worldwatch, 1997).

Recommendations originally developed for economically optimum fertilizer applications have led to increasing problems of groundwater pollution caused by leaching of nitrate from agricultural land (Groot and Houba, 1995). With growing public interest in agricultural impacts on the environment, especially water quality, high rates of N applications have come under increased scrutiny. Farmers are also beginning to question the need for high fertilizer application rates, especially as more information becomes available on how applications can exceed the physiological capacity of crops to absorb and use these synthetic nutrients (Contant and Korschning, 1997).

Although the application of synthetic N immediately augments the pool of inorganic N, not all of the fertilizer N applied is available for plant uptake. As with indigenous soil N and residue N, the availability of fertilizer N is soil, climate and time-dependent, and can be greatly affected by crop management factors. There are few sound data on the magnitude of losses of fertilizer N, but in general, only 30 to 40% of the N applied is recovered by crops. It has been suggested that much of the N unaccounted for is probably incorporated into SOM or roots (Sanchez et al., 1989).

Studies on N fertility suggest that N fertilizer behaves differently in NT soils than in CT soils (Rice and Smith, 1984; Blevins et al., 1977). Isotopic N tracers ($^{15}$N) have been used to follow the movement of fertilizer N in the soil-plant ecosystem. Many of the studies that have reported reduced crop recovery of fertilizer N in NT compared to CT systems have shown greater $^{15}$N immobilization in surface NT soils (Rice and Smith, 1984; Kitur et al., 1984). Poor fertilizer-N recovery has been ameliorated, however, by placing fertilizer N below the surface layer of NT soils, i.e., where biomass levels and concentrations of organic materials are lower, resulting in increased N availability, plant uptake and crop yields (Touchton and Hargrove, 1982; Mengel et al., 1982).

A study conducted by Stute and Posner$^9$ (1995) illustrates the variability in availability of fertilizer N due to climate. In 1991, they observed that mineral nitrogen concentrations in the surface 30 cm of soil did not reach their maximum until four weeks after application of fertilizer to a corn crop, despite the fertilizer being applied in a 100% mineral form (i.e., as NH$_4$NO$_3$). They attributed this to temporary immobilization during the decomposition of indigenous organic matter. From weeks 10-16 an increase in mineral N was observed, which the authors suggested was the result of

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$^9$ Site: Wisconsin; Soils: Plano silt loam (fine-silty, mesic Typic Argiudoll)
corn maturity. Despite identical management treatments in 1992, the initial net immobilization of fertilizer N that occurred the year before was not apparent. There was also no late-season mineralization, which the authors attributed to soil temperatures being average that year. This exemplifies how climate can influence soil N transformations and N availability.

Stute and Posner (1995) also found that by 10 weeks soils receiving 179 kg N had the same amount of inorganic N as soils receiving no fertilizer N, which suggests that fertilizer effects on inorganic soil N levels are temporary. They decreased markedly with the onset of rapid plant uptake, and by the time of plant physiologic maturity N levels were similar to background levels (i.e., soils receiving no N).

Despite the low levels of residual mineral N after the growing season, fertilizer N can contribute to long-term increases in organic N levels. It has been suggested that 20-40% of N applied as fertilizer remains behind in the soil in organic forms after the first growing season, however, only a small portion (< 15%) of this immobilized N becomes available to plants during the subsequent growing season, with N availability decreasing even further in succeeding years (Stevenson, 1986). This indicates that, while not all fertilizer N is available to plants for uptake, some of it does get conserved in the various SOM fractions.

In general, the application of fertilizer N can have a variable effect on soil microbial biomass, usually neutral or stimulatory (Campbell et al., 1995). Some studies have shown that long-term applications of manufactured fertilizers result in soils with lower biological activity relative to those receiving repeated additions of organic materials (Collins et al., 1992; Dick et al., 1988). However, both Salinas-Garcia et al. (1997) and Insam et al. (1991) found that nitrogen fertilization had little effect on soil microbial biomass.

This effect is highly dependent on the quality of C substrate available to the microorganisms. The size of the soil population is ultimately controlled by the rate at which energy-containing material (C substrate) is added to the soil (Russell, 1973). If materials with a low C/N ratio are present, the microorganisms might not require an exogenous N supply to decompose the residues, and thus, the added fertilizer will not have an effect on the size of the microbial population. According to Russell (1973), however, the rate of decomposition of a material with a low nitrogen content can be increased considerably if a suitable source of nitrogen is added, for under these circumstances the nitrogen supply obviously limits the maximum amount of microbial protoplasm that can be present, and, if it is too low, it limits biological activity.
mentioned previously, plant residues with less than 1.2% N induce a depletion of inorganic N within about one week, and the deficiency may not be alleviated in periods of several months or longer. For economic reasons, crop production often cannot wait for the net immobilization associated with the decomposition of high C/N ratio residues to run its course. Thus, N fertilizer is added bring the final nitrogen content of the residues to 1.2-1.5%, or a C/N ratio of 30-35, so that N mineralization can commence faster (Alexander, 1977). This fertilizer application is specifically for the microflora, not for the crop.

The amount of fertilizer applied affects the rate of decomposition, and consequently, the duration of immobilization. Green and Blackmer (1995) conducted a laboratory study to investigate the pattern of immobilization and mineralization induced by various treatments with corn residue, and found that net amounts of residue-induced immobilization of N tended to decrease with increasing rates of N applied. The time required for this immobilization also tended to decrease with increasing rates of fertilization. Green et al. (1995) also recently demonstrated that increases in fertilizer N should be expected to increase rates of corn residue decomposition under field conditions.

Similarly, in a long-term field study investigating the effects of tillage and N-fertilization on SOM, soil microbial biomass and C and N mineralization, Salinas-Garcia et al. (1997) found that N mineralization rates at flowering and harvest were significantly increased by higher N fertilization.

Both tillage and fertilizer placement affect the availability of inorganic N. Dowdell and Crees (1980) found no difference in net immobilization of fertilizer N between direct-drilled and plowed winter wheat. Frederickson et al. (1982) measured less immobilized fertilizer N in NT wheat soils than CT soils, but the surface duff layer was not included in their study. Most other researchers, however, have observed greater immobilization in NT soils. Generally, there is the potential for greater immobilization of surface applied N fertilizer in NT than CT soils (Cochrane et al., 1980), which Doran (1980) has attributed to a higher organic matter content and therefore a larger microbial population in the NT surface soils.

Rice and Smith (1984) reported greater N immobilization in NT than CT corn grown on three silt-loam soils. In their study, the maximum amount of fertilizer N immobilized for each plot was correlated with the percent organic C content of the surface 5 cm of soil. The authors suggested that this increased potential for immobilization of surface-applied N in NT soils could play a more important role in the decreased yields often observed in NT corn than leaching and denitrification,
Thomas et al., 1973).

As with organic residues, fertilizers can sometimes stimulate mineralization of indigenous organic N, although many dispute this idea (Stevenson, 1986; Jansson and Persson, 1982). This priming effect, when it occurs, may result from the fertilizer addition leading to an increase in the size and diversity of the microbial population such that the new community of organisms can degrade organic nitrogen compounds more readily than the original microflora (Alexander, 1977).

Tracers studies have been used to investigate the possible "priming" effect. Blackmer and Green (1995) added labeled N-fertilizer to soils where corn stover had been applied. They found that the stover additions prompted periods of net immobilization followed by periods of net mineralization. Most of the nitrate immobilized early in the study was labeled, however, most of the N subsequently mineralized was non-labeled. This observation indicates that little of the fertilizer N incorporated into microbial biomass during stover decomposition was mineralized to NO₃ during the 90-day study. Thus, the N mineralized had to have been derived from SOM or added stover, rather than from microbial biomass formed during the incubation.

Others have argued that this apparent stimulation of SOM mineralization is a regular feature of the microbial processes of mineralization-immobilization-turnover (MIT). For a detailed discussion of this theory, see Jansson and Persson (1982).

The above summary of literature on N availability in agricultural soils should make it obvious that crop management practices can greatly alter soil N reservoirs, both in the short and the long term. This has implications for tillage, crop residue and fertilizer management. For example, historical N fertilizer application rates may no longer be appropriate after several years of NT cropping. If farmers continue to apply high levels of fertilizers year after year, not realizing that NT soils might be able to contribute increasing amounts of mineral N with time, then overfertilization may result. This could lead to losses of N from the soil-plant system, which means economic losses for the farmer, and potentially negative impacts on the environment.

Subsequent sections of this paper report the findings of my study on N availability in four cropping systems in Mississippi, and the implications of the various crop management practices have been discussed with many of the above studies in mind.
In 1987, the U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) National Sedimentation Laboratory, in cooperation with Mississippi Agriculture and Forestry Experiment Station (MAFES) initiated a long-term, interdisciplinary study to identify and develop economically profitable and environmentally sustainable crop management systems for silty, upland soil resource areas in the Mid-South region of the United States (Dabney et al., 1997).

The research site is located on the A.E. Nelson Farm in northern Mississippi. The terrain is upland, sloping (4%). The deep loess soils are primarily Grenada silt loam (fine silty, mixed, thermic Glossic Fragidalf). The land had been used to produce cotton and other row crops in the past, but had been in pasture for at least two years before the USDA study commenced. The crop production plots (12 m long and 5.5 m wide), set up to measure crop yields and determine production economics of 14 cropping systems, are being farmed with methods and equipment normally used in the region or envisioned as superior to those commonly used (Dabney et al., 1997).

Cropping and Tillage Management Practices

A full schedule of sampling dates and crop management treatments can be found in Appendix 1. The following section provides information on the tillage, residue management and fertilizer treatments for each of the four cropping systems.

Cotton (*Gossypium hirsutum*): variety ‘DES 119,’ was planted in six 91-cm rows.

Conventionally tilled cotton (CO1)

Prior to planting, plots were spring chisel plowed and disked twice. Beds were formed with disk hillers followed by planting and cultivation (post-emergence - 4x). Cotton was planted on May 6, 1996. The plots received fertilizer applications of 45 kg N ha\(^{-1}\) and 55 kg N ha\(^{-1}\) on April 26 and June 6, respectively.

No-till cotton (CO3)

Cotton was planted (May 6, 1996) into killed wheat (*Triticum aestivum* L.), which was killed with glyphosate 12 days prior to cotton planting. The wheat cover crop had been planted in the preceding fall to increase the surface residues, soil protection and uptake of residual nutrients. The cotton plots received the same fertilizer applications as the CO1 plots, i.e., 100 kg N ha\(^{-1}\) total. The wheat crop was not fertilized.
Conventionally tilled Soybeans (SB1)

Plots were chiseled (1x) and disked (2x) prior to planting, which took place on May 16, 1996. The plots did not receive any synthetic nitrogen fertilizer.

No-till Soybeans (SB4)

In this system, the soybeans were doublecropped with winter wheat. The soybeans were drilled on June 18, 1996, one day after the wheat was harvested. Wheat residues were left on site. The soybeans did not receive any fertilizer, however, the wheat crop had received 90 kg N/ha.

4.0 METHODS

4.1 Field Procedures

Soil Incubations

The method used for determining inorganic N and N-mineralization rates was a modification of the in situ incubation method of Raison et al. (1987). Five replicate plots were sampled for each of the four treatments (CO1, CO3, SB1 and SB4), resulting in 20 sample plots. In each plot, three pairs of cores (approximately 5 cm diameter, 7.5 cm length) were inserted: one in the planted row, one between the rows in the wheeltrack, and one between the rows but not in the wheeltrack (hereafter referred to as “no-track”).

The cylinders were inserted vertically, to a depth of approximately three inches. One of the soil cores was removed immediately, placed in a mason jar and capped. This core was transported to the laboratory where it was stored in a refrigerator (4°C) until it could be analysed.

The second core from each pair was inserted within 20 cm of the first core, and was left in the ground for one to three weeks. The cylinder was not flush with the ground. This placement, combined with an aluminum cover, were designed to prevent entry of precipitation or run-off water, in an effort to minimize leaching losses. Also, the cover was used to prevent entry of light, thus minimizing new growth in the cores, which could affect soil nitrogen levels. The cover did not completely seal off the cylinder, thus allowing for some aeration.
schedule of sampling dates can be found in Appendix 1.

4.2 Laboratory Analyses

Ammonium and Nitrate Extraction

The soils were prepared and extracted for ammonium (\(\text{NH}_4^+\)) and nitrate (\(\text{NO}_3^-\)) analyses using the methods outlined by Bremner (1965) and Raison et al. (1987).

Two subsamples were taken from each core (0-2.5 cm and 2.5-7.5 cm depth). Each subsample was sieved (2-mm mesh), and 10 g of the sieved, field-moist soil was transferred to a 125 ml erlenmeyer flask. This sample was immediately extracted by shaking with 100 ml of a 1 N KCl solution in a rotary shaker for exactly one hour. The extract was centrifuged for approximately 10 minutes. The supernatant was transferred into a 50 ml bottle and stored in the freezer until it could be analysed for \(\text{NH}_4^+\) and \(\text{NO}_3^-\) on the TRAACs 800 autoanalyser. A blank was prepared from the 1 N KCl solution, for each set of 30 samples.

Moisture content was determined gravimetrically on subsamples (20-70 g) oven-dried for 12-16 hours at 105° C and cooled in a desiccator. All nitrogen concentrations are expressed on a dry-weight basis.

Ammonium and Nitrate Determination

The extracts were removed from the freezer and stored in the refrigerator overnight to allow the samples to thaw. The determinations of ammonium and nitrate were made using a computer controlled, continuous-flow wet chemistry analytical system with a colorimeter to detect changes in colour produced by the presence of nitrate and ammonium in the samples (TRAACS 800 model, Bran + Luebbe, Inc., Buffalo Grove, IL).

The automated procedure for ammonium utilizes the Berthelot reaction, in which the formation of a blue compound believed to be closely related to indophenol occurs when the solution of an ammonium salt is added to sodium phenoxide, followed by the addition of sodium hypochlorite (Markus et al., 1985). The absorbance is measured at 660 nm. The procedure for nitrate/nitrite-nitrogen is based on a reaction whereby nitrate is reduced to nitrite by an alkaline solution of hydrazine sulfate containing a copper catalyst (Markus et al., 1985).
(ppm) were corrected for the amounts found in the blank. Ammonium and nitrate concentrations were corrected for their total nitrogen content, i.e., NH$_4$$^+$-N and NO$_3$$^-$-N, and then their concentration per kg soil was determined. Thus, all concentrations are reported as mg nitrogen (NH$_4$$^+$-N and/or NO$_3$$^-$-N) per kg dry soil.

**Soil Mineral N and Mineralization Rates**

Mineral N measured in the first core of each incubation pair provides a measure of ammonium and nitrate in the bulk soil at that exact point in time. Thus, the values from each of the initial cores have been reported to gauge the changes in soil mineral N over the course of the season.

Net mineralization was determined by adding NH$_4$$^+$-N and NO$_3$$^-$-N in the first core, and subtracting this value from the NH$_4$$^+$-N + NO$_3$$^-$-N in the second core, then dividing the difference in soil mineral N by the number of days of the incubation. The net mineralization (if positive) or immobilization (if negative) rate is reported as mg N kg soil$^{-1}$ day$^{-1}$ (Anderson and Ingram, 1989).

**Total Soil Carbon and Nitrogen**

Soil samples taken from CO1, CO3, SB1 and SB4 plots on June 6, 1996, were analysed for total carbon and nitrogen using a LECO CR-12. Soil samples taken March 11-14, 1996, by Rhoton (1996) and coworkers were analysed using the same equipment. Both sets of data have been reported.

**Plant Analyses**

Fifteen plants from each replicate plot were combined to produce one sample per replicate. Samples from five replicates per crop (CT cotton, NT cotton, CT soybean, NT soybean) were collected at a number of sampling date throughout the growing season. Plant samples were dried at 70° C, and leaves ground in an electric mill. Samples were then analysed for total nitrogen and carbon on a LECO C-2000.

**4.3 Statistical Analyses**

In comparing tillage treatments, paired t-tests were used since the plots tested were from the same replicate blocks and so environmental differences (e.g., amount of rainfall received, temperatures, soil texture) were considered to be the same (Snedecor and Cochran, 1980).
significant differences and interactions between the four cropping systems.

5.0 RESULTS AND DISCUSSION

5.1 Total Carbon and Nitrogen

Total soil carbon (C) and nitrogen (N) for the production plots at the Nelson Farm were measured by Rhoton (1996) in March, one month before this study took place. The data presented in Table 1 are average values of the same five replicate plots used in this study. The soils were analysed for total carbon, not organic carbon, however, the two values should not differ significantly in these non-calcareous soils.

Tillage regime had an influence on both the concentration and the depth distribution of total soil C and N. Both total C and total N were statistically greater in the no-tillage (NT) 0-2.5 cm depth than the conventional tillage (CT) 0-2.5 cm depth for both cotton and soybeans (Table 1). It has long been known that tillage accelerates decomposition of organic matter (Giddens, 1957), leading to lower organic C and total N levels. Additionally, Meyer et al. (1997) reported that NT soybean and cotton systems at this site reduced soil losses by 70 to 90% compared to CT. Therefore, more surface organic materials were preserved in the NT than CT soils. At the 2.5-7.5 cm depth the differences between tillage treatments were not significant (P = 0.05).

The data also show that the total C and N were higher in the 0-2.5 cm increment than the 2.5-7.5 cm depth in the NT soils, but not in the CT soils. This depth distribution can be easily explained. In CT, the bulk of organic residues are mixed deeper into the soil by tillage and cultivation, distributing the organic matter more evenly throughout the plow layer (top 15 cm). In NT systems, however, the organic materials remain at the surface, resulting in a large difference between the organic matter content of the top 0-2.5 cm layer and the 2.5-7.5 cm soil underneath. The differences in total C and total N were statistically significant between the two depths for both cotton and soybean NT systems (Table 1).
<table>
<thead>
<tr>
<th>Crop</th>
<th>Depth (cm)</th>
<th>March\footnote{March data from Rhoton, 1996}</th>
<th>June</th>
<th>March</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT</td>
<td>NT</td>
<td>CT</td>
<td>NT</td>
<td>CT</td>
</tr>
<tr>
<td>Cotton</td>
<td>0-2.5</td>
<td>0.97\footnote{*} 1.96\footnote{**}</td>
<td>1.12</td>
<td>1.87</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2.5-7.5</td>
<td>0.91\footnote{**} 0.90</td>
<td>1.16</td>
<td>1.10</td>
<td>0.11</td>
</tr>
<tr>
<td>Soybean</td>
<td>0-2.5</td>
<td>0.98\footnote{**} 2.40\footnote{d}</td>
<td>1.10\footnote{**} 2.55</td>
<td>0.10\footnote{<strong>} 0.25\footnote{</strong>}</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.5-7.5</td>
<td>0.85\footnote{d} 0.96\footnote{d}</td>
<td>1.04</td>
<td>1.12</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\footnote{*} Significant difference between tillage treatments at 0.05 and 0.01 level, respectively (paired t-test)
\footnote{**} Significant difference between depths at 0.05 and 0.01 level, respectively (paired t-test)
\footnote{d} Significant difference between sampling dates at 0.05 and 0.01 level, respectively (paired t-test)

These trends have been reported by several others (Hadas et al., 1989; Wood and Edwards, 1992; Rice and Smith, 1984). For example, Rice and Smith (1984) sampled three different soils from CT and NT plots established 14 years earlier. They found significantly greater organic C and total N in the top 0-5 cm of NT compared to CT treatments in all three soils, but differences were not significant below this depth. Conversely, after six years of tillage, Lee et al. (1995) found no differences in organic C and total N in CT versus NT soils sampled to a depth of 20 cm despite having measured higher microbial CO\textsubscript{2} respiration in CT throughout the season, which should have resulted in less C being retained in CT soils (Holland and Coleman, 1987). It is possible that any differences that might have existed in the surface soils in the Lee et al. (1995) study were diluted to the point of being insignificant by the inclusion of the deeper soil.

Differences in total C and N between the four cropping systems (CT cotton: CO\textsubscript{1}; NT cotton: CO\textsubscript{3}; CT soybean: SB\textsubscript{1}; and NT soybean: SB\textsubscript{4}) were examined by performing one-way analysis of variance. The tests revealed the following significant differences between treatments:

Total C: SB\textsubscript{4} > CO\textsubscript{3} > SB\textsubscript{1} = CO\textsubscript{1} (March and June; \(P < 0.0001\))

Total N: SB\textsubscript{4} = CO\textsubscript{3} > SB\textsubscript{1} = CO\textsubscript{1} (\(P < 0.0001\))

These findings are somewhat surprising, since one of the most consistent effects of crop legumes is the improvement of soil reserves of organic N (Danso and Papasylianou, 1992). In this study the NT cotton had higher total N than CT soybeans. It is possible that eight years is not long
cropping systems. There are also other factors besides crop type (i.e., N-fixing vs. non-fixing crops) that affect total N. As mentioned in the literature review, tillage regime appears to exert a major influence on total C and N contents, with NT crops having higher levels than their CT counterparts. Perhaps just as important as tillage, however, are the amounts carbon and nitrogen inputs to the systems via organic residues and fertilizer N.

Table 2 provides data on estimated inputs via fertilizer and above-ground crop residues for each of the cropping systems. The nitrogen inputs in the NT systems were similar: both the cotton and soybean crops returned their own residues, as well as wheat residues, and both cropping systems received some N fertilizer inputs (the cotton plot in CO3 received 100 kg N ha\(^{-1}\), while the wheat doublecrop in SB4 received 90 kg N ha\(^{-1}\)). However, nitrogen input via crop residues was greater in the CO3 system because both the cotton residues and the entire wheat cover crop were returned to the soil; whereas in SB4, both soybean and wheat grains were harvested, leaving only the straw residues, which have a relatively low N content (Broder and Wagner, 1988). The large inputs of residues plus fertilizer N in these two cropping systems is consistent with their higher total N contents than the CT systems.

### Table 2. Estimated annual N inputs in the cotton and soybean cropping systems.

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Estimated N in crop residues(^{1})</th>
<th>Fertilizer N applied</th>
<th>Total N inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT cotton (CO1)</td>
<td>32</td>
<td>100</td>
<td>132</td>
</tr>
<tr>
<td>NT cotton (CO3)</td>
<td>37 (cotton)</td>
<td>100</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>43 (wheat cover crop)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CT soybean (SB1)</td>
<td>43</td>
<td>0</td>
<td>43</td>
</tr>
<tr>
<td>NT soybean (SB4)</td>
<td>47 (soybean)</td>
<td>0</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>25 (wheat doublecrop)</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

\(^{1}\) see Appendix 2 for calculations of residue N (above-ground) input.
CT systems. The nitrogen inputs in the CT cotton were almost three times that of CT soybeans, yet, total N levels in SB1 and CO1 were not significantly different.

It becomes increasingly enigmatic when the amount of N removed with the crop is factored into the picture. More nitrogen was removed from the SB1 system than the CO1 system at harvest time. The average CT soybeans yields for this region of Mississippi were estimated to remove 104 kg N/ha, while the average cotton yields removed approximately 48 kg N/ha (Appendix 2). Thus, not only did SB1 receive lower N inputs via soybean crop residues, there was also more N removed from the study site in the harvestable portions of the crop. And yet, SB1 soils had as much total N as CO1 soils. There are two possible explanations for this trend. The CO1 system could have lost considerably more N than SB1 via leaching, denitrification and/or erosion/runoff, or the leguminous soybean crop could have made up the difference through biological nitrogen fixation.

Estimates for amount of N fixed by soybeans range from 44-250 kg N ha$^{-1}$ (Peoples et al., 1994). Bergersen et al. (1985) found that soybean after previously fallowed soil fixed 143 kg N ha$^{-1}$, while previously cropped soils fixed 205 kg N ha$^{-1}$. Peoples et al. (1994), similarly found that fixation from fallow soils was lower than when soybean followed cereal crops or was double-cropped with wheat because soil nitrate levels were lower in cropped soils. High levels of soil nitrate at sowing have been shown to be a potent inhibitor of N$_2$-fixation (Streeter, 1988), however, nitrate levels were low when SB1 was planted (< 4 mg N/kg soil), thus, fixation should not have been greatly inhibited. Since the SB1 crop was planted after fallow, the Bergersen et al. (1985) mid-range estimate of 143 kg N ha$^{-1}$ fixed will be used for the sake of comparison.

To maintain the same total N content, inputs minus outputs must be approximately equal in the two cropping systems. In this study, inputs = (total N returned in crop residues + fertilizer N + N$_2$ fixed), while outputs = (N removed in grain + losses from leaching, denitrification and erosion/runoff). Most of these values have been estimated, however, losses due to leaching, denitrification and erosion/runoff were not measured, and are very difficult to estimate. Therefore, it will be assumed that losses in both systems are negligible for the purposes of this N balance exercise.

\[
\text{Total N} = (\text{N in crop residues + fertilizer + N}_2 \text{ fixed}) - (\text{N removed in grain + losses})
\]

CT Cotton \[= (32 + 100 + 0) \text{ kg N/ha} - (48 + 0) \text{ kg N/ha} = 84 \text{ kg N/ha}\]

CT Soybeans \[= (43 + 0 + 143) \text{ kg N/ha} - (104 + 0) \text{ kg N/ha} = 83 \text{ kg N/ha}\]
When N$_2$-fixation by the soybean crop is factored in, the total N returned to the soil is similar between CO1 and SB1. From a farm-economics and environmental standpoint, the SB1 system appears superior to CO1. CT soybeans do not incur the high fertilizer input costs, and, if it turns out that the above estimates of N$_2$-fixation are too high, then it probably means that fertilizer N from the CO1 system is being lost in large quantities, either to groundwater or to the atmosphere, which could pose environmental problems and economic losses for the farmer.

**June Data**

Additional soil samples taken in June, after the plots had undergone various tillage and fertilizer applications (Appendix 1), revealed the same pattern of organic carbon distribution (total nitrogen was not determined for these samples). At the 0-2.5 cm depth, there were significant differences due to tillage, i.e., the NT systems had greater total C than the CT systems, however, the differences were not significant at the 2.5-7.5 cm depth.

There were also significant differences in total C content between the two sampling dates (Figure 1). These results might provide some insight into the relative amount of biological activity in the four systems.

The amount of total C in CO1 increased significantly at both the 0-2.5 cm and 2.5-7.5 cm depths ($P = 0.05$ and 0.01, respectively). The cotton residues were incorporated into the soil in April, so it is reasonable that higher levels would be measured in June as opposed to March. Similar increases were found in SB1 and SB4, although the differences were only significant in the soybean plots at the 2.5-7.5 cm depth ($P = 0.01$ for both SB1 and SB4). As with CO1, the residues in SB1 were incorporated prior to the June sample date, so increases in total carbon are not unexpected.

In the SB4 cropping system, increases in total C can be explained by the presence of the wheat cover crop. In March, the crop would have been growing at a slow rate, and therefore, the amount of dry matter present would have been limited. In mid-May, however, the wheat crop had matured and was harvested, and the residues were left on the surface. This input of organic matter was the probable cause of the increase in total C at the 0-2.5 cm depth. At the 2.5-7.5 cm depth, the presence of a greater mass of roots in June than in March could have caused the increase in total C.

In the NT cotton plots, the amount of organic C decreased from March to June in the 0-2.5 cm depth (although the change was not significant), despite the addition of wheat residues on April 24. This could indicate that intense microbial activity occurred over this time period, and that a large amount of C was respired (lost from the system as CO$_2$) during the decomposition of the
Figure 1. Soil total carbon contents as affected by cropping system and sampling date.
* and ** represent significant differences between dates by paired t-test at the 0.05 and 0.01 levels, respectively.
wheat residues. The magnitude of C mineralization and release of CO$_2$ is proportional to the organic matter level of the soil, and the production of CO$_2$ is enhanced by the addition of organic materials (Alexander, 1977). Furthermore, as mentioned in the literature review, it has been found that fresh organic residues sometimes accelerate (i.e., induce a "priming effect") and sometimes reduce the rate of SOM decomposition (Scott et al., 1996; Alexander, 1977).

Despite having higher total soil carbon levels than CO$_3$, as well as an input of fresh substrate, SB4 did not have a similar decline in total C from March to June. This might be an indication that the rate of organic matter decomposition between March and June was not as great in SB4 as in the CO$_3$ system. The quality of wheat residues returned to CO$_3$ and SB4 differed, due to the early desiccation of wheat on CO$_3$, which could have resulted in a much slower residue decomposition rate (Wagger, 1989) and hence, delayed net mineralization of C and N in the SB4 system. This idea will be elaborated on in subsequent sections of this paper.

**Summary of Total C and N Results**

Overall, it appears that eight years of higher inputs of crop residues and N fertilizer have resulted in the greatest conservation of soil C and N in the NT systems at this site. The higher total C and N contents in the 0-2.5 cm and 2.5-7.5 cm soils in the NT systems suggests that there is a larger reserve of N in potentially mineralizable forms compared to the CT soils (Doran et al., 1985; Carter and Rennie, 1982).

Much of the literature suggests that in the first few years after cultivation, plowing results in more rapid net N mineralization and higher inorganic N contents in CT than NT systems (Dou et al. 1995; Doran and Power, 1983; House et al., 1984). However, with time, CT soils often mineralize less N than NT soils due to the decline in soil organic N in CT systems (Rice et al., 1986; Salinas-Garcia et al, 1997). Theoretically, the higher levels of organic matter in NT systems provide substrate for the maintenance of a larger soil microbial biomass pool, which leads to the higher C and N mineralization throughout the growing season (Salinas-Garcia et al., 1997). Furthermore, there is a greater conservation of N in the organic form within the NT ecosystem, e.g., larger populations of soil insects, microarthropods, earthworms, weeds and microorganisms (Doran and Smith, 1987), which results in a greater recycling of nutrients within the soil/plant ecosystem; whereas, with CT biological diversity is decreased (House et al., 1984), thus increasing the potential for leaching of nutrients released during the decomposition of residues. This phenomenon is time dependent, and varies with cropping system, climate and soils (Rice et al., 1986).
with their larger reserves of total C and N, have the potential to mineralize more N on a seasonal basis than the CT systems. The following section of this paper reports and discusses the data on mineralization rates and cumulative seasonal mineralized N in the CT and NT cotton and soybean systems.

5.2 Nitrogen Mineralization and Immobilization

Net mineralization and/or net immobilization of nitrogen represent the net effect of heterotrophic microbial activity in the soil (Jansson and Persson, 1982), therefore, the following net mineralization data are presented and discussed with microbial processes in mind. In this study, however, net decreases of soil inorganic N cannot be attributed to microbial immobilization alone. Losses of nitrate via leaching and denitrification, and losses of both ammonium and nitrate due to plant uptake also cause net decreases in inorganic N levels. Thus, in this study the terms net mineralization and net immobilization refer to the increases or decreases, respectively, in soil mineral N ($\text{NH}_4^+ + \text{NO}_3^-$) over the course of the incubation.

It must also be acknowledged that the measurements of low rates of net nitrogen mineralization are not proof of low microbial activity: a small net mineralization may be the result of low overall biological activity in the soil, or it may be the result of high activity in which the processes of immobilization and mineralization are working concurrently, thus resulting in low overall change in soil inorganic N over time (Jansson and Persson, 1982).

According to Alexander (1977), the seasonal pattern of microbial activity in temperate environments is well established, and is closely related to fluctuations in moisture and temperature. Biological activity also decreases with soil depth due to the relative abundance of organic matter and oxygen in the top few centimetres of soil. In general, microbial activity is highest in the spring, when soil temperature and microbial enzyme action increase and there is a ready supply of organic materials from the previous fall and winter. A decline follows during the hot, dry summer months as moisture conditions and substrate become limiting. In autumn, activity increases again due to the more favourable soil moisture status and availability of root or above-ground residues. Finally, in the winter the number of microorganisms diminishes, and most of the microbial community remains biochemically inactive, although they are ready for reactivation when the warmer temperatures of spring once again prevail.
Figures 2 and 3 present the seasonal patterns of net mineralization/immobilization in CO and NT cotton, and CT and NT soybeans for the 0-2.5 cm and 2.5-7.5 cm depths, respectively. The soybean cropping systems suffered great losses in several of the replicate plots, due to heavy grazing by deer, as well as chemical damage from herbicides\textsuperscript{10}. Consequently, it was decided to focus most attention on the cotton plots, on the assumption that the data were more representative of the changes in mineral N occurring over an average growing season in this region of Mississippi. The majority of the ensuing discussions will concentrate on the cotton cropping systems. However, soybean data have been included to provide a general idea of the effects of different crop species and fertilizer rates on nitrogen mineralization and soil inorganic N availability.

In both the cotton and soybean plots the net mineralization/immobilization rates were highest in the 0-2.5 cm depth, between April and mid-July (days 0 to 80), which corresponds to both the location and period of high microbial activity as outlined by Alexander (1977). After this period, the mineralization rates remained low and fairly constant at both depths for the remainder of the sampling season. There were a few bursts of activity, however, which could have been prompted by changes in soil moisture status (Salinas-Garcia, 1997) or application of certain crop management treatments. Specific events will be addressed later in this paper.

At the 2.5-7.5 cm depth the pattern of net immobilization/mineralization was similar to that in the surface 0-2.5 cm soils, however, between days 9 and 76 the rates were often an order of magnitude lower at the 2.5-7.5 cm depth. This is not surprising, since organic matter and microbial populations, the two main factors determining immobilization/mineralization, are greatest near the surface (Doran, 1980).

Net mineralization rates were also an order of magnitude lower in the soybean plots compared to cotton, which is most likely due to the addition of inorganic N fertilizer in the cotton systems. Rates were similar prior to the first fertilizer application on day 19. Upon fertilizer application, however, the rates greatly increased in the cotton plots. As mentioned in the literature review, fertilizer N can have a stimulatory effect on microbial populations if there is a readily available energy source (Russell, 1973). Crop residues would have been available in both CO1 and CO3, and as well, tillage in the conventional plots could have exposed previously unavailable organic matter through pulverization of soil aggregates. By the end of the summer (\textit{ca} day 120 in the cotton plots), the rates in the cotton plots were similar to the lower soybean mineralization rates,

\textsuperscript{10} According to the agronomist at this experimental farm, the soybean crops yields in the production plots used in this study were less than 50\% of the yields in soybean crops grown on the watershed plots at same experimental site (Dabney, 1997, pers. comm).
Figure 2. Net mineralization rates in CT and NT (a) cotton and (b) soybean plots (average of 5 replicate plots). Graphs show data from wheeltrack, row and no-track positions at the 0-2.5 cm depth.
Figure 3. Net mineralization rates in CT and NT (a) cotton and (b) soybean plots (average of five replicate plots). Graphs show data from wheeltrack, row and no-track positions at the 2.5-7.5 cm depth.
which was most likely due to a dearth of C substrates in all systems by the end of the season, consequently, low overall microbial activity (Alexander, 1977).

Although the magnitude of net mineralization rates adhere to the theoretical rise and fall in microbial activity, this does not provide an explanation for why net immobilization occurred at some points in time, while net mineralization dominated at others.

As outlined above, the processes of N-mineralization and N-immobilization involve the microbial transformations of organic N into inorganic forms and vice versa. The type, amount and location of organic substrates available to the microorganisms ultimately governs whether net mineralization or net immobilization of N occurs (Doran and Smith, 1987). In these four cropping systems, microorganisms have access to indigenous soil organic matter, as well as organic inputs from crop residues and weeds. The C/N ratios of soil for the cotton and soybean plots (Table 1) ranged from 8 to 10. It is known that very little nitrogen from soil is mineralized over the course of the season, perhaps a few kilograms per hectare, because much of the organic N is bound up in stable organic matter fractions, with turnover times ranging from one to thousands of years (Stevenson, 1986).

It has been suggested that differences in N mineralization are more closely related to the amounts of young organic matter\textsuperscript{11} than total N contents of the soil (Janssen, 1984). Therefore, this examination of patterns of net immobilization and mineralization will focus on how differences in young organic matter, in this case the addition of crop residues, might influence N availability in the four cropping systems.

Smith and Sharpley (1990) reported a general pattern of immobilization-mineralization for a wide range of crops from a study in which they investigated the effects of crop type and residue placement on soil N availability. The authors observed an initial depression of both indigenous and fertilizer-derived soil inorganic N with all non-leguminous residue additions, and the depression was enhanced when the residues were incorporated rather than left on the soil surface. They found that in many cases net immobilization due to crop residue addition was greatest during the first 14 days. Thereafter, immobilization decreased and in some cases net mineralization was evident by day 56.

Aulakh et al. (1991) observed the same trends for a range of residues, with immediate net immobilization occurring upon application of wheat, corn and soybean residues (C/N 82, 39, and 43, respectively). The apparent net immobilization of incorporated residues after 35 days ranged from 32-34 mg N kg\textsuperscript{-1}, while surface placement caused less change in mineral N, with net immobilization ranging from 22-30 mg N kg\textsuperscript{-1}. Net mineralization commenced immediately when hairy vetch (C/N

\textsuperscript{11} See p. 13 for a definition of young vs. old organic matter.
incorporated and surface-applied vetch, respectively.

Regardless of initial C/N ratio, all crop residues can be expected to eventually increase net soil mineralization (Black, 1968), as the liberation of carbon, as CO₂, lowers the C/N ratio of the substrate to the point where it meets the energy (C) and nutritional (N) requirements of the microorganisms (Alexander, 1977). Stevenson (1986) has cited 4-8 weeks as a reasonable estimate of the time required for net mineralization of N from added residues to commence.

The following section will focus on the pattern of mineralization/immobilization in the cotton systems, and the focus will be on the top 0-2.5 cm depth, since the differences were more marked in this surface layer. Emphasis will be placed on the major divergences from the Smith and Sharpley (1990) and Aulakh et al. (1991) studies, i.e., the large net mineralization between days 9-19 and the large net immobilization between days 43 and 60.

5.2.1 Divergences from the Expected
5.2.1.1 Early Net Mineralization

Unlike the CO1 plots, which followed Smith and Sharpley’s (1990) pattern of net immobilization following residue incorporation, the CO3 plots did not experience immediate net immobilization upon addition of the wheat residues. It was only after an initial flush of mineral N (between days 9 and 19), which was especially large in the wheeltrack and no-track positions, that net immobilization occurred (Figure 2).

The large increase in inorganic N between days 9 and 19 might have been due to: 1) the drying-rewetting of the soils; 2) the rapid decomposition of the wheat cover crop; 3) the stimulation of mineralization of indigenous organic N following the addition of C substrate and/or fertilizer N, i.e., a “priming effect”; or 4) sampling artefacts.

Drying and Rewetting

Drying and rewetting of soil results in enhanced decomposition of soil humus, with subsequent flushes of ammonium followed by nitrate (Stevenson, 1986; Russell, 1973). The drying and wetting of soils has been demonstrated to cause flushes in inorganic N ranging from 5.61 mg N kg⁻¹ in CT soils to 16.2 mg N kg⁻¹ in NT soils (Cabrera, 1993). The sources of the mineralized N are decomposable organic substrates derived partially from soil biota killed during the drying process, although various studies have shown that these contributions are small (Amato and Ludd, 1980; van Gestel et al., 1991), and partially from non-living SOM (Jenkinson, 1966). The drying-wetting cycle
as a result of physical disruption of the soil structure and desorption of C-compounds from the soil surfaces (van Gestel et al., 1991).

There was a brief period without any precipitation, i.e., between days 7 and 12, which could have caused the increase in mineral N measured in the incubated soil cores. However, several factors suggest that this was not the major cause of the apparent net N mineralization. The soil water content (SWC) of the incubated cores did not deviate from beginning to end of the incubation, thus, it is unlikely the soils dried out enough to induce the desiccation of a large portion of the microbial biomass, or greatly increase the availability of organic substrates, which are the two sources of mineralizable N made available during a drying phase (Stevenson, 1986).

Furthermore, less drying occurred in the NT than the CT soils, i.e., the NT soil cores had higher SWC than their CT counterparts at the end of the incubation (Figure 4), and yet the net mineralization was most evident in the NT soils. Therefore, the large net mineralization in the NT wheeltrack and no-track positions between days 9 and 19 cannot be attributed to a drying-wetting effect.

**Wheat Residue Decomposition**

It is possible that the wheat residues could have decomposed rapidly, resulting in net mineralization within the 10-day incubation, akin to the immediate mineralization following application of leguminous residues. This would have occurred if the residues contained nitrogen in excess of the requirements of the microorganisms decomposing the substrate. Unfortunately, the carbon and nitrogen contents of the killed wheat-crop residues were not determined for this study. However, using data from published studies involving wheat residues, an attempt will be made to deduce whether a flush of N from the residues could have occurred that early in the season.

Mature wheat residues generally have a fairly high C/N ratio, although a wide range in C/N ratios have been reported (Table 3). In the studies reporting the highest C/N ratios for wheat residues (e.g., Smith and Sharpley, 1990; Singh, 1995), the crop was sampled after senescence, and the grain was removed (and with it a significant amount of N) leaving only straw residues.

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12 In the wheeltrack and no-track positions, which experienced the greatest net mineralization, the SWC at the start and end of the incubation (% dry weight) were: wheeltrack - no change, and no-track - 28 vs. 26.

13 It has been suggested that net mineralization will commence at a C/N ratio less than 20 to 30:1 (Alexander, 1977).
Figure 4. Soil water content (% dry weight) in covered incubation cores in the wheeltrack, row and no-track positions of CO1 and CO3 cotton plots. 0-2.5 cm depth.
Table 3. Summary of some published reports of crop residue C and N characteristics.

<table>
<thead>
<tr>
<th>Crop</th>
<th>C content</th>
<th>N content</th>
<th>C/N</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Wheat</td>
<td>45</td>
<td>0.78</td>
<td>57.7</td>
<td>- aboveground portions excluding grain</td>
<td>Smith and Sharpley. (1990)</td>
</tr>
<tr>
<td></td>
<td>37.8</td>
<td>0.48</td>
<td>76</td>
<td>- straw</td>
<td>Singh (1995)</td>
</tr>
<tr>
<td></td>
<td>38.1</td>
<td>2.06</td>
<td>19</td>
<td>- straw</td>
<td>Huffman et al. (1996)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.92</td>
<td></td>
<td>- crop harvested prior to maturity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5 (g)</td>
<td></td>
<td></td>
<td>- (g) grain and (s) straw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0 (s)</td>
<td></td>
<td></td>
<td>- (s) straw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.56 (g+s)</td>
<td></td>
<td></td>
<td>- tropical/subtropical climates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.91 (g)</td>
<td></td>
<td></td>
<td>- (f) forage = all aboveground biomass including grain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.65 (f)</td>
<td></td>
<td></td>
<td>- crop harvested prior to maturity</td>
<td>Boman et al. (1995)</td>
</tr>
<tr>
<td></td>
<td>2.0 (g)</td>
<td></td>
<td></td>
<td>- crops mature</td>
<td>Olson and Kurtz (1982)</td>
</tr>
<tr>
<td></td>
<td>0.75 (s)</td>
<td></td>
<td></td>
<td>- lint and seed removed, i.e., stalks leaves and burrs remain</td>
<td>Olson and Kurtz (1982)</td>
</tr>
<tr>
<td></td>
<td>1.36 (g+s)</td>
<td></td>
<td></td>
<td>- elephant</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>1.4</td>
<td></td>
<td></td>
<td>- straw</td>
<td>Olson and Kurtz (1982)</td>
</tr>
<tr>
<td>Soybean</td>
<td>1.4</td>
<td></td>
<td></td>
<td>- crop mature</td>
<td>Olson and Kurtz (1982)</td>
</tr>
</tbody>
</table>

The residues in this study differed from most of the published literature on wheat residue decomposition in that the wheat was killed on April 9, before it had reached maturity, and the grain was returned as residues instead of being harvested. Both of these factors should lower the C/N ratio of the wheat residues, perhaps enough to result in immediate net mineralization. For example, it has been demonstrated that time of desiccation has an effect on N mineralization. Wagger (1989) found that rye cover crops killed early (e.g., April) had C/N ratios ranging from 27 to 36. Rye killed one month later, however, resulted in lower N concentrations and higher C/N ratios (e.g., 32 to 44) due to a proportionally larger increase in dry matter production compared to N accumulation between April and May.
approximately 2.0 percent (Olson and Kurtz, 1982). Boman et al. (1995) reported that the N content in winter wheat forage sampled between March 23 and April 19 (prior to maturity) was 1.65 percent. The conditions of the Boman et al. study were extremely similar to my study, since neither their wheat crop nor the wheat in my study received N fertilizer. Also, the dates of cover crop desiccation were similar (April 19 compared to April 24 in my study). Thus, an N content of approximately 1.65 percent seems a reasonable estimate for the wheat residues in this study.

To avoid appreciable immobilization of soil mineral N, while concurrently supplying the needs of soil microbes during crop residue decomposition, minimum residue-N contents of 1.5 - 1.7% (C/N ratio of 30-25) have been suggested (Alexander, 1977; Allison, 1973). From the preceding studies it appears plausible that within the 10-day incubation period net mineralization from the wheat residues occurred. However, it is unlikely that within the 10-day period mineralization rates as high as 27 mg N kg soil\(^{-1}\) day\(^{-1}\), as calculated for the NT wheeltrack position, could have occurred. Nicolardot et al. (1995) found that early desiccation of a rye crop (C/N ratio 14) resulted in the release approximately 10 mg N kg soil\(^{-1}\) over a period of 5 months, which corresponds to mineralization rates of less than 1 mg N kg soil\(^{-1}\) day\(^{-1}\). Similarly, Aulakh et al. (1991) reported that hairy vetch (C/N ratio of 8) only achieved mineralization rates ranging from 2.6 to 3.1 mg N kg soil\(^{-1}\) day\(^{-1}\).

Alternatively, it is possible that the wheat residues, because they contain a relatively high proportion of secondary compounds, such as polyphenols, decomposed slowly. Broder and Wagner (1988) reported that wheat harvested at maturity decomposed more slowly than soybean residues due to a lower proportion of more easily decomposable, soluble organic compounds in the wheat, with 47% versus 69% of the total organic matter of wheat and soybean, respectively, disappearing within 32 days of application. As mentioned previously, the wheat cover crop on CO3 was not fertilized over the winter, and so it is possible that the wheat was nutrient-stressed while growing. Some literature suggests that plants growing in nutrient-poor environments are likely to have higher concentrations of carbon-based secondary compounds, perhaps to offer more resistance against insect attacks, than plants on nutrient-rich sites (Chapin, 1980). Therefore, it is likely that the wheat had a high proportion of relatively difficult-to-decompose compounds, and consequently, the net mineralization between days 9 and 19 was not from residue-N release.

The greatest net mineralization occurred in the CO3 wheeltrack and no-track positions, which is where the wheat residues were concentrated. The row position had the lowest net
cotton residues, which have C/N ratios between 44 and 80, depending on the plant part (Torbert et al., 1995) Therefore, the cotton residues would have induced immobilization of N, resulting in a relatively lower net mineralization rate in the row position.

To summarize, it appears that the decomposition of the wheat residues could not have resulted in the high net mineralization rates occurring immediately after their desiccation. Thus, an alternative explanation is required. The explanation may lie in a phenomenon known as the “priming effect.”

**Priming Effect**

It has been found that the addition of fresh organic substrates can either accelerate or reduce the rate of humus decomposition (Alexander, 1977). The enhancement is known as priming, and the theory is that a large and vigorous microbial population is built up when organic (energy) material is added to the soil, and that these microorganisms subsequently produce enzymes that attack the native SOM (Stevenson, 1986).

It is possible that the addition of the residues and/or N-fertilizer stimulated mineralization of indigenous soil organic matter. In studies carried out by Hallam and Bartholomew (1953), less total C remained in soils incubated with plant materials than in soils incubated alone. More recently, Scott et al. (1996) observed that the addition of fresh wheat residues stimulated mineralization of native carbon. Scott et al. also found that the greatest native soil C mineralization occurred during the 0-10 day period, which coincided with their measurements of maximum microbial activity. This was the length of the incubation period during which the net mineralization in my study occurred. Therefore, it is possible that the net mineralization observed in the CO3 plots was either wholly, or in part, derived from the mineralization of N from indigenous soil organic matter.

In the Scott study, the C/N ratio of the residues was 19, and Parnas (1976) has suggested that a priming effect will occur at a residue C/N ratio equal to or less than 25. Therefore, if the wheat residues in my study had a high C/N ratio it is possible that they would not induce the priming effect that occurred in the Scott et al. study. Fertilizer N has also been reported by a number of Russian researchers, to stimulate the mineralization of indigenous soil organic matter (Sapozhnikov et al., 1968; Filimonov and Rudelev, 1977; Zamyatina et al., 1968), however, there is no universal agreement on whether this phenomenon exists (Stevenson, 1986; Jansson and Persson, 1982).

It is most likely that the addition of the wheat residues in combination with fertilizer N were able to induce the mineralization of indigenous SOM. If priming is a microbial growth-related
microbial growth. However, in the CO3 plots, the microorganisms would have had access to both a C source and an N source, thus stimulating microbial activity. The larger and more energetic community would then be able to degrade SOM more readily than the original microflora (Alexander, 1977). The mineralization of indigenous C would also have resulted in the mineralization of soil organic N because the C/N ratios of the soils in the cotton plots were less than 10. Carbon and nitrogen in this ratio should satisfy the energy and nutrient demands of many microorganisms.  

This scenario actually provides a better explanation for the pattern of N mineralization and immobilization observed in the NT cotton system. If the residues had a low C/N ratio, and net mineralization ensued within the first 10 days, then it is difficult to reconcile this with the net immobilization that occurred from days 19 to 60. Once the C/N ratio of residues has been lowered to the point where net mineralization commences, this net release of nitrogen continues because the carbon and nitrogen in the residues meet the needs of the microorganisms, and so immobilization of soil inorganic N no longer occurs.

If the wheat residues had a high C/N ratio they would require more time to decompose, and therefore, would cause a more prolonged net immobilization of inorganic N. In this scenario, after the initial enhancement of N levels between days 9 and 19 via stimulation of SOM mineralization (presumably), net immobilization of N by microorganisms decomposing the wheat residues would have predominated in the NT soils. The observed immobilization period lasted approximately 50 days (Figure 5). In the Smith and Sharpley study (1990) the residues with high C/N ratios caused net immobilization that lasted approximately 56 days.

As seen in Figure 5, the row position in CO1 also experienced net mineralization between days 9 and 19, although the net increase in mineral N during the incubation was nowhere near as large as the NT wheeltrack and no-track positions. Whether priming occurs or not depends on the type of organic substrates or plant remains added as well as soil characteristics (Alexander, 1977; Scott et al., 1996). In the conventionally tilled cotton plots, the residues from the previous cotton crop were incorporated into the soil. It is possible that the CO1 row position experienced net mineralization because more substrate or higher quality substrate was present within the row than between the rows. Prior to the incubation, the CO1 plots had been disked and hipped, which involved building raised rows. The soil in the newly built-up rows could have contained more of the

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14 According to Alexander (1977), microbial cells contain 5 to 15 parts carbon to 1 part nitrogen, however, 10:1 is a “reasonable” average for the predominant aerobic flora.
from either the residues or the SOM (upon application of fertilizer N).

One other possibility is related to soil structure. Higher habitable pore space for microorganisms should increase decomposition of incorporated substrates and enhance the possibility of native SOM mineralization (Scott et al., 1996). When the incubated cores from day 19 were being prepared for laboratory analyses it was observed that many of the samples from the conventionally tilled wheeltrack and no-track position had very poor soil structure. These two positions have been reported by Dabney (1997) as having higher bulk densities than the row position. The cores from the wheeltrack and no-track areas were difficult to extract from the incubation tubes and difficult to sieve because they were extremely compacted and did not break apart easily. Jensen et al., (1996) reported that air-filled porosities of compacted soils were only half as great as uncompactecl, cropped soils. The samples from the CO1 row position, on the other hand, were much easier to remove from the cylinders and sieve. This better soil structure could explain why low rates of N mineralization only occurred in the row position of CT cotton.

Priming has yet to be adequately explained as a phenomenon, and without the aid of isotopic tracers, it is impossible to discern whether the N mineralized came from the plant residues, SOM or microbial biomass. However, there is one more reason to believe that the net mineralization was due to a stimulation of SOM mineralization, and not simply from release of wheat-residue N. As mentioned in Section 5.1, the NT cotton plots were the only ones in which a decrease in total carbon occurred between March and June. If mineralization of SOM occurred between days 9 and 19 (April 26 - May 6), the loss of carbon during the process could explain why the total C levels were lower than they were in March. Although the addition of carbon to the system via wheat residues would have bolstered total C contents, these residues had 40 days to decompose before the June sampling occurred. With the high rates of microbial activity that likely accompanied the addition of the wheat residues and fertilizer during this period, it is possible that a large volume of CO₂ was liberated, thus lowering total soil C content.

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15 Bulk density of 1.5 g cm⁻³ in wheeltrack versus 1.35 and 1.15 g cm⁻³ in no-track and row, respectively. These are estimates made by Dabney (1997, pers. comm.) at the Nelson Farm plots for corn grown as part of the larger study, therefore, the soils were the same texture. It is acknowledged that the different crops and crop management treatments could also affect bulk density, e.g., number of passes with farm equipment, types of residues present, etc., however, these are the only data available for the site.

16 If 1 unit N incorporated into cell tissues results in the volatilization of 20 units of CO₂ (Alexander, 1977), then an N mineralization rate of 15 mg N/kg soil/day = 300 mg CO₂/kg soil/day x 10 days = 3000 mg CO₂ = 3 kg CO₂ evolved / kg soil during the incubation = 800 mg C/kg soil in this 10 day “priming” period.
Figure 5. Net mineralization rates in CT and NT cotton (average of five replicate plots).
Graphs show data from wheeltrack, row and no-track positions at the 0-2.5 cm depth.
Vertical bars represent standard error.
were apparently stimulated by the unique combination of fresh wheat residues plus fertilizer. The soybean plots did not receive any fertilizer, and no net mineralization was observed early in the season, and fertilizer without large inputs of organic matter (e.g., CO1) only stimulated a minor net mineralization in the row position. This is in agreement with the general theory that heterotrophic activity in soil is limited not by the supply of inorganic nutrients, such as nitrogen, but by the paucity of readily utilizable organic nutrients (Alexander, 1977). Under the conditions of this study, fertilizer plus wheat residues, combined with high soil water content, which would have allowed for increased contact between the residues and soil microorganisms (Scott et al., 1996), created an environment in which the rapidly expanding microbial population could attack indigenous SOM utilizing the energy from the wheat substrates provided.

5.2.1.2 High Net Immobilization

As outlined above, when residues decompose net immobilization of soil inorganic N (derived either from indigenous soil N or fertilizer N) may be observed initially, however, the degree of immobilization decreases with time, until the point where the C/N ratio of the residues meets the nutritional and energy requirements of the microorganisms. Smith and Sharpley (1990) determined that for most crop residues, immobilization of soil inorganic N was only evident during the first 14 days. Thereafter, immobilization decreased and by 56 days net mineralization was evident.

This trend is evident in the CO1 wheeltrack and row positions (Figure 5), and the CO3 wheeltrack position. In the CO1 and CO3 no-track positions, and the CO3 row position, however, there was a notable increase in net immobilization between days 50 and 60, following the second fertilizer application.

Fertilizer N cannot induce net microbial immobilization without an adequate C (energy) supply (Alexander, 1977). The no-till (CO3) system received larger and more diverse residue inputs early in the season, thus, it is plausible that there was enough substrate present, at various stages of decomposition, to induce high rates of immobilization of the second fertilizer N application (Green and Blackmer, 1995). What makes the high net immobilization rate in the CT no-track position suspect is that the plots did not receive any new additions of organic matter to provoke an increase in N immobilization. The lack of response to the fertilizer addition in the CO1 wheeltrack and row positions further calls the no-track immobilization into question.

The most likely explanation for the net immobilization in the CT no-track position is that the decrease in mineral N during the soil incubation was not the result of the added N being immobilized
Figure 6 reveals that the major disappearance of inorganic N during the incubation period was from the ammonium ion, not nitrate. Because high amounts of ammonium were added (55 kg N ha\(^{-1}\) NH\(_4\)NO\(_3\)), it is possible that some of the NH\(_4^+\) was converted to NH\(_3\) and then volatilized. However, these soils are non-calcareous, therefore, losses via volatilization are probably not significant. It is also possible that sequential denitrification/nitrification or leaching/nitrification occurred. In these scenarios, the nitrate would either be denitrified, due to anaerobic conditions in the soil cores, or leached from the cores due to saturated conditions. And then, when soil moisture conditions improved, nitrification would have ensued. Thus, there would have been little net loss of nitrate, but the ammonium levels would have decreased considerably.

High rates of denitrification are generally associated with soil water contents exceeding field capacity. Aulakh \textit{et al.} (1991) reported that during a 17-day incubation of soil at 90% water-filled pore space (WFPS), denitrification resulted in a decrease in nitrate from 83 to 14 mg N kg\(^{-1}\) soil\(^{-1}\), whereas soil incubated at 60% WFPS resulted in an increase to 97 mg N kg soil\(^{-1}\).

Determinations of %WFPS were not conducted in my study, however, the soil samples with high bulk density and high soil water content should have had the highest percentage of WFPS and hence, would be more prone to inducing denitrification (Jensen \textit{et al.}, 1996). As seen in Figure 7, the no-track position had the highest SWC for both NT and CT on the dates of high net immobilization. The wheeltrack soils had a higher bulk density than the no-track soils, however, because the wheeltrack soils were more compacted it is possible that during intense rainfall events much of the precipitation would have been lost as runoff, resulting in lower infiltration rates than in uncompacted soils. More than 6 cm of rain fell in the three days following the fertilizer application. Although the cores were covered, the three days of rain were probably enough to increase the SWC of the cores to high levels through diffusion, and the covers would have slowed the drying process by impeding evaporation, so the cores could have remained saturated for an extended period of time. Thus, denitrification and/or leaching could have resulted.

The wet period was followed by a dry period\(^{17}\) during which moisture conditions could have improved enough to promote nitrification of the ammonium. Therefore, by the end of the incubation, both ammonium and nitrate levels would have decreased, but not necessarily as a result of a large amount of N being immobilized in microbial biomass. This idea will be further discussed in Section 5.4.

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\(^{17}\) Between days 54 and 61, only 6.25 mm of rain fell.
Figure 6. Changes in NH₄⁺ and NO₃⁻ during 14 soil incubations in (a) CT no-track and (b) NT no-track cotton, at the 0-2.5 cm depth.
Figure 7. Net mineralization rates and soil water contents for the wheeltrack, row and no-track positions, 0-2.5 cm depth. Graph (a) CT cotton, and graph (b) NT cotton.
Figure 8 illustrates the cumulative amounts of N mineralized in the four cropping systems over the course of the season. The values were calculated by summing the amount of NH$_4^+$ and NO$_3^-$ for the dates when net mineralization occurred. The point of this exercise was to illustrate the total amount of N made available for plant uptake over the course of the season. Therefore, dates when net immobilization occurred were omitted since there was no net increase in plant-available N during these periods.

High organic C levels have been associated with increases in N mineralization (Campbell and Paul, 1978). Table 4 presents the data on cumulative mineralized N, as well as the total C and N data from Section 5.1. There were no significant correlations between total C or total N and the amount mineralized from each cropping system (for any of the positions). It was thought that the large amount of N mineralized in the CO3 plots (wheeltrack and no-track positions) might have obliterated any relationships, however, when these data were omitted there were still no significant correlations between total C or total N and $N_m$.

Table 4. Cumulative net N mineralized between April and December, 1996, in CT and NT cotton and soybeans, and total C and N data.

<table>
<thead>
<tr>
<th>Position</th>
<th>Depth</th>
<th>Cumulative net N mineralized</th>
<th>Cumulative net N mineralized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mg N kg$^{-1}$ soil</td>
<td>kg N ha$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>CO1</td>
<td>CO3</td>
<td>SB1</td>
</tr>
<tr>
<td>a</td>
<td>0-2.5 cm</td>
<td>10.47</td>
<td>233.37</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>45.44</td>
<td>23.83</td>
</tr>
<tr>
<td>c</td>
<td></td>
<td>9.37</td>
<td>264.91</td>
</tr>
<tr>
<td>a</td>
<td>2.5-7.5 cm</td>
<td>38.03</td>
<td>39.28</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>19.24</td>
<td>23.23</td>
</tr>
<tr>
<td>c</td>
<td></td>
<td>20.88</td>
<td>29.27</td>
</tr>
</tbody>
</table>

Total C (%) 0-2.5 cm 0.96 1.96 0.98 2.4
2.5-7.5 cm 091 09 0.85 0.96

Total N (%) 0-2.5 cm 012 020 0.1 0.25
2.5-7.5 cm 0.11 0.1 0.1 0.11

* - calculations for conversion to kg N/ha based on bulk densities of 1.5, 1.15 and 1.35 for the wheeltrack (a), row (b) and no-track (c) positions (Dabney, 1997, pers. comm.).
Figure 8. Cumulative net mineralized N ($\text{NH}_4^+ + \text{NO}_3^-$) in the wheeltrack, row and no-track positions of cotton and soybean plots (0-2.5 and 2.5-7.5 cm depths).
Increasing the input of organic matter has been found to increase N mineralization potentials and the proportion of total N present in the more available form of soil N (Bonde and Rosswall, 1987). Therefore, the amount of organic inputs might provide a better estimate of mineralizable N than total C and N.

The estimated amount of nitrogen returned in the CO1 cotton residues was 32 kg N ha⁻¹, as opposed to 80 kg N ha⁻¹ returned via the cotton (37 kg N) and wheat residues (43 kg N) in the CO3 plots, and 43 and 80 kg N ha⁻¹ for the SB1 and SB4 cropping systems, respectively (Appendix 2). Not all of this N would be mineralized over the course of the season. For example, Wagger (1989) found that 16 weeks after application of rye residue, only 41% of the initial residue N had been released. Although rates of decomposition have been shown to be more rapid in CT soils, on a seasonal timescale the same residues in CT and NT soils show no difference in degree of decomposition (House et al., 1984). Thus, it is not surprising that the by the end of the season cumulative mineralized N was highest in the NT systems, which received the greatest N inputs via crop residues. Similar findings have been reported by van Faassen and Lebbink (1994). They observed that cumulative N mineralization was greater in systems receiving more organic inputs than those receiving fertilizer N only (56 versus 44 kg N ha⁻¹, respectively).

By mid-season, i.e., day 90, there were only minor accumulations of mineralized N in CO1, CO3 and SB1, which is probably due to lack of mineralizable organic substrates. In the soybean plots, however, cumulative mineralized N increased steadily from day 70 to the end of the sampling period. By this point in the season (i.e., 60 days after wheat was harvested) the wheat residues could have induced N mineralization (Smith and Sharpley, 1990).

Toward the end of the study (days 180-220) there appears to be mineralization occurring in both SB1 and SB4. With the harvest of the soybean and cotton crops on days 176 and 178, respectively, some of the residues produced during harvest would have been available for decomposition, e.g., leaves inadvertently stripped from the plants by the harvest machinery.

It is probable that the increase in cumulative mineralized N in the soybean plots toward the latter part of the season resulted from the rapid decomposition of the soybean residues, while little increase was seen in the cotton plots due to the more resistant nature of their residues. Broder and Wagner (1988) observed more rapid decay of soybean than corn or wheat residues, and they related this high rate of decomposition to the larger proportion of easily decomposable water soluble organic constituents in the soybean residue. Residue components such as cellulose and lignin, which were higher in the corn and wheat litter, were found to degrade at slower rates (Broder, 1985). As seen in
explain why no net mineralization of the cotton residues occurred by the end of the sampling season.

Table 5. Chemical composition of cotton and soybean residues.

<table>
<thead>
<tr>
<th>Soluble components</th>
<th>Cotton stems*</th>
<th>Cotton leaves*</th>
<th>Soybean**</th>
</tr>
</thead>
<tbody>
<tr>
<td>hemicellulose</td>
<td>1.31</td>
<td>1.53</td>
<td>0.90</td>
</tr>
<tr>
<td>cellulose</td>
<td>4.17</td>
<td>2.36</td>
<td>2.22</td>
</tr>
<tr>
<td>lignin</td>
<td>2.26</td>
<td>1.3</td>
<td>1.19</td>
</tr>
<tr>
<td>N</td>
<td>1.0</td>
<td>3.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>

* data from Torbert et al. (1995)
** data from Broder and Wagner (1988)

Effects of Fertilizer on cumulative net mineralized N

El-Haris et al. (1983) compared the effects of tillage, N fertilizer rates and crop rotations on soil N mineralization potentials and cumulative mineralized nitrogen. The total amounts of N mineralized in the El-Haris et al. study were comparable to my study. In plots receiving 135 kgN ha\(^{-1}\), they reported cumulative \(N_m\) values of approximately 45 mg kg\(^{-1}\). This corresponds with the amount of fertilizer received by the cotton plots (approximately 100 kg N ha\(^{-1}\)), and in my study the CT cotton had an \(N_m\) of 45 mg kg\(^{-1}\) in the row position, although levels were lower in the wheeltrack and no-track positions, and the CO3 plots had much higher cumulative mineralized N values (>200 mg kg\(^{-1}\)) due to the "priming effect".

Hadas et al. (1989), found much higher accumulations of mineralized N during an 11-week field study. They recorded 138 and 78 kg N ha\(^{-1}\) in soils receiving 100 kg N and zero fertilizer, respectively. However, in their study, 25% and 45% of the N mineralization in fertilized and unfertilized plots, respectively, occurred below a depth of 60 cm. Thus, it is possible that the soils in my study were mineralizing considerable amounts of N at depths below 7.5 cm, i.e., the length of my incubation cores.

In the El-Haris et al. study, the greatest mineralization occurred in the incubation period immediately following fertilizer applications; after 4 weeks the cumulative \(N_m\) did not change very
In my study, it appears that this same situation occurred in the CO3 system, with the maximum accumulation occurring within the period immediately following the first fertilization (day 19), and little change occurring thereafter. However, in the CO1 system the accumulation of mineralized N occurred at various times throughout the season (Figure 7), suggesting that there was immobilization of a portion of the added fertilizer N from the incorporation of low N cotton residues, which became available more slowly.

**Effects of tillage and compaction on N\textsubscript{m}**

El-Haris et al., (1983) found that cumulative mineralized N was greater in the surface 0-5 cm than the underlying soils in a NT system, however, there was no difference in N\textsubscript{m} with depth in the CT soil. The mineralized N in the NT surface soils was also greater than that in the top 0-5 cm of the CT soil, whereas, at the 5-10 cm depth the CT system had a higher N\textsubscript{m} than the NT sub-surface soil (El-Haris et al., 1983). These findings parallel the relative amounts of total C and N often reported for CT versus NT soils (Rice and Smith, 1984), i.e., higher total C and N are often observed in the surface soils of NT systems, but in the subsoils CT systems have higher C and N contents. Others have reported that incorporation of residues in CT systems affected the rate at which N was mineralized, but had no significant effect on the total cumulative mineralized N amounts (Nicolardot et al., 1995; House et al., 1984).

In this study, the NT cotton mineralized more than CT at the 0-2.5 cm depth, although in the row position more N was mineralized in the CT system than in NT. It is possible that there was greater immobilization in the NT row due to the presence of a larger microbial population associated with the higher organic matter levels (Doran, 1980). In contrast to the El-Haris et al. study, at the 2.5-7.5 cm depth the CT cotton did not mineralize more than NT cotton, although the CT cotton did mineralize more than the NT soybeans at this depth. In agreement with the El-Haris et al. findings, the CT cotton 2.5-7.5 cm depth mineralized as much as the 0-2.5 cm depth in the same plots. This could be because the soils had the same substrate availability. Tillage and cultivation would have mixed residues into the soils, creating a fairly uniform (on a field scale) distribution of organic matter within the top 15 cm of soil.

Compaction in the CT systems appeared to have impeded mineralization at the 0-2.5 cm level in the cotton. The cumulative N\textsubscript{m} values were lowest in the wheeltrack and no-track, which had higher bulk densities than the row position. At the 2.5-7.5 cm depth, however, the wheeltrack had a
C-substrates and the microbial community, thereby enhancing N mineralization (Lee et al., 1996).

**Summary of Net Mineralization-Immobilization Results**

The apparent net rates of mineralization and immobilization did not differ greatly between tillage regimes for the same crop, e.g., cotton or soybean. However, up until mid-July (approximately day 100) the rates of N mineralization/immobilization in the cotton 0-2.5 cm depth were higher than both the 2.5-7.5 cm cotton soil samples, and the soybean systems. These high rates were undeniably influenced by the large inputs of fertilizer N, as well as organic inputs, which tended to concentrate in the surface soil. However, these effects were transient in nature, and by mid-summer the rates of mineralization and immobilization between the two systems and two depths were comparable.

The well-established pattern of immobilization followed by mineralization for non-legume residues (Smith and Sharpley, 1990; Aulakh, 1991) was evident in both CO1 and CO3, with both systems experiencing net immobilization from the start of the season until the end of July (approximately day 100), with the exception of the large net mineralization observed in the CO3 system between days 9 and 19.

By the end of the sampling season, the cumulative mineralized N followed the same general trend as the total C and N data (i.e., SB4 > CO3 > SB1 = CO1), with NT systems attaining higher N_m values than the CT systems. The only exception was that the no-till cotton plots mineralized more N than the SB4 plots, which was most likely due to the application of synthetic fertilizer in the cotton plots. Hadas et al. (1989) found that fertilized plots mineralized almost twice as much N as unfertilized plots in an 11-week study.

Furthermore, the no-till plots had higher organic matter contents, and greater additions of “young” organic materials (Janssen, 1984), and consequently, a larger amount of potentially mineralizable N. The NT cotton received the bulk of its organic inputs early in the season (April 24), and so the system had more time to decompose these materials, and hence cumulative mineralized N should be greater than SB4, which did not receive the majority of its organic inputs until mid-season (June 17). In the CT systems, the majority of the soybean residues, which contain more soluble C-components and therefore decompose faster than many other crops, would have been mineralized the previous fall (Broder and Wagner, 1988), and so comparatively less N than CT cotton would be mineralized over the course of the spring/summer season due to lack of substrate.
fact that the soil incubation methods used for determining the temporal changes in \( \text{NH}_4^+ \) and \( \text{NO}_3^- \) could have induced changes in mineral N that would not have occurred under prevailing field conditions. The introduction of sampling artefacts will be addressed after the data on soil inorganic N concentrations has been reported and discussed.

5.3 Soil Inorganic N

The processes of mineralization and immobilization are important in that they contribute to the availability of soil inorganic N. This section examines the seasonal pattern of N availability, as estimated by measurements of soil inorganic (plant available) N, with the ultimate aim of determining if the management practices imposed at this site have resulted in good synchrony between soil N availability and crop N requirements. It is important to remember that these measured N concentrations represent but a snapshot in time, however, the seasonal trends and relative amounts between cropping systems allow for general comparisons to be made.

Differences in crop management treatments, such as tillage events and residue additions, and their interaction with climate factors, represent potential sources of variation in ammonium and nitrate levels. For example, tillage can accelerate residue decomposition and N mineralization (Smith and Sharples, 1990; Fox and Bandel, 1986); crop residue amount, placement and quality influence the amount and timing of N release (Wagger, 1989; Broder and Wagner, 1988; Smith and Sharples, 1990); fertilizer applications increase the pool of readily available mineral N (El-Haris et al., 1983); and climate exerts an influence on both the microbial transformations of N, and the physical movement of inorganic N in the soil environment (Doran and Smith, 1987).

The conventional till and no-till cotton management systems both received 100 kg N fertilizer over the course of the season, as well as a number of herbicide and pesticide applications, however, the similarities end there. The CT cotton soils were repeatedly disturbed (cotton residues were tilled under, rows were built up for planting, inter-rows were cultivated and sprayed to stop weed proliferation) over the course of the season, whereas in CO3, all crop residues remained on the surface and weeds were killed only with herbicides. Furthermore, CT cotton lay fallow over the winter, while NT cotton had a winter cover crop of wheat. The wheat cover crop was killed prior to planting, and so during the cotton growing season there was a difference in substrate composition and quantity of residues available for microbial decomposition.
inputs other than the what was left of the soybean crop after harvest of the beans (e.g., stems, leaves and roots). No-till soybeans, on the other hand, were in rotation with a winter wheat crop, which received 90 kg N during its growing season. The wheat was harvested prior to the planting of the soybean crop, leaving only the wheat straw and roots as residues.

Figure 9 presents the seasonal trend of available $\text{NH}_4^+$ and $\text{NO}_3^-$ in CT and NT cotton, and includes the soybean systems for comparative purposes (0-2.5 cm depth). The levels of available inorganic N in the soybean systems are much lower than in the cotton plots during the early part of the season. This is not surprising, considering that the cotton plots received N fertilizer amendments of approximately 45 kg N ha$^{-1}$ at day 19 and 55 kg N ha$^{-1}$ at day 50, while the soybeans did not receive any synthetic N inputs. By day 100 (mid-July), the influence of the fertilizers appeared to have waned, and the inorganic N concentrations remained low (<5 mg N kg$^{-1}$ soil) in both cotton tillage systems. Between days 70 and 120 the available N in the soybean systems exceeded the availability in the cotton plots. By this point in the growing season, the only N available to the cotton would be that N mineralized from the SOM or plant residues, and as seen from the data in Section 3.2, N mineralization rates were either negative, i.e., net immobilization was occurring, or the rates were very low (<0.2 mg N kg soil$^{-1}$ day$^{-1}$). Net mineralization rates were also low in the soybean plots (< 0.25 mg N kg soil$^{-1}$ day$^{-1}$), however, by this stage of development the N-fixation capacity of the soybean plants would have been fully functional (Fageria et al., 1991), and so the systems were receiving N inputs that the cotton plots were not.

The following section will look at the cotton system in more depth, to determine possible effects of the different management systems on the availability of inorganic N.

5.3.1 Ammonium

It was expected that tillage system would have an effect on soil mineral N levels, because there were differences in the crop residues applied and different levels of soil disturbance prior to the fertilization, which has been reported to accelerate the mineralization of the soil inorganic N (Balesdent et al., 1990; Fox and Bandel, 1986). It was also anticipated that the three sampling positions (i.e., wheeltrack, row, no-track) would have different levels of soil inorganic N because of the compaction of the wheeltrack soils and the influence of plants within the rows. However, neither tillage nor position had a significant effect on $\text{NH}_4^+$ concentrations (two-way ANOVA, P=0.05). This is misleading, however, since the data were averaged over the entire season. It is evident,
Figure 9. Seasonal soil $\text{NH}_4^+$-N (a) and $\text{NO}_3^-$-N (b) levels in CT and NT cotton (CO1 and CO3, respectively) and CT and NT soybean (SB1 and SB4, respectively) plots, average of all positions, 0-2.5 cm depth.
Therefore, individual two-way ANOVAs were conducted for each sampling date. When analysed this way, significant differences were detected. The dates where there were significant differences are indicated in Figure 10.

At the first sampling date, ammonium concentrations were significantly higher in the NT system, which could be due to immobilization of N in CT following incorporation of the residues from the previous year's cotton crop. However, the incubation study for this time period did not reveal net immobilization in the CT soils. More likely, the presence of the growing winter wheat cover crop, with its resident microbial community, promoted mineralization of N from SOM or wheat residues. These levels would be low, due to poor substrate quality and suboptimal temperatures for microbial activity, yet large enough to result in the build-up of some ammonium in the CO3 soils.

Predictably, applications of fertilizer N had a dominating influence on the levels of inorganic-N in both CT and NT cotton plots. The pattern of $\text{NH}_4^+$ availability was closely related to the fertilizer applications: concentrations were highest on days 9 and day 50, the dates when fertilizer was applied. Following each application, $\text{NH}_4^+$ concentrations, in general, dropped off considerably (Figure 11). This is in agreement with many agricultural field studies where only nitrate accumulated to any degree (Subler et al., 1993; Hadas et al., 1989). In cropped soils, the aeration is usually good enough to permit rapid oxidization of ammonium to nitrate, and consequently, many researchers have used the production of nitrate-N, alone, as the indicator of net mineralization in soils (Weier and MacRae, 1993; Hadas et al., 1989). In my study, although the ammonium levels decreased immediately, some ammonium did accumulate after the fertilizer applications, and therefore, measuring only nitrate-N would have provided an inaccurate picture of inorganic N availability.

The accumulation of ammonium that followed the first fertilizer application most likely occurred because the nitrifier populations had not yet become active enough to oxidize all available ammonium due to suboptimal temperatures\(^{18}\) (Jensen et al., 1996). The accumulation was more evident in the NT soils than the CT soils. There are three possible explanations for this trend. First, 

\(^{18}\) In the two weeks prior to the initiation of this study, maximum daily temperatures (ambient) ranged from 7.2 to 26.7 °C, and the average of that period was 19.6°C. The soil temperatures would have been even lower. The temperature optima for many microorganisms falls between 25-30°C (Alexander, 1977), therefore, microbial activity would have been low, but still occurring. Furthermore, Stenger et al. (1996), found C/N of 20 for wheat roots at the same growth stage as the wheat on CO3, therefore as these roots decomposed net mineralization could have been occurring.

\(^{19}\) Production of nitrate decreases with decreasing temperatures below 30-35°C (Stevenson, 1986).
Figure 10. Soil NH$_4^+$-N content in CT and NT cotton systems for (a) 0-2.5 cm depth and (b) 2.5-7.5 cm depth. Vertical bars show standard errors. Dates where CT and NT are significantly different at the 0.001, 0.01 and 0.05 levels are indicated by "***", ** and *, respectively. Values are averages of 3 sampling positions and 5 replicate plots.
Figure 11. Comparison of soil inorganic N (NH₄⁺ and NO₃⁻) levels in CT and NT cotton following fertilization (45 kg N ha⁻¹ applied on day 9 and 55 kg ha⁻¹ NH₄NO₃ applied at day 50).
fertilization because more of the fertilizer N was applied to the surface of the NT soils. The fertilizer was incorporated into the CT soil, which meant that less would be concentrated in the top three inches.

Second, as reported in Section 5.2, the incubation cores inserted after the first fertilizer application (day 9) resulted in a large increase in mineral N over the course of the incubation. Some of the nitrogen mineralized during the incubation period would have accumulated in the soils as NH$_4^+$. There is actually a discrepancy between the amount mineralized during the incubation and the amount that accumulated in the soils. This will be addressed in Section 5.4.

The third possible reason why ammonium accumulated to a greater degree in NT soils is that the wheat residues created a buffer, which kept the soil temperatures lower than in CT, and in turn, resulted in relatively slower nitrification rates. Doran (1980) and Broder et al. (1984) attributed accumulation of NH$_4^+$ to slower nitrification rates caused by higher water contents and cooler soil temperatures in NT. Both studies also reported larger nitrifier populations in CT than NT soils. Although the size of the relative nitrifying populations were not studied here, the data in Figures 12 and 13 indicate a lag in nitrate accumulation in both NT and CT soils in all three positions, and both depths. The first fertilizer amendment took place on day 19, and the nitrate levels did not show a marked increase in either CT or NT until day 36 in the 0-2.5 cm layer, and day 50 in the 2.5-7.5 cm depth (which corresponds to the second fertilizer application).

Dou et al. (1995) also observed this phenomenon of delayed soil NO$_3^-$ peaks in both NT and CT soils after application of NH$_4^+$-based fertilizers. This suggests that CT soils did not have larger nitrifying populations, otherwise, we would have expected to see faster, more complete nitrification of the added ammonium. The findings of this study are more in agreement with Fox and Bandel (1986), who suggested that nitrification rates are probably not markedly different in CT and NT systems in the same environment, and Hadas et al. (1986), who found that after NH$_4^+$ addition, nitrification followed a sigmoidal curve, with the lag period lasting from 0.2 to 8 days before nitrification increased, depending on soil type and depth.

It is not surprising, then, that ammonium also accumulated in the CT and NT wheeltrack and CT row after the second fertilization at day 50. However, this accumulation probably had more to do with soil moisture conditions, because by this point in the season temperatures were ideal for nitrification (i.e., >30°C).

The site received rain (more than 100 mm) between days 50 and 62, thus the inhibition of nitrification due to poor aeration would be the most plausible explanation for the ammonium
Figure 12. Seasonal variations in soil $\text{NH}_4^+$-N and NO$_3^-$-N for CT and NT (0-2.5 cm depth) by position: (a) wheeltrack, (b) row, and (c) no-track. Vertical bars represent standard error. * and ** represent significant differences by paired t-test at the 0.05 and 0.01 level, respectively.
Figure 13. Seasonal variations in soil NH$_4^+$-N and NO$_3^-$-N for CT and NT (2.5-7.5 cm depth) by position: (a) wheeltrack, (b) row, and (c) no-track. Vertical bars represent standard error.

* and ** represent significant differences by paired t-test at the 0.05 and 0.01 level, respectively.
requirement of the nitrifying organisms (Stevenson, 1986). That the buildup in ammonium was seen in the wheeltrack positions fits well with this theory (Figure 12). Hansen et al. (1993) found that 107 mm of rain led to water-filled pore space (WFPS) of 81 and 73% in soils compacted by wheel traffic (bulk density 1.3 g cm\(^{-3}\)) and uncompacted soils (bulk density 1.21 g cm\(^{-3}\)), respectively. In this study, soils in the wheeltrack position had a higher bulk density than the other positions, which would most likely result in a higher WFPS, and consequently, more anaerobic conditions than the other positions.

By day 100, ammonium levels remained fairly constant, and very low. Differences in ammonium between tillage systems, sampling position and depth were barely perceptible, and remained insignificant until the end of the study period. From these results, it appears that on a seasonal basis, fertilizer applications largely controlled the availability of ammonium-N in the cotton plots.

### 5.3.2 Nitrate

Nitrate levels did not exhibit the same pattern of high levels at fertilization and low levels thereafter (Figure 14). Nitrification is obviously limited by the amount of N-substrate, i.e., ammonium, thus, it is not surprising that the pattern of nitrate accumulation tends to lag slightly behind accumulations of ammonium. The lag in nitrate accumulation after the first fertilizer application was discussed above. After the second fertilization, there was not the apparent delay in nitrification that occurred at the beginning of the sampling season (Figures 12 and 13), since temperatures had increased to between 28 and 35°C, which is within the range of temperatures optimum for growth of the nitrifying bacterial population (Stevenson, 1986).

Following the second fertilization, nitrate did not accumulate to high levels despite the fact that 55 kg ha\(^{-1}\) of NH\(_4\)NO\(_3\) was applied. This application rate corresponds to approximately 130, 175, and 150 mg N kg\(^{-1}\) in the wheeltrack, row and no-track positions\(^{21}\), however, the concentrations of nitrate in the three positions never exceeded 60 mg NO\(_3\)-N kg soil\(^{-1}\) (Figure 15).

It has been suggested that leaching losses in the summer will be restricted to periods of heavy rainfall, since evaporation rates are high during the warm summer months (Stevenson, 1986). As

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\(^{20}\) Both O\(_2\) and CO\(_2\) are required substrates for autotrophic nitrifying organisms. O\(_2\) and CO\(_2\) combine to form HCO\(_3\)\(^-\), which provides practically all of the carbon for cell synthesis of the organisms (Stevenson, 1986).

\(^{21}\) The different estimates of nitrogen in the wheeltrack, row and no-track positions result from the different bulk densities in the respective positions. Calculations for conversions from mg N kg soil\(^{-1}\) to kg ha\(^{-1}\) can be found in Appendix 4.
Figure 14. Soil NO$_3$-N content in CT and NT cotton systems for (a) 0-2.5 cm and (b) 2.5-7.5 cm depths. Vertical bars show standard errors. Dates where CT and NT are significantly different at the 0.001, 0.01 and 0.05 levels are indicated by "***", "**" and ", respectively. Values are averages of 3 sampling positions and 5 replicate plots.
Figure 15. Comparison of NO$_3$-N in wheeltrack, row and no-track positions for CT and NT cotton, 0-2.5 and 2.5-7.5 cm depths.
was a three-day period immediately after the fertilizer application when 60 mm of rain fell at the site, and on day 62, when 40 mm of rain were recorded. These two precipitation events quite possibly resulted in significant leaching losses.

There is evidence that both denitrification and leaching can be considerably greater in NT than CT soils (Rice and Smith, 1982; Thomas et al., 1980; Doran, 1980). In a survey of tillage studies at several locations in the United States, Doran (1980) found that NT surface soils (0-7.5 cm) were wetter, had higher organic matter contents, were less aerobic, and contained higher denitrifier populations than their CT counterparts. Generally, enhanced leaching of nitrate in NT soils has been attributed to greater water content, lower evaporation (due to surface mulch) and optimum capacity for infiltration of water (Thomas et al., 1980).

Figure 15 shows the seasonal nitrate levels in CT and NT for all three positions and both depths, as well as the amount of rainfall at the site between each sampling date. The data only go to day 100, since after this point in the season nitrate levels remained low. Presumably, if leaching occurred from the 0-2.5 cm depth, the levels at the subsequent sampling date would be lower in the surface soil sample and higher in the 2.5-7.5 cm depth. Admittedly, if water infiltration was extremely high, nitrate could have leached below the 2.5-7.5 cm depth, leading to no net increase. Furthermore, this does not take into account any nitrification that might have occurred between sampling dates. Despite these confounding factors, the figure does demonstrate that at this site, NT cotton did not appear to suffer greater losses during high rainfall periods than CT. Two-way ANOVA also did not detect a significant difference between NO\textsubscript{3} concentrations in the CT and NT soils (P = 0.05).

It is interesting to note that sampling position seemed to influence nitrate concentrations, and that this effect was more obvious in the NT soils than in the CT soils. The results of two-way ANOVA, for data from the entire sampling season, indicate that position had an effect on soil nitrate (P = 0.01). Nitrate tended to be lowest in the no-track and highest in the wheeltrack position at the 0-2.5 cm depth, while at the 2.5-7.5 cm depth the row position in the NT soils consistently had lower nitrate between days 50-100. The low levels in the row position are most likely due to the rapid uptake of N by the cotton crops during this stage of growth (Mullins and Burmester, 1990). Figure 16 shows nitrate and SWC data for the three positions (0-2.5 cm depth only). The low nitrate levels in the NT no-track, 0-2.5 cm depth (days 9, 22, 50 and 61), could be due to leaching and/or denitrification associated with higher SWC. Broder et al. (1984) found that high water contents in reduced tillage systems paralleled lower nitrifier and higher denitrifier populations as compared to
Conversely, high levels in the NT wheeltrack position (days 61, 76 and 90) could be due to a more suitable water regime for nitrification.

From this figure, it appears that if there is a relationship between SWC and nitrate in CT, the relationship is an inverse one, which is to be expected, since high SWC would promote leaching and denitrification. However, there were no significant correlations between SWC and nitrate levels. The lack of a definite relationship between soil nitrate and soil water content is possibly because N fertilization bolstered nitrifier populations which then remained high through the varying soil moisture conditions. Broder et al. (1984) also found that after application of N-fertilizer (44 kg NH₄NO₃), soil nitrifier populations increased six to nine-fold in the surface 0-15 cm layer, and this effect was not influenced by tillage.

Late in the season, tillage regime began to exert an effect on nitrate levels, with significantly higher levels occurring in NT than CT soils at both depths (Figure 14). Looking at Figure 16, it appears that the NT row position has the highest nitrate concentrations, and also the highest SWC. Rice and Smith (1984) found higher NO₃⁻ levels in NT soils and suggested that since water evaporated more quickly from plowed soils, that nitrification can sometimes be more rapid in NT. Indeed, nitrification rates have been found to be sensitive to moisture content, and often there are strong, positive correlations between soil moisture and NO₃⁻-N as soils dry (Miller and Johnson, 1964; Campbell et al., 1995). Thus, the relatively low soil water contents could have inhibited nitrification in the CT soils during this time. Alternatively, the row position could have had higher late-season nitrate concentrations because the plants had stopped utilizing soil N. Triplett et al., (1996) have found that NT cotton plants at this site reached maturity earlier than CT cotton plants.

The results of statistical analyses suggest that nitrate is influenced by depth of sampling, but not tillage regime. When data were averaged over the entire season, there were significant differences in NO₃⁻-N between the two depths (P=0.01) in both the CT and NT soils. This is predictable, since better aeration in the surface soils would tend to enhance nitrification in the 0-2.5 cm layer, and also, the fertilizers would tend to concentrate within the surface layer of NT soils. When two-way ANOVAs were conducted to test for differences between nitrate levels in CO1 and CO3 by sampling positions, there were only three occasions when there were significant differences between CT and NT wheeltrack and no-track positions at the 0-2.5 cm depth (Figure 12) and no dates where there were significant differences at the 2.5-7.5 cm depth (Figure 13).

Looking at these figures, it is clear that the patterns of nitrate accumulation were most similar between treatments in the wheeltrack and no-track positions at the 2.5-7.5 cm depth. These
Figure 16. Nitrate and soil water content by plot position (wheeltrack, row and no-track) in (a) CT cotton and (b) NT cotton, 0-2.5 cm depth.
such as plowing and cultivation. Often, plowing results in higher levels of soil nitrate in the surface soils of CT than NT cropping systems (Thomas et al., 1973; Rice and Smith, 1982; Broder et al., 1984). Rice and Smith (1983) have attributed this to the fact that the high organic matter zone in NT soil is frequently too dry to support much microbial activity, e.g., nitrifiers. Rice and Smith (1983) found that tillage did not affect nitrification when soils of both tillage treatments were maintained at the same soil water content. The NT plots in this study maintained higher SWC in the 0-2.5 cm depth than the CT soils (Figure 16). Therefore, it is possible that no differences in nitrate were observed between the CT and NT cotton systems because soil moisture conditions in the NT system were adequate to support a healthy nitrifier population throughout the sampling season.

**Summary of N availability**

There is an extensive body of literature suggesting that NT systems reduce the availability of inorganic N to crops due to greater denitrification (Doran, 1980; Rice and Smith, 1982), leaching (Thomas et al., 1980) and/or N immobilization (Dou et al., 1995; Rice and Smith, 1984). However, other studies have found that the lower N availability often observed in NT systems is a transient effect, and after several years of cropping the availability of mineral N in NT systems is equal or greater than that in CT (Salinas-Garcia, 1997; Rice et al., 1986). Rennie and Carter (1984) have suggested that on a seasonal basis, transient differences in available N are related to the amount of crop residues and degree of incorporation between tillage systems, which affects biological activity in soils.

Neither the levels of available N, nor the seasonal availability of N differed greatly between the two cotton cropping systems in this study, despite the fact that the NT cotton system received a much larger input of organic residues than the CT system. This suggests that nitrogen supplied from organic sources played a very minor role in N availability, relative to the dominating effect of fertilizer N on $\text{NH}_4^+$ and $\text{NO}_3^-$ levels in the soil.

The CT and NT cotton systems received equal inputs of fertilizer N, which suggests that either 1) N immobilization of fertilizer was not greater in the NT system, as has been suggested by other studies, or 2) net N immobilization was greater in the NT system, but losses of inorganic N via leaching and denitrification were greater in the CT system, resulting in similar mineral N levels in the two systems.
Levels of soil inorganic N sampled within the planted rows provide some information on the amount of nitrogen potentially available to growing crops from fertilizer applications, as well as N mineralized from decomposing residues and SOM. The timing of N fertilizer applications is well established, and is related to crop development stages (Below, 1995). For optimum N utilization from crop residues, however, mineralization must occur in time to meet crop N demand. If nitrogen mineralization occurs too early or too late, NO₃⁻-N in the soil will be vulnerable to leaching and denitrification.

Figure 17 shows soil inorganic N levels and N-mineralization rates in relation to the stages of growth for cotton plants. The highest rates of N uptake by cotton begin at about first flower, which generally occurs approximately 56 days after planting (Mullins and Burmester, 1990; Rosolem and Mikkelsen, 1989). At my site, flowering had occurred by 58 days after planting (day 77). During the period of rapid N uptake by cotton, mineral N concentrations remained relatively high (25 mg kg⁻¹) in the row position of the CT plots, reflecting a large available N pool in the soil profile in this treatment. Concurrently, in the NT cotton rows the soil mineral N levels were quite low (less than 10 mg kg⁻¹). The highest levels in the NT system occurred early in the season (days 10-50), before the onset of rapid N accumulation. At first glance, it appears that the high levels of soil-N in NT did not coincide with the period of rapid uptake, and that there was better synchrony between soil inorganic N availability and plant uptake in CT cotton than NT.

The following section examines more closely the effects of tillage and varied residue additions on synchrony between N availability and cotton uptake. Two aspects of synchrony will be addressed: sufficiency (i.e., was enough N made available to meet the cotton plants’ nitrogen requirements) and timeliness (i.e., did the pattern of N release result in the efficient use of mineral N).

**Sufficiency**

The fact that soil inorganic N levels were lower during the time of high demand does not necessarily mean that N availability in CO3 was not in synchrony with plant demands. The nutrient status of the cotton plants was assessed several times over the course of the growing season to look for N deficiencies, which would indicate an inadequate inorganic N supply. The results of leaf N analyses are presented in Table 6.
Figure 17. Soil inorganic N (NH$_4^+$-N + NO$_3^-$-N) and N mineralization rates in (a) CT and (b) NT cotton rows in relation to cotton phenology. P represents the period of maximum N uptake in cotton plants (Mullins and Burmester, 1990).
Sabbe and MacKenzie (1973) have reported that total N contents of 3.0-4.5% in the upper mature leaves of cotton plants are indicative of satisfactory plant nitrogen status. Less than 2.5% total nitrogen generally indicates deficiency and greater than 4.5% can be excessive. Using these guidelines, it appears that neither the CT nor the NT cotton plants suffered from nitrogen deficiencies at any sampling date.

In addition to the plant nitrogen status throughout the season, there is further evidence that cotton plants in the NT system were not nitrogen deprived. Yields in the NT crop were higher than the CT cotton yields (Dabney, 1997). Thus, it is possible that the low soil-N levels measured in the NT row position were simply a reflection of the fact that the plants were utilizing all inorganic N as it became available. Franzluebbers et al. (1995) has suggested that more frequent return of crop residues provides microorganisms with a more continual supply of C substrates, which leads to a more continual supply of mineralized N available for crop uptake. At the same time, there is less opportunity for loss of N through leaching and denitrification because only moderate levels of inorganic N would be present in the soil.

Alternatively, even though there were lower levels of inorganic N present during rapid uptake, the NT plants might have been able to accumulate more N early in the season, when it was available, and redistribute it as N availability from the soil declined. Both Rosolem and Mikkelsen (1989) and Gerik et al. (1994) have observed the translocation of N from leaves and other cotton plant parts to growing bolls. Measurements were made of cotton height and number of nodes per plant 18 days after emergence (day 43), and at this date there were already differences in plant...
nutrient status and phenology) (Table 8). There was a significant difference in carbon content (P=0.006), with NT plants having the higher % C, and although the differences were not significant (at the P=0.05 level), the NT plants also had higher N content. The NT cotton plants were also taller, had more developed nodes than the CT cotton plants, and the leaves were larger. Triplett et al. (1996) also reported a difference between phenology of the NT and CT cotton plants at this site. They found that seedlings of both treatments emerged at approximately the same time, however, excluding the first year of a four-year study, NT plants were larger, taller, had more bolls, more nodes and more fruiting sites, which led to earlier maturity and greater yield (Triplett et al., 1996).

These data show that early in the season the NT plants were indeed accumulating N at a higher rate, which possibly contributed to better early growth of the plants and consequently higher yields in the NT cotton plots. Increased yields in the NT cotton system compared to the CT cotton have been recorded at the site every year except for the initial year of the study. Researchers studying this phenomenon have attributed the higher yields to better water regime in NT (Triplett et al., 1996), however, no attempts have been made to relate the yields to nitrogen nutrition, despite the fact that cotton yields have been correlated to plant N uptake (Oosterhuis et al., 1983) and tillage-induced changes in plant growth parameters have been related to differences in N transformations (Rennie and Carter, 1984). Furthermore, Bauer and Black (1994) found that increasing water levels had not effect on growth and yield of wheat crops when soil available N was low. Yields only increased with added water when N was sufficient.

In this study, the addition of wheat cover crop residues plus fertilizer in the NT cotton plots stimulated mineralization of nitrogen early in the season. It is possible that this early mineralization and accumulation of inorganic N, especially ammonium, contributed to the improved yields in the NT cotton. There is evidence that some plants absorb ammonium more rapidly than nitrate during early vegetative growth (Olson and Kurtz, 1982), possibly because young plants lack a completely functional system for NO₃⁻ uptake and assimilation (Below, 1995). There were higher levels of ammonium in the NT row than the CT row in the weeks following cotton planting and emergence²². If the cotton plants were utilizing primarily ammonium during early growth, it is possible that the early availability of this preferred form of nitrogen led to faster establishment and leaf development, and therefore, higher rates of photosynthesis. Both fruit production and retention, and hence yields, are dependent on leaf development and the leaf's photosynthetic integrity (Gerik et al., 1994).

²² Cotton was planted on day 19. On day 22, NH₄⁺ levels were 5.395 ± 3.038 and 11.5 ± 5.2 mg kg soil⁻¹, in CT and NT, respectively. Emergence occurred on day 26. On day 36, NH₄⁺ levels were 1.32 ± 0.243 and 5.944 ± 1.375 in CT and NT, respectively. And at day 50, NH₄⁺ levels were 51.163 ± 14.618 and 66.312 ± 22.143 mg kg soil⁻¹ in CT and NT, respectively.
is clear from the plant N and yield results that the NT cotton plants were receiving adequate nitrogen. The plant N determinations reveal that CT cotton plants were receiving adequate supplies of N as well.

**Excess**

Synchrony of soil N availability with crop N requirements implies that adequate N will be supplied when the crop needs it. If excessive amount of N are supplied either before, during or after the crop uptake stage, losses can occur.

From Figure 17, it appears that there were accumulations of inorganic N in the CO3 system prior to planting. This coincides with the apparent priming effect observed between days 9 and 19, after application of fertilizer and wheat residues. In general, the first application of fertilizer is applied to meet the N requirements of the expanding microbial biomass, i.e., to prevent the depletion of the soil inorganic N pool that would occur during the decomposition of high C/N residues additions; this fertilizer is for the microorganisms, not the crop (Alexander, 1977). It is unlikely, then, that farmers and agronomists would expect such a large pulse of mineral N this early in the season.

The release of inorganic N occurred in the incubation that preceded planting, and shortly thereafter levels in the soil diminished dramatically.\(^\text{23}\) The rapid decrease in soil mineral N could not have been the result of rapid plant uptake, as the cotton did not emerge until day 26. Thus, the high levels of inorganic N presented the possibility for large losses of nitrogen from the system via leaching and denitrification. Fortunately, the net mineralization during the incubation led to higher levels of ammonium than nitrate (e.g., 48.9 ± 23.5 versus 18.7 ± 5.7 for NH\(_4^+\) and NO\(_3^-\), respectively) in the rows. The climate data suggest that the flush might not have resulted in large losses of the mineralized N at this early stage in the growing season, because rainfall was low (8.5 mm) and therefore, potential losses from nitrate leaching and denitrification would be limited. Furthermore, the presence of a large amount of residues would promote the immobilization of some of the mineralized N in the microbial biomass, even as mineralization of SOM was occurring (Smith and Sharpley, 1990).

\(^{23}\) Concentrations of inorganic N (NH\(_4^+\) + NO\(_3^-\)) in the incubation cores on day 19 ranged from 48.9 ± 23.5 in the row to 299.9 ± 100.5 mg kg soil\(^{-1}\) in the wheeltrack (average of 5 replicate plots); while in the bulk soil, concentrations on day 22 ranged from 11.5 ± 5.2 in the row, to 28.1 ± 12.4 mg kg soil\(^{-1}\) in the no-track.
conditions in this study year, there is some concern that if the apparent "priming effect" is an annual feature of the CO3 system, it is possible that in other years losses might be significant should the proper climate and soil conditions prevail (e.g., heavy rainfall and saturated soils).

Following the second fertilization at day 50, there was an immediate increase in soil inorganic N in both the CO1 and CO3 systems, but the levels declined rapidly in the NT system. Once again, the fertilizer was most likely rapidly immobilized in the CO3 system due to the presence of a larger supply of C substrate.

In the CT cotton system, there was an accumulation of inorganic N following the second fertilization, despite net immobilization rates (Figure 17), and the levels remained high well into the rapid uptake phase (e.g., to day 100). Figure 12 showed that the majority of the available N was in the ammonium form, which suggests that losses via leaching and denitrification could be kept to a minimum, as NH$_4^+$ is less mobile than NO$_3^-$. However, as with the accumulation of NH$_4^+$ in the NT system after the first fertilization, under certain circumstances, such as high temperatures combined with adequate moisture conditions, rapid nitrification could proceed. The timing of N accumulation in the CT system creates a greater potential for losses than the early-season accumulation in the NT system, because the higher summer temperatures (e.g., >30$^\circ$ C) are more conducive to rapid nitrification, and hence, may lead to the accumulation of the more mobile nitrate ion.

**Synchrony Summary**

The data on plant nutrient status suggest that the availability of N was synchronized with the cotton plants’ nutrient demands in both the CT and NT systems. On a seasonal basis, the nitrogen was available during the times of high plant N demand, and there was little available nitrogen left in the soils by the end of the rapid uptake stage (approximately day 140). No-till systems have been found to increase the possibility of late-season nitrate buildup, due to poor synchrony of N release from crop residues (Dou et al., 1995), however, in this study the accumulation of nitrate after cotton harvest was not very great in either the NT or CT system. In these cotton systems, late-season leaching losses would be probably be low, relative to the potential losses during the growing season. Nitrate accumulated in both the NT and CT system following fertilizer additions, which suggests that N was being supplied in excess of plant requirements, and that losses could result if adverse climate conditions prevail.
5.4 Anomalies and Artefacts

As mentioned earlier, there were some inconsistencies with the incubation data when compared with the bulk soil measurements, which suggest that there may have been methodological artefacts confounding the results.

In this study, the sequential coring method was used to determine *in situ* changes in soil mineral N. The basic assumption of this method is that N turnover processes inside and outside of the soil cores do not differ significantly. This assumption is invalid if there are deviations in water and organic matter supply, resulting in differences in soil microbial activity or size (Raison *et al.*, 1987; Rees, 1989). The use of sequential coring is well established in forest and natural ecosystem studies (e.g., Binkley and Hart, 1989; Raison *et al.*, 1987), however, in agroecosystems it has only recently gained some prominence (e.g., van Faassen and Lebbink, 1994; Subler *et al.*, 1995; Stenger *et al.*, 1996) as an alternative method to the more popular buried bag technique.

The use of open-ended cylinders, which are covered to prevent entry of precipitation, theoretically allow soil water content (SWC) of the core to fluctuate in response to the conditions in the surrounding bulk soil (Raison *et al.*, 1987; Subler *et al.*, 1995). Soil moisture equilibrium occurs because of the physical continuity between the soil in the cores and the surrounding soil at the bottom of the cylinder. Disadvantages include the potential for root regrowth through the bottom of the core, and the potential for movement of nitrate out of the soil core by diffusion or capillary flow (Subler *et al.*, 1995), both of which would result in an underestimation of net mineralization.

Differences were noticed between mineral N levels in the incubated soil cores and the mineral N levels outside of the cores (Figures 18-20). This is to be expected, since the bulk soil is exposed to precipitation events and other treatment factors that the covered cores are theoretically protected from (e.g., herbicide applications). However, there were a few occasions where the levels diverged so dramatically that they warranted further investigation. Comparisons were made between SWC in the covered incubation cores, and the “bulk soil” water content, to see if this might be responsible for the seemingly anomalous results.

Before these results are discussed, a brief definition of covered cores versus bulk soil will be provided. In this study, fourteen incubations were conducted. Two cores were inserted and one core

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24 All of the comparisons in this section were made between soils at the 0-2.5 cm depth only. Since microbial activity declines with depth (Alexander, 1977), if differences in immobilization or mineralization exist between the covered cores and bulk soil, they should be greatest in this surface layer where microbes are concentrated.
The second core was covered and left in the ground for approximately 1-3 weeks. When this core was removed a new incubation series began. Most of the series overlapped, i.e., the day that the covered, incubated core was removed the new set was put in. The first core of the new series, then, provided a sample of the soil left exposed to the vagaries of climate and crop management treatments, i.e., was representative of the bulk soil.

5.4.1 Soil water content: covered core versus bulk soil

The results of the soil water content comparisons between the covered cores and bulk soil demonstrate that, in general, the covered cores conserved more moisture than the bulk soil. From day 0 to 80, the covered cores had higher SWCs than bulk soil cores in all three positions in both tillage systems on all sampling dates except one25 (Figures 18 and 19). These differences were more often significant in the CT than NT system (Table 7). This can be related to the fact that the covers served a similar role as the surface residues in the NT system. Crop residues placed on the surface reflect light and insulate the soil, thus reducing soil temperatures and evaporative losses of water (Bond and Willis, 1969). The CT soils, which were not already protected by a surface mulch, experienced a relatively greater enhancement in soil moisture than the NT soils.

There were a few occasions when SWC was higher in the bulk soil than the covered cores. On the dates where this switch occurred (days 90, 104 and 133) the site had received rain within a few days prior to sampling (Figures 18 and 19). This suggests that there was not enough time for the water content in the covered cores to equilibrate with the bulk soil. Subler et al. (1995) also found that SWC in covered cores was sometimes higher and sometimes lower than the bulk soil (although not significantly so), however, no precipitation data were reported.

Others have reported differing soil water contents between covered cores and bulk soil. While bulk soil can fluctuate in response to small precipitation events, soil water content in the cores can only increase if there is a flux from below (Debosz and Vinther, 1989) and this is likely to happen only with relatively high rainfall and saturation of the profile (Jensen et al., 1996).

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25 On two dates, the incubation periods did not overlap. The first occurred at day 19. The covered core was removed on this day, but the new set was not installed until day 22. In the interim, the site received more than 30 mm of rain. So the “bulk soil” measurement was much higher than the covered core. Similarly, the fourth covered core was removed on day 43, while the new series was put in on day 50. In the interim, 29 mm of rain fell. However, this time, the new core had a lower SWC than the previous covered core, which suggests that the covered core had conserved more moisture than the bulk soil.
Figure 18. \( \text{NO}_3^- \) concentrations and SWC in bulk soil and covered cores in CT cotton, no-track position, 0-2.5 cm depth.
Figure 19. \( \text{NO}_3^- \) concentrations and SWC in bulk soil and covered cores in NT cotton, no-track position, 0-2.5 cm depth.
Figure 20. $\text{NH}_4^+$ concentrations in bulk soil vs. covered cores in (a) NT and (b) CT cotton, no-track position, 0-2.5 cm depth.
Table 7. Soil water contents (% dry weight) in bulk soil versus covered cores in CT (CO1) and NT (CO3)cotton plots.

<table>
<thead>
<tr>
<th>Day</th>
<th>Core 1</th>
<th>Core 2</th>
<th>CO1a1</th>
<th>CO1a2</th>
<th>P</th>
<th>CO3a1</th>
<th>CO3a2</th>
<th>P</th>
<th>CO1b1</th>
<th>CO1b2</th>
<th>P</th>
<th>CO3b1</th>
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<td></td>
<td>11.98</td>
<td>22.07</td>
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<tr>
<td>9</td>
<td>8</td>
<td></td>
<td>20.36</td>
<td>24.41</td>
<td>**</td>
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<td>27.94</td>
<td>15.89</td>
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<td>**</td>
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<td>*</td>
<td>18.03</td>
<td>20.52</td>
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a, b, c - wheeltrack, row and no-track, respectively.
(the number 1 following a, b, c represents the first core of the series, and 2 represents the second, i.e., covered core)

P-values - *, ** and *** represent significant differences in SWC between core 1 and 2 at the 0.05, 0.01 and 0.001 level, respectively
days 2, 22, 50 - significant differences determined using t-test
all other sampling dates - significant differences determined using paired t-test
bulk soil, which they attributed to a steady drying over the course of the incubation in the covered core, which did not reflect the changing soil moisture conditions in the bulk soil. In the Stenger et al. study the length of the cylinders was 30 cm. In contrast, the cylinders used in my study were only 7.5 cm long, which could have allowed for faster equilibrium between bulk SWC and covered core SWC, which is why the covered cores did not have lower soil water contents than the bulk soil. The faster equilibration with the bulk soil water content in my study should provide a closer approximation of actual soil conditions, however, there remains the obvious problem of higher moisture contents in the covered cores than the bulk soil.

5.3.2 Soil water content and nitrogen losses

The greater retention of soil moisture in covered cores can influence N transformations in different ways, depending on the timing and magnitude of the precipitation events. For example, if enough precipitation is received to saturate the covered cores, anaerobic conditions could lead to nitrate losses via denitrification and/or leaching; and ammonium build-up due to the inhibition of nitrification, and/or the continued mineralization of organic N to ammonium (Gale and Gilmour, 1988; Stevenson, 1986). If the sites receive rain toward the end of the incubation period, more leaching losses might occur in the bulk soil than the covered cores, since there would be little time for the cores to reach the same water content as the bulk soil. If moderate amounts of moisture are received, the conditions in the covered cores might be more conducive to nitrification than the bulk soil, especially if evaporation rates are high and bulk soils dry out quickly (e.g., when ambient temperatures are high). However, if small precipitation events occur, which wet the bulk surface soil but do not infiltrate deep enough to diffuse into the covered core, underestimations of net nitrogen mineralization can be expected (Stenger et al., 1996; Jensen et al., 1996).

Nitrogen transformations in response to the increase in SWC in covered cores should also differ depending on the tillage system and the three sampling positions. Soils with the same soil water content but different bulk densities will have differing degrees of water-filled pore space (Jensen et al., 1996), hence, at the same SWC, a compacted soil might experience denitrification, while an uncompacted soil could experience nitrification. The net result in the first case would be an apparent immobilization of N, while in the second case there would be no net change in total mineral nitrogen.

Jensen et al. (1996) used the covered core technique to estimate net N mineralization in compacted and uncompacted soils and found that the apparent net mineralization rate was higher in
uncompacted cropped soil. One of their major conclusions was that denitrification (although not measured) had possibly occurred in the cropped soil cores and the compacted pasture soils, concealing actual net-N mineralization. The uncompacted pasture soil had the highest air-filled porosity, and therefore was less susceptible to excessive waterlogging during wet periods (Jensen et al., 1996).

In my study, air-filled porosity was not determined. However, from personal observations while sieving the soils, it was noted that the CT wheeltrack and no-track soils were often more difficult to sieve because they were either wet and sticky (field-moist samples would not fit through a 2-mm sieve), or they were extremely hard (had to be dug out of the cylinder). On the dates where the samples were wet (days 8, 43 and 176), SWC was generally above 24% dry weight (Figure 18). On the dates where the samples were extremely compact (days 9, 19, 61, 76, 119), the SWC was approximately or less than 20% dry weight.

Presumably, if the CT wheeltrack and no-track soils were too wet to fit through a 2 mm sieve, there were fewer air-filled pore spaces on these dates. Therefore, more denitrification should occur. There is circumstantial evidence to show that this did indeed happen.

Figure 18 shows the nitrate levels and SWCs for the covered cores and the bulk soil (no-track positions26) in the conventionally tilled cotton system. The nitrate in the soil at day 22 (core 3.1) shows little change over the course of the incubation to day 36 (core 3.2), however, the concentration of nitrate in the bulk soil was quite high (> 20 mg N kg soil-1). The covered core had a SWC of 22%, while the bulk soil had a SWC of 12%. The original SWC at day 22 was around 25%. So, the covered core retained more moisture than the bulk soil, which coincided with the concentrations of nitrate being far lower than the concentrations in the bulk soil. It appears that the conditions for nitrification were better in the bulk soil, which had lower SWC, and presumably, lower water-filled pore spaces. Consequently, the bulk soil would be less prone to denitrification than the covered cores. Therefore, it can be concluded that during this particular incubation, the covered cores provided poor estimates of what was actually occurring in the soil.

During the fourth incubation series, the initial SWC was 12% (core 4.1), and at the end of the incubation the covered core (core 4.2) had 27% SWC. The bulk soil was not measured at this date, however, three days hence, even with 2.8 cm of rain, the moisture content of the bulk soil was only 14% (core 5.1). In addition to the rain, there were high temperatures between the start and end of the incubation. Thus, the covered core prevented evaporation of the water, i.e., prevented drying, despite

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26 The row and wheeltrack experienced similar trends to the and no-track position.
5.4.2 Priming revisited

The application of wheat residues plus fertilizer (day 9) apparently stimulated the mineralization of soil organic nitrogen within the incubation tubes in the CO3 wheeltrack and no-track positions, however, there was no parallel rise in the levels in the bulk soil when measured three days later (Figure 20). Attempts to explain why no concomitant priming effect was observed in the bulk soil are confounded by the fact that the covered incubation cores were removed on day 19, while the bulk soil was not sampled until day 22.

There are three possibilities of why the high levels of inorganic N in the covered cores were not seen in the bulk soil: 1) a priming effect occurred in the bulk soil, but the mineralized N was subsequently immobilized; 2) a priming effect occurred, but the high concentrations of ammonium

...
between days 19 and 22; or 3) no priming occurred in the bulk soil, i.e., the priming effect was an artefact of the sampling process.

**Sequential Priming and Immobilization**

It is possible that N mineralized from SOM and plant residues was subsequently reimmobilized by microorganisms, since there was a large amount of C substrate present to encourage continued growth of the microbial population. Within the covered cores, the amount of organic matter would have been limited to whatever was present at the time of sampling. But in the bulk soil, the microorganisms could have been introduced to new substrate as soil moisture conditions changed and carried them to new microsites (e.g., with the 8.5 mm of rain at day 12, or the 31.25 mm of rain on days 19 and 20). Cotton was planted on day 19, so the wheeltrack microorganisms would have been introduced to new substrate by the wheel traffic.

It seems highly improbable, assuming that the levels in the covered core did indeed reflect actual conditions at day 19, that the ammonium level in the bulk soil could have decreased from 299.88 ± 100.47 to 15.37 ± 3.18 mg N kg soil⁻¹ in the wheeltrack and 274.62 ± 154.29 to 28.12 ± 12.14 mg N kg soil⁻¹ in the no-track position by day 22 (Figure 20). This would translate to net immobilization rates of 98 and 82 mg N kg soil⁻¹ day⁻¹ in the wheeltrack and no-track, respectively.

In a laboratory study, Recous and Mary (1990) observed maximum immobilization rates as high as 17 mg N kg soil⁻¹ day⁻¹ when 500 mg C-glucose were added with fertilizer N (50 mg (NH₄)₂SO₄ kg soil⁻¹) to soils. Therefore, it appears that although abundant C substrate was available in the NT cotton system, it is doubtful that the large quantities of N mineralized in the covered cores could have been immediately reimmobilized.

**Sequential Priming, Nitrification and Leaching**

The site received approximately 3 cm of rain between days 19 (when the covered core was removed) and 22 (when the bulk soil was sampled). That there was a difference in both NO₃⁻ and NH₄⁺ between days 19 and 22 (Figures 19 and 20) suggests that leaching was not responsible for all of the difference between inorganic levels in the covered core and bulk soil, since NH₄⁺ ions are largely immobile in soil. It is possible that sequential nitrification of NH₄⁺ followed by leaching of the newly formed nitrate occurred. However, it is highly probable that the rates of nitrification in these NT soils were still low at this early stage in the season. The ambient temperatures were between 28 and 30°C, however, due to the presence of the wheat residues the soil temperatures
it seems unlikely that such high concentrations of ammonium could have been nitrified and lost from the system.

**No Priming Effect**

It is possible that the large net mineralization between days 9 and 19 was induced by the cores themselves. It has been suggested that in hot climates the presence of metal tubes might stimulate mineralization by heating the surface soils that are in contact with the tube (Raison *et al.*, 1987). The maximum daily temperatures attained during the course of the incubation ranged from 19.4 to 31.7° C, with an average daily temperature of 26.4° C. Raison *et al.* (1987) found that the presence of metal tubes did not have a warming effect on incubated soil at an air temperature of 22° C. Therefore, it seems unlikely that the enhanced mineralization within the tubes was related to higher field temperatures.

The insertion of the cores could have disturbed the soil enough to have stimulated mineralization of SOM by revealing previously unavailable substrates, however, Raison *et al.* (1987) reported that very little soil compaction resulted from driving in the tubes, even in wet soils, therefore, they concluded that the soils within tubes could thus be considered as largely undisturbed. There is the possibility that even if the insertion process did not greatly affect the soil structure within the core, the procedure could have put the wheat residues directly in contact with the soil, thereby permitting the soil microorganisms greater access to the C substrate. This explanation seems reasonable, however, if the priming effect was related to better contact between soil microorganisms and the wheat residues, it begs the question of why there was not an apparent priming effect in the wheeltrack bulk soil sample.

Another possible explanation as to why there were large increases in mineral N levels in the incubation cores but not the bulk soil is that N transformations occurred while the cores were in storage. The cores were stored at 4° C for approximately one month before they were analysed for mineral N content. At this temperature microflora slowly mineralize organic complexes (Alexander, 1977). It is highly improbable that either a large amount of mineral N could have been mineralized or immobilized under these storage conditions. In a study conducted under optimum conditions for microbial growth, Bonde and Rosswall (1987) reported maximum rates of 27 mg N kg⁻¹ week⁻¹. Even at these maximum rates, the difference in mineral N between the bulk soil and incubated soil cores (i.e., > 200 mg N kg soil⁻¹) is not accounted for.
From Figure 19 it appears that there was little change in soil moisture content between the beginning and end of the incubation. The SWC of the bulk soils would have fluctuated in response to the small rainfall event (< 1 mm) and the subsequent dry period. Scott et al. (1996) reported a greater stimulation of organic C mineralization with surface applied residues than incorporated residues when both were kept moist throughout the incubation period. They concluded that the lack of contact between litter and soil particles does not retard decomposition of surface litter as long as litter moisture levels are maintained. Salinas-Garcia et al. (1997) have observed temporary decreases in soil microbial biomass during drying conditions, which further supports this idea. It is possible, then, that because the soils in the covered incubation core remained moist, whereas the bulk soil would have experienced some drying, that contact between the soils and residues lasted throughout the incubation period. This would have enabled the soil microbial population to greatly exploit the added C substrate, increase their population size, and concurrently mineralize SOM.

None of the explanations, alone, provide a definitive or entirely convincing picture of what was happening between days 9 and 22 in the NT soils. It is highly possible that several of the proposed processes were occurring simultaneously, with the net result being a priming effect in the incubated cores and very little change in mineral N in the bulk soil. This serves to highlight the fact that microbially mediated N transformations are not straightforward, but can change depending on variety of management and climate factors.

Summary of Anomalies and Artefacts

The above discussions indicate that there is the potential for the covered core incubation method to provide poor estimations of actual net mineralization and immobilization, and the degree of inaccuracy is dependent on sampling position. In my study, soil texture (related to bulk density), SWC, and hence, degree of air-filled versus water-filled pore spaces differed in the wheeltrack, no-track and row positions. These differences can account for some of the differences in net mineralization/immobilization rates. In general, covered cores in the more compacted soils, e.g., CT wheeltrack, have the potential to overestimate net immobilization by increasing nitrate losses via denitrification.

Conversely, when soils are not as compacted or have greater aeration, e.g., the NT soils, net nitrogen mineralization can potentially be enhanced within the covered cores due to more optimum soil moisture conditions (Stenger et al., 1996).
Total C and N

The four cropping systems had been in operation for eight years before this study was initiated. Over the course of those eight years, the differences in crop management practices (tillage, residue additions and fertilizer additions) produced significant differences in total C and N in the four cropping systems. The greatest conservation of soil C and N occurred in the NT systems at this site. The high levels of total C and N in the NT systems suggest a larger reserve of potentially mineralizable N, however, total C and N did not appear to be a reliable predictor of N mineralization rates since the NT soybeans, which had the highest total C and N, experienced much lower net mineralization rates during the early part of the season than the cotton systems.

Net mineralization/immobilization

Tillage apparently played a minor role in the net mineralization and immobilization of N at this site. These findings are in contradiction to many others (e.g., Dou et al., 1995; Fox and Bandel, 1986), who have found that mineralization activity increases after plowing due to soil disturbance and better aeration. No such stimulations were observed in this study. This demonstrates the complexity and unpredictability of N transformations under varying conditions.

A large stimulation of net mineralization was, however, observed in the NT system. The most likely explanation for this phenomenon is that the addition of an energy source (fresh wheat residues) an adequate N supply to meet microbial nutritional requirements (N fertilizer), and soil water conditions that allowed for maximum microbial access to these substrates, combined to induce rapid microbial growth and mineralization of indigenous soil N. There is evidence that this priming effect occurred within the incubation cores, but it is not clear to what extent this increase in net mineralization occurred in the bulk soil. It is highly possible that the apparent priming effect, if it did occur in the field as well as the incubation tubes, was an anomaly, brought about by optimum climate conditions and residue characteristics, i.e., not an annual occurrence. Therefore, there is a definite need to characterize nitrogen release from the wheat cover crop, and to determine if the residues (and/or fertilizer) regularly induce mineralization of SOM.

If a priming effect is a regular occurrence in the CO3 system, the potential exists to time cover crop desiccation and fertilizer amendments so as to bring about the release of N from the residues or SOM when the crops require it, thereby lowering the fertilizer inputs and reducing the potential for nitrate accumulation and subsequent losses.
the season were undeniably influenced by the large inputs of fertilizer N, as well as organic inputs, which combined to increase microbial activity and therefore, increased the rates of N transformations. However, these effects were transient, and by mid-summer the rates of mineralization and immobilization between the cotton and soybean systems were comparable.

By the end of the sampling season, the cumulative mineralized N followed the same general trend as the total C and N data, with NT systems mineralizing more N than the CT systems. Thus, even though the mineralization rates were not consistently higher in NT systems, over the course of the growing season the NT soils mineralized more N than the CT soils. This suggests that after 8 years of cropping these systems could have attained a new equilibrium, and on a seasonal basis the ability of the soils to mineralize N might be influenced by the amount of total C and N in the soil. If this is the case, it is possible that previously recommended fertilizer application rates for NT cotton might no longer be appropriate.

Janssen (1984) has suggested that mineralization rates are more closely related to the amount of "young" organic matter, rather than total N. The findings of my study lend some support to this idea. The SB4 and CO3 soils had similar total N contents, yet the CO3 system mineralized more N (when the N mineralized during the apparent priming effect is included). The amount of N estimated to be returned in the wheat residues in CO3 was almost twice that returned in the SB4 crops (Appendix 2). Thus, it is possible that the addition of more N via organic matter could have played an even greater role than total N in determining the amount of N mineralized over the course of the season.

Both CO3 and SB4, i.e., the NT cropping systems, had higher total C and N contents and higher cumulative mineralized N than both CO1 and SB1, however, SB4 did not have greater plant-available N than CO1 throughout the season. This suggests that the fertilizer N in the cotton systems largely controlled the readily available N pool, while other factors, such as organic matter inputs, influenced the amount of N that could be mineralized over the course the a growing season.

These results highlight the need for understanding when N mineralization is occurring, so that if fertilizers are used, they are not added at a time when the soil system is already supplying sufficient mineral N to the plants.

**Plant-available N**

Inorganic N levels were higher in NT cotton early in the season, which is most likely due to the fact that the NT cotton system retained more of the fertilizer N at the surface, while in CT cotton
the fertilizer was incorporated into the soil. The larger input of organic residues at the beginning of the season also stimulated mineralization rates in the NT system, which increased mineral N levels slightly. However, the effects of differences in the quality and quantity of added residues were short-lived. Four weeks after the wheat had been killed in NT and the cotton stubble had been incorporated in CT the differences in net mineralization/immobilization rates and soil mineral N levels between the CT and NT cropping systems were statistically indistinguishable.

The influence of fertilizer N on mineral N levels was also temporary. Within 50 days of the fertilizer application there was little difference in NH$_4^+$ and NO$_3^-$ levels between cotton, which received 100 kg N ha$^{-1}$ and soybeans, which did not receive any fertilizer.

Neither the levels of available N, nor the seasonal availability of N differed greatly between the CT and NT cotton systems in this study. This suggests that either N immobilization was not greater in the NT system, as has been suggested by other studies, or net N immobilization was greater in the NT system, but losses of inorganic N via leaching and denitrification were greater in the CT system, with the result that mineral N levels in the two systems were similar.

Quantification of leaching and denitrification losses, or the use of isotopic tracers to determine actual immobilization of N in microbial biomass, would be useful in better understanding the extent of mineralization and immobilization processes in these systems.

**Synchrony**

Both the inorganic N data and the plant nitrogen data suggest that there was adequate nitrogen present throughout the period of crop uptake in both cotton tillage systems. Following the second fertilization, more plant-available N was present in the CT soil, even though the CT and NT systems received the same amount of synthetic N fertilizer, and by that point in the season the systems were mineralizing comparable amounts of N. This likely reflects a greater sequestration of fertilizer N in organic forms (i.e., greater immobilization) in the NT system, rather than losses due to leaching and/or denitrification, for two reasons. First, the nitrate levels in the soils were similar throughout the sampling season, even after heavy rainfall events. If the NT system was experiencing greater losses, one would expect to see lower nitrate levels. Second, total N levels in the NT system were higher, suggesting that an accumulation of N must occur on an annual basis. Since the NT
The potential for leaching losses from the CT system existed, due to the higher levels of inorganic N present in the soils after the second fertilizer addition. The potential for early-season losses from the NT system also existed, however, it was not possible to determine if the large net N mineralization measured was a true representation of what was occurring in the NT soils, or whether it was an artefact introduced by the sampling methodology.

**Sampling Artefacts**

It is highly likely that the sequential covered core method for measuring N mineralization introduced errors that obscured actual net mineralization rates. There is reason to believe that the covered cores overestimated net immobilization rates during wet periods, especially in the wheeltrack position. The higher SWC consistently measured in the covered cores as compared to the bulk soil, combined with the high bulk density (therefore, high water-filled pore space) had the potential to create anaerobic environments and therefore enhance nitrate losses via denitrification. Rather than the nitrogen remaining in the system in organic form, i.e., through microbial immobilization, the covered cores could have induced actual N losses from the system.

Conversely, during dry periods, the covered cores could have overestimated net mineralization by retaining moisture and creating conditions more conducive to microbial activity than conditions that existed in the bulk soil.

Despite the problems associated with the incubation cores, net N mineralization rates measured in my study were comparable to other studies using this method (e.g., Stenger et al., 1996). If sequential coring is to be used to study mineralization rates, it is recommended that a better system be devised for covering the cores, otherwise the losses induced by moisture retention might obscure the actual extent of the mineralization or immobilization processes. Others have used polyethylene covers instead of aluminum, which might increase aeration, which would decrease potential denitrification, and increase evaporative losses, which would better reflect the drying that occurs to the bulk soil. However, the use of short incubation cylinders, as used in this study, is recommended, as they are more sensitive to changes in moisture that can take place in the surface soils when small precipitation events occur.

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27 The only N added to the system is what is present in the wheat seed since the wheat crop was not fertilized. During its growth, residual N left from the CO3 cotton crop and N mineralized from the SOM supply its nitrogen requirements.


Whisler, F.D., Engle, C.F and Baughman, N.M. 1965. The effect of soil compaction on nitrogen transformations in the soil. West Virginia Agricultural Experiment Station Bulletin 516.


## TREATMENTS (COTTON PLOTS - 1996)

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<td>CO1 - chiseled and disked (1x)</td>
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<td>8-Apr</td>
<td>CO1/CO3 - M1.1 in</td>
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<td>24-Apr</td>
<td>CO3 - sprayed with Roundup (1 qt/acre + 25% surfactant)</td>
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<td>25-Apr</td>
<td>CO1/CO3 - M1.2 out</td>
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<tr>
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<td>26-Apr</td>
<td>CO1/CO3 - fertilizer applied 13-13-13 @ 250 lb/acre</td>
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<td>CO1 - disked and hipped (1x)</td>
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<td>CO1/CO3 - M2.1 in</td>
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<td>6-May</td>
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<td>CO1/CO3 - planted cotton DPL#119</td>
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<td>CO3 - sprayed 0.75 lb/acre Cotoran, 1.5 lb/acre Dual, 3 oz/acre Zorial,</td>
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<td>1pt/acre Paraquat</td>
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<td>CO1/CO3 - applied 0.25% surfactant - banded on all plots</td>
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<td>row middles sprayed with 1.5 pt Gramoxone and 1.5 lb Karmex (no insecticides/fungicides used)</td>
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<td>9-May</td>
<td>CO1/CO3 - M3.1 in</td>
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<td>13-May</td>
<td>CO1/CO3 - cotton has emerged</td>
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<td>20-May</td>
<td>CO1/CO3 - sprayed Bidrin 0.2 lb/acre</td>
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<td>CO1/CO3 - broadcast Select 2 EC 8 oz./acre</td>
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<td>CO3 - banded 1.8 oz/acre Staple</td>
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<td>5-Jun</td>
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<td>CO1/CO3 - applied 1 lb/acre Malthion to control boll weevil</td>
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<td>CO1/CO3 - applied 16 oz/acre Methyl Parathion (bw control)</td>
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<td>CO1/CO3 - 0.8 qt. Cotoran + 2.4 pt MSMA direct sprayed 1 qt/acre Roundup sprayed</td>
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<td>69</td>
<td>25-Jun</td>
<td>CO1/CO3 - sprayed 1 pt/acre Meth Parathion</td>
</tr>
<tr>
<td>72</td>
<td>28-Jun</td>
<td>CO1/CO3 - sprayed 1 pt/acre Meth Parathion</td>
</tr>
<tr>
<td>76</td>
<td>2-Jul</td>
<td>CO1/CO3 - M6.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO1 - cultivated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO1/CO3 - M7.1 in</td>
</tr>
<tr>
<td>77</td>
<td>3-Jul</td>
<td>CO1/CO3 - cotton blooming</td>
</tr>
<tr>
<td>82</td>
<td>8-Jul</td>
<td>CO1/CO3 - applied 1 lb/acre Blazer + 2 lb/acre MSMA</td>
</tr>
</tbody>
</table>
90  16-Jul  CO1/CO3 - M7.2 out
     CO1/CO3 - M8.1 in
     CO1/CO3 - 1 pt/acre Meth Parathion + 0.25 Orthene
97  23-Jul  CO1/CO3 - applied 1 pt/acre Methyl Parathion (bw control)
103 29-Jul  CO1/CO3 - applied 16 oz/acre Methyl Parathion (bw control)
104 30-Jul  CO1/CO3 - M8.2 out
     CO1/CO3 - M9.1 in
110 5-Aug   CO1/CO3 - applied 15 oz/acre Methyl Parathion (bw control)
114 9-Aug   CO1/CO3 - applied 3.2 oz/acre Karate
117 12-Aug  CO1/CO3 - applied 9 oz/acre Assana XL
119 14-Aug  CO1/CO3 - M9.2 out
     CO1/CO3 - M10.1 in
121 16-Aug  CO1/CO3 - applied 1 pt/acre Methyl Parathion
124 19-Aug  CO1/CO3 - cotton opening on lower bolls
128 23-Aug  CO1/CO3 - applied 16 oz/acre Methyl Parathion
133 28-Aug  CO1/CO3 - M10.2 out
     CO1/CO3 - M11.1 in
153 17-Sep  CO1/CO3 - applied broadcast spray 2 pt/acre prep
155 19-Sep  CO1/CO3 - M11.2 out
     CO1/CO3 - M12.1 in
     CO1/CO3 - handpicked cotton
159 23-Sep  CO1/CO3 - applied broadcast spray 1.3 pt/acre Defoliant 6
173 7-Oct   CO1/CO3 - M12.2 out
     CO1/CO3 - M13.1 in
178 12-Oct  CO1/CO3 - machine harvested cotton
197 31-Oct  CO1/CO3 - M13.2 out
     CO1/CO3 - M14.1 in
209 12-Nov  CO3  - drilled wheat
220 23-Nov  CO1/CO3 - M14.2 out
222 25-Nov  CO3  - good stand of wheat in CO3
<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>24-Apr</td>
<td>SB1/SB4 - M1.1 in</td>
</tr>
<tr>
<td>8</td>
<td>2-May</td>
<td>SB1/SB4 - M1.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1 - chisled and disked (1x)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1 - fertilized - disked in 300 lb/acre 0-20-20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1/SB4 - M2.1 in</td>
</tr>
<tr>
<td>21</td>
<td>15-May</td>
<td>SB1/SB4 - M2.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1 - disked and do-all (1x)</td>
</tr>
<tr>
<td>22</td>
<td>16-May</td>
<td>SB1 - planted (drilled) 9 seeds/ft of soybean DPL415</td>
</tr>
<tr>
<td>23</td>
<td>17-May</td>
<td>SB1/SB4 - M3.1 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1 - sprayed 2.8 oz/acre Scepter, 1.5 pt/acre gramoxone, 0-25% surfactant/acre</td>
</tr>
<tr>
<td>29</td>
<td>23-May</td>
<td>SB1 - has emerged</td>
</tr>
<tr>
<td>36</td>
<td>30-May</td>
<td>SB1/SB4 - M3.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1/SB4 - M4.1 in</td>
</tr>
<tr>
<td>42</td>
<td>5-Jun</td>
<td>SB1 - applied oz/acre Select + 1% crop oil</td>
</tr>
<tr>
<td>48</td>
<td>11-Jun</td>
<td>SB1 - Rep 2, 5 damaged by deer</td>
</tr>
<tr>
<td>54</td>
<td>17-Jun</td>
<td>SB1/SB4 - M4.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB4 - wheat harvested</td>
</tr>
<tr>
<td>55</td>
<td>18-Jun</td>
<td>SB4 - soybeans planted</td>
</tr>
<tr>
<td>57</td>
<td>20-Jun</td>
<td>SB1/SB4 - M5.1 in</td>
</tr>
<tr>
<td>69</td>
<td>2-Jul</td>
<td>SB1/SB4 - M5.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1/SB4 - M6.1 in</td>
</tr>
<tr>
<td>83</td>
<td>15-Jul</td>
<td>SB1/SB4 - M6.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1/SB4 - M7.1 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- soybeans blooming</td>
</tr>
<tr>
<td>84</td>
<td>16-Jul</td>
<td>SB4 - Applied 0.2 lb/acre Actofen (Cobra 2E 12.8oz) + 1pt crop oil</td>
</tr>
<tr>
<td>85</td>
<td>17-Jul</td>
<td>SB1/SB4 - deer and chemical damage:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- rep 1: SB1 21%D; SB4 25% D+C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- rep 2: SB1 50%D; SB4 60-70%C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- rep 3: SB1 good; SB4 70-80% D+C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- rep 4: SB1 good; SB4 95-100%D+C(maj. D)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- rep 5: SB1 60% deer; SB4 50% deer</td>
</tr>
<tr>
<td>97</td>
<td>29-Jul</td>
<td>SB1/SB4 - M7.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1/SB4 - M8.1 in</td>
</tr>
<tr>
<td>112</td>
<td>13-Aug</td>
<td>SB1/SB4 - M8.2 out</td>
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<td></td>
<td></td>
<td>SB1/SB4 - M9.1 in</td>
</tr>
<tr>
<td>126</td>
<td>27-Aug</td>
<td>SB1/SB4 - M9.2 out</td>
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<td></td>
<td></td>
<td>SB1/SB4 - M10.1 in</td>
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<td>147</td>
<td>17-Sep</td>
<td>SB1/SB4 - M10.2 out</td>
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<td></td>
<td></td>
<td>SB1/SB4 - M11.1 in</td>
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<tr>
<td>166</td>
<td>6-Oct</td>
<td>SB1/SB4 - M11.2 out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB1/SB4 - M12.1 in</td>
</tr>
</tbody>
</table>
176 16-Oct  Height of beans - R1SB1 23"; SB4 12"
    - R2SB1 13"; SB4 9"
    - R3SB1 16"; SB4 7"
    - R4SB1 19"; SB4 not enough to measure
    - R5SB1 deer; SB4 deer

SB1/SB4 - soybeans harvested

183 23-Oct  SB1/SB4 - M12.2 out
          SB1/SB4 - M13.1in

201 10-Nov  SB1/SB4 - M13.2 out
          SB1/SB4 - M14.1in

204 13-Nov  SB4 - drilled wheat (Pioneer)

205 14-Nov  SB4 - sprayed Roundup at 1 qt/acre
          SB4 - wheat emerging

222 1-Dec  SB1/SB4 - M14.2 out
**Estimate of N potentially released from crop residues**

The values as cited from Olson and Kurtz (1982) reported N content of the various plant parts for "good" yields.

The soybean yield data from Triplett et al. (1997) should give a general idea of average yields for crops under the management systems in my study. The data are not from the production plots used in my study, however, they were conducted on larger experimental plots at the same experimental site (therefore, the same soils and climate), i.e., Nelson Farm, Mississippi. The values cited reflect the average yields for the crops from the period 1988-1995. The cotton yield data from Triplett et al. (1996) are from the production plots used in my study, therefore, and represent the average of yields from 1988-1992.

**Conventionally tilled cotton (representative of CO1)**

1. Estimated Amount of Cotton Residue

   Actual cotton lint yield (Triplett et al., 1997) = 1932 kg/ha
   Ratio of lint/stalks+leaves+burrs (Olson and Kurtz, 1982) = 4220/5000
   Estimated amount of residue from stalks+leaves+burrs: $1932/x = 4220/5000 = 2289$ kg residue/ha

2. Estimated N returned in residue

   70 kg N/5000 kg stalks+leaves+burrs (Olson and Kurtz), therefore, x kg N/1828.4 kg residue,
   \[ x = \frac{70 \times 2289}{5000} = 32 \text{ kg N/ha returned from CO1} \]

3. Estimated N removed with harvested cotton

   Estimated N in cotton = 105 kg N/ha per 4220 kg seed cotton/ha (Olson and Kurtz, 1982) = 0.025 kg N/kg
   Actual seed cotton yield (Triplett et al., 1996) = 1932 kg/ha
   Estimated amount of N in grain yield = 0.025 kg N/kg grain x 1932 kg grain = 48.3 kg N/ha

**No-till cotton (representative of CO3)**

1. Estimated Amount of Cotton Residue

   Actual seed cotton yield (Triplett et al., 1996) = 2240 kg/ha
   Ratio of seed cotton/stalks+leaves+burrs (Olson and Kurtz, 1982) = 4220/5000
   Estimated amount of residue from stalks+leaves+burrs: $2240/x = 4220/5000 = 2654$ kg residue/ha

2. Estimated N returned in cotton residue

   70 kg N/5000 kg stalks+leaves+burrs (Olson and Kurtz, 1982), therefore, x kg N/1828.4 kg residue
   \[ x = \frac{70 \times 2654}{5000} = 37.16 \text{ kg N/ha returned from CO3} \]

**Wheat covercrop on no-till cotton**

1. Actual wheat yield (Triplett et al., 1997) = 2620 kg/ha

2. Estimated N returned in residue

   1.65 % N in forage crop, harvested before maturity (Boman et al., 1995), therefore, 1.65% of 2620 Mg/ha = 43.23 kg N/ha returned from the wheat residue
Conventionally tilled soybean (representative of SB1)

1. Estimated Amount of Soybean Residue (SB1)

Actual soybean grain yield (Triplett et al., 1997) = 1610 kg/ha
Ratio of grain/straw (Olson and Kurtz, 1982) = 2800/5400
Estimated amount of residue from straw: \( \frac{1610}{x} = \frac{2800}{5400} = 3105 \) kg residue /ha

2. Estimated N returned in residue

75 kg N/5400 kg straw (Olson and Kurtz, 1982), therefore, \( x \) kg N/3105 kg residue
\[ x = \frac{75 \times 3105}{5400} = 43 \] kg N/ha returned in soybean residue

3. Estimated N removed with harvested soybeans.
180 kg N/ha per 2800 kg grain/ha (Olson and Kurtz, 1982) = 0.064 kg N/kg grain
Actual soybean grain yield (Triplett et al., 1997) = 1610 kg/ha
Estimated amount of N in grain yield = 0.064 kg N/kg grain x 1610 kg grain = 103.5 kg N/ha

No-till soybean (representative of SB4)

1. Estimated Amount of Soybean Residue (SB4)

Actual cotton lint yield (Triplett et al., 1997) = 1750 kg/ha
Ratio of grain/straw (Olson and Kurtz, 1982) = 2800/5400
Estimated amount of residue from straw: \( \frac{1750}{x} = \frac{2800}{5400} = 3375 \) kg residue /ha

Estimated N returned in residue

75 kg N/5400 kg straw (Olson and Kurtz, 1982), therefore, \( x \) kg N/3375 kg residue
\[ x = \frac{75 \times 3375}{5400} = 46.9 \] kg N/ha returned in soybean residue

Wheat doublecrop with no-till soybean

1. Estimated Amount of wheat straw residue

Actual wheat grain yield (Triplett et al., 1997) = 2960 kg/ha
Ratio of grain/straw (Olson and Kurtz) = 5400/6000
Estimated amount of residue from straw: \( \frac{2960}{x} = \frac{5400}{6000} = 3289 \) kg residue /ha

2. Estimated N returned in residue

0.75 % N in straw harvested at maturity (Olson and Kurtz, 1982), therefore, 0.75% of 3289 kg/ha = 24.67 kg N/ha returned in the wheat residue.