THE EFFECTS OF CULTIVATION ON SOIL NITROGEN MINERALIZATION

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I. INTRODUCTION

Nitrogen (N) is one of the most important plant nutrients in arable agriculture. The nitrogen cycle in soils is largely microbially mediated, and a major compo-

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nent involves the transformation of organic N into plant-available mineral forms, primarily nitrate (NO_3–N) and ammonium (NH_4–N). The transformation from organic N into ammonium N is termed *mineralization,* while the oxidation of ammonium into nitrate is termed *nitrification.* Ammonium levels are usually relatively low in arable soils as it is mineralization that is typically the limiting step (Wild, 1988) and hence forms the focus of this review. The opposing process of *immobilization* essentially involves the conversion of mineral N into organic N by microorganisms, with the balance between mineralization and immobilization processes (*net* mineralization) determining the effect on the magnitude of the soil mineral nitrogen (SMN) pool. Inputs of organic N to the soil N system may derive from manures, nitrogen fixation, and crop residues while mineralization–immobilization processes also involve native soil organic matter.

The mineralization–immobilization balance is of pivotal importance as it controls the supply to and magnitude of the plant-available mineral N pool. Fertilizer N additions are used to supplement this plant-available N in the soil. It is recognized by many that a major limitation to improving fertilizer recommendations is our ability to determine the magnitude and dynamics of soil N supply reliably (Sylvester-Bradley *et al.,* 1987; Jarvis *et al.,* 1996). Thus an enhanced understanding of the factors regulating the mineralization process will enable improvements to be made to the current imprecise nature of fertilizer recommendations. In addition to such agronomic benefits, environmental concerns have arisen in recent years regarding the susceptibility of soils to nitrate leaching. Loss of nitrate from soil systems via leaching depletes soil N reserves over the long term and can therefore carry an agronomic cost as a result of the decline in underlying soil fertility. Leached nitrate also plays a contributory role in the eutrophication of freshwater bodies, while high levels of nitrates have been linked to human health issues (McLaren and Cameron, 1990). In response to concerns over nitrate concentrations in drinking water, there is now worldwide political and legislative pressure to decrease nitrate lost from the soil via leaching. To maintain such levels of control on drinking water quality, strategies are being developed aimed either at preventing nitrate inputs to water courses through improved land management and limitations on atmospheric pollutant emissions or at treating nitrate inputs once they have reached water courses (Burt *et al.,* 1993). The UK Department of the Environment (DoE) concluded that effective land-use management and pollution abatement measures would prove to be the more economical of these two options (DoE, 1988).

The impact of cultivation practices on soil physical properties (e.g., structure, water retention, aggregate stability, aeration, bulk density) and soil biochemical processes (e.g., mineralization, nitrification) is of considerable importance in the effective sustainable management of soils as an international resource. Cultivation plays an important role in influencing the physical condition of the soil: It may be used to obtain a good seedbed, to kill weeds, to undo the damage caused by previous traffic over the land, or to increase the permeability of the surface or subsoil layers, which will allow better aeration and drainage in the soil, improving root penetration and influencing water retention properties (Wild, 1988; McLaren and Cameron, 1990). Lal (1991) identified the judicious use of tillage as a powerful tool to overcome problems associated with low infiltration, surface crusting, poor drainage, soil compaction, burial of weeds and surface debris, and pest management.

Physical processes that disrupt the soil structure, such as cultivation, may influence soil N mineralization and nitrification due to their effects on soil porosity, aeration, and hydraulic conductivity, and because the physical disruption may bring microbial populations into contact with fresh, previously unavailable substrate. The effects of cultivation on soil per se and its effect on the mineralization of crop residues are inexorably linked, and it is therefore difficult to discriminate between effects on the decomposition of indigenous N and crop residue N. The effects of particular cultivation techniques may differ according to soil type, previous crop, and cultivation method and timing, and literature reports have been far from consistent regarding the presence, magnitude, and persistence of any detectable effect of different cultivation techniques on N supply to succeeding crops (Balesdent *et al.*, 1990; Radford *et al.*, 1992; Ekeberg and Riley, 1996; Kapusta *et al.*, 1996). Tillage may also increase the flux of CO_2 from soils through enhanced biological oxidation of soil carbon by increasing microbial activity (e.g., due to residue incorporation), and this has implications for fluxes of this greenhouse gas and the role of soil as a sink in the global C balance. Of particular importance to agriculture and fertilizer recommendations is the question of whether the disturbance caused by cultivation results in a change in the absolute magnitude of net N mineralization, or whether it simply modifies the temporal dynamics of the release of N into plant-available forms. For recommendations, there is also an inevitable trade-off between what is ideal in principle and what is agriculturally practical, for example, in terms of cultivation timing.

Jarvis *et al.* (1996) highlighted the importance of time and type of cultivation on the release of nitrate from soils. They stated that there was much qualitative but less quantitative information on specific cultivation effects. However, the scope of their review was necessarily wide, so that a more detailed review of cultivation research results is justified. Our aims are to summarize available methods of measuring mineralization, assess the effects of cultivation on soil physical properties (which will influence biochemical processes), and review evidence for the effects of cultivation on N mineralization. Within the review, we aim to quantify the size (or reported ranges) of cultivation effects on the mineral N pool, including the effects on the overall magnitude and temporal dynamics of N release; to examine the reasons for cultivation apparently increasing mineralization; and to provide information on areas where further research is required.

II. METHODS OF MINERALIZATION MEASUREMENT

A range of direct and indirect methods have been used to monitor decomposition and the release of organically bound N in soil systems.

A. Soil Microbial Biomass

The soil microbial biomass is a key feature mediating nutrient cycling in soil systems and represents an important reservoir for potentially available plant nutrients: Jenkinson (1990) considered it as the eye of the needle through which virtually all nitrogen must pass. Saffigna *et al.* (1989) emphasized the value of measuring C in the soil microbial biomass, defined as that living part of the soil organic matter excluding plant roots and fauna larger than amoeba i.e., >5000 μm^3 (Jenkinson and Ladd, 1981), as a sensitive indicator of changes in soil organic matter following contrasting cultivation practices. However, larger organisms such as earthworms and beetles also play a vital role in nutrient cycling and can also serve as indicators of the degree of soil disturbance. Direct measurement of soil microbial biomass populations involves counting numbers and sizes of organisms and is exceptionally tedious and open to some contention as it requires assumed chemical composition and density values (Jenkinson *et al.,* 1976).

Indirect methods are more popular, one of the most frequently used being the chloroform fumigation–extraction technique (Brookes *et al.,* 1985). This involves fumigating a soil sample with $CHCl_3$ and comparing the N mineralized in the fumigated soil with the N mineralized in an unfumigated control. The flush in mineralization typically observed following fumigation is due to the recolonizing microbial population decomposing the cells killed by the fumigant. Assuming that 68% of the N in the original microbial biomass is mineralized (Shen *et al.,* 1984), then the difference in N mineralized between fumigated and unfumigated soils provides a measure of soil microbial biomass N, as under most conditions the decomposability of other soil organic matter fractions is little, if at all, affected by the $CHCl_3$ fumigation (Jenkinson and Powlson, 1976). A similar method can be used as a measure of microbial biomass C from CO_2 release following fumigation and inoculation (Jenkinson and Powlson, 1976). However, these methods have sometimes failed to identify changes in microbial biomass C or N concentrations in spite of contrasting management regimes (Ritz and Robinson, 1988) and the techniques at best provide only a crude assessment of biomass C and N, and hence some qualitative assessment of mineralization processes.

Researchers are becoming increasingly interested in biomass community structures, and the tools for studying the effects of perturbations on such structures are now available. For example, biomarkers such as sterols can be used to monitor fungal biomass and lipid phosphorus can monitor bacterial biomass (O'Donnell, 1997). Such novel techniques can help to increase our understanding of the soil biomass and how factors such as cultivation can affect it.

B. Microbial Respiration

Soil respiration is the sum of all respiratory activity within the biologically active soil layers, with the primary sources of CO_2 evolution being microbial and root respiration. As the mineralization of organic materials is a microbially mediated process, measuring CO_2 evolution (and neglecting any contribution from root respiration) can serve as an indirect measure of microbial activity in response to the disturbance caused by cultivation practices. Measurements of CO_2 efflux from soil have traditionally been made using alkali (e.g., NaOH, KOH) traps to quantify the cumulative gas respired in a closed chamber and hence infer the size and activity of the microbial biomass. The CO_2 absorbed is then determined by titrating the resulting solution against a dilute acid, usually HC1. However, such chemical absorption techniques can underestimate the gas efflux and are only capable of providing a single integrated measurement. Any laboratory incubations have the advantage of allowing the researcher greater control over abiotic conditions (moisture, temperature, redox) than is possible in the field, but depend on creating an artificial environment that may mean that results bear little relationship to processes occurring under undisturbed field conditions.

A novel technique, substrate induced respiration (SIR), uses patterns of utilization of contrasting C substrates to assess the functional biodiversity and activity of soil organisms (Garland and Mills, 1991; Garland, 1996). Recent research has found that differences in SIR responses between substrates gradually decline with increasing soil disturbance from pasture through ley to arable soils (Degens and Harris, 1997), with higher topsoil SIR rates (and greater microbial biomass) under minimum tillage compared with conventionally tilled soils (Kandeler and Böhm, 1996). Results suggest that differences in SIR between management regimes reflect the smaller microbial biomass in arable compared with grassland soils and arise from differences in the composition of mineralizable soil organic matter (Degens and Harris, 1997). However, the range of microorganisms cultured in this technique can be much smaller than the whole soil microbial community and therefore may not provide an accurate indicator of changes in the activity and diversity of the greater microbial community under field conditions.

A variety of closed or open chamber methods are available for use in the field (King, 1997), with the most widely used method of measuring CO_2 concentrations being infrared gas analysis (King and Harrison, 1995). However, although CO_2 efflux provides a means of characterizing microbial activity in the soil that may be influenced by cultivation practices, measurements of CO_2 evolution may be somewhat confounded by the release of CO_2 from the roots of test crops growing in the same sampled soil volume, and such determinations do not actually quantify net N mineralization of the incorporated residue material, which must be inferred from the change in the temporal and spatial dynamics of microbial activity. Furthermore, there is evidence that short-term CO_2 flux from tilled soils is influenced more by mass flow processes related to a tillage-induced change in porosity than to changes in current soil microbial activity (Reicosky *et al.,* 1997).

C. Isotopic Labeling

Isotopic labeling of ^{15}N has proved a useful, if relatively expensive, technique with which to monitor the mineralization of organic N. One approach, the "isotope dilution" method (Barraclough and Puri, 1995), involves quantifying the dilution of a labeled ammonium solution injected into the soil as the proportion of labeled N present in the soil mineral nitrogen pool decreases over time due to the mineralization of unlabeled organic matter, including residue material. $^{15}N/^{14}N$ isotope ratios are then typically determined by mass spectrometry. However, this method assumes that the basal N mineralization is the same in the presence or absence of residue material: If, following residue incorporation, part of the soil microbial biomass switches from decomposing indigenous soil organic matter to decomposing the fresh residue, then the N mineralization resulting from residue decomposition will be underestimated as the basal mineralization rate will have dropped (Watkins and Barraclough, 1996).

This technique allows field or laboratory measurement of *gross* rather than *net* mineralization and presents the opportunity to study gross N mineralization dynamics unconfounded by the processes such as nitrification and plant uptake, which can consume NH_4. However, this means that immobilization of N, and hence net N mineralization, is not determined, and yet it is this net result that will ultimately determine the soil nitrogen supply to any succeeding crop.

An alternative approach is to label (enrich) either a crop residue or fertilizer with ^{15}N and monitor its movement through the soil–plant system. This can prove particularly useful as part of an N budget approach where major losses are quantified in addition to changes within the soil N pool. This can be achieved by measuring test crop recovery of labeled N, together with using either lysimeters or porous pots to quantify solute fluxes. However, gaseous losses via denitrification and volatilization may account for a significant component of the labeled N applied (e.g., 10–20%; Dowdell and Webster, 1984), and when these fluxes are not measured this results in incomplete recovery of ^{15}N in measured soil and plant components.

D. Temporal Changes in Soil Mineral Nitrogen

Another method involves monitoring the change in SMN (the total of NH_4–N and NO_3–N) and the change in plant N uptake of a test crop over time following contrasting cultivation techniques and compared to a no-till or direct drilled control. This method is very widely used and assumes that other pathways for N loss, such as denitrification and volatilization, are negligible during the monitored period, so that all the N released by mineralization will be reflected in the change in soil nitrogen supply (SNS = SMN + plant N). Under rain-fed conditions, this method may require the estimation of nitrate leaching losses over winter.

A recent development has been the use of soil cores incubated *in situ* under field conditions to determine net N mineralization. This technique was originally developed to measure net N mineralization of native soil organic matter (SOM) in grasslands (Hatch *et al.,* 1990, 1991) but has recently been adapted for arable soils (Bhogal and Shepherd, 1996). Six duplicate pairs of soil cores are taken, with one from each pair being bulked and extracted immediately while the others are incubated for a week in the field in sealed Kilner jars injected with 2% acetylene to inhibit nitrification and denitrification. Jars are incubated in a covered trench to ensure that their temperature approximates that in the undisturbed soil. The difference in NH_4^+ concentration between pre- and postincubation samples yields a measure of net N mineralization. As the method measures absolute changes over time, it is less prone to the limitations associated with the more usual "snapshot" approach to measuring SMN, and has the advantage of representing actual temperature conditions in the field. However, soil cores are contained within airtight jars and thus are not subject to precipitation inputs or evaporative losses, while the disturbance caused by sampling can lead to overestimates of net mineralization compared to an N balance approach (Bhogal *et al.,* in press). The time over which net mineralization may be measured is also limited to around 7 days: Longer periods may yield spurious results as microbial activity becomes progressively restricted by oxygen depletion in the sealed jars.

E. Control Plots

Field-based methods of indirect determination of N mineralization invariably include a (usually zero-tilled or direct drilled) control treatment that may be bare fallow or have the same test crop as the cultivated plots. The effect of cultivation on N mineralization is often determined from comparisons of SNS, yield, grain %N, and N offtake at test crop harvest from cultivation and control treatment plots: Determination of SNS is required rather than SMN alone to make allowance for crop N uptake. If a bare fallow control is used, then there are potential difficulties associated with contrasting temperature and/or soil moisture conditions under the bare fallow control plots, rendering them different from treatment plots, while the lack of a test crop may modify nitrate leaching losses and influence mineralization rates as there will be no crop N uptake "sink" for SMN and no rhizosphere interactions associated with the release of root exudates. Thus results of research comparing cultivated treatment plots with bare fallow plots should be interpreted with care, as differences in SMN will be due to the combined effect of differences in nitrate leaching and any additional N mineralized following the disturbance caused by cultivation.

From a scientific standpoint, a further problem is that it is difficult, if not impossible, to discriminate between physical and biological effects, that is, between (i) the effect of cultivation on physical structure and water retention properties that may influence crop growth and rooting patterns (e.g., increased N uptake in a ploughed vs a direct drilled control due to a more permeable soil structure in the former assisting root penetration and hence nutrient availability), and (ii) the disturbance caused by the cultivation process stimulating additional N release via net mineralization.

F. Which Method?

It is clear that no one method is capable of providing all of the information typically required in field studies, with each method having associated limitations. This is undoubtedly why relatively little progress has been made in understanding and quantifying soil N mineralization in comparison with the large amount of time and effort dedicated to the task in recent years.

Techniques for studying soil biomass are available but are generally crude, difficult to interpret, and have limited applicability in cultivation studies, although newer methods may reveal more about population dynamics in detailed process studies. The measurement of CO_2 efflux can prove a useful guide for characterizing the effects of cultivation on soil microbial activity, particularly if field-based and automated, but root respiration can confound the interpretation of such results. Substrate induced respiration can be a valuable laboratory tool for determining population functionality but cultures will represent only a small component of the soil microbial community, and therefore results may not provide an accurate indictor of changes in the activity and diversity of the greater microbial community under field conditions. ^{15}N techniques are expensive and require careful interpretation, but remain a useful tool in detailed process studies. In contract, the N balance approach is a more straightforward method giving snapshots of soil N status, though spatial variability may necessitate considerable replication and there may be a need for other input/output fluxes to be quantified. Recently developed incubation methods are more labor-intensive, but can provide much greater information on the temporal dynamics of N mineralization in the field. However, care is required as the technique ultimately chosen should not itself alter the rate or amount of mineralization. This use of control plots is necessary in all experiments, but more than one type of control (e.g., bare/undisturbed and bare/cultivated plots) may be required to factor out the effects of tillage per se from other treatment effects. In short, it is necessary to choose the method that best suits the objectives of the experiment: Literature reports have included all the above methods in experiments designed to characterize and quantify cultivation effects on N mineralization with its associated environmental and agronomic implications for land management and the maintenance of long-term soil fertility.

III. CULTIVATION EFFECTS ON SOIL PHYSICAL CONDITIONS

A. Cultivation Techniques

Soil cultivations are used to control weeds, destroy and bury residues, level the soil surface, remedy compaction in subsoil layers, and create a seedbed with a suitable tilth for the next crop (Chamen and Parkin, 1995). It is important to understand fully the cultivation methods used in soil tillage since these ultimately affect the environment for biological activity and hence N mineralization.

Primary cultivation techniques either completely invert the soil (mouldboard ploughs) or mix the soil down to a working depth (rotary cultivators and disks). The traditional method of obtaining a good seedbed is to plough the land with a mouldboard plough, which turns a furrow slice, then to work this furrow slice down into a suitable tilth for the seedbed using secondary tillage implements such as cultivators, harrows, and rolls (Wild, 1988). In contrast, disk ploughs have large typically vertically mounted concave disks instead of shares and mouldboards and, unlike mouldboards, they do not completely invert the soil. However, the mouldboard plough and disks do have limitations, especially on finer-textured soils: They may compress soil in the furrow slice if the soil is wet, leaving it in larger clods requiring further cultivations to break them down into a suitable seedbed, and they can create a compacted plough pan beneath the cultivated layer, which may subsequently restrict drainage, aeration, and root penetration.

More recent innovations include the use of rigid or spring tine and chisel cultivators, which do not invert the soil but generally cause less subsoil compaction than conventional mouldboard ploughs and disks: These have proved most useful on heavier soils, reducing the cost and time required to produce a good seedbed for the next crop (Wild, 1988). Rotary cultivators have a series of blades rotated by a shaft set orthogonal to the direction of travel, with the degree of pulverization controlled by the speed of rotation of the blades, the speed of the tractor, and the position of the shield that recirculates clods back through the rotor. Such implements have a great advantage of being capable of producing a good tilth in only one operation, although this can lead to greater damage to the soil through misuse in wet conditions. Light rollers may also be used to crush soil clods, break surface caps, and consolidate the uppermost few centimeters of the soil to keep soil in contact with seeds and plant roots and help conserve moisture (McLaren and Cameron, 1990).

Zero, reduced, or minimum tillage may be used as an alternative to conventional ploughing, and typically leads to soil conditions that differ markedly from those under more conventional arable systems: Compared with conventional cultivations, effects of reduced tillage typically include greater bulk density, root penetration resistance, structural stability, and pore connectivity, but lower porosity and soil nitrogen availability, with often little effect on overall crop yield (McLaren and Cameron, 1990; Wild, 1988). In minimum tillage, the soil is lightly worked with a cultivator or harrow before drilling, whereas in direct drilling the seed is drilled straight into the undisturbed soil: Such simplified cultivation techniques are being adopted by cereal growers in many countries (Cannell, 1985).

Direct drilling requires much smaller energy inputs to plant new crops (35–80 MJ ha^{-1}) compared with conventional ploughing techniques (200–360 MJ ha^{-1}): It also has the advantages of allowing greater flexibility due to the reduced workload and improving soil and water conservation (Douglas *et al.*, 1986; Wild, 1988). However, minimal cultivation techniques may not be feasible on lighter textured soils because of their tendency to slump. Furthermore, any economy in time and fuel cost is offset by the necessity to use herbicides or extra machinery and labor in addition to a small amount of supplementary N, which may be required to maintain crop yields. The accumulation of plant residues near the soil surface, which would otherwise be buried in conventional ploughing operations, can also interfere with drilling, germination, and seedling growth such as through the anaerobic fermentation of straw releasing substances toxic to seedlings (Harper and Lynch, 1981). Without conventional cultivations, organic matter and nutrients such as N tend to accumulate at or near the soil surface, and this may restrict mineralization rates in the soil beneath (Wild, 1988; Chamen and Parkin, 1995).

In conclusion, the choice of cultivation is strongly influenced by soil type. Greater flexibility is possible on heavier soils, which may be managed under reduced tillage systems with rotational ploughing.

B. Cultivation Effects on Soil Physical Properties

Ploughing and cultivation increase soil aeration (Granli and Bøckman, 1994), and the physical disruption caused by intensive cultivation can result in excessive breakdown of soil aggregates and produce a tilth that is very fine and loose (Scullion *et al.,* 1991). The reduced aggregate stability often identified in ploughed soil is frequently associated with increased porosity and aeration and a decrease in soil bulk density within the plough depth (Ekeberg, 1992; Stokes *et al.,* 1992), and such changes in bulk density have been found to be inversely related to rates of N mineralization (Kemper, *et al.,* 1971). In contrast to the effects of ploughing, minimum cultivation can lead to a loss of soil pores, and this will reduce the rate at which water enters (infiltration) and drains through (hydraulic conductivity) a soil. A key effect of cultivation practices is to modify a soil's drainage characteristics by disrupting the connectivity and continuity of soil pores, especially the larger, intrapedal pores that may connect the near-surface region to deeper layers in the profile, in addition to the possible development of a smeared plough pan restricting rooting and drainage below the cultivation depth (Chamen and Parkin, 1995). Any such modification to soil moisture status can influence redox conditions and hence influence rates of soil microbial activity, including mineralization.

The amount of organic matter in soil is critical for maintaining the stability of soil aggregates, and this is also influenced by cultivation techniques. Intensive cultivation increases organic matter decomposition and can thus lead to a decrease in a soil's organic matter content: Thus in addition to minimum- or zero-tillage systems generally possessing higher bulk densities and more water-stable aggregates near the soil surface, such cultivation systems also tend to have greater organic matter contents (Hill, 1990: Kladivko *et al.,* 1986). Changing from a conventional to a zero-tillage system can improve soil structure as organic matter content and soil organic C content increase, both of which appear strongly related to soil aggregate stability (Kladivko *et al.,* 1986; Havlin *et al.,* 1990; Carter, 1992), and this increased structural stability can greatly reduce soil erosion as well as having agronomic benefits such as decreasing labor and machinery costs (Featherstone *et al.,* 1991). This is supported by Rasmussen and Collins (1991), who reported from 10 different studies comparing the effects of noninversion compared with conventional tillage over periods ranging from 5 to 44 years in duration, and found that topsoil C and N contents increased by an average of 1–2% in noninversion tillage systems compared with conventional cultivation.

In a long-term study into tillage effects on soil properties in Ohio, USA, Mahboubi *et al.* (1993), growing maize (*Zea mays* L.), sampled a silt loam under continuous mouldboard ploughing, chisel ploughing, or zero tillage for the 28-year period beginning in 1962. Results indicated that increasingly intensive cultivation resulted in less organic C, higher porosity, few water-stable aggregates, a smaller mean weight diameter[1] of water-stable aggregates, and lower saturated hydraulic conductivity. Such results concur with those of Arvidsson and Håkansson (1996),

[1]The sum of the mass fraction of soil remaining on a sieve after sieving multiplied by the mean aperture of the adjacent meshes (Besnard *et al.,* 1996).

who concluded that ploughing largely restores the macroporosity of the of the soil within the plough layer, with the main effect of no tillage and soil compaction being on the interaggregate bonding.

Evidence suggests that in addition to changing the aggregate size and stability, tillage changes a soil's total porosity, pore size distribution, and the continuity and connectivity of soil pores (Addiscott and Dexter, 1994). For example, Dowdell *et al.*, (1979) found 3% (v/v) greater oxygen concentrations at 15 cm depth in a direct drilled compared with a ploughed clay soil, which was attributed to the development of a system of continuous large pores and channels that would otherwise have been disrupted by ploughing. As the size of soil aggregates increases, this also tends to increase the range of pore sizes, and thus tillage operations that result in a finer tilth will typically reduce the pore size in a given soil. In a long-term experiment comparing mouldboard ploughing and direct drilling for 22 years, Ball *et al.* (1996) found the surface of a Gleysol and a Cambisol to be more stable, less compactable, and have greater plasticity limits under direct drilling compared with conventional ploughing, with these differences correlated to total carbon and carbohydrate concentrations with depth and tillage treatment.

Timing of cultivations with respect to soil moisture conditions can also have a significant influence on soil physical conditions and hence on microbial processes. Cultivations such as ploughing can result in serious soil compaction if conducted when the soil is too wet, and this can result in short-term effects relating to the bulk density of the plough layer, structural effects that persist after ploughing, and subsoil compaction including plough pan formation. In a review of 21 long-term field experiments in Sweden, Arvidsson and Håkansson (1996) compared standard (control) seedbed preparation (mouldboard ploughing in autumn) with three harrowings in spring and compacted (extra traffic in autumn) soils over 259 site-years. The extra traffic significantly ($P < 0.05$) decreased the porosity and the proportion of large pores, increased the tensile strength of dry aggregates, caused a mean yield loss of 11.4%, and on clay and loam soils also decreased the proportion of fine aggregates and the gravimetric water content in the seedbed. Plant N uptake was lower ($P < 0.05$) in the compacted treatments, and yield loss was mainly influenced by soil type, being <10% on sands, 10-20% on clay loams, and >20% on clay soils. Such evidence indicates that any beneficial effect of cultivation in creating a good seedbed, burying trash, and stimulating microbial activity to release mineral N must be counterbalanced by the risk that excess traffic and overcultivation, especially on heavier soils, not only will damage soil structure, but also can cause serious subsurface compaction and ultimate yield reduction.

Given the overwhelming evidence of physical changes in soil properties due to contrasting tillage practices, one important issue is the persistence of such effects. The duration of cultivation effects was studied by Arvidsson and Håkansson (1996), who reported that within 4–5 years after the termination of their traffic treatments, the yield loss had disappeared and yields had returned to the control level. This suggests that cultivation effects on soil structure, and possibly mineralization, may be relatively short-lived, and these issues are discussed further in Section IV.

The method of cultivation can have an important impact on the magnitude and pattern of water use through its effects on the rooting patterns and water distribution within the soil profile. Early work found that approximately 10% more water was stored in arable soils that had been direct drilled compared to those that had been conventionally ploughed, which enabled a winter wheat crop to extract up to 22 mm more water from the direct drilled soil (Goss *et al.,* 1978). This is consistent with more recent research by Shepherd and May (1992), who reported that a loamy sand soil dried out significantly more after ploughing than after direct drilling. For vegetable crops, deeper cultivations have been shown to be beneficial because they allow roots to penetrate deeper into the subsoil and extract more water from the topsoil region (Wild, 1988), resulting in greater utilization of water held at greater depths, which can feed through to give higher yields (Rowse and Stone, 1980).

Direct drilled soil typically has a higher surface reflectance coefficient (albedo) and higher thermal diffusivity than ploughed soil (Hay *et al.,* 1978) and this is one reason unploughed soil is often cooler than ploughed soil (Ekeberg, 1992; Fortin *et al.,* 1996; Ekeberg and Riley, 1996). This can result in a delay in planting and maturation, which could be either an advantage or a disadvantage: Areas with a long growing season could have greater yields at reduced cost, while in other areas this could result in the need to harvest under unsatisfactory (wet and cold) conditions or before the crop has matured sufficiently (Ekeberg and Riley, 1996). However, in some circumstances a large accumulation of residues at the surface of reduced tillage soils can have an insulating effect, leading to slightly (e.g., 1°C) higher temperatures at sunrise compared with ploughed soils (Franzluebbers *et al.,* 1995).

Any difference in temperature between cultivated and uncultivated soils will modify rates of microbial processes such as mineralization, which researchers generally consider to follow a Q_{10} response pattern with microbial activity typically doubling for a 10°C change in soil temperature (Quemada and Cabrera, 1995, 1996). Furthermore, the different temperature conditions typically reported for reduced tillage compared with conventional cultivations can influence crop root growth, which research has found to be 2.6 to 5.1 times greater at a soil temperature of 25°C than at 18°C (Mackay and Barber, 1984).

Cultivation therefore has major effects on soil structure and physical characteristics. Tillage typically increases porosity and aeration, but with associated decreases in the mean diameter and structural stability of soil aggregates. It reduces soil bulk density and pore connectivity and continuity, which can lead to a smaller water holding capacity and lower saturated hydraulic conductivity. Ploughed soil may also be slightly warmer than unploughed soil, with resulting feedback effects on soil evaporation, microbial activity, and crop growth (see below). Increasingly intensive cultivation practices tend to decrease soil organic matter status (soil organic C and N), with implications for long-term soil fertility/sustainability and erosion risk. By modifying the physical environment and abiotic conditions (water content and temperature), cultivation practices have direct effects on soil microbial activity, which governs nitrogen cycling processes, including mineralization, crop growth, and N uptake.

IV. CULTIVATION EFFECTS ON NITROGEN MINERALIZATION

A. Interactions with Soil Texture

In his classic work, Hans Jenny (1941) noted that, in general, soil organic matter levels tended to increase with increasing clay content of soils, and thus for a given climate, topography, and vegetation, fine-textured soils generally had more organic matter and, therefore, total (predominantly organically bound) N compared to their coarser-textured counterparts. This organic matter accumulation is thought to be the combined result of the effect of clay in stimulating microbial growth and activity (Bondietti *et al.*, 1971; Martin *et al.*, 1976) and the development of organoclay complexes that may have a reduced susceptibility to biodegradation (Stevenson, 1982).

Cultivation generally leads to a temporary increase in soil mineral nitrogen, most probably because the soil disturbance thus caused leads to a larger pool of carbon substrates being made available to support greater microbial activity (Wild, 1988). This is thought to occur as the physical disruption of soil aggregates caused by tillage practices results in the exposure of microsites where organic matter was previously physically protected from microorganisms or their enzymes (Adu and Oades, 1978). Physical protection of organic matter in soils is thought to be associated with encrustation by clay particles (Tisdall and Oades, 1982) and/or entrapment in small pores within soil aggregates that may be inaccessible to microbes (Elliot and Coleman, 1988). Organic matter bound to the <2-μm clay particle fraction has been shown to concentrate microbial biomass and its metabolites (Amato and Ladd, 1980) and may contribute to a temporary or transient pool of organic material (Tisdall and Oades, 1982), although this will be dependent on its relationship to larger aggregates constituting soil structure, with laboratory incubations revealing that short-term C and N mineralization is faster from macroaggregates than from microaggregates (Gupta and Germida, 1988; Gregorich *et al.*, 1989; Cambardella and Elliot, 1994).

There are thought to be two main features that account for differences in soil organic N mineralization in different aggregate size classes:

(i) differences in pore sizes, which means that organic material may be protected from degradation within soil aggregates (Jocteur-Monrozier *et al.,* 1991; Ladd *et al.,* 1992);

(ii) differences in the "quality" (e.g., relative decomposability, as measured e.g., by C/N ratio) of particulate organic matter in different aggregate size classes, which means that N turnover in macroaggregates may be faster because of the presence of large, fresh plant debris promoting more rapid microbial activity (Balabane, 1996). It is these larger macroaggregates that may be most vulnerable to physical disruption during conventional cultivation.

Indirect evidence for the physical protection of organic matter in soil includes (a) drying of soil samples and disruption of soil aggregates before incubation can increase organic C and N mineralization during the first few weeks after the start of the incubation (Cabrera and Kissel, 1988; Gregorich *et al.,* 1989); (b) net mineralization of soil organic matter and the decomposition of added plant material appears more rapid in sandy compared with clay soils (Ladd *et al.,* 1990; Hassink *et al.,* 1990; Verberne *et al.,* 1990). The lower net N mineralization in the heavier clay soils is thought to be caused by this greater physical protection of soil organic matter and microbial biomass (Verberne *et al.,* 1990), with the most recent fractionation studies of fresh and indigenous soil organic matter suggesting that mineralization appears to be more strongly influenced by this physical position and protection rather than by the substrate's chemical composition (Balesdent, 1996).

As a major influence on soil structure, evidence suggests that clay content is particularly important in influencing N mineralization as organic N is often intimately associated with the clay fraction in soils, with more clay-rich soils often possessing higher total %N concentrations. This is confirmed by Franzluebbers *et al.,* 1996), who found the amount of mineralizable C and N per unit soil microbial biomass C decreased with increasing clay content, indicating that the soil microbial biomass was more active in undisturbed coarse-textured soil than in undisturbed fine-textured soils. However, once soils are disturbed the opposite is true, as grinding soil samples of differing textures results in much greater mineralization in clay-rich soils due to the release of readily mineralizable organic N previously inaccessible to microbial degradation (Haynes, 1986; Hassink, 1992). A major hypothesis to account for the retention of such organic matter is that the soil mineral matrix protects soil organic matter against faunal predation (biodegradation), either through adsorption of substrates to mineral surfaces or by sequestration in aggregates at sites inaccessible to microbes (Van Veen and Kuikman, 1990). Physical protection is likely to be less in cultivated than in uncultivated soils because tillage periodically breaks up soil aggregates and exposes previously protected soil organic matter (Balesdent *et al.,* 1990). This physical protection may explain why fine-textured (>40% clay) soils have been found to contain 1.2 to 1.5 times more soil organic C (SOC) and 2.5 to 3.5 times more soil microbial biomass C compared with coarse-textured (<15% clay) soils (Van Veen *et al.*, 1985; Van Gestel *et al.*, 1991), although the higher SOC content in finer-textured soils could also be due to differences in C input, rather than long-term decomposition dynamics, since they tend to be more fertile than their coarser-textured counterparts (Franzluebbers *et al.*, 1996).

In field soils, Adu and Oades (1978) concluded that as much as 90% of the organic matter may be inaccessible to the soil microflora and extracellular enzymes, with physical disruption caused by mechanical cultivation resulting in a flush of microbial respiratory activity measured as $^{14}CO_2$ evolution as microorganisms are brought into contact with fresh, previously unavailable substrate. Contemporary research by Besnard *et al.*, (1996) studied the decomposition of a labile pool of particulate organic matter (POM), including plant residues, in a loamy forest soil introduced into maize cultivation, and found that cultivation decreased the mean weight diameter of stable aggregates from 2.55 to 2.04 and 1.23 mm after 7 and 35 years of continuous maize production, respectively, with the proportion of stable aggregates decreasing from 78 to 47% of the soil mass after cultivation, primarily due to a loss in macroaggregates >200 μm. Cultivation reduced the C/N ratio in these macroaggregates from 30 in the forest soil to 24 and 21 after 7 and 35 years of continuous maize production, respectively. Results suggested that cultivation resulted in the loss of C from outside the aggregates, with the POM fraction occluded within microaggregates (50–200 μm) found to turnover more slowly. Other research has shown that young POM from maize residues can act to stabilize soil aggregates in cultivated silty soils (Puget *et al.*, 1995), with cultivation resulting in a decrease in the relative proportion of carbohydrates in SOM and an increase in carboxyl C, phenolic C, and aromaticity of the SOM (Lessa *et al.*, 1996).

Research by Hassink (1992) investigated the hypothesis that disrupting soil structure increases mineralization rates in loams and clays more than in sandy soils, and that this increase can be used to estimate the fraction of physically protected organic matter that might be made available following cultivation. C and N mineralization was measured in undisturbed and in finely and coarsely sieved moist or dried/remoistened soil. N mineralization rates were significantly ($P < 0.05$) lower in the undisturbed samples, with a regression analysis of the data from 1991 and 1992 revealing that variations in the proportion of the clay+silt component (i.e., <50 μm) between different soils explained 71% of the observed variation in N mineralization rates over 84-day monitoring periods. This is consistent with ^{15}N research by Balabane (1996), who found that recently immobilized N associated with the clay fraction was rapidly sequestered in microaggregates <100 μm. Skjemstad *et al.* (1993) also found that a considerable proportion of soil organic matter was physically protected within clay- and silt-sized aggregates, with material external to clay- and silt-sized aggregates being largely proteinaceous in contrast to internal material, which more closely resembled humic acids.

From their research, Hassink (1992) found that fine sieving caused a temporary increase in mineralization that was much larger for N than for C and for loams and clays compared with sandy soils, with relative increases in N mineralization averaging 150% for loams and clays but only 5% for sands in the 2 weeks after fine sieving relative to coarsely sieved control soils: These findings are consistent with other research by Cabrera and Kissel (1998) and Schöder *et al.* (1989). In loams and clays, small pores constitute a higher percentage of the total pore space compared with sandy soils, and Hassink (1992) found that (a) the fraction of pores <1.2 μm and (b) the clay content both significantly affected N mineralization rates. The first finding (a) was thought to be because most small voids in soil are filled with carbohydrates, many of which are attached to clay particles (Foster, 1986), but this material cannot be reached by microorganisms and was therefore physically protected against decomposition, with the physical disruption caused by sieving exposing part of this fraction to rapid microbial degradation. As the mineralization flush following disturbance was significantly greater for N than for C, this suggests that any physically protected organic matter had a lower C/N ratio than the rest of the soil organic matter, which is consistent with this being more readily mineralizable organic matter susceptible to rapid mineralization following physical disruption of the soil structure. The sandy soils studied by Hassink (1992) had generally higher C/N ratios than the loams and clay soils, possibly, as Chichester (1969) and Cameron and Possner (1979) reported, because C/N ratios decrease with decreasing particle size because organic material coated with clay particles has a better physical protection than organic material around sand particles.

Such results are in agreement with earlier research by Tisdall and Oades (1982), who found that aggregates between 2 and 20 μm in diameter contain most of the micropores and soil C and N: Such aggregates contain bacteria surrounded by clay particles, cell-wall remnants, and other microbial decay products. If substrates made available by physical disruption are of microbial origin, they will have a narrow C/N ratio, which may also explain why the relative increase Hassink (1992) detected in N mineralization due to sieving was much larger than the relative increase in C mineralization. N mineralization was 0.04–0.06%/day for sieved but 0–0.02%/day for undisturbed sand, and 0.02–0.06%/day for sieved but 0–0.02%/day for undisturbed clay and loam soils over the first 2 weeks following disturbance; C mineralization was between 2.4 and 6.3 times greater than corresponding N mineralization rates.

However, this flush of N mineralization was relatively short-lived, with Hassink (1992) reporting that values were significantly ($P < 0.01$) higher than undisturbed control soils only during the first 5 days (loams and clays) or the first 2 weeks (sands) following physical disturbance. Other researchers have reported equally ephemeral effects of structural disturbance, such as cultivation, on C and N mineralization rates (Richter *et al.,* 1982; Dowdell *et al.,* 1983; Nordmeyer and Richter, 1985), again suggesting that the compounds that are made accessible are very easily decomposable. However, although there does appear to be evidence suggesting a significant effect of soil type on the effects of cultivation on N mineralization rates, no clear relationship has ever been described between pore-size distribution and the physical protection of organic matter from microbial decomposition, although researchers such as Hassink (1992) suggest that it is the small pores that contain physically protected organic matter with a low C/N ratio that can be mineralized very quickly following physical disruption such as cultivation.

Therefore, two explanations may account for the observed effects of cultivation inducing a "flush" of microbial activity resulting in increased soil nitrogen mineralization: (i) The physical protection of soil organic matter, as the physical disturbance caused by cultivation fractures soil peds and brings microorganisms and soil fauna into contact with fresh, previously unavailable (physically protected) substrate; (ii) the modified soil environment conditions (aeration, water content, temperature) induced by cultivation, which will directly influence growth and activity of the soil biomass. Cultivation disrupts soil structure, decreasing aggregate size and the C/N ratio in macroaggregates. The soil mineral matrix protects soil organic matter against biodegradation either through adsorption of substrates to mineral surfaces or by sequestration in aggregates at sites inaccessible to microbes. There is an interaction between mineralization potential and soil type: Clay-rich soils possess larger amounts of physically protected soil organic matter within structural aggregates and are characterized by greater mineralization potentials. This accounts for net mineralization of soil organic matter and the decomposition of added plant material being more rapid in sandy than in more clay-rich soils under undisturbed conditions, whereas the reverse is true after conventional cultivations due to the release of readily mineralizable organic N previously inaccessible to microbial degradation. Effects of cultivation on mineralization are typically relatively short-lived, with differences from uncultivated controls detectable only for several weeks following tillage.

B. Effects on Soil Fauna

In a study comparing 13 years of conventional mouldboard (CT) ploughing to 15 cm depth versus no tillage (NT) on a clay loam in the southeastern United States, Beare *et al.* (1994) found an 18% increase in organic C in the plough layer of the NT relative to the CT treatment, which they attributed to differences in the assimilation and decomposition of SOM under the different tillage regimes.These authors reported far more variable temperature and moisture conditions in the surface soils of CT treatments that would influence microbially mediated processes, while the greater biological activity near the soil surface of NT treatment soils helped to incorporate particulate organic matter within macroaggregates and hence increase their structural stability.

These results concur with the findings of Ball *et al.* (1996), who identified increased organic C and carbohydrate concentrations near the surface of direct drilled plots compared to the more uniform distribution in ploughed plots of a Cambisol and a Gleysol under winter barley in southeastern Scotland, and this accumulation of organic matter near the surface of no-till soils has been reported by other researchers (Blevins *et al.*, 1983; Douglas and Goss, 1982). The accumulation of organic material at the soil surface in direct drilled plots may lead to greater biological activity compared with ploughed soil (Douglas, 1977; Hoffman *et al.*, 1996a,b) and this is reflected in the greater microbial biomass measured in direct drilled compared to ploughed soils (Lynch and Panting, 1980, 1982). In particular, direct drilled soils have been found to possess significantly more fungal propagules, but not bacteria, in the 0- to 5-cm layer compared to unploughed controls (Barber and Standell, 1977): Fungi are frequently the largest component of the soil biomass (Anderson and Domsh, 1975). This is consistent with other research by Lee and Pankhurst (1992), who concluded that the initial breakdown of plant tissues was predominantly mediated by bacteria in ploughed systems, whereas fungi dominated under direct drilled conditions: This may be encouraged by the development of acidic surface layers of decomposing crop residues in direct drilled systems. However, in contrast, Campbell *et al.* (1989) actually found a narrowing of the biomass C/N ration from 9 to 5 following 6 years of zero tillage, which was attributed to a shift from a microbial population dominated by fungi to one with a greater preponderance of bacteria and actinomycetes.

Thus, tillage practices can also influence decomposition processes controlling N cycling and mineralization by modifying the soil faunal population. The agronomic significance of soil fauna depends on the intensity of cropping systems, since grazing, tillage, fertilization, and pesticides generally tend to reduce the species complement and their population densities (Anderson, 1988). Other research has found that noninversion tillage systems can increase populations of gamasid mites, earthworms, and *Collembola* in experiments conducted in Germany and on a range of soils from sandy loams to clays in the United Kingdom (Edwards and Lofty, 1982; El Titi and Landes, 1990). This is consistent with other research by Rovira *et al.* (1987) and experimental work on a silt loam at Rothamsted, UK, which revealed more earthworms and soil arthropods such as surface predatory beetles, springtails, and insects, but fewer mites and slugs after 6 years of direct drilling compared with conventional ploughing in fields sown to winter wheat (Patterson *et al.*, 1980). Similarly, Carter (1991b) reported an increase of 140–160% in earthworm biomass in rotary harrowed or direct drilled plots compared to conventional ploughing of a sandy loam soil.

Earthworms can represent the primary agent for incorporating residues in untilled soils, and their burrows may enhance deeper storage of soil water (Mackay and Kladivko, 1985), while earthworm casts are active microsites for denitrification and N_2O production (Elliot *et al.*, 1990; Knight *et al.*, 1992). Nagel *et al.* (1993) found that CO_2 production and nitrate release were enhanced by mesofauna, but lowered by earthworms due to a transient immobilization of nutrients in microorganisms that increase dramatically during the passage through the earthworm gut (Edwards and Fletcher, 1988). Thus a decrease in earthworm biomass has been associated with an increase in soil inorganic N (Lee and Pankhurst, 1992), which is consistent with reports of greater soil nitrate concentrations and nitrate leaching losses in soils under conventional cultivation compared with those under reduced tillage systems.

Despite this greater faunal activity in direct drilled soils, there is evidence suggesting that such minimum tillage regimes may restrict nitrate availability as the presence of a mulch of dead vegetation, often with a wide C/N ratio, tends to stimulate immobilization near the surface of direct drilled or untilled soils (Kitur *et al.*, 1984). This would explain why untilled soils can contain significantly less nitrate–N than cultivated ones, particularly during autumn (Dowdell *et al.*, 1983), although other causes of lower levels of nitrate–N in untilled soils may include increased leaching due to improved pore connectivity (Goss *et al.*, 1978) and greater denitrification losses of N_2O and N_2 associated with higher soil moisture contents and an additional source of readily available C in the soil (Aulakh *et al.*, 1984).

Mineralization should therefore be considered as the net effect of all soil biological processes, including the contribution from macrofauna such as earthworms and soil arthropods, rather than purely a function of the population dynamics of the soil microbial biomass alone. The physical disruption caused by cultivation has a profound effect on soil faunal populations, activity, and location in the soil profile. Earthworm and beetle populations decrease when a direct drilled soil is ploughed, with ploughing leading to a shift in microbial populations from one dominated by fungi to one with a greater preponderance of bacteria and actinomycetes.

C. Effects on Yield

Given the typically smaller soil nitrate levels under minimum tillage systems, it is not surprising that long-term cropping experiments on corn, wheat, and barley have shown that without added N, or with N at low rates, crop N uptake and yields are often lower on untilled compared to tilled soils, although with adequate fertilizer N supply similar or greater yields can be achieved without tillage (Kitur *et al.*, 1984; Smith and Howard, 1980; Ellis *et al.*, 1982; Haynes, 1986; Dick *et al.*, 1992).

However, such conclusions have not been universally observed (Ekeberg and Riley, 1996; Kapusta *et al.*, 1996) with crop yields sometimes showing no difference following establishment by direct drilling or conventional ploughing (Webb *et al.*, 1991). This variable response may be a result of prevailing weather conditions during research studies, as other research by Carter (1991a) found that shallow tillage and direct drilling may produce similar grain yields as mouldboard ploughing only when environmental conditions were optimal, with wet or dry seasons favoring ploughing and direct drilling, respectively, due to their effects on soil moisture status. In a separate study, Ekeberg and Riley (1996) compared the effects of tillage systems on the yield and nutrient uptake of potato (*Solanum tuberosum* L.) in Norway from 1987 to 1993. In their research, the effects on potato yield of a conventional, labor-intensive treatment using autumn mouldboard ploughing and two passes with a spring-time harrow in spring were contrasted with planting directly into untilled barley stubble with straw removed. Results on a morainic, stony loam soil indicated a pattern of distinct yield curves for the different cultivation treatments expressed as functions of harvest date: The yield curve for direct planting was steeper, crossing that of conventional tillage on 10 September and thus predicting higher tuber yield for direct planting when harvesting after this date, but lower tuber yields compared with conventional tillage in the case of early harvesting. This difference was largely attributed to cooler soil and delayed growth and hence maturation in the case of direct planting. Nutrient uptake of the plants was consistently greater (57, 11, and 41 kg N/ha) with direct planting, despite the same fertilizer being applied to both treatments, and was attributed to the direct planted crops making better use of the applied fertilizer or the increase in topsoil organic matter, and hence nitrogen, found after a number of years without ploughing (Ekeberg, 1992).

In a novel approach making use of the natural difference in ^{13}C content between C_3 and C_4 (maize) plants, Balesdent *et al.* (1990) measured C and $^{13}C/^{12}C$ ratios and found that mineralization of the indigenous soil organic C was approximately double on conventionally ploughed compared with zero-tilled experimental plots. However, less organic carbon accumulated in the zero-tilled plots after harvest due to lower yields of maize in these plots. Saffigna *et al.* (1989) also used measurements of organic C in a study of the effects of cultivation practices on soil organic matter dynamics. Following 6 years of growing sorghum on an Australian Vertisol in central Queensland, these authors detected an increase in biomass C of 14–21% as a result of zero compared with minimum tillage (composed of 10 cm depth disk/tine cultivation).

In a detailed study of the long-term effects of contrasting cultivation systems on the yield of corn over 20 years on a silt loam in Illinois, USA, Kapusta *et al.* (1996) found that yields were equal in conventional till, reduced-tillage (chisel cultivator), alternate-tillage (cycle of NT 2 years, CT 1 year), and zero-tillage systems all receiving broadcast NPK fertilizer. These results are consistent with earlier work by Griffith *et al.* (1988), although Kapusta *et al.* (1996) also found that yields were 15–18% lower in NT treatments compared to the other tillage systems if no fertilizer or N only was applied in the spring. Dick *et al.* (1992) studied the effects of cultivating fields under no tillage for the previous 5 years on maize yield and N uptake using six levels of fertilization on a silty loam soil. Grain N concentrations were consistently lower for maize grown under NT compared to CT, yet grain yields were generally higher, especially at high fertilizer N rates. This increased efficiency of N for grain production was attributed to the greater amount of water measured in the soil under NT management in all 5 years of the study. Spring ploughing also affected N availability to maize, although this was more pronounced in the second crop rather than the first crop after ploughing. Overall, grain yields and N uptake resulted in low fertilization rates proving more effective for the CT treatment, whereas high fertilization rates increased grain yields and N uptake for NT so that it equalled or exceeded those from CT treatments: This is a pattern reported by a number of other researchers (Meisinger *et al.*, 1985; Rice *et al.*, 1986; Thiagalingam *et al.*, 1991).

Tillage effects are also profoundly affected by prevailing weather conditions. Radford *et al.*, (1992) reported that zero tillage with stubble retention stored the most water during the fallow periods, but the least soil mineral nitrogen. As a result, this treatment outyielded all other treatments during dry years but produced one of the lowest yields during the wettest year. There is also evidence that the accumulation of nutrients in the uppermost 5 cm of NT soils can result in taller plants compared to other tillage systems, possibly due to the enhanced water and nutrient availability (Griffith *et al.*, 1988; Dick *et al.*, 1991).

A number of other researchers have found that minimum-tillage systems promote soil water retention and can reduce soil temperature (Bennett *et al.*, 1973; Johnson and Lowery, 1985; Wilhelm *et al.*, 1986), which can mean that crop emergence and early season growth may be delayed (Imholte and Carter, 1987) even though root extraction of water and nutrients may be greater with zero tillage than under conventional ploughing (Hargrove, 1985). However, such effects mean it can be difficult to identify the precise reasons for observed differences in N mineralization, SMN, and crop yield and N uptake due to contrasting cultivation practices: Differences could be (i) due to physical effects on soil structure and hydraulic properties due to contrasting soil water and temperature status influencing crop growth and development and acting as abiotic controls on microbial activity; (ii) due to the accumulation of C and N in residues near the surface of direct drilled plots modifying soil N cycling processes (in contrast to the more uniform residue distribution in ploughed soil); or (iii) due to the physical disturbance caused by cultivation making previously physically protected substrate available for microbial decomposition. Observed tillage effects are most probably the net result of all of these different influences.

Due to their effects on soil water and temperature conditions, minimum- or zero-tillage cultivations are usually most successful on well-drained soil, rather than on poor or imperfectly drained soil, especially under wet soil conditions (Griffith *et* *al.*, 1988; Herbek *et al.*, 1986). Poorly drained soils with relatively high organic matter contents cropped to corn have been found to yield generally less with NT compared with CT because of lower soil temperatures and excess moisture retention in the spring (Kapusta *et al.*, 1966). On well-drained soils, crop yields are generally similar under direct drilled and conventional ploughing systems under optimal fertilization regimes and weather conditions. However, direct drilled crops typically require a small amount (ca. 20 kg/ha) of additional fertilizer N to achieve the same yields as crops grown following conventional ploughing, largely as a result of the greater immobilization of mineral N near the surface of no-till soils due to the accumulation of carbonaceous crop residues.

D. Previous Crop and Residue Management

The mineralization dynamics of N from the preceding crop's harvest residues will largely depend on the nature of the organic N added, C/N ratio and N content of the residue, residue placement, the degree of contact with the soil matrix, tillage and cropping practices, as well as soil temperature, moisture, and aeration (Iritani and Arnold, 1960; Frankenberger and Abdelmagid,1985; Smith *et al.*, 1987; Breland, 1994; Kuo *et al.*, 1996). Cereal straw residues may be baled and removed, incorporated by cultivation, or left on the soil surface. Legislation has now outlawed burning as a method of residue disposal in the United Kingdom. Such residues' relatively high C/N ratio (e.g., 70–100 for cereal straw) may promote rapid immobilization of soil mineral N as microbial populations are unable to satisfy their N demand from such carbonaceous substrates. Leaving residues on the soil surface can reduce SMN supply to a succeeding crop as the limited N supply can severely limit decomposition, while research suggests that the alternative of incorporating residues by cultivating can greatly increase their decomposition rate (Brown and Dickey, 1970).

It is difficult to assess the true significance of the management of previous crop residues such as stubble on crop growth, as it may not be possible to discriminate between any phytotoxic effects of stubble in reduced cultivation systems from other adverse effects on plant growth such as the immobilization of N caused by stubble incorporation and the often lower levels of nitrate in the soil profile under reduced-tillage systems (Thompson, 1992). Stubble retention modifies soil moisture (and hence redox) conditions by storing incident precipitation and mitigating soil evaporative loss, which accounted for a difference of 5–10 mm after successive rainfall events in the weighing lysimeter study of Freebairn *et al.* (1987). The increased risk of localized anaerobicity may be exacerbated by direct drilling into zero-till plots where planting equipment does not fully close the drill slot after seeding (Scott Russell *et al.*, 1975), and this in turn may result in problems in seedling emergence due to fungal or bacterial colonization generating phytotoxins such as the antibiotic patulin or acetic acid (Thompson, 1992). For example, in a long-term experiment on an Australian Vertisol, Thompson (1992) reported that stubble retention caused far greater depression of vegetative growth of barley (*Hordeum vulgare* L.) in zero tillage compared with mechanical tillage of the fallow.

Swift *et al.* (1979) noted that the surface area and volume of detritus particles will significantly influence their susceptibility to enzymes and to ingestion by soil animals, and hence to decomposition. In general, more finely divided, macerated, or ground plant material decomposes more quickly than coarse material as it exposes a greater surface area for microbial colonization and enzymatic activity (Moore, 1974; Haynes, 1986). Thus crop residue management such as chopping and incorporation can have a significant influence on N mineralization and soil mineral nitrogen supply in the postharvest period, with chopping materials with a wide C/N ratio promoting the rapid immobilization of inorganic mineral N (Smith and Sharpley, 1990). This is supported by research on maize stalk pith that found that finely chopped particles immobilized six times as much inorganic N in the first month after incorporation compared with more coarsely chopped particles (Sims and Frederick, 1970). In such situations, much of the residue N is retained by incorporation into microbial cells with some of this later converted into recalcitrant humic substances while, in contrast, the C present is progressively reduced via CO_2 evolution so that the C/N ratio of the residue narrows as decomposition proceeds, eventually resulting in a net release of N via mineralization. The critical N content above which net mineralization will occur is generally considered to be in the range 1.4–1.8%N or at a C/N ratio of <25–30 (Haynes, 1986).

The magnitude and temporal duration of such microbial immobilization is of considerable agronomic importance, as by temporarily reducing soil mineral nitrogen supply the incorporation of such cereal residues may reduce a soil's susceptibility to overwinter nitrate leaching by up to 25 kg N/ha (Nicholson *et al.*, 1997) and/or restrict N supply to a succeeding crop (Thompson, 1992). Research by Smith and Sharpley (1990) detected a depression in net mineralization in the first 14 days after incorporating residues of alfalfa, corn, oat, peanut, sorghum, soybean, and wheat with C/N ratios of 16, 64, 40, 27, 36, 54, and 58, respectively, into eight contrasting soil types. This depression in net mineralization was enhanced when residues were mechanically incorporated into the soil rather than being left on the soil surface, and was greater for the residue N compared with the older, indigenous soil N.

Other research by Goss *et al.*, (1993) found that, although residues from oats produced an amount of mineralized nitrogen similar to wheat, oilseed rape residues released N equivalent to that from cereal residues to which 26 kg N/ha had been added. These authors concluded that the nature of the previous crop was particularly important in determining the nitrate leaching loss over the winter period, with most of the enhanced nitrate leaching losses observed under conventional ploughing compared to direct drilling being derived from the mineralization of residues from the previous crop, that is, from the more labile organic N fraction.

Other studies have investigated the effects of cultivation on different crop genera with characteristically lower C/N ratio residues.For example, in a study examining the effect of antecedent legume crops and tillage on the distribution and dynamics of N in a sandy loam soil in Canada, Soon and Clayton (1996) used zero tillage and conventional tillage in a randomized block design with three crop sequences: pea–wheat, red clover green manure–wheat, and wheat–wheat. No significant differences were detected in plant N uptake or yield due to tillage method or previous crop, and there was no significant difference in the amount and distribution of soil mineral nitrogen due to tillage method. Francis *et al.* (1992) investigated the effects of different tillage practices on changes in SMN after cultivating a temporary leguminous pasture, and similarly found no difference between the effects of mouldboard ploughing and chisel ploughing on the accumulation of mineral N or the amount of nitrate leached over winter. However, timing of cultivation proved important, with overwinter nitrate leaching losses totalling 78, 40, and 5 kg N/ha for cultivations carried out the previous March, May, and July, respectively: The experimental site was in New Zealand and therefore these months represented early autumn, late autumn, and winter, respectively. Such data concur with current UK recommendations delaying cultivations until as late as practicable to reduce nitrate leaching risk (MAFF, 1991).

Hoffman *et al.* (1996a,b) recently quantified the effect of soil tillage on net N mineralization under sugar beet and found that although the cumulative amount of N mineralized over the growing season and the period of highest N mineralization did not differ between conventional and reduced cultivation, tillage method did affect the mineralization rate in the uppermost 30 cm of a sandy loam soil profile. The N mineralization rate was higher at 0–10 cm in the reduced tillage soil, whereas for the conventionally tilled treatment it was consistently greater at 10–20 cm depth.

Research has also compared the effect of minimal tillage of a soil previously under rotational fallow: Campbell *et al.* (1989) found cumulative net N mineralization over 16 weeks to be 40 $\mu g\ g^{-1}$ soil more under direct drilling compared with the same Chernozem soil retained under fallow. Overall, attempts to quantify the magnitude of any mineralization flush associated with cultivation exposing readily mineralizable organic material, which was previously physically protected, may be somewhat confounded by the effect of the chemical composition and management of the previous harvest's residues, which may restrict nitrate availability, and any such effect will be more pronounced after incorporating residues with wider C/N ratios.

Therefore, the chemical composition and relative abundance of N in crop residues, which may be crudely expressed using C/N ratios, play critical roles in governing the residues' relative decomposability and the consequences for soil mineral nitrogen supply. Long-term retention of stubble in no-till systems can increase the size and turnover of the microbial biomass, the respiration of organic C, and the gross mineralization of N compared with conventional cultivations, due to the accumulation of organic material at (or close to) the soil surface and modifications to prevailing soil moisture conditions. However, this may translate into less net N mineralization under zero-till conditions, especially in cereal cropping systems characterized by carbonaceous residues. More finely divided or macerated residues will decompose more rapidly as a result of the greater surface area exposed for microbial colonization and decomposition. Similarly, leaving residues on the soil surface tends to reduce their rate of decomposition compared with residue incorporation.

E. Timing and Frequency of Cultivation

Soils under no-tillage management may sometimes be ploughed for crop rotation purposes or to correct a pest or soil management problem. Pierce *et al.* (1994) investigated whether soil properties created by long-term no-till management were retained after a single ploughing and return to no tillage for a loam soil in the United States. Compared with long-term NT, both conventional tillage CT and a single ploughing of no-tillage areas decreased bulk density by 0.17 to 0.28 Mg m^{-3}, increased total porosity from 0.03 to 0.10 m^3 m^{-3}, increased macroporosity by 0.05 to 0.13 m^3 m^{-3}, and decreased microporosity by 0.03 to 0.05 m^3 m^{-3}. The single ploughing of no-till areas enhanced N mineralization over both CT and NT by 9.8 to 18.4 g m^{-3} in the surface 5 cm, and the residual effects of this single cultivation were still evident 1 year after ploughing. However, after 4 or 5 years after the single cultivation, most soil properties had returned to levels similar to those prior to disturbance, although C and N concentrations in the uppermost 5 cm of the soil still remained lower than those that had accumulated under long-term NT.

Other research has indicated that the effect of cultivation on mineralization is strongly dependent on the number of years under the tillage method considered (Carter and Rennie, 1982; Staley *et al.*, 1988), with smaller proportions of physically protected soil organic matter in soil that was ploughed annually compared with the same soil that had remained untilled for many years (Balsedent *et al.*, 1988, 1990) because soil under long-term ploughing will have reached a stable equilibrium typically characterized by lower total C and N contents. The corollary to this is that soil recently brought into reduced tillage will typically have higher fertilizer N demand during the first few years due to initial immobilization processes (Baeumer and Köpke, 1989), with Manzke *et al.* (1992) reporting that 15 years were required before a new steady state between immobilization and mineralization was obtained after reverting to a zero-tillage system.

There are profound differences in the effect of cultivation with depth, however, with Doran (1987) reporting that microbial biomass and potentially mineralizable nitrogen in the surface layer (0–7.5 cm) of no-till soils were 34% higher than those of ploughed soils, although the opposite was true at 7.5–15 cm depth. A similar pattern was reported by Carter and Rennie (1982), who also identified clear differences in mineralization with depth under contrasting cultivation regimes. These authors found that for 2-week incubations of four different soils (two clay loams, one loam, and one silt loam) under optimal water and temperature conditions, zero tillage resulted in cumulative C mineralization averaging +43% at 0–5 cm depth but −30% at 5–10 cm depth while cumulative N mineralization averaged +53% at 0–5 cm depth but −18% at 5–10 cm depth, with all changes relative to measurements under conventional cultivation. This provides strong evidence that, compared to conventional cultivation, reduced tillage results in a substantial increase in mineralization potential within the near-surface zone, although this may be partly compensated for by a concomitant decline in mineralization potential in deeper subsurface layers.

The timing of cultivations may also be an important consideration in governing mineralization and N supply to a succeeding crop. Cultivation when the soil is warm and moist typically leads to the greatest amount of N mineralization, with mouldboard and chisel ploughing operations resulting in reduced nitrate leaching if they were delayed until late winter (Watson *et al.,* 1989; Vinten *et al.,* 1994). However, this is not always a practical option, especially on heavier soils that may be waterlogged this late in the year: On such soils, delayed cultivations would risk later spring sowings and soil damage such as compaction and plough pan development due to the wet conditions (Chamen and Parkin, 1995).

In a study of the effect of type and timing of cultivations on N mineralization in a shallow calcareous loam overlying chalk in Lincolnshire, UK, Stokes *et al.* (1992) found that a 7-week delay in soil disturbance after harvest of the preceding vining pea crop reduced nitrate concentration at 0–30 cm depth from 88 to 55 kg N/ha in mid September, with a similar experiment showing that a 3-week delay in cultivation after oilseed rape reduced nitrate levels from 262 to 150 kg N/ha at 0–30 cm depth in late October. Thus the timing of cultivation may be crucial in governing the magnitude of N release and hence its availability to subsequent crops and susceptibility to nitrate leaching. However, there is a trade-off, because if delaying cultivations leads to late establishment of the next winter sown crop, then yields may be compromised and the later crop establishment may lead to increased nitrate available for overwintering leaching.

Physical protection of soil organic matter—which is thought to be an important factor in controlling mineralization potential—is increased under no-till regimes (Section IV). This will increase the size of the pool of labile organic N and C, which is physically protected but may subsequently be made available following rotational ploughing or periodic cultivation. No-till systems have significantly greater potentially mineralizable N and microbial biomass in the near-surface zone, but less in subsurface layers, compared to conventionally ploughed systems. Delaying cultivations can be a successful means of reducing soil nitrate concentrations and hence limiting overwinter nitrate leaching losses, but such environmentally motivated advice must be balanced with the practical agronomic requirement to avoid adversely restricting crop establishment and final yield. Thus the timing of cultivations and their relationship to crop establishment and N demand are critical factors governing the fate of N from any mineralization flush resulting from the tillage process.

F. Soil Mineral Nitrogen and Nitrate Leaching

Cultivation is an oxidative process since it typically promotes good aeration (provided the soil is not excessively wet) and the rapid decomposition of soil organic matter, and consequently promotes increased mineralization of organically bound nitrogen (Campbell, 1978; Haynes, 1986). Decomposition of soil organic matter is generally most rapid in the first 25 to 50 years of cultivation and reaches steady-state conditions within 50 to 100 years after conversion to arable cropping (Allison, 1973). Thus, artifact effects from previous site management such as the ploughing up of grassland may account for the higher mean SMN concentrations found in some shallow soils overlying chalk, which otherwise would be expected to have generally lower total topsoil N contents and hence N availability (Williams *et al.,* 1996).

The effect of cultivation in promoting a mineralization flush conveys considerable argonomic and environmental importance, as research on clay soils indicates that crops grown after conventional mouldboard ploughing have between two and four times greater soil solution nitrate concentrations at 30 and 60 cm depths compared to direct drilled crops, and this difference persists throughout the winter months (Dowdell and Cannell, 1975). The potential for overwinter nitrate leaching is therefore greater in ploughed soils, while direct drilled crops frequently require greater fertilizer N inputs compared to crops grown following ploughing. This is supported by Colbourn (1985), and in more recent research by Catt *et al.* (1992), who found that tillage increased overall nitrate leaching losses by 24% compared to direct drilling in hydrologically isolated plots in the Brimstone Farm experiment on a clay soil in Oxfordshire, UK.

At the same site, Goss *et al.* (1993) found that conventional ploughing (20 cm depth) for autumn-sown cereal crops increased overwinter nitrate leaching losses by 21% relative to direct drilling, mainly as a result of the enhanced mineralization of soil organic matter. However, in the spring, direct drilling actually *increased* nitrate leaching losses following fertilizer applications (Goss *et al.,* 1988), probably as a result of greater bypass (macropore) flow in direct drilled plots compared to ploughed ones, because ploughing would have disrupted the continuity and connectivity of macropore channels involved in solute transport.This slightly greater loss of spring-applied N has been proposed as one reason why larger applications of spring fertilizer N are often required in direct drilled systems to achieve yields comparable to similar fields under conventional cultivation (Cannell, 1985). In contrast, research has found that soil-derived N from the mineralization of organic N is often distributed in fine pores within the soil matrix and so is less readily displaced by water flowing in macropores (Youngs and Leeds-Harrison, 1990; Goss *et al.*, 1988, 1993).

In the study reported by Goss *et al.* (1993), mean nitrate leaching losses for 1981–1988 (excluding 1984) under wheat were 30 kg N/ha in ploughed soil but only 23 kg N/ha in direct drilled plots, with corresponding values under oats of 43 and 30 kg N/ha, and under oilseed rape of 41 and 27 kg N/ha, respectively. Over the entire period 1981–1988, winter leaching losses of NO_3–N were consistently greater by 1–21 kg N/ha from ploughed plots compared to those that had been direct drilled (Fig. 1), although a portion of this N could have been residual fertilizer applied the previous spring rather than the mineralization of indigenous organic N resulting from the cultivation process per se. To discriminate cultivation effects with greater confidence, Goss *et al.* (1993) calculated apparent net mineralization using an N budget approach taking account of changes in plant N and SMN over time plus any loss of N in monitored mole drains. Apparent net mineralization was variable, but consistently less under direct drilling. For plots under winter wheat after an oat harvest, cultivation had little effect in autumn and winter 1988 when fluxes were 26 and 31 kg N/ha for direct drilled and ploughed plots, respectively, although a larger effect was evident when fluxes were summed over

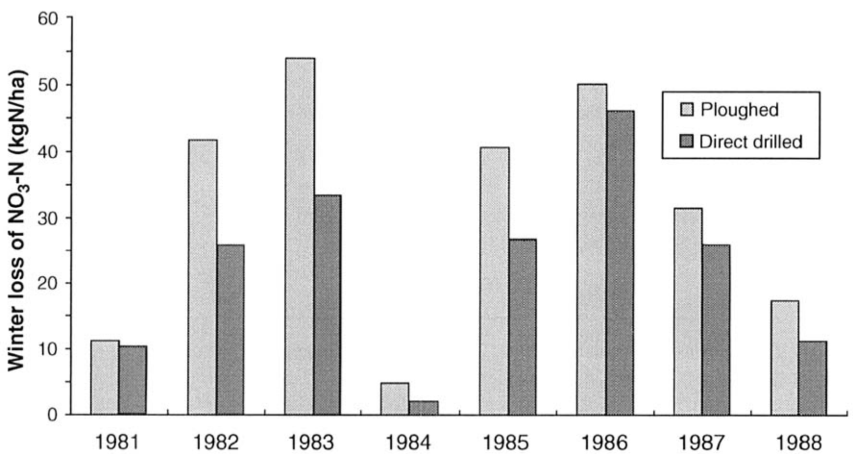

Figure 1 Effect of cultivation on overwinter nitrate leaching. Adapted from Goss *et al.* (1993).

the whole year with only 67 kg N/ha mineralized in direct drilled plots but 83 kg N/ha in plots under conventional cultivation.

Radford *et al.* (1992) also found that zero tillage and stubble retention reduced water use efficiency compared with conventional cultivations, with results indicating higher soil water status but lower soil nitrate concentrations under zero-tillage systems. Ammonium concentrations were always negligible, but levels of NO_3–N showed a reasonably consistent pattern of tillage effects over the 3-year study on a Typic Natrustalf sown to wheat, with conventional tillage with disks responsible for 14–38 kg/ha more NO_3–N at sowing and 20–49 kg N/ha more NO_3–N at harvest compared with zero tillage (Table I): This additional nitrate left at harvest would be vulnerable to leaching the following winter. Cameira *et al.* (1996) also reported lower soil nitrate concentrations under minimum tillage compared to conventional cultivation of irrigated maize on a Fluvisol in Portugal, and attributed this to lower nitrification and mineralization in the minimum-tillage system as well as a larger loss of nitrate by denitrification due to the less aerobic soil conditions (Doran, 1980). This is plausible, as denitrification losses are often greater from undisturbed compared with ploughed soil (Linn and Doran, 1984; Staley *et al.,* 1990), with Burford *et al.* (1981) reporting fluxes of 5.4–8.6 kg N_2O–N ha^{-1} a^{-1} from no-till plots compared with only 0.9–5.6 kg N_2O-N ha^{-1} a^{-1} from ploughed plots.

The results reported by Goss *et al.* (1993) and Radford *et al.* (1992) are consistent with the findings of monthly SMN measurements after cultivation of five adjacent fields in an replicated trial on a clay soil in Cambridgeshire, which also sug-

Table I

Effect of Tillage Practices on Nitrate–Nitrogen at 0–60 cm Depth at Sowing and Harvest[a]

	NO_3–N, 0–60 cm depth at sowing (kg N/ha)			NO_3–N, 0–60 cm depth at harvest (kg N/ha)	
Tillage treatment	1985	1986	1987	1986	1987
Z	37	44	76	51	22
RB	49	49	58	69	30
RD	69	60	90	88	54
CB	58	69	75	68	29
CD	71	82	90	100	42
LSD, $P = 0.05$	21	20	ns	ns	20

Note. Z, zero tillage; R, reduced tillage; C, conventional tillage; B, blade plough; D, disk plough; LSD, least-significant difference; ns, not significant.

[a] Reprinted from *Soil & Tillage Research,* **22,** Radford *et al.,* "Fallowing practices, soil water storage, plant-available soil nitrogen accumulation and wheat performance in South West Queensland," p. 86, 1992, with kind permission of Elsevier Science–NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

gested that cultivation may typically release up to 20 kg N/ha in the 2 months following ploughing or deep tine cultivation (ADAS, unpublished data). On a similar soil type, Dowdell *et al.* (1983) also reported that SMN levels in January were 12–65 kg N/ha greater at three sites subject to autumn ploughing compared with direct drilling.

Despite this evidence, the disturbance caused by cultivation has not always been found to increase SMN status (Soon and Clayton, 1996), and the ultimate fate of any additional soil mineral N will be strongly dependent on soil type, which will control its susceptibility to nitrate leaching. If crops are to make use of any flush of additional mineral N made available as a result of the cultivation process, they must be planted as early as possible to enable them to use this SMN before it is leached out of the soil. Measurements by Dowdell and Cannell (1975) revealed no differences in denitrification or leaching losses of N from soils with conventional or direct drilled crops; crop N offtake explained only a third of the recorded differences in soil mineral N concentrations, with the authors concluding that the remaining differences were due to less mineralization of organic nitrogen in the direct drilled plots.

Any effect of reduced tillage in conserving N may, however, only be transient. Catt *et al.* (1992) reported results from comparisons of direct drilled, shallow tine, and deep plough cultivations on a heavy clay soil in Oxfordshire, UK. Shallow tine cultivations decreased nitrate leaching losses and associated drainflow concentrations, but only for the first year, while once plots that had been direct drilled for 8 consecutive years were disturbed and deep cultivated they lost 23–43% (1.8–8.3 kg N/ha) more nitrate overwinter than plots conventionally ploughed throughout the same 8-year period. Such effects only lasted for 1 year, but influenced crop yield and N offtake for 2 years, with results indicating that although direct drilling and shallow tine cultivation can carry short-term (1–2 years) benefits, they only succeed in slowing mineralization, reducing nitrate leaching, and storing organic N temporarily with subsequent disturbance hastening mineralization rates once again.

V. CONCLUSIONS

Soil cultivation may influence the magnitude and temporal and spatial dynamics of mineralization by altering (i) soil temperature, (ii) soil structure, aeration, and hydraulic properties, (iii) the amount and distribution of organic residues with depth, and (iv) the degree of physical protection preventing a proportion of soil organic matter from being microbially degraded. All four of these factors are important influences on the magnitude and activity of the soil biomass.

The bulk of evidence indicates that increasingly intense cultivation practices tend to reduce the stability of soil structure. Any such effects are exacerbated by high soil water status and hence are potentially worse in finer-textured soils. Research indicates that cultivation techniques can significantly modify soil physical properties, with more intensive cultivation leading to less organic C, higher porosity, and fewer water-stable aggregates. In contrast, the accumulation of residues at or near to the soil surface means that soils under reduced- or zero-tillage systems are often cooler, wetter, and more compact than those under conventional tillage such as mouldboard ploughing, and this increased soil water retention and lower temperature can mean that crop emergence and early season growth may be delayed.

Ploughing and cultivation tend to decrease aggregate size and introduce a more oxidized environment, which will accelerate organic matter mineralization. Research suggests that this is linked to a more easily mineralizable fraction of particulate organic matter associated with macroaggregates that are fractured by the physical disruption caused by tillage, allowing microorganisms to gain access to fresh, previously unavailable (physically protected) substrate. In addition to minimum- or zero-tillage systems generally possessing higher bulk densities and more water-stable aggregates near the soil surface, such cultivation systems also tend to have greater organic matter contents. There is a significant interaction with soil type: Loams and clay-rich soils with larger pools of organic C and N are characterized by much greater amounts of physically protected (and readily mineralizable) soil organic matter, some of which will be made available as a result of cultivation. Most importantly, contrasting tillage practices result in fundamentally different depth distributions of organic residues in soils, and this is largely responsible for minimum-tillage systems typically leading to an accumulation of organic C and N near the soil surface. The increase in total organic C detected after 3–10 years of NT management has been attributed to immobilization of fertilizer and crop residue N. Rates of CO_2 evolution appear greater following mouldboard ploughing compared to disking, chisel ploughing, or zero tillage, with small but consistent differences in efflux between treatments still evident 19 days after initial tillage.

No-till plots have been found to possess 71–132% greater mineralization potentials in the 0- to 5-cm surface zone compared to conventionally ploughed soils, but the opposite was the case in subsoil layers due to the incorporation of crop residues through ploughing. This increased pool of labile N under reduced tillage has implications for the rotational ploughing of such soils. However, minimum tillage and stubble retention typically reduce the levels of soil NO_3–N primarily due to increased nitrogen immobilization, especially near the soil surface. The greater continuity and connectivity of vertically oriented macropores has been proposed as an explanation for the slightly greater leaching of spring fertilizer N sometimes reported from direct drilled plots. However, in general, differences in the pattern of water movement under no-till or conventional ploughing regimes typically lead to less cumulative nitrate leaching under reduced cultivation, as research suggests that the nitrate derived from mineralization of organic nitrogen is distributed in fine pores within the soil matrix and so is less readily displaced by water flowing in macropores.

Conversely, tillage experiments often reveal that the more frequent and intensive the cultivation technique, the greater the level of NO_3–N during the subsequent months. By reducing the mean aggregate diameter, cultivation leaves a greater surface area exposed for microbial colonization and enzymatic activity (Haynes, 1986), and the resulting enhanced mineralization can lead to greater nitrate leaching losses (if autumn ploughed) and a concomitant decline in soil organic matter content. Table II presents a summary of a number of reported changes in net mineralization, SMN, and nitrate leaching losses under conventional compared with reduced-tillage systems.

The cultivation of arable soils induces a mineralization flush typically responsible for between two- and four-fold increases in soil solution nitrate concentrations. Reported research consistently indicates that this release of labile organic N is responsible for 5–65 kg N/ha more SMN following conventional ploughing compared with minimum cultivation, with the effect often only detectable during the first 1–2 years following cultivation. The fate of this additional pool of mineral N is strongly site-dependent (soil/crop type, weather), and may lead to an increase of 20–50% (up to 25 kg/ha/a) in nitrate leaching losses following ploughing compared with the same soil left uncultivated or direct drilled (Table II). In contrast, net N mineralization under minimum-tillage management may be 5–25

Table II

Overview of Reported Changes in Net N Mineralization, SMN, and Overwinter Nitrate Leaching Losses in Conventionally Ploughed Compared with Direct Drilled Soils

Reference	Increase in net N mineralization (kg N/ha/a)	Increase in soil mineral N concentration	Increase in nitrate leaching losses
Catt *et al.* (1992)	—	—	2–8 kg N/ha (23–48%)
Dowdell and Cannell (1975)	—	200–400% NO_3-N	—
Dowdell *et al.* (1983)	—	12–65 kg/ha (January)	—
Radford *et al.* (1992)	—	14–38 kg/ha (sowing); 20–49 kg/ha (harvest)	—
Powlson (1980)	6–9	—	—
Goss *et al.* (1993)	16	—	1–21 kg N/ha (21%)
ADAS (unpublished data)	20	—	—

kg N/ha/a less than that found in conventionally ploughed soils, partly because the accumulation of carbonaceous crop residues at or near the surface of direct drilled soils promotes greater immobilization of available N leading to lower soil solution nitrate concentrations.

Although conventional cultivation typically results in greater SMN concentrations than direct drilling, any increased SMN availability due to more mineralization under conventional ploughing is not necessarily translated into detectable differences in crop yield. Furthermore, N uptake by crops under different tillage systems do not appear to differ substantially, possibly due to the typically larger levels of SMN in the conventionally ploughed soils making them vulnerable to greater nitrate leaching losses during the winter months. However, when soil moisture is not limiting, cereal yields are generally greater under conventional rather than under a zero- or minimum-tillage system when zero or low levels of N fertilizer are applied to well-drained soils, although when higher rates of N are applied grain yields are often similar. Thus no-till soils tend to require slightly (ca. 20 kg N/ha) increased fertilizer N additions for crop yields to match those following conventional cultivations. The greater treatment effects under limited fertilization regimes are probably indicative of the greater soil mineral nitrogen supply following cultivation due to increased rates of N mineralization, with ^{15}N research revealing the tendency for enhanced N immobilization in reduced tillage fields due to the accumulation of relatively carbonaceous residues near the soil surface.

Research suggests that the mineralization flush caused by intensive cultivation can persist for several years following reversion to reduced or zero-till systems, enhancing SMN levels, increasing nitrate leaching risk, and potentially contributing additional N to subsequent crops. However, the release of N into mineral forms following the spring cultivation of fields previously under reduced-tillage regimes may not be so great as to permit reductions in fertilizer N inputs to spring-sown crops. There is limited evidence suggesting that by enhancing N mineralization in the short term, repeated conventional cultivations could lead to net N mineralization being reduced over the longer time scale (compared with zero-tillage systems) as soil organic N reserves may become progressively depleted.

VI. MANAGEMENT IMPLICATIONS

In terms of environmental policy, there are indications that more intensive cultivations, such as ploughing, can increase N mineralization and soil mineral nitrogen levels by up to 65 kg N/ha in the months following tillage, compared with zero- or reduced-tillage systems. This additional pool of soil mineral nitrogen will be primarily in nitrate form and thus is potentially vulnerable to leaching, especially during the winter months and on the lighter soil types, with research suggesting increased losses of up to 25 kg N/ha/a when a soil under reduced cultivation is conventionally ploughed. The widespread adoption of direct drilling or other alternative reduced cultivation practices would therefore result in a reduction in nitrate leaching losses in the short term, and this would lead to smaller loadings of nitrate being leached into ground and surface water bodies. Research suggests that such reduced cultivation practices would not, in general, result in significant losses in crop yield if minimal tillage is restricted to appropriate soil types, with the majority of evidence suggesting that the effects of such contrasting cultivation practices on yield are generally negligible.

Research indicates that the mineralization flush resulting from the cultivation process is influenced by soil type and by the timing and frequency of cultivation practices. Recent evidence indicates that any increase in N mineralization following cultivation may be relatively short-lived, and this suggests that sowing should be undertaken as soon as possible after deep cultivations to maximize the utilization of additional mineral N by the developing crop. Further work is required to characterize the timing of N release following different cultivation methods so that the dynamics of the flush of additional SMN can be synchronized as far as possible with crop N demands: Efficient utilization of the additional SMN released by cultivation has agronomic importance through the improved precision associated with the use of fertilizer N, and environmental significance by restricting the potential for nitrate leaching.

This review supports current UK advice for decreasing nitrate leaching by delaying cultivations in the autumn until as late as practicable (MAFF, 1991). Although minimum cultivation methods will decrease nitrate leaching losses in the autumn and winter months, this technique may not be appropriate on lighter-textured soils with relatively high proportions of silt and fine sand particles due to their propensity for structural instability and compaction. However, innovative techniques have been developed for establishing sugar beet on light soils by direct drilling (for erosion control) and such approaches should be explored for autumn crops. Cereals following the harvest of potatoes provide another opportunity for a rapid establishment of the next crop to decrease nitrate loss.

This review has shown that there can be large differences in soil N supply following the two extremes of cultivation (no till and mouldboard ploughing) of as much as 65 kg N/ha: This is sufficiently large to be agronomically significant, and allowance should therefore be made for this additional pool of plant-available N when planning future fertilizer recommendations. However, there is relatively little published information on the effect of the rotational ploughing of no-till fields (which may be undertaken periodically to resolve a pest or soil management problem) or the effect of the reversion of no-tillage sites back into conventional cultivation on temporal patterns of N mineralization and the consequent implications for soil and water quality and soil fertility. The influence of cultivation date after set-aside[2] also warrants further investigation.

[2]Land temporarily taken out of crop production under the EU Common Agricultural Policy.

There is considerable evidence to suggest that due to typically greater N immobilization and slightly increased denitrification losses, reduced-tillage systems may require a small amount (up to 25 kg/ha) of additional fertilizer N in order to equal the yields under conventional cultivations: This need for supplementary seedbed N was acknowledged in earlier versions of UK fertilizer recommendations, but was not included in the most recent update (MAFF, 1995). Additional practical research is required to improve the mineralization component of fertilizer recommendations for these two extremes of cultivation (no till vs ploughing); The need for such research has been recently acknowledged (Shepherd *et al.*, 1996) and would have agronomic benefits in terms of more efficient use of fertilizer N and associated environmental benefits by reducing nitrate leaching risk. However, refinements for cultivation systems within these two extremes would not be feasible given the current state of knowledge on the temporal dynamics of soil mineral nitrogen supply.

An overview of the key findings of this review are summarized in Table III. Reduced cultivation systems can significantly reduce nitrate leaching losses and may also contribute to reduced erosion risk. However, one of the most pertinent questions is the medium- to long-term sustainability of such minimum-tillage systems and the ultimate fate of the observed increases in soil organic C and N. Is this

Table III

Summary of the Typical Effects of Conventional and Reduced Cultivations

Conventional tillage	Reduced tillage
←	→
Reduced aggregate stability	Greater aggregate stability
Reduced mean aggregate diameter	Increased mean aggregate diameter
Higher porosity	Lower porosity
Lower bulk density	Higher bulk density
Reduced soil pore continuity/connectivity	Greater soil pore continuity/connectivity
Reduced physical protection of SOM	Greater physical protection of SOM
Increased erosion risk	Reduced erosion risk
Warmer, drier soil	Cooler, wetter soil
Biomass dominated by bacteria	Biomass dominated by fungi
Fewer earthworms and soil arthropods	More earthworms and soil arthropods
Lower organic matter content	Higher organic matter content
Less total organic C and N	More total organic C and N
Residue C and N incorporated to depth	Residue C and N accumulated at surface
Lower mineralization potential	Greater mineralization potential
Increased nitrogen mineralization	Increased nitrogen immobilization
Increased SMN concentrations	Reduced SMN concentrations
Increased nitrate leaching risk	Reduced nitrate leaching risk
Follow standard ferilization guidelines	Small additional fertilizer N required
Similar yields achievable under optimal moisture and fertilization regimes	

additional N incorporated into more stabilized forms with a beneficial effect on soil structure and aggregate stability, or does it remain more labile and simply serve as a temporary store for a pool of readily mineralizable N that may pose future environmental problems when it is remineralized once the land is ploughed again? This sustainability issue is an important one that needs to be addressed before greater confidence can be placed in management solutions, such as reduced-tillage systems, aimed at reducing nitrate leaching risk while maintaining underlying soil fertility and yield potential.

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