

The Mineralisation of Nitrogen
in Cover Crops:
A Review

Martyn Silgram¹ & Roland Harrison²
ADAS

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¹ ADAS Wolverhampton, "Woodthorne", Wergs Road, Wolverhampton WV6 8TQ

² ADAS Boxworth, Boxworth, Cambridge CB3 8NN

EXECUTIVE SUMMARY

Management of N in cropping systems is becoming increasingly important as attention is focusing on reducing non-point sources of nutrient pollution. Cover crops have the potential to reduce nitrate leaching losses and store considerable quantities of nitrogen (*e.g.* 25-50kgN/ha or more) over-winter for release via mineralisation following destruction in the spring. Cover crop mineralisation can be considered in terms of the interaction of residue composition with environmental factors. Residue composition is a function of species, dry matter and N concentrations, which in turn are a function of sowing date, destruction date and growing (seedbed) conditions: soil N availability, temperature and moisture supply.

The generic inverse relationship between C/N, lignin, cellulose or soluble carbon contents and plant age accounts for the importance placed on sowing and destruction dates as a means of manipulating cover crops to maximise their potential N contribution to the succeeding crop. Research tends to show that earlier sowing and later destruction dates can promote yield depressions of the subsequent crops compared with later sowing and earlier destruction dates, probably due to their effect in widening cover crop C/N ratio at destruction and reducing the time available for mineralisation of the residues before the harvest of the next crop.

Concentrations of cellulose and lignin are greater in grasses and more mature plant material compared with legumes and young plant material, with legume residues from cover crops such as crimson clover and hairy vetch typically having C/N ratios of 8 to 15, which contrast with wider ratios of up to 60 reported for cereal cover crops such as wheat and rye. The typically narrower C/N ratio of legumes tend to lead to more rapid mineralisation than is commonly observed for other cover crop genera. However, residue composition is an all-encompassing term, and it is probable that in choosing a single parameter to represent this (*e.g.* C/N ratio), other aspects are ignored. Thus, for example, the C/N ratio of above-ground material may be identical for leguminous and non-leguminous cover crop species, but mineralisation of their incorporated residues may differ markedly as lignin linkages in plants differ between legumes and non-legumes, with those in non-legumes generally resulting in a greater proportion of the dry matter being resistant to decomposition.

In terms of soil type, there is evidence that the N mineralisation of added plant material such as cover crop residues are more rapid in sandy compared with heavier, clay-rich soils, with N mineralisation negatively correlated with clay content. The majority of reported research indicates that, under temperate European conditions, only a relatively small proportion of cereal cover crop N, typically *ca.* 5-30%, is released in the short term *i.e.* during the growing season of the subsequent spring-sown crop, although this proportion may be somewhat larger for legume residues. Overall, research has found the resulting effects of cover cropping are generally small and appear highly variable, sometimes showing positive, negative, or no overall effect on the yield and N uptake of succeeding spring-sown crops.

Practical recommendations include establishment of cover crops in late August or early September *i.e.* soon after the previous harvest. The link between surface area, physical accessibility to microbial degraders and a substrate's relative decomposability (*e.g.* C/N ratio, lignin content) suggests that incorporation (rather than chemical destruction) and using cultivation techniques such as rotovators which macerate the residue and mix it with the soil, should tend to encourage the early release of the N contained in the cover crop residues. Incorporation of residues by ploughing or rotovation should increase the opportunity for microbial degradation and represent a preferable option than the more costly alternative of

chemical destruction which would also leave residues at the soil surface where they may interfere with seedling emergence.

As N stored in cover crops is often not fully utilised by the following crop due to the limited mineralisation of cover crop residues, any reduction in nitrate leaching when cover crops are grown could result in an accumulations of organic N over time, particularly in rotations where cover crops are grown repeatedly. In the longer term, repeated use of cover crops could therefore cause the *potential* for N mineralisation (and hence nitrate leaching) to increase. However, in many rotations the usual mix of spring and autumn planted crops will mean that cover crops are employed infrequently (*e.g.* only one year in three). In these circumstances, the accumulation of organic N should tend to be small, and will be reduced further if yields and N offtake increase as a result of cover crop incorporation. Given the considerable importance of cover cropping as a UK and internationally adopted strategy to ameliorate nitrate leaching losses to ground and surface waters, further research is required to clarify the longer term impacts of repeated cover cropping on soil N status, SMN and nitrate leaching risk in the years following the harvest of the first spring sown crop.

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1. INTRODUCTION

1.1 Background

Cover crops are typically grown to conserve N by reducing N losses via over-winter leaching which would otherwise occur if the ground was left fallow following summer harvest (DoE, 1986). In the UK, cover crops are mostly used on lighter textured (*e.g.* sands, sandy loams) or shallow (*e.g.* overlying chalk) soils which are susceptible to nitrate leaching losses during the winter period. They are not usually grown on the more nitrate-retentive silt soils, as no yield benefits have been observed (Cook & Froment, 1996). Cover crops are either undersown in spring or direct sown after harvest and represent probably the single most effective short-term control measure to limit nitrate leaching in arable cropping rotations (Shepherd *et al.*, 1996). They are consequently required in Nitrate Sensitive Areas (NSAs) and are recommended in Nitrate Vulnerable Zones (NVZs) (MAFF, 1994) and as part of the code of good agricultural practice for the protection of water (MAFF, 1993). In NSAs, farmers accepting a basic rate payment are required to sow a cover crop on land which would otherwise be bare between 1 October and 1 January. In addition to reducing nitrate leaching losses, the additional organic material in cover crops incorporated into soil has the potential to improve soil structure and fertility (Rogasik *et al.*, 1996). Although considerable research has been undertaken over the last decade to quantify the ability of cover crops to take up nitrogen from soil over-winter to reduce nitrate leaching losses, there is relatively little information available on the release and ultimate fate of nitrogen from cover crop residues after destruction (Turley *et al.*, 1992; Hayward, 1992; Platte & Przemec, 1996; Allison & Armstrong, 1992).

If cover crops reduce nitrate leaching, then soil nitrogen (N) is likely to accumulate, increasing the risk of nitrate leaching in subsequent years, unless a substantial portion of the immobilised N in the cover crop is made available to subsequent spring-sown crops (Harrison & Peel, 1996). Incorporation of cover crop residues may provide additional N for a succeeding crop, as microbial decomposition of organically-bound N in residue material will tend to increase levels of soil mineral nitrogen (SMN) available for subsequent plant uptake. This mineralisation of N from the incorporated cover crops 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 & Arnold, 1960; Frankenberger & Abdelmagid, 1985; Smith *et al.*, 1987; Breland, 1994; Kuo *et al.*, 1996).

Predicting the quantity and timing of N release from cover crop residues thus represents an important research objective, which may allow savings to be made in fertiliser N applications with implications for N supply later in the crop rotation. Current UK fertiliser recommendation systems take no account of the contribution of N from cover crop residues to a succeeding crop, so there is a consequent risk of over-fertilising the following crop if substantial quantities of N are mineralised from the decomposing plant material. Management of residue material should aim at encouraging a rapid, timely release of N which is synchronised as far as possible with crop N demand, thus avoiding build-up of N reserves and the risk of potentially larger N losses later (Shepherd *et al.*, 1996).

1.2 Review Objectives

Compared to the research effort devoted in recent years to characterising the ability of different cover crop species to take up N over the winter period, relatively little research has focused on the pattern of release of this organic N back into mineral form, its availability to succeeding crops, and the fate of this nitrogen following cover crop incorporation in the

Annex

spring. This review discusses the methods available for measuring the mineralisation of cover crop residues (Section 2), and then focuses on the available literature concerned with the influence of species, composition and C/N ratio, soil type, abiotic factors and site management on the fate of organic N in the cover crops once they are killed and/or incorporated into the soil (Section 3). Particular attention is given to the release of this pool of N into plant-available mineral forms and hence the availability of cover crop N to succeeding spring-sown crops.

2. EXPERIMENTAL TECHNIQUES

2.1 Direct Methods

A variety of direct and indirect methods are currently in use to quantify the temporal pattern of N release from decomposing crop residues. Direct methods include isotopic labelling with radiotracers such as ^{15}N and ^{13}C , measurement of N mineralisation using an *in situ* core incubation technique, and the loss in mass of litter bags decomposing under field conditions.

2.1.1 The Buried Bag Technique

The buried bag method involves placing green manure residues, with or without soil, into mesh or polythene bags and burying them in the field for incubation at a predetermined depth within the plough layer (*ca.* 0-25 cm depth). Low density polythene bags are used which prevent moisture loss while allowing substantial gas exchange: periodic withdrawal of the bags allow the loss in C and organic N over time to be determined. This method has been widely used in nutrient cycling studies (*e.g.* Campbell *et al.*, 1974; Van Schreven, 1968; Smith *et al.*, 1977; Westermann & Crothers, 1980): it prevents the plant uptake of N mineralised from the buried residue material, allowing incubation under a test crop rather than requiring a bare fallow soil where different temperature conditions may result in different N mineralisation rates (Carsky *et al.*, 1990). It also has the great advantage of providing a relatively straightforward method for measuring net N mineralisation over time under actual field conditions. However, polythene bags may reduce N accumulation due to inadequate O_2 diffusion which is exacerbated under moist soil conditions since moisture films are relatively impermeable to gases (Bremner & Douglas, 1971; Carsky *et al.*, 1990), while the alternative of using mesh bags mean a proportion of the material may be lost through the gaps in the mesh. If soil is not added to the bags then this also overlooks the important influence of the degree of intimate association of the residues with the soil, which limits the relative accessibility of the fresh organic substrate to microorganisms and hence will influence the rate of residue decomposition.

Conclusion: Straightforward technique, but some limitations associated with use of mesh or polythene bags.

2.1.2 Isotopic Labelling

Isotopic labelling of ^{15}N has proved a useful, if relatively expensive, technique with which to monitor the mineralisation and fate of the N taken up by cover crops during the winter months. One approach, the “isotope dilution” method (Nishio *et al.*, 1985; Barraclough & Puri, 1995), involves quantifying the dilution of a labelled ammonium solution injected into the soil as the proportion of labelled N present in the soil mineral nitrogen pool decreases over time due to the mineralisation of unlabelled organic matter, including residue material. $^{15}\text{N}/^{14}\text{N}$ isotope ratios are then determined by mass spectrometry. However, this method assumes that the basal N mineralisation 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 mineralisation resulting from residue decomposition will be underestimated as the basal mineralisation rate will have dropped (Watkins & Barraclough, 1996).

The pool dilution method can also work in reverse, using ^{15}N enriched cover crop material incorporated into soil and injections with unlabelled NH_4 , with any involvement of the residues in mineralisation resulting in a change in the ^{15}N abundance of the NH_4 pool. This technique allows field or laboratory measurement of *gross* rather than *net* mineralisation, and

presents the opportunity to study gross N mineralisation dynamics unconfounded by the processes such as nitrification and plant uptake which can consume NH_4 . However, this means that immobilisation of N, and hence net N mineralisation, is not determined, and yet it is this net result which will ultimately determine the soil nitrogen supply to any succeeding crop. The relatively narrow C/N ratios commonly found in immature cover crop material may, however, render this a less significant disadvantage in the context of cover crop experiments.

An alternative approach is to label (enrich) either a crop residue or fertiliser addition 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 over time. This can be achieved by measuring test crop recovery of labelled N, together with using either lysimeters or porous pots (Section 2.5) to quantify solute fluxes. However gaseous losses via denitrification and volatilisation may account for a significant component of the labelled N applied (e.g. 10-20%; Dowdell & Webster, 1984), and as these fluxes are often not measured, this often results in incomplete recovery of ^{15}N in measured soil and plant components.

Conclusion: Expensive; useful for process studies; requires careful interpretation.

2.1.3 *In Situ* Core Incubation

A recent development has been the use of soil cores incubated *in situ* under field conditions to determine net N mineralisation. This technique was originally developed by IGER to measure net N mineralisation of naive soil organic matter (SOM) in grasslands (Hatch *et al.*, 1990, 1991) but has recently been adapted for use in arable soils (Bhogal & Shepherd, 1996). Six replicate pairs of soil cores *ca.* 35 mm diameter are taken from the plough layer using a standard auger. One core from each pair is bulked with the other replicates and extracted immediately using the standard procedure with 2M KCl (MAFF, 1986). The other core from each pair is sealed in a Kilner jar with the other replicates, with 2% acetylene injected into the jars to prevent nitrification and hence inhibit N loss via denitrification. Kilner jars are incubated in a covered trench at the edge of the field so that their temperature approximates that of the undisturbed soil. The incubated cores are finally extracted after 7 days, with the net N mineralisation/immobilisation calculated from the change in mineral N over the one week period.

Although cores may disintegrate during sampling, for light-textured arable soils, recent test results indicate that there is no significant benefit of retaining cores intact by using sleeves (A.Bhogal, personal communication). The method measures absolute changes in soil mineral nitrogen (SMN) over time, so is less prone to the limitations associated with the more usual “snapshot” approach to measuring SMN, and also has the advantage of representing actual temperature conditions in the field. However, there is the disadvantage that soil cores are contained within airtight jars and thus are not subject to precipitation inputs or evaporative losses. The time over which net mineralisation may be measured is also limited to around seven days, as longer periods could result in misleading results as microbial activity becomes progressively restricted by oxygen supply in the sealed Kilner jars.

Conclusion: A new technique, not yet fully tested on arable soils or in residue experiments, but appears a promising method for quantifying N mineralisation under field conditions.

2.2 Indirect Methods

Indirect methods have been widely used to monitor residue decomposition and the release of organically-bound N, and include measuring soil microbial biomass C and N, measuring the change in SMN over time in sequential soil samples, laboratory incubations of soil/residue mixtures, and the determination of CO₂ efflux as a measure of microbial respiratory activity.

2.2.1 Soil Microbial Biomass

The soil microbial biomass is a key feature of nutrient cycling in soil systems and represents an important reservoir for potentially available plant nutrients. Saffigna *et al.* (1989) emphasised 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 µm³ (Jenkinson & Ladd, 1981), as a sensitive indicator of changes in soil organic matter following contrasting management practices. Direct measurement of microbial biomass involving counting numbers and sizes of organisms are exceptionally tedious and open to some contention as they require 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 CHCl₃ and comparing the SMN in the fumigated soil with that in an unfumigated control. The flush in SMN typically observed following fumigation is due to the decomposition of the cells killed by the fumigant by the recolonising microbial population. Assuming that 68% of the N in the original microbial biomass is mineralised (Shen *et al.*, 1984), then the difference in N mineralised in 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 CHCl₃ fumigation (Jenkinson & Powlson, 1976). A similar method can be used as a measure of microbial biomass C from CO₂ release following fumigation and inoculation (Jenkinson & Powlson, 1976). However, these methods have sometimes failed to identify changes in microbial biomass C or N concentrations in spite of contrasting management regimes (*e.g.* Ritz & Robinson, 1988) and the techniques at best provide only a crude assessment of biomass C and N, and hence some qualitative assessment of microbial decomposition processes.

Conclusion: Crude, limited applicability for residue management studies, difficult to interpret.

2.2.2 Microbial Respiration

Soil respiration is the sum of all respiratory activity within the biologically active soil layers, with the primary sources of CO₂ evolution being microbial and root respiration. As the mineralisation of organic materials is a microbially-mediated process, measuring CO₂ 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 CO₂ 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 CO₂ absorbed is then determined by titrating the resulting solution against a dilute acid, usually HCl. However, such chemical absorption techniques can underestimate the gas efflux and are only capable of providing a single integrated measurement. 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 which may mean that

results bear little relationship to respiratory processes occurring under undisturbed field conditions.

A variety of closed or open chamber methods are available for use in the field, and a comprehensive review of measurement techniques has been presented by King (1997). The most widely used method of measuring CO₂ concentrations is using infra red gas analysis (IRGA) (e.g. King & Harrison, 1995). Each gas possesses a unique absorption spectrum which distinguishes it from other gases, with the amount of energy absorbed at its peak wavelength being directly proportional to the gas concentration. IRGA measures the attenuation of infrared radiation at a specific wavelength passing through a defined volume of air to quantify the concentration of gas that absorbs at that wavelength: for CO₂ this is 4.26 µm (Woodward & Sheehy, 1983). However, although CO₂ efflux provides a means of characterising microbial activity in the soil which may be influenced by cultivation practices, measurements of CO₂ evolution may be somewhat confounded by the release of CO₂ from the roots of test crops growing in the same sampled soil volume, and such determinations do not actually quantify net N mineralisation of the incorporated residue material which must be inferred from the change in the temporal and spatial dynamics of microbial activity.

Conclusion: Useful, particularly if measurements are field-based & automated, but requires care in interpretation.

2.2.3 Soil Mineral Nitrogen

Another indirect method uses an N balance approach, monitoring the change in soil mineral nitrogen, which is the total of NH₄-N and NO₃-N components, and the change in plant N uptake of a succeeding crop over time after cover crop destruction. Such measurements at best represent snapshots of SMN at different points in time, which will be strongly influenced by previous temperature and rainfall conditions. This method is very widely used and assumes that other plausible pathways for N loss, such as denitrification and volatilisation, are negligible during the monitored period, so that all the N released from the residue mineralisation will be reflected in the change in soil nitrogen supply (SNS=SMN+plant N). However, contemporary research by Barraclough (1997) tested the implicit hypothesis that assumes all of the N in organic substrates is mineralised to NH₄ before assimilation by growing microorganisms, and found that N mineralisation during the decomposition of low molecular weight substrates such as amino acids can occur by a direct route in which the substrate is assimilated into the cell, deaminated, and only the surplus released into the soil NH₄ pool: such a route would mean that only measuring temporal changes in soil NH₄ concentration could underestimate the actual mineralisation occurring in the soil.

Under rainfed conditions, this method may additionally require the estimation of nitrate leaching losses using porous pots (also called suction cups or solution samplers) buried in the field. Such porous ceramic or PTFE samplers have been found to provide a reasonable measure of *in situ* soil solution concentrations over a limited range of pore sizes (e.g. Nagpal, 1982; Webster *et al.*, 1993) and are best-suited to coarse-textured soils, although their use poses certain (as yet unresolved) problems as it is unclear how measured soil water concentrations relate to the actual solute flux: their validity for use in field situations is beyond the scope of this review, but has been discussed in detail by Lord & Shepherd (1993), Webster *et al.* (1993) and more recently by Silgram (1997).

Conclusion: Straightforward method giving snapshot of soil N status; spatial variability may necessitate considerable replication; requires other input/output fluxes to be quantified.

2.2.4 Control Plots

Field-based methods of indirectly determining N mineralisation invariably compare the measurements from residue-amended plots with an unfertilised (nil cover crop) control treatment which may be bare fallow (e.g. Bowen *et al*, 1988; Carsky *et al.*, 1990) or have the same test crop as the residue-amended plots. The effect of cover crop incorporation on a succeeding crop is usually determined from comparisons of the accumulation of mineral N, together with yield and grain %N at test crop harvest from residue-amended and control treatment plots. The potential difficulties here are (a) using a bare fallow control may modify temperature and/or soil moisture conditions within the control plot, rendering them different from treatment plots, while the lack of a test crop may modify nitrate leaching losses and influence mineralisation rates as there will be no crop N uptake “sink” for SMN and no rhizosphere interactions associated with the release of root exudates; (b) the approach using an unfertilised test crop in a control plot assumes that the test crop root density distribution is the same in amended and unamended plots and thus the only difference is the presence or absence of crop residues. In practice, the presence or absence of a N-rich source may modify rooting patterns of a growing test crop as it actively searches for nitrogen: typically the most important nutrient in arable agriculture.

Conclusion: Necessary in all controlled experiments, but may require more than one type of control.

3. LITERATURE DATABASE

Mineralisation can be considered in terms of the interaction of residue composition with environmental factors. Residue composition is a function of species, dry matter (DM) and N concentrations, which in turn are a function of sowing date, destruction date and growing (seedbed) conditions: soil N availability, temperature and moisture supply. Residue composition is an all-encompassing term, and it is probable that in choosing a single parameter to represent this (e.g. C:N ratio), other aspects are ignored. Thus, for example, the C:N ratio of above-ground material may be identical for leguminous and non-leguminous species, but mineralisation of their incorporated residues may differ markedly. Subsequent sections discuss the influence of species, the chemical composition of residues, and environmental and management effects on cover crops and the mineralisation of their residues. The variables influencing N uptake by cover crops are considered first, as they will govern the potential value of the residues as N sources to succeeding crops, and this is followed by a discussion of the factors governing the mineralisation of cover crop residues.

3.1 Factors Affecting Choice of Species

Cover crops and green manures differ from arable crop residues such as straw incorporated at harvest, as cover crops are usually grown in the autumn when soils would otherwise be bare and are incorporated as young and immature materials before the sowing of a new crop in the spring (Shepherd *et al.*, 1996). Cover crops used in UK agriculture are often a combination of weeds and seed shed at harvest (volunteers), together with some added seed to provide adequate ground cover (Lord, 1995). Many different species are grown as cover crops, including cereals, legumes and brassicae, although some (e.g. phacelia, mustard) are susceptible to frost and so will return defoliated residues to the soil earlier, while other crops may be grazed over-winter, returning N as faeces and urine.

The selection of cover crop species is generally dependent on ease of establishment, relative growth rate, winter hardiness, ease of destruction and cheapness and availability of seed (Christian *et al.*, 1996). Winter barley (*Hordeum vulgare*) grows rapidly in the autumn but may suffer more winter die-back than winter wheat (*Triticum aestivum*). Rye (*Secale cereale*) and ryegrass (*Lolium perenne*) grow slowly in autumn but increase dry matter faster than barley or wheat at low temperatures during the winter: rye is hardy and tolerant of less fertile soils. Phacelia (*Phacelia tanacetifolia*) is an annual herb which has been used as a green manure after barley for many years in Germany (Christian *et al.*, 1996). Forage rape (*Brassica napus*) and white mustard (*Sinapsis alba*) grow well in early autumn: forage rape is grown after cereals to feed stock in winter, while white mustard only survives mild winters and is a traditional green manure crop before winter wheat. White mustard has been found to take up more mineral N than rye, wheat, barley, ryegrass or phacelia in a number of recent cover crop trials (Froment & Cook, 1995; Christian *et al.*, 1996). The most popular species commonly sown in Nitrate Sensitive Areas (NSAs) include winter barley, forage rape and stubble turnips (Froment & Cook, 1995). The selection of species is influenced by soil type, with cover crops such as phacelia and white mustard popular on loamy peat soils as they form a large tap root which breaks down the soil and produces a finer seedbed for the subsequent crop (Cook & Froment, 1996).

3.2 Factors Affecting Cover Crop N Uptake

3.2.1 Effect of Species on Cover Crop N Uptake

The N uptake of cover crop species over-winter is of pivotal importance as it governs their efficiency in reducing nitrate leaching and their potential contribution as a N source to a

subsequent spring-sown crop. Evidence from a number of ADAS studies suggest that the magnitude of N recovered by cover crops over the winter period may be influenced by cover crop species (Table 1; Froment & Cook, 1995; Christian *et al.*, 1996) which could be due to factors such as the higher N content in brassicas compared with cereals. However, this contrasts with other research by Allison *et al.* (1996) in 18 experiments from 1989 to 1994 on sandy loam soils overlying chalk or limestone which found no significant difference in dry matter accumulation in cereal (barley, rye) compared with non-cereal (phacelia, mustard, oil radish, fodder radish, buckwheat) cover crops. The nutrient accumulation performance of cover crop species is essentially influenced by the characteristic vigour and intensity of root spreading in the soil profile, with Rogasik *et al.* (1996) reporting markedly higher root and shoot growth in juvenile oil radish compared with mustard and Phacelia.

Table 1. N uptake (kgN/ha) of different cover crop species in 1991 and 1993 (Froment & Cook, 1995)

Cover Crop Species	Year	
	1991 (Dry Autumn)	1993 (Wet Autumn)
Volunteer Wheat	15	45
Forage Rape	-	48
Winter Barley	20	51
Winter Rye	22	55
Phacelia	25	39
Oilseed Rape	15	-
White Mustard	30	57
Stubble Turnips	-	63

The yield and N uptake of cover crops can range from 10-150 kgN/ha (Jensen, 1991; Sorensen, 1992; Christian *et al.*, 1992). The ranking of the N uptake capacity of cover crops in the order brassicaceae > graminaceae > leguminosae has been proposed by Kunkel (1989) based on the results of extensive field studies in Germany, and this species difference will convey considerable importance in governing the magnitude of the potential store of N over-winter for supply to subsequent crops. In a recent study, Macdonald *et al.* (1996b) reported that forage rape proved the most effective species for reducing nitrate leaching losses to 17 kgN/ha compared with rye (23 kgN/ha), volunteers/weeds (26 kgN/ha), winter barley (33 kgN/ha) or fallow (34 kgN/ha).

3.2.2 Effect of Husbandry & Site on Cover Crop N Uptake

Recent UK research suggests the most important determinants governing cover crop establishment and N uptake appear to be drilling date and prevailing weather conditions during the growing period as drilling after mid-September can significantly reduce cover crop N recovery (Froment & Cook, 1995; Macdonald *et al.*, 1996b), while N uptake by cover crops appears strongly related to accumulated temperature (day degrees >0°C) and prevailing moisture conditions, and to a lesser extent to the N status of the soil (Harrison *et al.*, 1996b; Harrison & Peel, 1996; van Dijk *et al.*, 1996).

There is some evidence that previous cropping history can have a bearing on the value of cover crops as sinks for soil mineral N. Cover cropping may be particularly important after root crops to which organic manures have been applied (Smukalski *et al.*, 1992) due to the more labile nature of the organic N applied. Recent research by Shepherd & May (1992) on a loamy sand indicates that the management of the previous harvest residues and the method of establishing a cover crop can be of considerable importance in determining its N uptake at the time of incorporation, and hence its agronomic value to any succeeding spring-sown crop. In

a comparison of plough/press/drill, disc/drill/roll, broadcast/disc/roll and direct drilling for cover crops, these authors found that chopping and incorporating the straw from the previous harvest prior to cover crop establishment in early September consistently reduced N uptake of a winter barley cover crop by 2-7 kgN/ha for all establishment methods, presumably due to the immobilisation of N caused by the incorporation of such carbonaceous substrates. Establishing the cover crop by ploughing improved crop cover throughout the winter months and increased N uptake in March to 25 kgN/ha compared to 10-12 kgN/ha using all the other cultivation techniques studied, probably due to ploughing producing better seed/soil contact (Shepherd & May, 1992) and/or the physical disturbance caused by ploughing stimulating additional mineralisation.

There is a more substantial body of evidence suggesting that cover crop development may be influenced by soil type: lighter, shallower soils may lead to more limited growth and N uptake unless measures are taken, such as using rolls, to conserve soil moisture and consolidate the seedbed (Cook & Froment, 1996). Harrison & Peel (1996) reported variable effects of cover crops on subsequent test crop yields based on four cover crop trials involving seven sites with a wide range of soil types including peat, clay, loamy sand, silty clay loam and calcareous clay loam overlying chalk: this series of experiments investigated the effect of cover crop species and sowing/destruction dates on cover crop N uptake, and the subsequent N mineralisation and yield and N uptake of spring-sown test crops. Analysis of the data for 1991/2 and 1992/3 from the main experiment, which used a randomised block design with two replicates at each of the seven sites, revealed differences in cover crop N uptake due to cover crop species, site, year and site-year interactions.

Harrison & Peel (1996) established linear relationships between cover crop N uptake and accumulated day degrees $>0^{\circ}\text{C}$, and attributed differences in the gradient term for this relationship to contrasting soil N status and available soil moisture at their seven field sites, both of which are strongly dependent on soil type. The relationships between cover crop N uptake and above-ground dry matter (AGDM) were generally linear (gradient term 0.039-0.053 kgN/kgAGDM), but was sometimes best described by a two-line “broken stick” model with a reduced gradient term (0.014-0.035 kgN/kgAGDM) beyond a threshold value (*ca.* 500 kgAGDM/ha) which was strongly influenced by site and year. There appeared to be a significant effect of soil type, with the sites on the two lighter-textured, and hence least N retentive, soils having the shallowest slope gradients.

As a whole, research results indicate that soil type can have a measurable influence on the value of cover crops as N sinks, and support the suggestion from other researchers that cover crops should be managed to maintain a relatively narrow C/N ratio. This requires that destruction should be geared to accumulated dry matter (DM) rather than a calendar date, with biomass not exceeding *ca.* 1-2 tDM/ha (Allison & Armstrong, 1992; Cook & Froment, 1996; Harrison & Peel, 1996): this limit should ensure that N available for leaching has been substantially reduced whilst preventing water use by the cover crop from becoming excessive so that N supply to the subsequent crop is not impaired (Muller *et al.*, 1989; Rogasik *et al.*, 1992; Allison & Armstrong, 1992). Regressions against thermal time from 18 experiments in Suffolk, Lincolnshire and Yorkshire from 1989 to 1994 indicate that this upper limit of 2 tDM/ha can be achieved in about 1000 degree days (Allison *et al.*, 1996). However, any effect of soil type which will control time of ploughing (especially on heavier soils), and therefore cover crop destruction, may be relatively unimportant in contrast to prevailing weather conditions which will govern the extent of cover crop growth and N uptake, in addition to influencing destruction - as prolonged periods of frost will kill all but the hardiest cover crops (Allison *et al.*, 1996) and regulate microbial activity controlling the dynamics of residue decomposition and N supply to succeeding crops.

3.3 Effect of Cover Crop Species on Residue Composition & Mineralisation

If crops are allowed to reach maturity, their residues typically possess a relatively high C/N ratio (e.g. 70-100 for cereal straw) and this may promote rapid immobilisation of soil mineral N as microbial populations are unable to satisfy their N demand from such carbonaceous substrates. 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 CO₂ evolution so that the C/N ratio of the residue narrows as decomposition proceeds, eventually resulting in a net release of N via mineralisation. In contrast, as cover crops are usually destroyed in the spring before the plant reaches maturity, net mineralisation of cover crop residues is usually more rapid as N contents typically lie at or above the critical level of 1.4-1.8 %N and C/N ratios are generally <25-30 which is generally considered to be the limit for net mineralisation to occur (Haynes, 1986). For example, Wagger *et al.* (1985) noted the impact of C/N ratio on the release of residue N: when C/N ratios increased from 27 to 38, these authors reported that net N mineralisation of the applied residue N decreased from 33 to 12% in the first year following incorporation.

C/N ratios are dependent on plant age and grow wider as the crop matures (e.g. Harrison & Peel, 1996): hence cover crop C/N ratios tend to be strongly influenced by sowing date and prevailing weather conditions as well as crop species, all of which can influence the relative degradability of the resulting residues and thus the temporal dynamics of their contribution to the N supply of succeeding spring-sown crops. Vandendriessche *et al.* (1996) concluded that cover crops could be categorised into three groups depending on their impact on soil N supply: (i) winter-hardy plants, such as ryegrass and winter barley, which they found to contribute negligible amounts of N to the following sugar beet crop; (ii) plants with a well-developed aerial component such as phacelia and mustard, which demonstrated significant amounts of net N mineralisation, with crop and weather factors determining whether this contributed to greater N availability to the test crop; (iii) legumes such as vetch, which had amongst the highest N uptake and released their N over a longer timecourse compared with phacelia and mustard. This section discusses research focusing on the influence of non-leguminous and leguminous cover crop species on residue composition at destruction, the subsequent mineralisation of the residue material, and the effect on test crop yield. Differences between legume and non-legume cover crops are highlighted because lignin linkages in plants differ between legumes and non-legumes, with those in non-legumes generally resulting in a greater proportion of the dry matter being resistant to decomposition (Van Soest, 1964).

3.3.1 Effect of Species on Residue Composition & Mineralisation: Non-legumes

Research by Kuo *et al.* (1997) found that repeated cover cropping with rye or annual ryegrass from 1987 to 1992 increased soil organic C by up to 1.0 g/kg in the surface soil compared to a control with shepherd's purse, indicating a rapid degradation of cover crop residues after incorporation into the soil. In their work, soil carbohydrate concentrations averaged between May 1992 to April 1994 were significantly affected (P=0.05) by cover crop species (rye, ryegrass, vetch and canola) at both 0-15 cm and 15-30 cm depths. Other results from an ADAS study indicate that, at the majority of seven sites studied, the different cover crop species in Table 1 had no effect on the growth, development and yield of spring-sown test crops, even when using low fertiliser N rates to maximise the yield benefits associated with any increased soil nitrogen supply derived from the decomposing residues (Froment & Cook, 1995). However, this contrasts with some other research both in the UK and overseas

(discussed later), which have sometimes identified yield reductions of subsequent test crops (e.g. Macdonald *et al.*, 1996a; Davies *et al.*, 1996; Garwood *et al.*, 1998), although this is more likely with species such as rye if allowed to continue to grow and become stemmy (Froment & Cook, 1995).

In a recent ^{15}N experiment on a silty clay loam at Rothamsted, Macdonald *et al.* (1996b) used a randomised block design and a spring barley test crop to measure the mineralisation of labelled cover crops of forage rape (*Brassica napus*), rye (*Secale cereale*), or a mixture of volunteer cereals and weeds, which were contrasted with a winter barley crop left to maturity and a bare fallow control. N uptake by the cover crops was 22-32 kgN/ha in spring for all species but resulted in winter barley containing twice as much (6 kgN/ha) labelled N than the forage rape and volunteers/weeds, probably due to the deeper rooting of the earlier sown crops enabling greater utilisation of mineral N from the subsoil compared with the later sown winter barley. After cover crop destruction, the subsequent decomposition of the residues will be governed by microbial activity which, in turn, will be controlled by substrate availability, temperature and soil water potential (Stott *et al.*, 1986).

Following a moist winter with 268 mm drainage, Macdonald *et al.* (1996b) found recoveries of ^{15}N at test crop harvest were 3-7% of that applied as labelled KNO_3 the previous autumn, with a further 55% accounted for in the soil to a depth of 1m. In terms of the labelled N in cover crops at the time of spring incorporation, 12% and 9% of forage rape and rye respectively were taken up by the spring barley test crop at harvest. The corresponding recoveries for the previous, much drier year with only 39 mm of over-winter drainage were 22% and 12% respectively, and this consistently larger recovery after forage rape in both drier and wetter years indicates that the net mineralisation of the N in forage rape cover crops was more closely synchronised with the N demands of the spring test crop than was the case with rye. Possible reasons for this difference between species are discussed in the following section.

Macdonald *et al.* (1996a) investigated this effect of species on residue mineralisation by analysing for differences in the chemical composition of cover crop material (Table 2). They found larger carbohydrate and smaller C/N ratio in the forage rape material, which provides a plausible explanation for the more rapid N mineralisation of the forage rape residues compared to those of rye, as the chemical composition of residue material is often a good guide to its relative decomposability and hence its value in supplying N to a succeeding crop (e.g. Rahn *et al.*, 1992; Quemada & Cabrera, 1995a,b). A number of laboratory studies have indicated that temperature and moisture are most important in the early stages of decomposition when soluble C and N compounds are readily available, but C and N availability become major limiting factors during later stages (Roper, 1985; Knapp *et al.*, 1983; Schomberg *et al.*, 1994). This is consistent with the results of a companion laboratory-based study using an ^{15}N pool dilution technique and packed soil cores incubated with or without cover crop amendments (Macdonald *et al.*, 1996c). In this work, the same cover crops as in Table 2 were harvested (including roots), dried, coarsely milled and mixed with moist, sieved sandy loam topsoil to give a equivalent incorporation rate of 3t/ha of dry matter. This laboratory experiment found gross N mineralisation in amended soils was 0.5-7.0 times more than in control soils, with gross N mineralisation rates during the first 24 days of the incubation (10°C , 80% relative humidity) following residue incorporation of $0.4\text{-}1.2 \mu\text{gN g}^{-1}$ oven dry soil d^{-1} for forage rape which was always significantly greater than the $0.3\text{-}0.8 \mu\text{gN g}^{-1}$ oven dry soil d^{-1} measured for rye.

Table 2. Chemical characterisation of cover crop residues at incorporation (Macdonald *et al.*, 1996a).

Chemical Composition (% dry weight)	Forage Rape	Rye
Water-soluble carbohydrate	29.2	24.7
Phenolics	0.89	0.63
Cellulose	11.9	14.4
Hemicellulose	4.5	9.8
C	42.5	35.5
N	3.0	2.2
C/N ratio	14	16

Macdonald *et al.* (1996c) also found CO₂ fluxes for forage rape and rye peaked 3 days after incorporation at 18 and 10 µgC g⁻¹ oven dry soil d⁻¹ respectively, declining to 3 and 4 µgC g⁻¹ oven dry soil d⁻¹ after 50 days and remaining consistently greater than the 2 µgC g⁻¹ oven dry soil d⁻¹ evolved by the control soil. These results indicate that both rates of C mineralisation and gross N mineralisation were increased by the incorporation of forage rape and rye, but that the two species decomposed at contrasting rates: with forage rape, C and N mineralisation were greater but lasted a shorter time than rye, whereas for rye mineralisation rates were smaller but more persistent. Macdonald *et al.* (1993c) attributed this difference in mineralisation dynamics to the forage rape containing a higher soluble carbohydrate content (29.2%) compared to the rye (24.7%), and the lower C/N ratio of the forage rape cover crop (Table 2).

However, in contrast to the results of Froment & Cook (1995) and Harrison *et al.* (1996a), both the 1992 and 1993 grain yields reported by Macdonald *et al.* (1996b) were 3-4 t/ha for the spring test crop, although this was 1 t/ha less than yields after an over-winter bare fallow control. This may reflect the smaller amount of inorganic N (40 kgN/ha) present in the 0-50 cm soil depth under the cover crops in spring compared with that under bare fallow (57 kgN/ha), and indicates that in this case there was a significant overall negative effect of the cover crops on the subsequent spring-sown barley test crop. Such evidence suggests that although cover crops can undoubtedly reduce over-winter nitrate leaching losses, the species of cover crop selected and its C/N ratio at destruction can have a detectable influence on the ultimate recovery of its additional N by a succeeding spring-sown crop, although under some circumstances any such beneficial effect may be negated by the significant yield penalty which may be associated with using a cover crop as an integral part of an arable cropping rotation. In contrast, a winter barley crop grown to maturity in the same study proved more effective at decreasing over-winter leaching losses than cover crops, and did not suffer from any such yield penalty (Macdonald *et al.*, 1996a). This difference may be a reflection of differing rooting depths: a late-sown, shallow rooted winter barley may take up more N from the near-surface zone in the autumn compared with an earlier sown, deeper rooting cover crop, and conversely in the spring a well-established winter barley crop will have access to N in deeper subsoil layers compared with a shallower rooting spring barley crop.

Platte & Przemec (1996) reported results from a pot trial monitoring the fate of ¹⁵N labelled roots and shoots of young *Lolium perenne* and a *Trifolium pratense/Lolium perenne* combination when incorporated into an alluvial soil/sand mixture with wheat grown as a test crop. Detailed analyses for SMN, total N, microbial biomass N (N_{mic}) and C and plant N uptake provided a comprehensive picture of the dynamics of N decomposition and the fate of the labelled plant N. In terms of the fate of the incorporated residue N, Platte & Przemec (1996) found a small proportion of ca. 10% of labelled plant N in the microbial biomass, with SMN levels substantially increased for seven months following incorporation. Compared

with control (unamended) pots, adding the fresh organic material enhanced total N_{mic} turnover by 9-14% with soil-derived (*i.e.* unlabelled) mineral N two or three times higher in pots containing the fresh green manure. These data indicate that by providing a fresh (labelled) organic substrate for the soil microbial biomass, incorporating the fresh plant material also stimulated the mineralisation of indigenous soil organic N, although it was unclear whether this increase in microbial activity (or “priming” effect) was due to the added substrate or due to the physical disturbance caused by the incorporation process *per se*.

At test crop harvest, Platte & Przemec (1996) found as much as 50% of the labelled N in the shoots of the wheat test crop, with no effect of the two different plant materials: the remaining labelled plant material was bound in microbial biomass, in humus or adsorbed by clay. Other researchers (*e.g.* Landman, 1990) have also reported rapid mineralisation of cover crop residues: using ^{14}C and ^{15}N labelling, Amato & Ladd (1980) estimated 33% of the N in *Medicago littoralis* leaves with a C/N ratio of 8.7 were mineralised within 34 days after incorporation in a calcareous soil, whereas Schrage (1990) concluded that *ca.*70% of the N contained in plant material incorporated in spring had been mineralised by the end of July, demonstrating that under some circumstances cover crops have the potential to enhance N supply in cropping systems. However, the relatively rapid mineralisation of residues reported by these researchers and the high recovery of N by the test crop in the study by Platte & Przemec (1996) discussed above contrast with the 5-30% of cereal cover crop residues mineralised during the growing season of the succeeding crop under UK conditions based on the results of other research (*e.g.* Macdonald *et al.*, 1996b,c; Harrison *et al.*, 1996a). It is possible that the much higher N recovery reported by Platte & Przemec (1996) may have been a product of the small scale pot trial undertaken, with more thorough mixing of residue with soil leading to a more intimate association of residue and soil than is possible when cover crops are incorporated using machinery in field situations, and this could have enhanced mineralisation of the incorporated material. However, the lack of a significant effect of cover crop species on N mineralisation in the work of Platte & Przemec (1996) should be considered in the context of other research which has found that species effects are often less important than residue quality in determining the time-course of mineralisation (*e.g.* Nicolardot *et al.*, 1995), with species effects on N mineralisation often minimal after the first week of incubation (Kuo *et al.*, 1996).

3.3.2 Effect of Species on Residue Mineralisation: Legumes

Carsky *et al.* (1990) grew seven legumes and maize from December 1986 to April 1987 in a Brazilian Oxisol and reported C/N ratios at incorporation of 15.0-19.9 for the legumes and 24.1 for maize. When leguminous species are used, the biologically fixed N released during residue decomposition may reduce fertiliser N requirements for a succeeding crop (Power, 1990). Crops were rotovated to 20cm depth, and a test crop of maize planted two weeks after cover crop incorporation, leaving bare plots as a control. The release of N through net mineralisation was calculated over a full year (including a second maize test crop) as the accumulation of SMN in buried polythene bags containing soil (and residue) sampled following cover crop incorporation. There were strong relationships ($r^2=0.90, 0.92$) between N content of the above-ground maize test crop and the N availability estimated by the change in SMN using the “fallow soil” and “buried bag” methods (where the “fallow soil” estimate was the sum of profile SMN at planting and the accumulation of N in bare fallow plots until harvest): this suggests such methods are a satisfactory means of determining N release from buried crop residues (Section 2). At harvest, 69% of the N estimated to be available using these techniques was found in the above-ground maize test crop. However, the fallow soil method slightly over-estimated the N available to the test crop as more N was mineralised in the bare fallow than in the cropped soil: this may have been due to more optimal moisture

conditions in the fallow soil resulting from less evapotranspiration compared with the cropped soil, or may be due to higher soil temperatures under fallow than those in the cropped soil (Carsky *et al.*, 1990).

In an allied experiment at the same site, Bowen *et al.* (1993) reported results of N release from the same legume cover crops when incorporated into uncropped soil. Inorganic N in the soil was consistently higher in cover crop amended compared with bare plots throughout the 150 day monitoring period. Comparing SMN results in 1986 for uncropped soil (0-1.2 m) 150 days after incorporating no cover crop residue or *Mucuna aterrima* (131 kgN/ha, C/N 18), SMN levels were 75 kgN/ha and 175 kgN/ha respectively. Similarly, SMN results for 1984/5 in uncropped soil after incorporating no residue or *Calopogonium* (142 kgN/ha, C/N 19) were 80 kgN/ha and 185 kgN/ha respectively after 150 days. Overall, although different legumes took up varying amounts of N prior to incorporation, there appeared to be no significant differences in the mineralisation dynamics of different legume species, although differences in SMN were influenced by cover crop C/N ratio at incorporation. For all seven legume species studied, regression of cover crop organic N incorporated against cumulative inorganic N released ($r^2=0.86$, $n=16$; $P=0.066$) revealed that 61% of cover crop N was mineralised in the first 150 days after cover crop incorporation, although this decomposition rate may have been more rapid than that typically observed in UK soils due to higher temperatures enhancing microbial activity under Brazilian conditions.

3.3.3 Effect of Residue Composition on Mineralisation: Legumes

Although Bowen *et al.* (1993) found that individual legume species did not release their N at different rates, this contrasts with research by Rannells & Wagger (1996) which compared N release following incorporation of five cover crop species or mixtures in 1993 and 1994. In their work using litter bags on the soil surface, N release rates from cover crops increased in the order rye < rye/crimson clover < rye/hairy vetch = crimson clover < hairy vetch, with N release after 8 weeks of field decomposition estimated as 24 (rye), 48 (rye/crimson clover), 60 (crimson clover), 108 (rye/hairy vetch) and 132 (hairy vetch) kgN/ha. This is consistent with Wagger (1989) who found 75-80% of hairy vetch and crimson clover residue N was released after 8 weeks decomposition, compared to only 50% N released from rye residues. Rannells & Wagger (1996) also found that N release through mineralisation was very closely related to residue C/N ratio at spring incorporation, which varied from 40 for rye, to 26 for rye/crimson clover, 18 for rye/hairy vetch, 17 for crimson clover and 11 for hairy vetch. Thus legume species had consistently narrower C/N ratios than the rye, and cumulative net N mineralisation was inversely related to residue C/N ratio. This is a pattern typical of many reports of the N mineralisation dynamics of different cover crop species following incorporation (*e.g.* Quemada & Cabrera, 1996a,b). Rannells & Wagger (1996) found differences in the proportion of residue N mineralised were still discernible after 16 weeks, with consistently more rapid N mineralised from the legumes compared with rye. Surprisingly, lignin concentrations were *lowest* for the rye monoculture and *highest* for the hairy vetch in both years, although it may be misleading to compare lignin concentrations across genera because lignin linkages in plant differ between legumes and non-legumes, with those in non-legumes generally resulting in a greater proportion of the dry matter being resistant to decomposition (Van Soest, 1964).

Except for the lignin data, these results concur with research by Wagger (1989) and Rannells & Wagger (1992) who found greater N release from cover crops with narrower C/N ratios and lower concentrations of cellulose. Wagger (1989) also found the N release from crimson clover at the full bloom stage proceeded more slowly than residue desiccated at the later vegetative stage, probably due to increased proportions of structural carbohydrates and lignin

(Ranells & Wagger, 1992). Concentrations of cellulose and lignin are greater in grasses and more mature plant material compared with legumes and young plant material (Ranells & Wagger, 1996), with legume residues from cover crops such as crimson clover and hairy vetch typically having C/N ratios of 8 to 15, which contrast with wider ratios of up to 60 reported for cereal cover crops such as wheat and rye (Clark *et al.*, 1994), and this may account for the contrasting decomposition dynamics between cover crop species reported by authors such as Ranells & Wagger (1996), Wagger (1989) and Quemada & Cabrera (1996a,b). Thus the typically narrower C/N ratio of legumes can lead to more rapid mineralisation than is commonly observed for other cover crop genera. For example, Power & Broadbent (1989) reported that 50% of legume cover crop N was mineralised during the summer growing season of the subsequent test crop, with Ranells & Wagger (1996) reporting that in several studies the actual recovery of legume cover crop N by test crops such as wheat, corn and barley ranged from 11-28%, which represented about half of the total amount of cover crop N mineralised during the period.

However, C/N ratio alone may be an inadequate measure of mineralisation potential as, for example, although Kuo *et al.* (1997) found very different C/N ratios in their ryegrass (54-61) and hairy vetch (10-29) cover crops, the half-lives for the degradation of biomass C in the two cover crops were found to be virtually the same (21-30 days). Jenkinson & Rayner (1977), Gale & Gilmour (1988) and Buchanen & King (1993) have reported similarly short half-lives for the mineralisation of clover shoots, ryegrass and alfalfa residues. In detailed field studies of the effects of chemical composition of ¹⁵N- labelled residues of white clover, red clover, subterranean clover, field bean and timothy on residue mineralisation, Muller *et al.* (1988) reported that (in order of importance) lignin, cellulose, hemicellulose and N content were the variables best explaining observed differences in residue N mineralisation. Research indicates that cellulose, lignin and C/N ratio together can frequently serve as good predictors of the relative decomposability of cover crop residue material (*e.g.* Macdonald *et al.*, 1996a,b), while other authors have found the water-soluble components in the plant material (Andren, 1987) and the polyphenol content (Fox *et al.*, 1990) can be important factors. Concentrations of cellulose and lignin are greater in grasses and more mature plant material compared with legumes and young plant material (Ranells & Wagger, 1996), which may explain why researchers have often identified rather greater mineralisation from legume cover crop residues compared to those from non-legume species (*e.g.* Wagger, 1989; Quemada & Cabrera, 1996a,b).

3.3.4 Effect of Residue Composition on Mineralisation: Different Crop Components

Using a buried bag technique in 1992 and 1993, Kuo *et al.* (1997) reported a rapid decomposition of the above-ground cover crop biomass C, with half-lives averaging 31-55 days; data for the carbohydrate component alone were similarly rapid with an average half-life of 40-51 days. However, the decomposition of cover crop material is not only dependent on the overall C/N ratio of the residue material, but may also be different for individual crop components. For example, both Thorup-Kristensen (1994) and Schröder (1996b) concluded that N from a *Lolium multiflorum* cover crop was less efficiently utilised by a subsequent crop than the N from *Secale cereale*, which was attributed to the relatively large C yields in the roots of *Lolium multiflorum* even though their shoots had similar C/N ratios of ca. 16-20. Schröder (1996a) reported that test crop recovery of N from *Trifolium pratense* (shoot C/N 15) was double that from *Lolium multiflorum* (shoot C/N 16), even though the shoot yield of the latter was twice as high: it was concluded that this may have been due to the relatively large N storage in the subterranean parts of the clover and its relatively low C/N ratio (Schröder, 1996).

Annex

Research by Quemada & Cabrera (1995a,b) studied the C and N mineralisation from the leaves and stems of wheat, rye, oat and crimson clover cover crops decomposing on the surface of 95.5 g of a loamy sand soil packed into laboratory columns. Chopped 1cm lengths of leaves only, stems only, or both leaves and stems (50% of each) were added to the soil surface at the equivalent of 3000 kgDM/ha, with the soil maintained at 55% porosity and the soil and residues incubated at 35°C and 98% relative humidity for 160 days. Soil columns were leached periodically with 160 ml 0.01M CaCl₂, with leachates analysed for total and inorganic N and total C. Cumulative CO₂, N₂O and NH₃ efflux were also determined periodically, with net N mineralisation calculated as the total of leached inorganic N and gaseous N losses.

Chemical characteristics of the different cover crop components used by Quemada & Cabrera (1995a,b) are presented in Table 3, together with cumulative net N mineralisation measured during the 160 day incubation period. Other research has found that decay rate constants are different for carbohydrate, cellulose and lignin fractions of residue material, with the relative ease of decomposability systematically decreasing in the order carbohydrate>cellulose>lignin, although the absolute values ascribed to such decay rate constants differ between researchers (*e.g.* Godwin & Jones, 1991; Vigil *et al.*, 1991; Bowen *et al.*, 1993). Thus, during decomposition there is typically a rapid loss of soluble carbohydrate material, followed by the relatively rapid disappearance of cellulose from the residue, with lignin proving the most recalcitrant substrate fraction (*e.g.* Schomberg *et al.*, 1994).

Table 3. Initial C/N ratio, carbohydrate, cellulose and lignin contents of stems, leaves and stems + leaves of four cover crops, and their cumulative net N mineralisation (After Quemada & Cabrera, 1995b).

Treatment	C/N ratio	Carbohydrate (% total C)	Cellulose + Hemicellulose (% total C)	Lignin (% total C)	Cumulative net N mineralisation kgN/ha [†]
Clover leaves	10.1	66.2	28.2	5.6	100
Clover leaves+stems	15.2	49.7	40.4	9.9	65
Clover stems	31.9	33.2	52.6	14.2	31
Rye leaves	28.9	38.6	58.8	2.6	34
Rye leaves + stems	44.7	32.6	63.0	4.4	21
Rye stems	98.9	26.9	67.0	6.3	15
Wheat leaves	13.1	39.8	56.0	4.2	70
Wheat leaves + stems	22.9	44.4	49.3	6.2	39
Wheat stems	86.5	49.0	42.7	8.3	15
Oat leaves	12.8	44.8	51.6	3.6	71
Oat leaves + stems	21.7	38.1	55.6	6.3	41
Oat stems	78.8	31.4	59.6	9.0	14

[†] measured over 160 days' incubation

Table 3 indicates that there was a significant effect of cover crop species and stem versus leaf components on residue composition and C/N ratio. Overall, cover crop C/N ratio varied with species in the order rye>wheat≥oat>clover, while on an individual species basis, cover crop stems consistently possess the highest lignin content and C/N ratio compared with cover crop leaves. On both a species and a cover crop component (leaf versus stem) basis, the more carbonaceous (*i.e.* wider C/N ratio) substrates were subject to consistently less net N mineralisation during the 160 day monitoring period. Contrasts in C/N ratio between species were closely related to differences in cumulative net mineralisation which varied from the equivalent of 39 to 65 kgN/ha. Assuming carbon represents 40% of dry matter, then

calculating from data in Table 3 reveals that 74.1-82.4% of the whole (leaves + stems) cover crop material was mineralised during the 160 day period. Such evidence supports the general assumption that C/N ratio can often serve as an acceptable (if simplistic) measure of residue “quality” and the relative decomposability of organic substrates, with cumulative net mineralisation inversely related to residue C/N ratio both for different cover crop species and for different residue components.

However, these findings indicate that N mineralisation varied substantially by 19-69 kgN/ha between individual crop components (converted from gN/m², Table 3). Furthermore, Quemada & Cabrera (1995a) found that the temporal dynamics and cumulative totals of C and N mineralisation from leaf/stem mixtures were different from those predicted from isolated leaves and isolated stem components. Results indicated a strong interaction between stems and leaves during early stages of decomposition, with residue C/N ratio or the reciprocal of residue N content (g/kg) proving the best predictors of the net N mineralisation of cover crop material at seven different times during the incubation period (Quemada & Cabrera, 1995a). Their findings also suggest that as well as representing the characteristics of different chemical constituents such as overall C/N ratio and % lignin, mechanistic models of cover crop residue decomposition may also require separate decay functions ascribed to individual cover crop components based on their contrasting C/N ratios and N mineralisation dynamics.

This interaction between leaves and stems has also been reported by other researchers: Collins *et al.* (1990) showed that when a mix of winter wheat parts (stems, leaves *etc.*) decomposed together, cumulative CO₂ evolution was significantly larger than that predicted by summing cumulative CO₂ evolution measured from individual plant components. These authors hypothesised that the decomposition of the mixture was stimulated by fungal hyphal extensions from residue components with high substrate concentration to adjacent components with lower substrate concentrations. In addition to these differences between cover crop leaf and stem components, Reeves *et al.* (1993) report that the C/N ratio of roots of Gramineae crops is usually more than 40, thus further complicating the overall picture of the mineralisation of any given cover crop material. Such results indicate that research which considers residue components (*e.g.* above-ground) in isolation may not achieve a representative measure of C and N mineralisation dynamics if the residue material had been left whole: under field conditions, incorporation of cover crop residues would typically bury the crop whole.

3.4 Environmental Effects on Cover Crop Mineralisation & Test Crop Yield

3.4.1 Soil Texture & Site Effects

In terms of the value of N to subsequent crops, research on light to medium textured soils found that cover crops had little effect on establishment and yield of sugar beet but generally depressed its N uptake (Allison & Armstrong, 1992). This was attributed to reductions in SMN due to cover crop uptake and the cover crops’ relatively high C/N ratio (*e.g.* 33 for Phacelia) which meant there was no net mineralisation of the cover crop residue during test crop growth, with cover crop N being inversely proportional to the N uptake by the sugar beet test crop. For the sugar beet test crop, the accumulated of nitrogenous impurities in the beet root was closely related to N uptake, with higher concentrations of impurities associated with low sugar percentages and reduced sugar extraction efficiencies at the processing factory. Allison & Armstrong (1992) found that cover cropping generally reduced α -amino impurities, as might be expected if N uptake is reduced. However, these results contrast with Ninane *et al.* (1996) and Muller *et al.* (1989), with the latter using ¹⁵N labelled cover crops and finding that although N uptake and sugar yield were sometimes reduced following cover

crops, they did also contribute a small amount of N to the overall N uptake by the sugar beet test crop.

The relatively small proportions (9-12%) of cover crop N which Macdonald *et al.* (1996b,c) reported as being recovered by their succeeding test crop closely resemble the findings of Harrison *et al.* (1996a) who measured yield, N uptake and the change in SMN under a test crop of spring barley after a winter barley cover crop was incorporated in the spring. Using a randomised block design and a scaling (or loading) factor to determine the proportion of test crop N originating from cover crop residues with greater confidence, these authors reported that 8% and 13% of cover crop N was recovered by the spring test crop on a silty clay loam (at Terrington) and a loamy sand (at Gleadthorpe) respectively. SMN values in the spring following harvest were increased by cover crop incorporation and indicated that 17% of the cover crop N had been transformed into mineral form one year after its incorporation.

Harrison *et al.* (1996a) also reported a significant ($P < 0.05$) positive effect of cover crop treatment on test crop grain yield, grain %N, grain N offtake and total crop N offtake on the loamy sand, but no significant treatment effect at the silty clay loam site. Cover crops increased grain yields by over 12% to 2.47 t/ha (85% dry matter) at Gleadthorpe, but they remained far below yields at the more fertile Terrington site (4.40 t/ha). The differences in response and N recovery between the two sites was thought to be most probably a reflection of the higher levels of indigenous N in the heavier textured soil, which had an SMN content of 69 kgN/ha at spring incorporation compared with only 47 kgN/ha in the loamy sand. However, the unusually warm and dry conditions may have also played a part in limiting mineralisation rates at the two sites, together with the residue characterisation which indicated a relatively high cover crop C/N ratio of *ca.* 24, close to the net mineralisation/immobilisation threshold of 25-30 (Haynes, 1986).

The different soil types may have played a significant role in influencing the decomposition of the residues in the study by Harrison *et al.* (1996a), as a number of other researchers have found the net mineralisation of soil organic matter and the decomposition of added plant material such as cover crop residues appear more rapid in sandy compared with heavier, clay-rich soils (Ladd *et al.*, 1990; Hassink *et al.*, 1990; Hassink, 1992; Verberne *et al.*, 1990; van Dam & Fu, 1996) with N mineralisation negatively correlated with clay content (Thomsen *et al.*, 1996). Indeed, sandy soils often have higher C/N ratios than loams and clay soils (*e.g.* Hassink, 1992); Chichester (1969) and Cameron & Possner (1979) reported that C/N ratios tend to decrease with decreasing particle size because organic material coated with clay particles has a better physical protection than organic material around sand particles. The lower net N mineralisation of native soil organic matter typically found in heavier clay soils is thought to be caused by this greater physical protection of soil organic matter and microbial biomass (Verberne *et al.*, 1990). The same principle applies to incorporated cover crop residues, with net N mineralisation favoured by minimising the contact between the N source and the sites where microorganisms and metabolites are physically protected against further degradation (Hassink *et al.*, 1993; Van Veen *et al.*, 1985). The effect of minimising this soil contact will partly depend on soil type, since clay and loam soils have more protective sites than sandy soils (Hassink *et al.*, 1993). Several authors have demonstrated that most of the native C and residual ^{14}C from decomposing substrates is generally associated with these clay and silt sized fractions in soil (*e.g.* Amato & Ladd, 1980; Christensen, 1992).

3.4.2 Abiotic Effects on Residue Mineralisation

Intimately associated with soil type is the effect of soil moisture and temperature which govern microbial activity, including decomposition processes, in soils. Residue mineralisation rates will therefore be influenced by the water retention and thermal conductivity characteristics of different soil types, and will vary depending on the weather conditions prevailing in any given experimental year. For example, during the moist conditions in 1993, Ranells & Wagger (1996) found only 10% of N in the hairy vetch (C/N 11) and 29% of N in the rye (C/N 40) cover crop residues remained after 8 weeks, but this difference between the two species widened to 27% in the drier summer of 1994. Quemada & Cabrera (1996) investigated the abiotic controls on the decomposition of crimson clover (*Trifolium incarnatum* L.) residues in a loamy sand soil, and found that the effect of matric potential on CO₂ evolution was enhanced as temperature increased, with net N mineralisation increasing with matric potential until it reached a maximum between -500 and -30 kPa.

Considering temperature (T) effects, Van Scholl *et al.* (1997) found that from 1-15°C, the influence of T on cover crop residue mineralisation could be adequately described by the Arrhenius equation, with a linear increase of $\ln(k)$ with T^{-1} where k is the relative mineralisation rate in day⁻¹. Measurements by Van Scholl *et al.* (1997) also indicated that cover crop mineralisation was significant even at low temperatures (1°C), which concurs with independent results reported by van Dam & Fu (1996). Vigel & Kissel (1995) studied the influence of temperature on the mineralisation of residues in soils with near-optimum soil water contents, but they found that measured Q₁₀ response functions were dependent on both the residue's C/N ratio and the incubation time, such that a single generic Q₁₀ value was inadequate for describing the effect of temperature on the mineralisation of N from cover crop material across a range of residue quality. Vigel & Kissel (1995) conclude from their work that the effect of temperature on residue mineralisation tends to be greatest early on in the decomposition process for residues with narrow C/N ratios (such as leguminous cover crop residues), whereas the opposite is true for more carbonaceous materials. This suggests that different Q₁₀ coefficients may be needed to represent the influence of temperature on mineralisation for cover crop residues with contrasting C/N ratios, and this is plausible given the differing sensitivities of components of the soil fauna and microbial biomass to fluctuations in soil temperature.

3.5 Husbandry Effects on Residue Mineralisation & Test Crop Yield

3.5.1 Undersown vs Direct Sown Cover Crops

In an experiment evaluating undersowing as a method of cover crop establishment, Wallgren & Lindén (1994) reported the results of 22 field trials in Southern Sweden from 1989-1992 which investigated the effects of cover crops on the accumulation of SMN, and the yield and N uptake of test crops. Five treatments were compared: spring barley without a cover crop and spring barley with red clover; white clover, perennial ryegrass and a red clover/perennial rye grass mixture as undersown cover crops. Plots were split and received either 0 or 80 kgN/ha in spring. For all treatments, ploughing-in of cover crops was conducted in early October, late November, or late March. Wallgren & Lindén (1994) found that cover crops reduced the grain yield of the main crop, spring barley, in the first year by 1-3%, presumably due to increased competition for water and nitrogen. From 41 kgSMN/ha to 90 cm depth at main crop harvest, SMN levels increased in bare soil and under the clover catch crops until late November, whereas SMN remained low or even decreased under ryegrass and the red clover/ryegrass mixture.

In this study, early incorporation of the cover crops by ploughing in October or November caused SMN levels to increase through the winter, especially following red and white clover cover crops, in contrast to bare plots left unploughed until spring where SMN concentrations

remained near-constant: this demonstrates that the accumulations of mineral N caused by early ploughing-in of cover crops can increase nitrate leaching risk over-winter. With respect to nitrogen, Wallgren & Lindén (1994) found the clover and red clover/ryegrass mixture increased N supply to the subsequent barley test crop by 35 and 15 kgN/ha respectively compared with the nil cover crop (bare fallow) treatment. In contrast, pure ryegrass appeared to have no significant effect on test crop N supply. The reported effects were due to the net mineralisation of the clover and clover/ryegrass mixtures during the growing season of the subsequent test crop. The clover and clover/ryegrass mixtures also increased yields of the test crop by 10-16%, with the pure ryegrass increasing test crop yields by a smaller (9%) margin.

Other research by Watson *et al.* (1992) compared perennial ryegrass, Italian ryegrass and red clover cover crops which were undersown in oats in the spring or direct sown after harvest at two sites in Scotland. Undersowing had no effect on levels on soil mineral nitrogen at 0-30cm depth in October compared with direct sown cover crops, in spite of the undersown crops having had much greater opportunity to become established: this may be the result of competition for water and nutrients with the main oat crop, in contrast with the cover sown directly post-harvest which would have had no such competition. More importantly, undersowing had no detectable effect on final test crop yield compared with direct sowing post-harvest, with the *higher* crop yield at the more fertile of the two sites also associated with the *poorer* establishment of undersown cover crops, presumably due to the greater soil fertility encouraging greater cereal crop growth and hence increased competition for nutrients with the cover crop.

In general, the relatively late harvesting of maize can provide unfavourable conditions compared to crops which allow for earlier planting of a cover crop (Elers & Hartman, 1988). Under these conditions, undersown cover crops may perform better than cover crops sown after harvesting maize, although if planted too early, undersown cover crops may compete with the main crop for water and N and reduce its yield (Schroder *et al.*, 1992). Furthermore, the greater age of undersown cover crops may often lead to wider C/N ratios at destruction compared with direct sowing, with implications for increasing the risk of restricting SMN availability due to N immobilisation and the resulting delayed release of N into mineral form.

3.5.2 Effect of Cover Crop Sowing & Destruction Dates on Mineralisation

Cover crops are typically drilled as ploughing is slow and will promote additional mineralisation of nitrogen, whereas minimal cultivations may conserve moisture and increase work rates. In practice, one of the main constraints on cover crop management is time of sowing, which is strongly influenced by the date at which the previous crop is harvested and cleared: for winter barley this may be mid-July, whereas some crops such as peas, beans and potatoes grown in beet rotations on lighter soils may delay cover crop sowing until September or October (Allison *et al.*, 1996) which will limit cover crop growth and performance as over-winter SMN “sinks” and hence restrict their value to succeeding spring-sown crops. Cover crop establishment may often be delayed if planted too early due to dry seedbed conditions, and such circumstances can mean that there may be little difference in emergence dates for cover crops drilled in late August and in mid-September.

Traditionally, land is ploughed in the autumn and allowed to weather over-winter so that minimal cultivations are required before drilling in the spring. Delayed ploughing because of a cover crop could adversely affect seedbed conditions. Certain crops, such as potatoes and peas are particularly sensitive to seedbed conditions and substantial yield losses can result if these are unfavourable (Turley *et al.*, 1992). In this context, Hayward (1992) investigated the

effects of three ploughing dates (1 December, 1 February and 1 March), two fertiliser N rates (50 and 200 kgN/ha) and bare fallow, winter wheat or winter rye cover crops on SMN and the subsequent yield of a potato crop at three sites with loamy sand, silty clay loam over chalk or deep stoneless silty clay loam soil. Cover crop N uptake at destruction varied from 8.2-23.1 kgN/ha, but did not have any significant effect on the total yield of the test crop of potatoes at two of the three sites, irrespective of incorporation date: the pattern of response at the third site was inconsistent.

This lack of an effect due to differing destruction date is consistent with research by Wagner-Riddle *et al.* (1994) who found no significant effect of early or late destruction dates of a rye cover crop on soybean yield in two successive years, but contrasts with the findings of many other researchers (*e.g.* Wallgren & Lindén, 1994; Cook & Froment, 1996; Harrison & Peel, 1996). The lack of a destruction date effect in the research by Wagner-Riddle *et al.* (1994) was attributed to timely rains replenishing the water used by the rye cover crop: they postulate that if there had been a shortage of rain, test crop yields may have been decreased under the late cover crop destruction treatment. In Hayward's (1992) research, only site and fertilisation proved significant ($P < 0.01$) influences on potato yield, the former due to the contrasting soil fertility and weather patterns at the different sites, and the latter indicating that in spite of the additional N conserved by the use of cover crops, standard fertiliser additions of 200 kgN/ha were still required to achieve the best potato yield, suggesting that the cover crop N was not being mineralised in time to contribute to test crop N demand.

However, in contrast to Hayward (1992) and Wagner-Riddle *et al.* (1994), Shepherd & May (1992) found that varying destruction dates, in this case resulting from the differing sensitivities of cover crop species to frost, can have an important bearing on the mineralisation of their residues. They found that early dieback of a frost-sensitive mustard cover crop resulted in rapid release of nitrate in the spring, with SMN in March totalling 45 kgN/ha at 0-90 cm depth compared with only 25 kgN/ha for a cover crop of phacelia, although if this frost-kill occurs too early then some of this mineralised N may be leached before it can be taken up by a subsequent spring-sown crop.

In a study described earlier, Harrison & Peel (1996) found that the effect of cover crops on the yield of potatoes or peas was small and was not significant ($P < 0.05$) for individual site-years. However, in contrast to Hayward (1992), if test crop yields were expressed as a percentage of the overall average yield for individual cover crop sowing date treatments and N rate applied to the following crop, then treatments did indicate a small but consistent trend of cover crop sowing date on subsequent test crop yields, with average yields across all site-years reduced by *ca.*2% due to earlier cover crop sowing in August compared with an increase of 1-3% for cover crops sown in October. Furthermore, the date of cover crop destruction also influenced test crop yields, with later destruction (February) suppressing test crop yields in comparison with earlier destruction (December). The evidence from these experiments indicate that greater amounts of N are taken up by early sown cover crops, but that their greater maturity may lead to wider C/N ratios at destruction and hence less rapid mineralisation of their residues.

In general, much published research suggests that early sowing of a cover crop soon after the harvest of the previous crop (*e.g.* in late August) and delayed destruction can promote yield depressions of the subsequent crops compared with later sowing and earlier destruction dates (Wallgren & Lindén, 1994; Cook & Froment, 1996; Harrison & Peel, 1996): this is probably due to their effect of widening cover crop C/N ratios at destruction (*i.e.* reducing residue "quality") and limiting the time available for the N released by cover crop mineralisation to contribute to test crop N supply. The fact that delayed destruction can detrimentally affect

subsequent crop yields is especially true for undersown cover crops which will have had greater opportunity to become established during the previous summer: delaying destruction of these cover crops until late the following spring can significantly reduce subsequent crop yields due to the wider C/N ratio in the residue leading to reduced SMN supply to the next spring-sown crop (Wallgren & Lindén, 1994).

3.5.3 Cover Crop Management

Based on results for forage rape, oil radish, phacelia and white mustard, fertilisation of cover crops at 30-50 kgN/ha has been proposed if the SMN content falls short of 40 kgN/ha, in order to establish a productive winter cover crop (Rogasik *et al.* (1992), although clearly N applications should be kept to a minimum to avoid exacerbating nitrate leaching losses. Research by Macdonald *et al.* (1996a) in a study described earlier reported that, in the presence of cover crops, a substantial proportion of the labelled KNO₃ fertiliser applied in autumn was immobilised by the soil organic matter by the following spring. This was partly a result of crop N uptake and subsequent N returns to the soil in above-ground plant material and roots, but direct immobilisation of mineral N by the soil microbial biomass, enhanced by carbon inputs from plant tops, roots and root exudates may also have played a part.

When leguminous species are used, the biologically fixed N released during residue decomposition may reduce fertiliser N requirements for a succeeding crop (Power, 1990). Fertilisation of the test crop can also influence N recovery of cover crop N: for example, Schroder *et al.* (1996) reported that only N-deficient maize test crops benefited from the additional N provided from the mineralisation of incorporated rye and grass cover crop residues. However, Harrison & Peel (1996) found that applying two different N fertiliser rates to the test crop following the incorporation of cover crop residues did not significantly influence test crop yield relative to the average yield across all site-years. When data from bare fallow plots were included in their calculation of average yields, the yield deviation across all site-years, destruction dates and two N rates was +2.6% for bare ground, -2.7% for winter rye and -1.7% for winter barley. Two allied experiments using potatoes and peas as test crops also revealed equally small and variable effects of cover crops on test crop yields when averaged over 12 site-years (Table 4).

Table 4. Average yield deviation across 12 site-years, 2 N fertilisation rates and 3 cover crop destruction dates (after Harrison & Peel, 1996).

Cover Crop Treatment	Test Crop: Potatoes	Test Crop: Peas
Bare Ground	-1.2%	+2.7%
Winter Rye	+1.0%	-1.4%
Winter Wheat	-1.3%	0.0%

The physical disturbance caused by cultivation is known to increase mineralisation as microorganisms are brought into contact with fresh, previously unavailable substrates (Haynes, 1986), and this can influence SMN levels, nitrate leaching risk and N uptake of established cover crops. For example, establishing an oil radish cover crop by conventional cultivations has been found to increase SMN levels by up to 100 kgN/ha compared with conservation tillage methods following a wheat crop in a research trial in Germany (Rogasik *et al.*, 1992). Furthermore, destruction of cover crops can delay seedbed preparation in the spring, which can deplete soil moisture reserves and adversely affect the establishment of crops such as onions and beet crops, normally sown in February or early March (Cook & Froment, 1996). An ideal tillage system would ensure the availability of the nutrients taken up by cover crops for subsequent crops and prevent early nutrient losses as a result of intensive mineralisation Rogasik *et al.*, 1992).

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 colonisation and enzymatic activity (Moore, 1974; Haynes, 1986). This is consistent with the findings of Sørensen *et al.* (1996) who reported that the grinding of subclover leaves favours, on addition to soil, a more intimate contact between the plant constituents and the soil matrix, thereby enhancing opportunities for the colonisation by decomposer organisms that are more protected against predation. Thus cover crop residue management such as rotovating and ploughing (as opposed to chemical destruction) should tend to have a beneficial influence in increasing residue N mineralisation and soil mineral nitrogen supply in the post-incorporation period, and also avoid the expense associated with herbicide use.

Killing cover crops and leaving their residues on the soil surface as a mulch can conserve soil water by reducing soil surface evaporation which could be important in drier climates, although such mulches can interfere with the seedbed conditions for the subsequent spring crop, and can harbour pathogenic organisms (Wagner-Riddle *et al.*, 1997). Research indicates that surface residues also persist longer than incorporated residues because of less intimate association with the soil body and due to greater fluctuations in water and temperature which adversely affect the microbes colonising surface residues, thereby slowing decomposition (Douglas *et al.*, 1980). This is supported by research by Schomberg *et al.* (1994) who found that decomposition rate constants were consistently up to three times greater for buried residues compared with those left on the soil surface after chemical destruction. Such results suggest that incorporation of cover crop residues will encourage more rapid decomposition and release of mineral N compared with leaving residues on the surface following chemical destruction, and incorporation is therefore more likely to lead to mineralisation of cover crop residues being synchronised with the N demands of a succeeding spring-sown crop.

4. SYNTHESIS

An understanding of N release from cover crop residues may lead to management options aimed at synchronising N availability to the N demand of a succeeding crop, and thereby foster more efficient nutrient management in arable cropping rotations (Ranells & Wagger, 1996). The effective use of cover crops in arable rotations requires that they fulfil two criteria: firstly they reduce nitrate leaching, and secondly they do not adversely affect the agronomic performance of the rotation system in either the short (*i.e.* single year) or longer term (Harrison & Peel, 1996). In summary, a balance must be sought between two opposing influences. On the one hand, the environmentally-motivated desire for a cover crop to be planted early after the previous harvest so as to allow adequate time for crop establishment to maximise the uptake of mineral N which would otherwise be vulnerable to loss via nitrate leaching or denitrification, as a key aim is to establish green cover as quickly as possible before leaching starts (Shepherd & May, 1992). On the other hand, the agronomic desire to restrict the development of the cover crop (by manipulating sowing and destruction date) so that (a) the cover crop is destroyed in good time for the establishment of a spring-sown crop and (b) the C/N ratio of the cover crop does not become too wide which might cause N immobilisation of the incorporated residue, and reduce rather than enhance the N supply to (and yield of) any succeeding spring-sown crop (*e.g.* Wallgren & Lindén, 1994; Cook & Froment, 1996).

4.1 Cover Crop Species & Composition

Understanding the influence of crop residues on decomposition and nutrient dynamics is critical for minimising environmental non-point source pollution and efficient resource management. The potential of cover crops as N sources to succeeding crops is strongly influenced by their capacity for N uptake. The ranking of the N uptake capacity of cover crops in the order brassicaceae > graminaceae > leguminosae has been proposed by Kunkel (1989) based on the results of extensive field studies in Germany. In the UK, white mustard has been found to take up more mineral N than rye, wheat, barley, ryegrass or phacelia in a number of recent cover crop trials (Froment & Cook, 1995; Christian *et al.*, 1996). The added appeal of species such as phacelia, mustard and buckwheat is that they are killed by frost and thus do not require chemical applications or cultivations to destroy them, and yet they still have the potential to store considerable quantities of nitrogen *e.g.* 25-50 kgN/ha or more (Shepherd & May, 1992; Froment & Cook, 1995) and can potentially begin releasing their N earlier in the spring. However, they carry the associated risk that they may cease to take up N well before drainage finishes, and the considerable seed costs may preclude their selection as the first choice for cover crops by farmers. In contrast, cereals are much cheaper and typically appear equally effective as candidate cover crops provided they are destroyed early in the spring before C/N ratios become too wide. Furthermore, the efficiency with which cover crops take up N and serve as potential N sources for succeeding crops will be strongly influenced by prevailing weather conditions: all cover crop species will be slow to establish in dry autumn conditions, while wet soils in the spring may make their incorporation and the sowing of the follow-on crop difficult (Catt *et al.*, 1992).

The decomposition of cover crop residues is affected by a suite of inter-related factors, including temperature, moisture, aeration, pH, available nutrients, lignin content and age and size of material, and although in individual studies it is often difficult to attribute effects to a specific factor (Thorup-Kristensen, 1994), data available in the literature does indicate that temperature, moisture, residue C/N ratio and location on or within the soil are usually the most important variables (Parr & Papendick, 1978; Reddy *et al.*, 1980). Lignin linkages in plants differ between legumes and non-legumes, with those in non-legumes generally

resulting in a greater proportion of the dry matter being resistant to decomposition (Van Soest, 1964). Legume residues from cover crops such as crimson clover and hairy vetch typically have C/N ratios of 8 to 15 or 20, which contrast with wider ratios of up to 60 reported for cereal cover crops such as wheat and rye (Clark *et al.*, 1994), and such differences may account for the contrasting decomposition dynamics reported between legume and non-legume cover crop species (*e.g.* Ranells & Wagger, 1996; Wagger, 1989; Quemada & Cabrera, 1996a,b). However, although there may be a marked difference between legume and non-legume cover crops in terms of their relative decomposability, other species effects are often less important than residue quality in determining the time-course of mineralisation (*e.g.* Nicolardot *et al.*, 1995), with species effects on N mineralisation often minimal after the first week of incubation (Kuo *et al.*, 1996).

Variations in the chemical characteristics of different cover crop species convey considerable importance in governing the uptake and ultimate release of N from mineralisation of cover crop material and hence their value to succeeding crops. However, research indicates that C/N ratio alone may be inadequate for characterising this residue “quality”, as for example, Kuo *et al.* (1997) found that in spite of having very different C/N ratios, ryegrass (C/N 54-61) and hairy vetch (C/N 10-29) cover crops had virtually the same half-life for the degradation of their biomass C (21-30 days), an observation supported by results from other researchers (Jenkinson & Rayner, 1977; Gale & Gilmour, 1988; Buchanen & King, 1993). Concentrations of cellulose and lignin are greater in grasses and more mature plant material compared with legumes and young plant material (Ranells & Wagger, 1996), with research indicating that cellulose, lignin and C/N ratio together can frequently serve as good predictors of the relative decomposability of cover crop residue material (*e.g.* Macdonald *et al.*, 1996a,b). Other authors have found the water-soluble components in the plant material (Andren, 1987) and the polyphenol content (Fox *et al.*, 1990) to be important factors.

Other research has found that decay rate constants are different for carbohydrate, cellulose and lignin fractions of residue material, with the relative ease of decomposability systematically decreasing in the order carbohydrate>cellulose>lignin, although the absolute values ascribed to such decay rate constants differ between researchers (*e.g.* Godwin & Jones, 1991; Vigil *et al.*, 1991; Bowen *et al.*, 1993). Thus, during decomposition there is typically a rapid loss of soluble carbohydrate material, followed by the relatively rapid disappearance of cellulose from the residue, with lignin proving the most recalcitrant substrate fraction (*e.g.* Schomberg *et al.*, 1994). The relative decomposability of cover crop residues also typically differs significantly between shoot and root components, with the “better” quality (*i.e.* narrower C/N) shoot material being subject to more rapid mineralisation (*e.g.* Quemada & Cabrera, 1995b). The generic inverse relationship between C/N, lignin, cellulose or soluble carbon contents and plant age (Frankenberger & Abdelmagid, 1985; Waksman, 1929) accounts for the importance placed on sowing and destruction dates as a means of manipulating cover crops to maximise their potential N contribution to the succeeding crop (*e.g.* Clark *et al.*, 1997).

4.2 Agronomic Implications

In practice, integrating a cover crop into a rotation can result in additional work, expense and potential delays in spring crop establishment for farmers with little perceived benefit as, at best, the resulting effects of cover cropping are generally small and appear highly variable (McVay *et al.*, 1989), sometimes showing positive (*e.g.* Catt *et al.*, 1992; Wallgren & Lindén, 1994; Torbert *et al.*, 1996), negative (*e.g.* Macdonald *et al.*, 1996b; Richards *et al.*, 1996; Martinez & Guiraud, 1990), or no overall effect (*e.g.* Hayward, 1992; Froment & Cook, 1995; Knott, 1996) on the yield and N uptake of succeeding spring-sown crops. There are

many plausible reasons for this variability in reported results, including the effect of soil type, cover crop species, sowing and destruction dates, and the contrasting moisture and temperature regimes in experiments reported by different researchers. It is often difficult to discriminate any increased N supply due to cover crop mineralisation from the effects of cover crops on soil conditions: for example, cover crops modify soil moisture status through increased transpiration losses in excess of the cereal stubble which may otherwise be present, and this can reduce water availability to a succeeding spring crop: each tonne of cover crop dry matter was estimated to require 40 mm of soil water (Machet & Mary, 1989; Allison & Armstrong, 1992) which may represent a larger proportion of available water capacity in coarser, sandier-textured soils compared with loams (Wild, 1988).

Research comparing cover crop versus bare ground treatments indicate effects are usually small over a wide range of cover crops and site-years, suggesting that the mineralisation of cover crop residues is generally limited (Harrison & Peel, 1996), although this has not always been found to be the case (*e.g.* Carsky *et al.*, 1990; Bowen *et al.*, 1993). However, results of research comparing cover crops with bare plots should be interpreted with care, as differences in SMN will be due to the combined effect of differences in nitrate leaching and N mineralised from cover crop residues (Section 2). Thus, in dry winters with limited drainage, differences in nitrate leaching between bare ground and cover crop treatments will be small and the dry conditions may also limit cover crop growth and N uptake: hence effects on subsequent crops are also likely to be small (*e.g.* Christian *et al.*, 1996). In wetter winters, nitrate leaching from bare fallow plots may exceed that from cover crop treatments, and cover crop N uptake may be of the same magnitude as nitrate leaching from bare plots (Harrison & Peel, 1996). In these circumstances, the effect of the cover crop on the N uptake and yield of a test crop is dependent on the rate of mineralisation of the cover crop residues: if decomposition is limited then effects on following crops will again be difficult to detect, whereas more rapid decomposition which enhances N supply to a succeeding crop will provide a measurable potential benefit to a succeeding crop. The ultimate value of cover crops thus depends not only on husbandry, but also crucially relies on the prevailing weather conditions which will regulate cover crop growth and N uptake.

In terms of soil type, research results indicate that the net N mineralisation of soil organic matter and the decomposition of added plant material such as cover crop residues do appear more rapid in sandy compared with heavier, clay-rich soils (Ladd *et al.*, 1990; Hassink *et al.*, 1990; Hassink, 1992; Verberne *et al.*, 1990; van Dam & Fu, 1996) with N mineralisation negatively correlated with clay content (Thomsen *et al.*, 1996). This is supported by several authors who have demonstrated that most of the native C and residual ¹⁴C from decomposing substrates is generally associated with the clay and silt sized fractions in soil (*e.g.* Amato & Ladd, 1980; Christensen, 1992). Overall, published research tends to show that earlier sowing and later destruction dates can promote yield depressions of the subsequent crops compared with later sowing and earlier destruction dates (Wallgren & Lindén, 1994; Cook & Froment, 1996; Harrison & Peel, 1996): this is probably due to their effect in widening cover crop C/N ratio at destruction and reducing the time available for mineralisation of the residues before the harvest of the next crop. However, reported results are not all in agreement with these conclusions (*e.g.* Hayward, 1992). In practice, the main constraint on cover crop management is time of sowing which will depend, in part, on when the previous crop is harvested and cleared: for winter barley this may be mid July, whereas some crops such as peas, beans and potatoes grown in beet rotations on lighter soils may delay cover crop sowing until September or October (Allison *et al.*, 1996) which will limit cover crop growth and performance as over-winter SMN “sinks” and hence their value to succeeding spring-sown crops.

Based on the research reported here, and in the context of MAFF guidelines (MAFF, 1993, 1994), practical recommendations include establishment of cover crops in late August or early September *i.e.* soon after the previous harvest. The link between surface area, physical accessibility to microbial degraders and a substrate's relative decomposability (*e.g.* C/N ratio, lignin content) suggests that incorporation (rather than chemical destruction) and using cultivation techniques such as rotovators which macerate the residue and mix it with the soil, should tend to encourage the early release of the N contained in the cover crop residues. Incorporation of residues by ploughing or rotovation may increase the opportunity for microbial degradation and represent a preferable alternative to the (possibly) more costly alternative of chemical destruction which would also leave residues at the soil surface where they may interfere with the establishment of the succeeding crop. An option worthy of further investigation is the concept of bicultures, as mixing different cover crop species may increase relative decomposability by modifying overall C/N ratios, for example by sowing a mixture of a cereal (*e.g.* rye) and a legume (*e.g.* clover) cover crops together (*e.g.* Ranells & Waggoner, 1996), and reports of the results of such investigations into the effects of bicultured cover crops on patterns of N release are rare.

4.3 Short & Long Term Effects

The contrasting results reported by researchers studying the effects of cover crops on subsequent crops makes modifications to spring fertiliser recommendations difficult, and this variability may be due to contrasting species, sowing and incorporation dates, as well as the precipitation and temperature regimes during both the period of cover crop growth and test crop development. The majority of reported research indicates that, under temperate European conditions, only a relatively small proportion of cereal cover crop N, usually *ca.* 5-30%, is released in the short term *i.e.* during the growing season of the subsequent spring-sown crop (*e.g.* Gutser & Vilsmeier, 1989; Thorup-Kristensen, 1993; Macdonald *et al.*, 1996b,c; Harrison *et al.*, 1996a; Silgram & Harrison, 1998). This is consistent with early work by Jenkinson (1977) on residue C and detailed pot studies of mineralisation kinetics which have found a large proportion of N released during incubations is due to mineralisation of a labile fraction which decomposes rapidly and comprises about one-third of the cover crop residue N (Tamai *et al.*, 1989; Yadvinder-Singh *et al.*, 1988). However, rather larger proportions of *ca.* 30-70% cover crop N are reported to have been mineralised in the short term from leguminous cover crop species with narrower C/N ratios, and for many species under warmer, wetter conditions more conducive to rapid microbial decomposition (*e.g.* Carsky *et al.*, 1990; Bowen *et al.*, 1993; Quemada & Cabrera, 1996a,b). In UK situations, such results raise the important question of the fate of the remaining amount - which for cereals may be the majority - of organic N in cover crops incorporated into the soil in the spring. Is this cover crop N released to the next crop during autumn and spring the following year, and if so might this release increase nitrate leaching losses in subsequent winters, or does the organic N from the cover crop material gradually accumulate over time and lead to an overall increase in soil organic matter status? If cover crops reduce nitrate leaching in the winter in which they are grown, but do not improve the long-term nitrogen balance of the system they will simply have altered the time course or pathway of N loss (Thorup-Kristensen, 1993).

There is some evidence that cover cropping can increase the amounts of inorganic N left in the soil profile after harvest of the subsequent crop and increase net N mineralisation the following winter (Thorup-Kristensen, 1993; Macdonald *et al.*, 1996b). Although much more research is required in this area to investigate the long term effects of using cover crops in arable rotations, the rather limited evidence currently available suggests that even for cover crops possessing a reasonably narrow C/N ratio of 14 or 16 there may be a detectable carry-

over effect to subsequent years, with the magnitude of nitrate leaching losses during the winter *after* cover crop incorporation being significantly (9-15 kgN/ha) *greater* where cover crops had been grown the previous winter compared with a previous crop of winter barley grown to maturity (Macdonald *et al.*, 1996b). These results are consistent with those of Catt *et al.* (1992) who concluded that cover cropping could increase nitrate leaching losses in later seasons, and Jensen (1990) in a field trial in Denmark who found that 20% of ¹⁵N-labelled ryegrass cover crop residues was recovered in the following crop with 52% still remaining in the soil as organic N one year after incorporation. Further evidence is provided by Harrison & Peel (1996) who reported that 12% of the cover crop N incorporated into a loamy sand soil in the spring was lost via nitrate leaching in the 144 mm of drainage during the following winter. Such increased losses could be the result of greater production of mineral N caused by the mineralisation of the incorporated residues, combined with decreased uptake of mineral N from the subsoil by the subsequent spring sown crop compared to that by a winter sown crop allowed to reach maturity.

Based on existing evidence, it appears that under temperate European conditions, N stored in cover crops is not usually utilised by the following crop to any great extent due to the limited mineralisation of cover crop residues, and any reduction in nitrate leaching when cover crops are grown could therefore result in an accumulations of organic N over time, particularly in rotations where cover crops are grown repeatedly (Jensen, 1990; Harrison & Peel, 1996; Schroder *et al.*, 1996). For example, 113 kgN/ha accumulated in a rotation involving cover crops grown in 3 years out of 4 compared to bare ground in a trial on a calcareous loam in East Anglia (Davies *et al.*, 1996; Garwood *et al.*, 1998). In the longer term, repeated use of cover crops could therefore cause the *potential* for N mineralisation (and hence nitrate leaching) to increase. However, in many rotations the usual mix of spring and autumn planted crops will mean that cover crops may be employed infrequently (*e.g.* only one year in three). In these circumstances, the accumulation of organic N will tend to be small, and may be smaller if yields and N offtake increase as a result of cover cropping (Shepherd & Garwood, 1997). Given the considerable importance of cover cropping as a UK and internationally adopted strategy to ameliorate nitrate leaching losses to ground and surface waters, further research is required to clarify the longer term impacts of repeated cover cropping on soil N status, SMN and nitrate leaching risk in the years following the harvest of the first spring sown crop.

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