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D.J. Hatch · A. Bhogal · R.D. Lovell
M.A. Shepherd · S.C. Jarvis

Comparison of different methodologies for field measurement of net nitrogen mineralization in pasture soils under different soil conditions

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Abstract Net mineralization was measured in free-draining and poorly drained pasture soils using three different field incubation methodologies. Two involved the use of enclosed incubation vessels (jar or box) containing C_2H_2 as a nitrification inhibitor. The third method confined soil cores in situ in an open tube in the ground, with an anion-exchange resin at the base to retain leached NO_3^- (resin-core technique, RCT). Measurements were made on three occasions on three free-draining pastures of different ages and contrasting organic matter contents. In general, rates of net mineralization increased with pasture age and organic matter content (range: 0.5–1.5 kg N ha^{-1} day^{-1}) and similar rates were obtained between the three techniques for a particular pasture. Coefficients of variation (CVs) were generally high (range: 10.4–98.5%), but the enclosed incubation methods were rather less variable than the RCT and were considered overall to be the more reliable. The RCT did not include C_2H_2 and, therefore, newly formed NO_3^- may have been lost through denitrification. In a poorly drained pasture soil, there were discrepancies between the two enclosed methods, especially when the soil water content approached field capacity. The interpretation of the incubation measurements in relation to the flux of N through the soil inorganic N pool is discussed and the drawbacks of the various methodologies are evaluated.

Key words Net nitrogen mineralization · Field incubation · Soil water · Soil cores

D.J. Hatch (✉) · R.D. Lovell · S.C. Jarvis
IGER, North Wyke, Okehampton, Devon, UK
DAVID.HATCH@BBSRC.ac.uk
Tel.: +44-1837-82558

A. Bhogal, M.A. Shepherd
ADAS Gleadthorpe, Mansfield, Nottinghamshire, UK

Introduction

Measurements of net mineralization of N in soils are important if a closer match between available N and plant requirements is to be achieved with consequent reduction in N losses (Jarvis et al. 1996). Improved allowance for the contribution of N from soil sources would enable better use of fertilizer and avoid the development of imbalances between supply and demand, which can ultimately lead to losses through denitrification and leaching. Direct field measurements of net mineralization can be obtained by the incubation of soil cores in Kilner preserving jars (Hatch et al. 1990) which provides a convenient method for obtaining an integrated set of measurements in conditions, which as far as possible, attempt to follow climatic changes in the natural environment. A major advantage is that the problem of sampling heterogeneous areas of grassland under cutting/grazing managements can be at least partly overcome by taking a number of soil cores from a representative cross-section over the experimental site. Other inaccuracies, due to unquantifiable losses of N from nitrification-denitrification and/or plant uptake, are minimized by means of a nitrification inhibitor (C_2H_2) which denies NO_3^- to the denitrifying process, and photosynthesis is temporarily curtailed during the incubation period. Gaseous loss of N is an important consideration, since N_2O may continue to be emitted at soil temperatures (10 cm) as low as –1.5 C (Fey et al. 1999). Recently, incubations with C_2H_2 have been successfully employed to resolve the relative contribution of N_2O from the respective nitrification-denitrification pathways (Muller et al. 1998). The same method has also been widely used to determine both short-term and seasonal N release of inorganic N in grassland soils (Gill et al. 1995; Ledgard et al. 1998). A conceptual model (Fig. 1), illustrating the component measured by field incubation, shows how net mineralization is derived from the flux of N released from organic matter, which is then potentially available to the various removal processes of plant uptake, leaching and denitrifi-

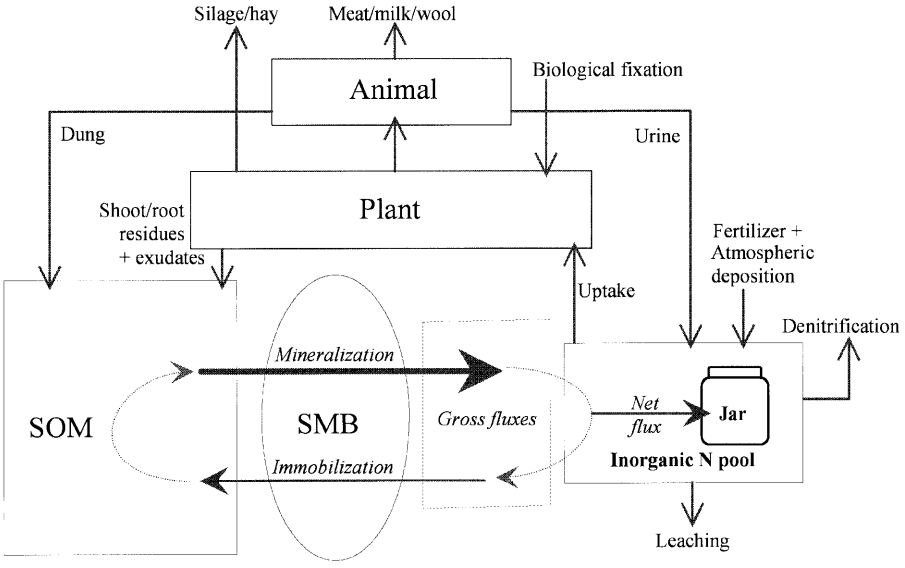

Fig. 1 The flux of N through the soil inorganic N pool as measured by the jar incubation method and the various processes relating to it

cation. A cumulative value, obtained from successive periods of jar incubation measurements, provides an estimate of the seasonal flux of N through the mineral N pool. Thus, some of this N may have been recycled several times through the N pool during a growing season (returned via plant/animal residues, or re-released from the microbial biomass), but will contribute to the overall net flux through an annual cycle. Of course, net values only provide limited information about the outcome of the opposing processes of gross mineralization and immobilization that culminate in the release of N into the inorganic N pool. Thus, "a small net effect may be the result of low overall biological activity in the ecosystem, or it may be the result of high activity in which the processes work in opposite directions" (Jansson and Persson 1982). Such information concerning gross rates can only be obtained using expensive and time-consuming ^{15}N labelling techniques (Hatch et al. 2000), but these methods are not conducive to extended investigations. Therefore, to obtain estimates of net N released that is potentially available to crops, requires techniques that provide information of agronomic importance and which are capable of being extended on a seasonal scale.

There are disadvantages, however, associated with soil coring: the cut surfaces of conventional cylindrical cores are exposed to altered conditions of aeration (Smith and Arah 1990), even when packed tightly into the incubation jars. Scholefield et al. (1997) have used square section cores, assembled without air gaps, to make a composite turf for laboratory incubation under controlled conditions, thus avoiding extreme alterations in the O_2 regime. This approach has been adapted recently to measure denitrification by using square soil cores fitted tightly into a specially made plastic box to avoid exposure of surfaces to air (Jarvis et al. in press), and was also examined for use in estimating net mineralization. Both the box and the jar method involve sealed incubation vessels whereby soil cores are isolated from natural wetting/drying cycles during the incubation. Previous work (Jarvis et al. in press) showed that, whilst there was good agreement in a well-drained soil, the agreement was poorer between the enclosure methods in a clay soil which was near to field capacity (FC). Here, we examine the extent to which soil water content (SWC) can affect the measurement in a poorly drained soil, so that the limitations associated with enclosed incubation methods can be identified. Additional measurements were also made with these two methods on freely drained soils and were compared with an in situ method using exposed soil cores, known as the resin-core technique (RCT). The RCT allows rainfall and leaching to proceed naturally (Bhogal et al. 1999), but does not prevent denitrification losses. Results obtained with the three different methods were compared to determine the most satisfactory method for field measurements.

Materials and methods

The experiment was conducted at two sites to provide a range of soils and conditions. There were four replicate groups of soil cores used for each measurement period.

Site 1

Measurements were made at ADAS Rosemaund, Herefordshire, UK (annual rainfall 650 mm) using three pasture types: Banky (2-year ley), Prestons (6-year ley) and Oakey (>50-year permanent pasture), with contrasting soil organic matter (SOM) contents of 3.1%, 4.1% and 6.3%, respectively. These pastures were based on the same soil type (a silty clay loam red sandstone of the Bromyard series) which had a history of sheep grazing with regular applications of fertilizer N. Sheep were withdrawn from the pastures in 1995 and a final application of N fertilizer (60 kg N ha^{-1}) was applied in August. Thereafter, fertilizer was withheld and the pastures were maintained under a cutting regime (4 cuts $year^{-1}$). Two sets of field measurements were obtained in July 1997 (incubations 1 and 2), each conducted over a 7-day period on all three pastures, and further measurements were made in November 1998 on Banky and Oakey only (incubation 3).

Site 2

Another series of measurements was made using two experimental areas on the IGER farm at North Wyke Research Station, Devon in S.W. England (annual rainfall 1030 mm). These were both long-term grazed swards: the soil at the first area (De Bathe) was a well-drained, coarse sandy loam of the Bromsgrove series and the second area (Rowden) was a poorly-drained, silty clay loam of the Hallsworth series. The background treatment of both areas was a conventional N managed grass sward, predominantly of ryegrass (*Lolium perenne* L.), receiving 280 kg N ha^{-1} $year^{-1}$. Measurements were made on both soils on one occasion during June 1997 (incubation 4). A further comparison was made on the poorly drained soil in August 1998 to determine whether different soil water conditions affected the measurement (incubation 5). Two plots (each approximately 3 m^2) were marked out on the sward, one of which was irrigated (ca. 100 l) twice daily for the 2 days preceding the soil sampling. SWC increased by ca. 10% with irrigation and was then close to FC (65%).

N mineralization by jar incubation

Sixteen cylindrical soil cores (37 mm diameter × 100 mm deep) were taken from each experimental area and placed in four replicate 1-l glass Kilner jars (4 cores jar^{-1}), as described previously (Hatch et al. 1990). The jars were sealed with a gas-tight, opaque plastic lid incorporating a rubber septum. Air was withdrawn from the headspace (10 ml) using a hypodermic syringe inserted through the septum. An equivalent volume of C_2H_2 was added to the vessel to provide a concentration of 2% C_2H_2 (v/v) in the headspace to inhibit nitrification. Loss of NO_3^- was then restricted to denitrification of "native" NO_3^- which was already present in the soil at the start of incubation. The jars were incubated in the field in suitably sized holes near the sampling site for 7 days. Between days 3 and 4 of the incubation, the jars were vented to refresh the headspace in order avoid O_2 depletion and CO_2 build up, after which C_2H_2 was again added and the incubation allowed to continue (Bhogal et al. 1999).

N mineralization by box incubation

Sixteen square sectioned soil cores (45 × 45 × 100 mm deep) were packed into a pair of identical plastic boxes (8 cores box^{-1}) as described by Jarvis et al. (in press). The cores were segregated within each box into two replicate groups, each comprising four soil cores. Thus, each pair of boxes represented four replicate groups of cores enabling direct comparisons to be made with an equivalent number of soil cores undergoing jar incubation. The soil cores were supported in the box on a perforated stainless steel mesh floor raised on pillars to leave a space beneath the floor. A temporary reduction in air pressure within the top of the box was created by withdrawing 50 ml air from the headspace. The box was then tilted onto its side, and an equivalent volume of C_2H_2 was introduced into the under-floor space to provide 2% C_2H_2 (v/v) in the total air-space. The box was then returned to an upright position and the internal pressure was allowed to equilibrate. Effective infusion of C_2H_2 into the soil cores was then achieved as C_2H_2 (which is lighter than air) migrated into and around the soil cores, drawn by the reduced pressure in the headspace. As with the jar method, the boxes were placed in the ground near to the sampling site for an incubation that lasted for 7 days. Between days 3 and 4 of the incubation, the boxes were vented to refresh the headspace which was recharged with C_2H_2, before the incubation continued through to day 7.

N mineralization by in situ (RCT) incubation

An additional comparison was made at Rosemaund using sheathed cores which were incubated in situ over ion-exchange resin bags to intercept any leached N (Bhogal et al. 1999). Briefly, this consisted of a metal tube (55 mm diameter × 100 mm deep) which was inserted into the ground to confine a soil core. The tube was removed and a 3-cm layer of soil was excavated from the lower end of the soil core. A nylon bag containing anion exchange resin (Dowex 1 × 8) was pressed against the base of the soil core and the remaining space was filled with a cylindrical block of gypsum (Hatch et al. 1998). The metal tube was then carefully replaced into the original hole whilst leaving the surface of the core exposed to the prevailing weather conditions. The block of gypsum helped to maintain contact with the surrounding soil, but prevented any direct exchange of NO_3^- from sources outside the soil core; any NO_3^- that leached directly from the soil core was captured by the resin during an incubation period of 7 days. The soil cores within the metal tubes were incubated without an infusion of C_2H_2, so that if the conditions were conducive, both nitrification and denitrification could proceed normally, but were not accounted for in the method.

Calculation of net mineralization

At the start of incubation, additional soil cores were obtained which were used to provide the "baseline" starting values for all three methods; these were extracted immediately. The soil samples, both before and after incubation, were crumbled and thoroughly mixed, but stones and pieces of undecomposed, identifiable plant material were removed. Moist soil (100 g) was shaken with 200 ml of 2 M KCl for 1 h and the suspension was then filtered using Whatman no. 1 filter paper. Soil extracts were analysed for NH_4^+ and NO_3^-, using automated segmented flow colorimetry (Searle 1984; Kempers and Luft 1988). For both methods employing C_2H_2 (jar and box) the mean daily rates of net mineralization were calculated from the differences in the NH_4^+-N at the start and end of each incubation period. For the RCT, net mineralization was estimated from the difference in soil inorganic N (NH_4^+-N + NO_3^--N) at the start and end of incubation, including any NO_3^- retained in the resin bag. Recovery of adsorbed NO_3^- from resin was by displacement with 1.5 M H_2SO_4; this was analysed as for the soil extracts. Gravimetric SWC was determined from sub-samples of soil taken at the start and at the end of incubation, after drying at 105 C for 24 h. Bulk density was also calculated from the volume and dry mass of the soil sampled with conventional cylindrical corers (25 mm diameter) at the start of each incubation period. Water-filled porosity (WFP) and air-filled porosity were then calculated from this data after allowing for the volumes of stones and fine earth in the samples. Statistical analysis of the data was by ANOVA and Student's *t*-test, using standard statistical software.

Results

Site 1

In each of the three incubations at Rosemaund (incubations 1–3), gravimetric SWC increased with the age of the pastures, reflecting SOM contents and corresponding water-holding capacities (Table 1). In all three pastures, gravimetric SWC was significantly lower ($P < 0.001$) in incubation 2 and there were corresponding changes in the proportions of WFP and air-filled porosity. Total porosity in the soils also tended to increase with the age of the pastures.

During the incubations in July (incubations 1 and 2), there was good agreement between the three methods for measuring net mineralization and no significant differences found between rates in the three pastures (Fig. 2a,b). However, when a combined estimate using

Table 1 Percentage by weight of water and by volume of water-filled porosity and air-filled porosity. Values are means ± SE ($n=4$). *Banky* 2-Year ley; *Prestons* 6-year ley; *Oakey* >50-year permanent pasture; *DeBathe* long-term grazed sward, well drained; *Rowden* long-term grazed sward, poorly drained

Soil type	Gravimetric water content (% dry weight)	Water-filled porosity (% volume)	Air-filled porosity (% volume)	Total porosity (% volume)
Incubation 1				
Banky	28.1 ± 0.28	34.3 ± 0.60	19.5 ± 1.62	53.8 ± 1.05
Prestons	34.7 ± 0.25	38.4 ± 1.08	19.8 ± 2.31	58.2 ± 1.25
Oakey	42.0 ± 0.34	38.6 ± 0.94	26.7 ± 1.65	65.3 ± 0.73
Incubation 2				
Banky	16.4 ± 0.63	19.4 ± 1.24	36.6 ± 2.61	55.9 ± 1.44
Prestons	24.4 ± 0.65	27.5 ± 1.09	30.0 ± 1.80	57.5 ± 0.79
Oakey	25.9 ± 0.76	25.2 ± 1.17	38.3 ± 2.09	63.5 ± 1.02
Incubation 3				
Banky	28.8 ± 0.26	35.2 ± 0.73	18.6 ± 2.06	53.8 ± 1.33
Oakey	43.4 ± 1.40	39.8 ± 1.41	25.5 ± 2.05	65.3 ± 0.93
Incubation 4				
DeBathe	17.0 ± 0.41	12.8 ± 0.050	58.7 ± 1.71	71.5 ± 1.26
Rowden	52.8 ± 1.03	27.9 ± 1.62	52.2 ± 2.85	80.0 ± 1.27
Incubation 5				
Rowden	50.1 ± 0.97	40.4 ± 1.42	29.2 ± 2.56	69.5 ± 1.22
Rowden (irrigated)	60.7 ± 0.42	50.3 ± 1.76	18.4 ± 2.89	68.7 ± 1.15

a mean of the three independent methods was used (Fig. 3), the lowest rates in both incubations were associated with the 2-year ley, but this was only statistically significant in incubation 1 ($P<0.05$). Net mineralization rates in the three pastures were generally higher (Fig. 3) in incubation 2 and with correspondingly higher air-filled porosity (Table 1) than in incubation 1, but were only statistically significant in Oakey ($P<0.05$). When the measurements were repeated in November (incubation 3, Fig. 4), comparing only the 2-year ley (Banky) with the permanent pasture (Oakey), mineralization rates were similar to those found in July (incubations 1 and 2). There was again no difference between the estimates obtained with the three methods, although CVs were higher (CV >80%) with the RCT. There was also no difference between the 2-year ley and permanent pasture even when estimates from all three methods were combined.

CVs ranged between 10.4% and 49.3% for the box and 22.8% and 76.9% for the jar methods, and 38.9% and 98.5% for the RCT with overall, respective, mean CVs of 31.7%, 44.5% and 64.6%.

Site 2

There was no difference between the rates of net mineralization measured by either the jar or box method in the relatively dry, freely drained DeBathe soil (SWC 17.0%). However, in the poorly drained Rowden soil (SWC 52.8%), the jar method appeared to give a higher value, although this was not statistically significant (incubation 4, Fig. 5a). When the test was repeated with the Rowden soil in incubation 5 (Fig. 5b), gravimetric SWC (50.1%) was similar to that in incubation 4, whereas in the irrigated area (SWC 60.7%) it was close to FC. There was no difference between the results of

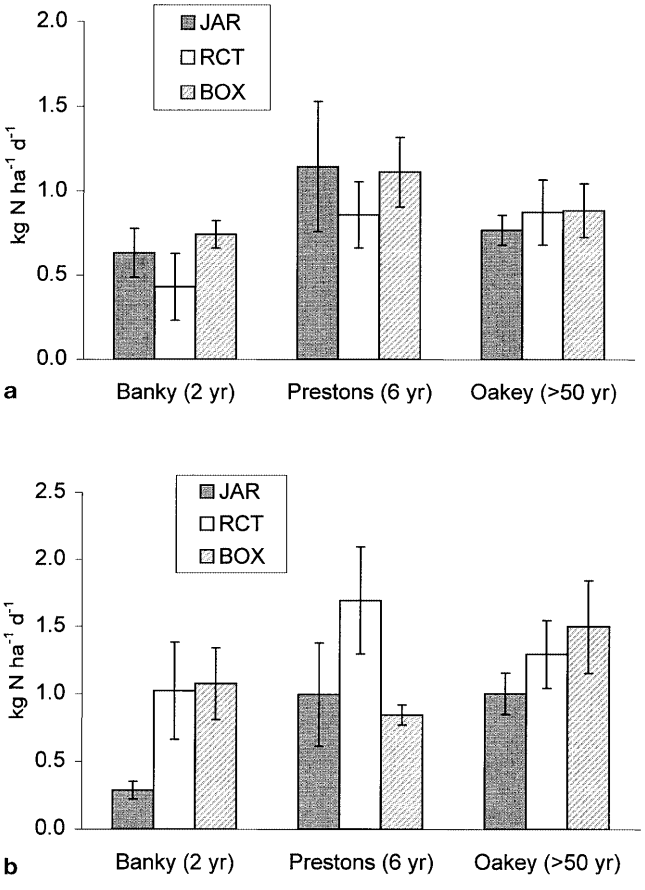

Fig. 2a,b Net mineralization measured at site 1 (Rosemaund) by three field incubation methods in three pastures of different ages; means ± SE ($n=4$). **a** incubation 1, **b** incubation 2

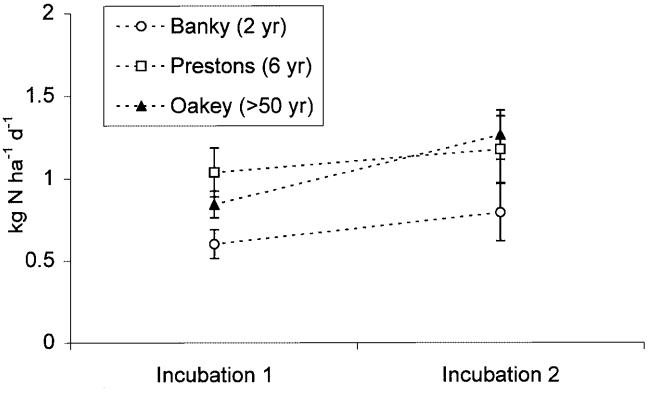

Fig. 3 Net mineralization measured at site 1 (Rosemaund) by a combination of field incubation methods in three pastures of different ages; means ± SE ($n = 12$)

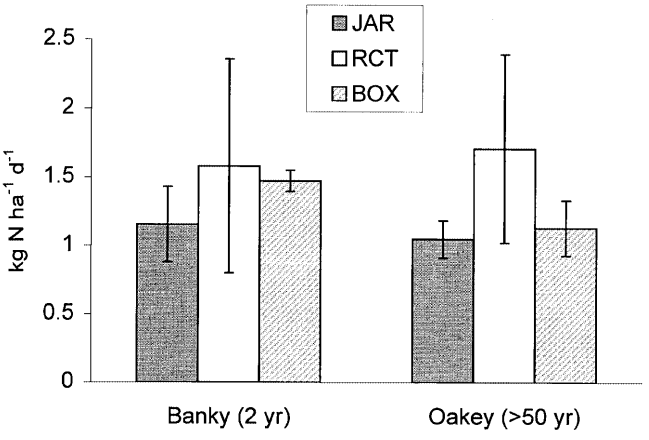

Fig. 4 Net mineralization measured at site 1 (Rosemaund) by three field incubation methods in two pastures of different ages; means ± SE ($n = 4$) (incubation 3)

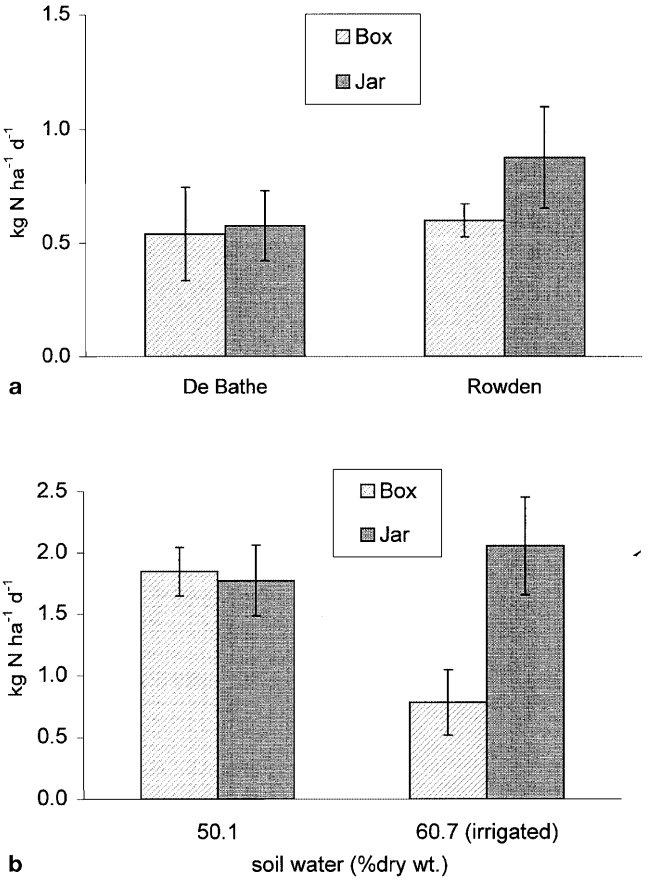

Fig. 5a,b Net mineralization measured at site 2 (IGER) by **a** two field incubation methods in pastures on two on different soil types (incubation 4) and **b** two field incubation methods in a pasture on poorly drained soil with different soil water content (incubation 5); means ± SE ($n = 4$)

the jar and box methods in the poorly drained soil (without irrigation) at 77% of FC, but in the irrigated area, net mineralization was significantly higher ($P < 0.05$) when measured by the jar method.

Discussion

There is no absolute standard method for field mineralization against which to compare different techniques (Jarvis et al. 1996). The approach adopted here was to compare net mineralization values over the same period, using two or more different methods. This will highlight any aspects that differ greatly from the combined estimate using alternative methods. Since the methodology may directly influence the rates of some of the processes involved (Jarvis et al. in press), it is important to define carefully the conditions under which such measurements are obtained. Fluxes through the soil N pools are complex and mineralized N then becomes available for immobilization into various sinks, only a proportion of which will be accessed by plants. Both of the enclosed incubation methods evaluate the total flux of released N through the inorganic N pool, as illustrated in Fig. 1, and results will invariably exceed estimates of mineralization based only on N off-take in herbage.

All the methods used in this study alter the soil conditions to a greater or lesser extent. The enclosed methods (jar and box) temporarily isolate the soil from natural environmental influences, especially fluctuations in soil moisture. It is necessary, therefore, that incubations are short term, e.g. ≤ 7 days, in order to remain responsive to changing soil conditions, and O_2 concentrations should not be allowed to fall to levels which have been shown previously (Parkin and Tiedje 1984) to stimulate anaerobic processes (viz $< 3\%$ O_2). However, in another study, a build-up in CO_2 concentration was not found to greatly affect microbial decomposition rates (Jenkinson 1977). In this context, the use of a nitrification inhibitor (C_2H_2) has benefits which both simplify the soil analysis (only changes in NH_4^+-N are monitored) and avoids the complication of newly mineralized N being denitrified: a process that may be seriously underestimated by methods employing C_2H_2 (McKen-

ney et al. 1996; Bollman and Conrad 1997). There is less disturbance to the soil with RCT incubation and also less concern over the aeration of the soil, but without a nitrification inhibitor, losses of more mobile NO_3^--N could occur (following nitrification) through leaching (measured) and denitrification (unknown). Another consideration with the RCT is that the soil cores remain in situ for the duration of the incubation, so that the inherent spatial variability associated with soil heterogeneity is retained for the duration of measurements. Bhogal et al. (1999) have discussed the problems of spatial variability encountered when measuring mineralization in arable soils with enclosed and open (RCT) soil incubation methodologies. They attributed highly variable rates to an uneven distribution of crop residues and root exudates. In grazed pasture soils, returns of animal excreta will generate both spatial and temporal variability, therefore here, as in arable soils, it is important that sufficient replication of treatments is undertaken within the practical considerations of the experiment. However, on the basis of the high CVs obtained, a higher level of replication would have been indicated, especially if the main purpose of the comparisons was to distinguish temporal changes in rates.

The direct effect of SWC on rates of soil processes has been long recognized (Birch 1964). In our experiments, the three sward types at Rosemaund provided a range of SWC (16–43%) in a free-draining soil. There was a tendency for the rate of mineralization to increase with SWC, but no conclusion could be drawn because SWC was also directly related to the age of pastures and SOM contents, which would have had additional influences on process rates. Differential effects on the consumptive and productive processes of N turnover and a lack of correlation between gross and net rates of mineralization (Hart et al. 1994) suggest that these processes do not respond equally to the controlling factors. For example, whilst SWC may affect the availability of organic substrates for decomposition, a decrease in air-filled pore space could limit the aerobic processes associated with mineralization and nitrification. It should be emphasized that net rates of mineralization do not reflect the level of activity of the processes involved in the release of inorganic N, but nevertheless relate directly to the supply of N available for plant uptake, since the measurement represents the surplus N remaining after microbial immobilization. Hence, net rates have an agronomic significance, but provide only limited information about the mechanisms involved.

On all sampling occasions, and in each pasture type, there were no significant differences in rates of net mineralization measured by the three incubation methods; for free-draining soils, therefore, they would appear equally valid. Within each method, however, there were differing degrees of variation, with the highest % CV associated with the in situ method (RCT), suggesting that some of the mineralized N may have been lost from the RCT samples by denitrification. This would not have been the case with the enclosed methods because NO_3^- would not have been produced in the presence of C_2H_2. Because of this, we consider the enclosed core methods (with C_2H_2) to be the more reliable in pasture soils, especially where (in the absence of C_2H_2) the potential for denitrification may be high due to a ready supply of NO_3^--N and C. On the other hand, the RCT may be suited better to arable soils (Bhogal et al. 1999) where the soil is less compacted and intact soil cores are more difficult to obtain.

Incubation 4, using both soil types at IGER, was conducted under similar SWC conditions to those encountered by Jarvis et al. (in press), viz SWC ca. 17% and 53% for the free-draining and poorly drained soils, respectively. The discrepancy found by those authors between the jar and box methods for poorly drained soil, however, was not observed in incubation 4 of the present study, suggesting that the water content in the previous study may have been at a "critical point", i.e. SWC approximately 80% of FC. The subsequent measurement (incubation 5) in poorly drained soil ($\pm$ irrigation), suggests that small changes in the remaining air-filled pore space of the soil cores may become critical when SWC approaches FC, because soil processes could then be sensitive to additional aeration, which is more likely with the jar method. Hence, when the diffusion of O_2 becomes restricted, the additional aeration afforded by the exposed surfaces of conventional cores (jar incubation) may lead to a marked increase in aerobically driven processes and over-estimates in the measurements.

There were no differences in rates of net mineralization measured with the enclosed methods in either of the free-draining soils in our experiment (incubations 1–4). For example, when all the values obtained by the jar method at Rosemaund (site 1) were pooled ($n = 12$) and compared with those obtained by the box method, there were no significant differences between them. Our results, therefore, suggest that the jar and box methods tend to be in good agreement for free-draining soil incubations. This was confirmed over a range of conditions and suggests that discrepancies between the two methods are likely to be confined to wetter, poorly drained soils. On average, the findings from the comparisons made on the poorly drained soil suggest that, for this soil type, the jar method over-estimates by a factor of 2.7 when SWC is close to FC (see irrigated soil, Fig. 5b). Appropriate calibration of data under such conditions is therefore recommended when jar incubation is employed.

Whilst these methods are generally in good agreement, if the rates were sustained over a growing season, the absolute amounts released would appear to be very large compared to estimates based on herbage N offtakes, as shown previously (Jarvis et al. 1996). An explanation may be found in the substantial N recycling that occurs within grassland systems (Fig. 1). Grass leaves have a high turnover and new leaves are produced at intervals of about every 11 days (Parsons

1988). If a leaf is neither grazed, nor removed by cutting, then it will senesce and return to the soil litter. This can represent a substantial source of N (Parsons et al. 1991) that would not be registered in herbage off-take, and some of the N in the litter would then become available for further recycling. As much as 0.42 kg N ha^{-1} day^{-1} can be transferred from herbage to soil in a grazed grass sward (Thomas et al. 1990). Additional inputs will also come from the efflux of N from the roots into the soil. The total uptake of N in herbage, stubble and roots in intensively managed grass swards is in the range of 300–700 kg N ha^{-1} $year^{-1}$ (Whitehead 1995), but only about half of this N will be accounted for in herbage off-take. It should be possible to improve this estimate of net mineralization from herbage off-take by including any changes in inorganic N in the soil profile (0–90 cm) between harvests and/or leached from below 90 cm depth (Mengel 1991). Field measurements of mineralization provide valuable information about the ability of the soil to release N, which would not be revealed from measurements based only on the size of the soil inorganic N pool, since the ability of the soil to replenish this pool is a good indicator of its inherent fertility. However, the proportion of the inorganic N pool accessed by plants is ill-defined and the outcome will depend on other competing processes, e.g. microbial immobilization. There is, therefore, a need to take account of the recycling of N through the whole system and, in particular, the quality of the litter from unharvested plant material, before meaningful predictions and adjustments to fertilizer use can be made. The challenge is to relate these measurements directly to plant requirements, but the methods available are likely to be too time consuming to be applied routinely as part of wider fertilizer recommendations. However, even in general terms, the data from soil incubations can provide a firmer basis on which to compare the relative fertility of different soils and management systems, against which fertilizer requirements could then be adjusted.

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