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Soil respiration, nitrogen mineralization and uptake in barley following cultivation of grazed grasslands

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Abstract Soil tillage was studied as a strategy to synchronize N mineralization with plant demand following ploughing of two types of grazed pastures [ryegrass/white clover (*Lolium perenne/Trifolium repens*) and pure ryegrass]. The swards were either rotovated and ploughed or ploughed only. Soil respiration, as determined by a dynamic chamber method, was related to net N mineralization and to plant N uptake in a subsequent spring barley crop (*Hordeum vulgare*). Diurnal variations in temperature were important for the CO_2 flux and care must be taken that temperatures during measuring periods are representative of the daily mean. Soil tillage increased the CO_2 flux considerably compared with untilled soil with total emissions of 2.6 and 1.4 t C ha^{-1}, respectively, from start of April to end of June. Sward type or rotovation did not markedly influence accumulated emissions. Rotovation significantly increased the content of nitrate in the soil until 43 days after rotovation, showing that net N mineralization occurred rapidly during this period, in spite of low soil temperatures (5–10 °C). Rotovation increased barley grain yield by 10–12% and N-uptake by 14%. For both sward types, rotovation caused an extra N-uptake in harvested plant material of about 12 kg ha^{-1}. The availability of soil inorganic N at the early stages of barley was important for the final yield and N-uptake. The results indicated that soil biological activity was not enhanced by rotovation and that the yield effect of rotovation was mainly caused by quicker availability and better synchrony between N mineralization and plant uptake due to earlier start of decomposition.

Keywords Soil tillage · CO_2 flux · N mineralization · Soil respiration · Grassland

Introduction

Nutrient accumulation in grazed pastures can lead to considerable build-up of soil organic N levels (Cuttle and Scholefield 1995). Therefore, the ploughing of grassland is followed by a flush of plant litter decomposition and a large increase in the mineralization-immobilization turnover of N (Francis et al. 1995) usually resulting in a net N mineralization as pasture residues have low C:N ratios. Ideally, this net N mineralization should be synchronized with subsequent crop demand, leading to increased yields and reduced leaching losses (Francis 1995; Goss et al. 1998; Stenberg et al. 1999).

Management options to synchronize N mineralization with plant demand include soil tillage. Tillage disrupts soil aggregates and exposes soil organic matter and microbial cellular tissue to rapid oxidation because of improved availability of O_2 and increase in decomposition surfaces (Dao 1998). Gupta and Germida (1988) found that most of the soil organic matter lost during cultivation of grassland soils could be attributed to mineralization of organic matter binding microaggregates into macroaggregates.

One strategy to improve the utilization of nitrogen from grassland is using soil tillage to increase mineralization in periods with high plant uptake in the spring and to reduce soil tillage in the autumn where leaching losses may occur. In humid, temperate climates, spring incorporation of the pasture into soil prevents leaching losses, but difficulties with synchronizing N release with crop demand may occur if net N mineralization is delayed by low temperatures or an initial immobilization phase.

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This study investigates the effect of soil tillage strategy on the turnover of soil organic matter following incorporation of different temporary grass swards. Soil respiration was used as a measure of soil biological activity, and we evaluated whether daytime CO_2 flux measurements with a dynamic chamber method could be used to estimate daily flux rates. Furthermore we investigated how the soil biological activity related to net N mineralization and plant uptake in the subsequent spring barley crop.

Materials and methods

Field experiment

The experiment was located in the Burrehøjvej field at Research Centre Foulum in the central part of Jutland (9°34′E, 56°29′N). The soil is classified as a typic Hapludult with 8.4% clay, 28.9% silt, 56.5% sand, 3.6% C and pH 5.6. In the previous three years (1994–1996) grass-clover and pure ryegrass were grazed by dairy cattle approximately 150 days $year^{-1}$ at an average stocking density of 4.8 cows ha^{-1}. The grass-clover, a mixture of perennial ryegrass and white clover was unfertilized, whereas 300 kg N $ha^{-1}year^{-1}$ was applied to pure ryegrass in mineral fertilizer (calcium ammonium nitrate). The swards were arranged in a block design in the field with two replicates.

In spring 1997, parts of each sward were either rotovated and ploughed or directly ploughed. The soil tillage treatments were placed randomly inside two blocks in each sward in plots of 6×6 m, yielding four replicate plots per treatment. Thus, the experiment had a split-plot design with pasture type as main plot factor and tillage as sub-plot factor. Plots were rotovated on 1 April to a depth of 6–8 cm and ploughed on 10 April to a depth of 20–22 cm. After two passes with a spring tine harrow, spring barley was sown on 15 April. The barley did not receive any fertilizer.

Immediately before the start of soil tillage operations, roots and tops of each sward type were sampled. In each plot, 16 soil cores (5.2 cm diameter) were sampled to a depth of 20 cm for determination of root biomass. The soil cores were washed gently on a 425 μm sieve and the remaining material was transferred to a white tray, where the root material was separated from soil mineral particles by decanting at least three times and finally by removal of non-root material using tweezers. For determination of above-ground biomass before soil tillage, grass tops were sampled in $2 \times 0.25\ m^2$ in each plot by cutting at the soil surface. Dry matter, C, N and lignin contents were determined in all root and top samples.

In each plot, above-ground plant biomass was sampled 39, 49, 61 and 104 days after rotavation during the growth of the barley in $4 \times 0.25\ m^2$ plots. In mid-August, harvest yields were obtained from an area measuring 3×3 m using a plot combine. Sub-samples were taken for determination of dry matter and N content. Soil was sampled from April to August (14, 30, 43, 58, 77, 100 and 151 days after rotovation) to a depth of 20 cm. From each plot, 16 soil cores (22 mm) were sampled, bulked and mixed. Ammonium and nitrate content were determined in 1 M KCl (1:5 w/v) soil extracts (Technicon 1974; Best 1976).

Soil surface CO_2 flux

For determination of the CO_2 flux, a dynamic system was used that consisted of a chamber (100 mm diameter, 150 mm high) coupled to a portable infrared gas analyser (IRGA) in a closed circuit (SRC-1 and EGM-1, respectively; PP Systems, Hitchin, Herts, UK). Soil temperature at 5 cm depth was measured concurrently using an attached temperature probe. For equipment details see Jensen et al. (1996).

The dynamic chamber was used in only one of the four replicated plots per soil tillage treatment and sward type. Six areas of 1×1 m with the soil kept bare were marked in each of the four plots. Three untilled reference plots were established in the undisturbed grass sward by gently removing the grass turf. On each day of measurement, the flux chamber was placed in the centre of each area of bare soil (36 squares total) three times during the day: 7–9 a.m., 10–12 a.m. and 1–3 p.m. Within each period, measurements in the same plots were spread across the whole 2 h period. Mean daily rates were then calculated as the arithmetic mean of all 18 replicated measurements within each treatment over the 7 a.m.–3 p.m. period.

Between 7 April and 25 June, the CO_2 flux was measured on 23 days avoiding measurements on rainy days or just after rainfall. On seven occasions rainfall started during the measurement period. Because of uncertainty regarding the influence of rainfall on the CO_2 flux from the soil pore space (Jensen et al. 1996) these measurements were excluded from the data.

To investigate short term spatial and diurnal variations in soil surface CO_2 flux, 25 points with an internal distance of 1 m in a 5×5 grid were marked in a ploughed part of the grass-clover field. The CO_2 flux was determined in all points 11 times during 36 h on 12–13 June (days 73–74 after sward rotovation).

Results and discussion

Incorporated pasture residues

The quantities of plant residues incorporated into the grass-clover or ryegrass fields were 9.4 and 12.1 t DM ha^{-1}, respectively (Table 1), with about 95% as roots in the 0–20 cm soil depth. These quantities are higher than those found in other studies (e.g. Høgh-Jensen and Schjørring 1997; Hauggaard-Nielsen et al. 1998) and this may be due to the greater age and more intensive use of the present pastures. Most residue C and N was found in ryegrass swards, but the C:N-ratio of these residues was lower than that of grass-clover. This difference can be explained by considering the N balance of the two systems. In pure ryegrass, the N-surplus (input in fertilizer, N_2-fixation, urine and manure minus output in grass biomass) over 3 years accumulated to about 980 kg N ha^{-1}, whereas the surplus in grass-clover swards was about 750 kg N ha^{-1} (Eriksen and Søegaard 2000). Higher fertilizer input and lower

Table 1 Pasture plant residues (top and roots to 20 cm soil depth) incorporated into soil

		t DM ha^{-1}		Carbon kg ha^{-1}	Nitrogen kg ha^{-1}	C:N-ratio	% lignin
		Average	SE				
Grass-clover	Top	0.6	<0.1	200	18	11	2
	Root	8.8	1.3	3180	156	20	10
Ryegrass	Top	0.6	<0.1	240	15	16	7
	Root	11.5	1.2	4100	283	15	6

N-uptake in herbage were the reason for the higher N-surplus in pure grass compared with grass-clover.

Soil surface CO_2 flux

The CO_2 flux was strongly influenced by the soil temperature. The flux always increased when comparing morning measurements with those in the afternoon (results not shown). The mean temperature of the three periods agree with the daily mean temperature (Fig. 1) when comparing to soil and air temperatures at the Meteorological Station at Research Centre Foulum.

Over 36 h in June, soil temperatures and CO_2 flux were measured concurrently in 25 points within a small area (Fig. 2). Variations due to changes in temperature were larger than the spatial variability in the field. Thus, the SD of the mean at any time was below 0.02 g CO_2 m^{-2} h^{-1} (Fig. 2) whereas the difference between minimum and maximum average flux rate over time exceeded 0.07 g CO_2 m^{-2} h^{-1}. Minima and maxima of the CO_2 flux closely followed those of the temperature with a delay of 2–3 h. The point not included in the course of the line was measured just after a very small shower. The rainfall was too low to be registered by the electronic rain gauge, but it clearly affected the CO_2 flux temporarily. This strong, but short-lived, effect of rainfall in the diurnal variation experiment, was also found by Rochette et al. (1991), and was probably caused by water physically displacing CO_2 in the topsoil. Thus it seemed reasonable to exclude rainfall-related events from the data.

The first and last three measurements over the 36 h corresponded to the measurement programme used in the main experiment, including tillage treatments and sward types. Thus, a comparison between the "working day" measurements and the "around the clock" measurements was possible. The average flux in the two adjacent "working day" measurements was 0.505 and 0.513 g CO_2 m^{-2} h^{-1}, whereas the comparative "around the clock" measurement showed an average of 0.534 g CO_2 m^{-2} h^{-1}. This difference in CO_2 flux was less than 5%, which we find satisfactory considering that this was one of the days with the highest diurnal temperature variation during the experiment. Similarly, Mielnick and Dugas (2000) compared CO_2 flux rates in a tall-grass prairie measured during midday (2 h), daytime (12 h) and day + nighttime (24 h) and found that they differed by less than 10%.

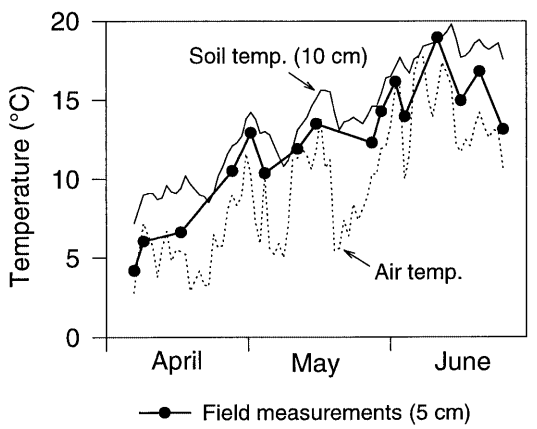

Fig. 1 Mean soil temperatures (5 cm depth) in three measurement periods compared with daily mean soil (10 cm depth) and air temperature

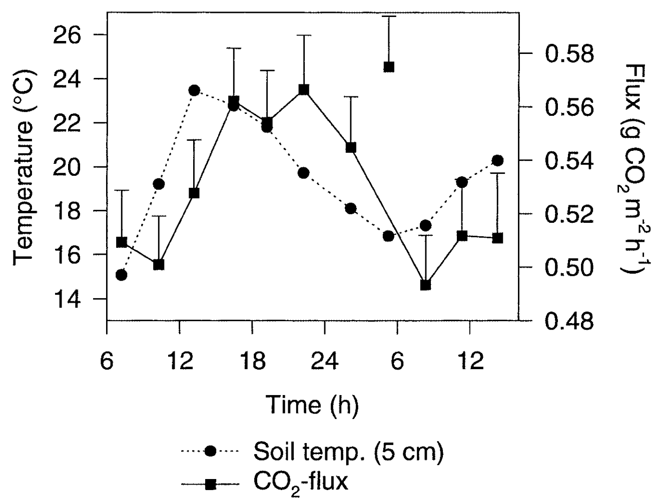

Fig. 2 Soil surface CO_2 flux and soil temperature (5 cm depth) during 36 h in June in a ploughed grass-clover field. The *omitted point* was caused by a short rainfall event (see text). *Error bars*: SE (n=25)

Temperature has commonly been found to be the major factor explaining annual variations in CO_2 flux (e.g. Buyanovsky et al. 1986; Duiker and Lal 2000; Rayment and Jarvis 2000) and differences due to management practices have been shown largely to be indirect effects on soil temperature (Wagai et al. 1998). Our study clearly shows the importance of diurnal variations in temperature for the CO_2-flux and emphasizes that care must be taken that temperatures during measuring periods are representative of the daily mean, in agreement with Anderson (1982). The large spatial variations in the field can be overcome by taking a large number of measurements (Rochette et al. 1991; Dugas 1993). The CO_2-flux did not appear to have any spatial structure or it occurred only at a very small scale, as suggested by Rochette et al. (1991).

Soil tillage increased the CO_2 flux considerably compared with the untilled soil (Fig. 3). Variations were higher after ploughing compared to where rotovation was carried out prior to ploughing. No clear difference was found between the two sward types in terms of soil respiration. Tillage has in some cases been found to have only a minor effect on field-CO_2 emissions throughout a crop growth period (Wagai et al. 1998; Aslam et al. 2000). In most cases, effects have been in the short-term, within hours or days after the tillage operations (Franzluebbers et al. 1995; Reicosky 1997; Reicosky et al. 1997; Ellert and Janzen 1999). Reicosky

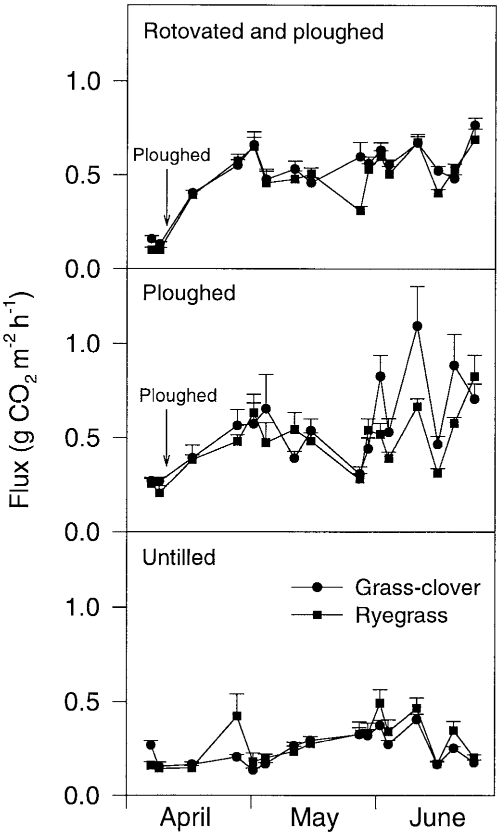

Fig. 3 Soil surface CO_2 flux in grass swards subjected to different soil tillage strategies. *Error bars*: SE ($n=6$)

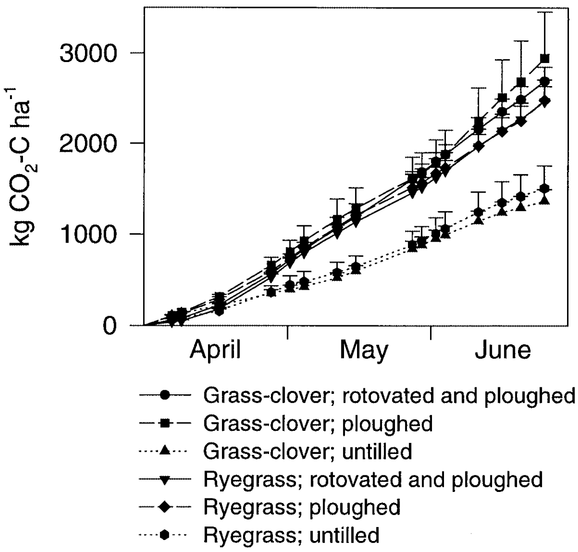

Fig. 4 Cumulated CO_2-emission from different grass swards subjected to different soil tillage strategies. *Error bars*: SE ($n=6$)

et al. (1997) found the greatest CO_2 flux within 2 h after tillage and suggested these short-term fluxes were due to the physical release from soil pores and solution rather than the result of an increased microbial activity. Increases in CO_2-emissions following tillage may originate partly from immediate physical release caused by tillage-induced changes in soil physical characteristics, and partly from increased microbial degradation of newly exposed protected soil organic matter and plant residues made more available by the tillage impact. In this experiment, our primary aim was to investigate effects of tillage method for pasture incorporation over the growth period of barley. Therefore, the exclusion of the initial days following rotovation and data related to rainfall seems justified.

The cumulated CO_2 emission was calculated by summing the flux in each time interval using the average values at both end points of the interval (Fig. 4). Following soil tillage the average total emission was 2.6 t C ha^{-1} and without soil tillage only 1.4 t C ha^{-1}. Sward type or rotovation did not markedly influence the accumulated emissions. From April to June the cumulated CO_2-emission in the tilled treatments was about 41% and 23% of the quantity of C in plant residues being incorporated in grass-clover and ryegrass fields, respectively. This estimate of C loss from incorporated pasture residues is based on the assumption that no decomposition of pasture roots occurred in the untilled treatment. This is clearly unlikely as the grass layer was removed in this treatment. Furthermore, any bias in the CO_2 flux methodology may also contribute to errors in such cumulative estimates. Due to the global change issue and the question of C sequestration in soils, methodologies for measuring soil surface CO_2 flux have received great interest over the past decade and a number of comparative studies have been published (e.g. Jensen et al. 1996; Bekku et al. 1997; Norman et al. 1997; Le Dantec et al. 1999). The general conclusion has been that dynamic chamber methods do not have large biases if used appropriately, but that the temporal and spatial variation in flux rates is so large that integration over time requires more or less continuous measurements. The temporal pattern illustrated in Fig. 3 and cumulated in Fig. 4 may therefore be biased by the non-continuous measuring schedule, perhaps missing important peaks in the pattern.

Soil inorganic N

Rotovation significantly increased the content of nitrate in the soil (Fig. 5) at the first three sampling dates (14, 30 and 43 days after rotovation) but with a decreasing level of significance (1‰, 1% and 5%, respectively). After 43 days, nitrate content was no longer affected by the rotovation treatment. Similarly, the content of exchangeable soil ammonium never showed any significant effects of rotovation, although low soil temperatures in April led to accumulation of ammonium. The increase in inorganic N content following cultivation (Fig. 5) probably reflects net N mineralization in the early part of the growth season (until mid May) where plant N uptake was insignificant. Evidently, significant

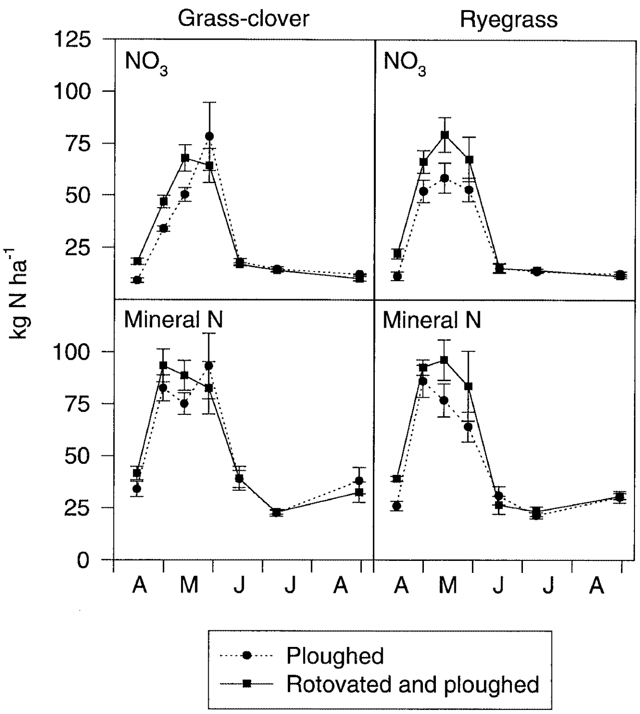

Fig. 5 Nitrate (NO_3) and mineral N (NO_3+NH_4) content in 0–20 cm soil depth following different soil tillage strategies for incorporation of grass swards. *Error bars*: ±SE ($n=4$)

net N mineralization occurred during this period, with the major part of the inorganic N already being released within the first 4 weeks after rotovation. This fast mineralization has also been observed in other studies (e.g. Hauggaard-Nielsen et al. 1998), but may seem surprising due to low soil temperatures (5–10 °C during this period. However, recently it has been proposed that disproportionately high N mineralization from green plant residues may occur at low temperatures (Magid et al. 2000). Andersen and Jensen (2000) have also found similar results and showed that the gross N immobilization decreases much more than the gross N mineralization at low temperature, thus causing net N mineralization to be little or even negatively influenced by temperature compared with C mineralization. This has important implications for synchronization with plant demand if temperature effects on net N mineralization can be more or less disregarded.

In incubation studies, N mineralization rates of disturbed soils has often been considerably higher than in undisturbed soils (e.g. Cabrera and Kissel 1988; Stenger et al. 1995). In the field, autumn stubble tillage has been shown to significantly increase nitrate leaching during autumn and winter (Hansen and Djurhuus 1997) probably as a consequence of increased N mineralization. Tillage-induced N mineralization during the growing season has only received little attention. When ploughing and rotavating soils in June, Powlson (1980) found slightly faster N mineralization than in the untilled soil, at a site previously under grass.

The two sward types only showed difference in nitrate content at one sampling date. Thirty days after rotavation the content of nitrate was significantly higher after the ryegrass sward than after the grass-clover sward ($P<0.001$). Conversely, significantly more ammonium was found in the soil after incorporation of grass-clover at 14, 30, 43 and 77 days after rotavation. This may be caused by the higher N-surplus during the pasture phase of the rotation, since a decreasing ratio of ammonium to nitrate content has been found on grassland soils receiving a high N input (Watson and Poland 1999). In this work the number and/or the activity of nitrifiers increased with increasing fertilizer N input.

Barley yield

Rotovation and ploughing compared with ploughing alone significantly increased grain dry matter of the spring barley by 10–12% and the N-uptake by 14% (Table 2). The yield or N-uptake in straw was not significantly affected by the rotovation treatment. The effect of rotovation at harvest was similar for both sward types.

However, sampling of above-ground plant biomass during the growth season revealed that the two types of grass histories were differently affected by the soil tillage procedures (Fig. 6). Where barley followed grass-clover, no significant effects of rotovation were observed at any point before maturity, contrary to the clear yield effect of rotovation. Breland (1994) observed similar findings, and proposed that this could be caused by mineralization of clover residues being retarded by even mixing into the soil compared with concentrated placement obtained by ploughing. In the current study, the inconsistent effects following grass-clover were more probably caused by the general uncertainty of the sampling technique. Where the barley crop followed cultivation of a ryegrass pasture, dry matter production and N-uptake were significantly increased by rotovation until 49 and 61 days after rotovation, respectively.

Table 2 Yield of spring barley at maturity following spring cultivation of different grazed pastures

	Grass-clover history		Ryegrass history	
	Grain	Straw	Grain	Straw
Yield (t DM ha^{-1})				
Ploughed	4.28	3.69	4.16	3.29
Rotavated and ploughed	4.72	3.72	4.67	3.50
$LSD_{0.95}$	0.17	0.64	0.43	0.57
N-uptake (kg N ha^{-1})				
Ploughed	76.9	42.8	72.5	37.0
Rotavated and ploughed	88.0	44.0	82.9	38.3
$LSD_{0.95}$ ($n=4$)	6.9	8.3	7.8	9.3

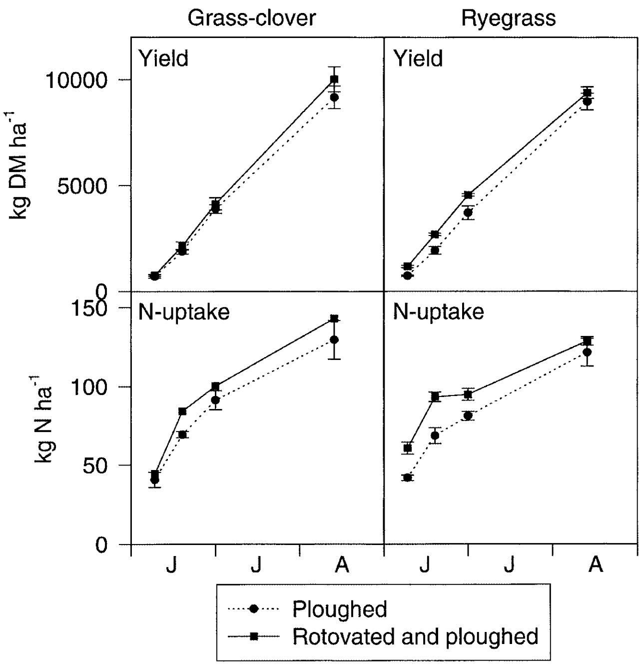

Fig. 6 Dry matter production and N-uptake following different soil tillage strategies for incorporation of grass swards. *Error bars*: ±SE ($n=4$)

Conclusion

Rotovation of the grass sward prior to ploughing significantly increased barley yields and N-uptake. For both sward types, rotovation caused an extra N-uptake in harvested plant material of about 12 kg ha^{-1}; this higher plant N uptake, probably decreased losses by nitrate leaching in the following autumn and winter.

Grain yields of barley were similar for the two types of grassland, but as the amount of C and N incorporated with the swards was higher (70% and 28%, respectively) for pure ryegrass than grass-clover, the degradability of the grass-clover residues must have been higher. This was also supported by similar net N mineralization patterns (Fig. 5). Huge yield effects were observed at harvest, although the effect of rotovation on soil inorganic N levels was only significant in early spring. This agrees with the finding of Hauggaard-Nielsen et al. (1998) that the availability of soil inorganic N at the early stages of barley is a key factor for the final barley yield and N-uptake.

The yield effect of rotovation may have been caused by increased mineralization due to tillage-induced exposure of soil organic matter to oxidation. However, the CO_2 flux measurements failed to detect any differences in soil respiration between the tillage treatments, indicating that soil biological activity was not enhanced by rotovation. This further suggests that the effect of rotovation was mainly caused by quicker availability and better synchrony between N mineralization and plant uptake due to the earlier start of decomposition.

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