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Soil N dynamics and N yield of barley grown on Breton loam using N from biological fixation or fertilizer

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Summary. Soil N dynamics and barley yields (*Hordeum vulgare* L.) were compared in pot experiments using surface samples from a Gray Luvisol under three cropping systems at Breton, Alberta: (1) an agroecological 8-year rotation including cereals, forage, and fababeans (*Vicia faba* L.) as green manure, from wich two plots were selected, one following fababeans, and the second following 3 years of forage; (2) a continuous grain system, with fertilizer N at 90 kg ha^{-1} year^{-1}; and (3) a classical Breton 5-year rotation [following oats (*Avena sativa* L.)] involving forage and cereals, without returning crop residues to the land, selecting one plot with PKS treatment and a second as control. The fertilizer N equivalent for the cropping system; "A_N" value and "A" value (analogous to A_N, but in fertilizer ^{15}N units, soil biomass, and C and N mineralization were monitored. In the first agroecological plot (after fababeans), grain and total plant biomass production were 116% greater than from the continuous grain treatment. Barley plants in the two agroecological plots derived 48.5% and 37.8%, respectively, of their N requirement from non-labelled soil N sources not present in the continuous grain plot. At crop maturity, the recovery of ^{15}N microbial biomass was 1.5 times higher in soil from the first agroecological plot than from the continuous grain plot. The fertilizer N equivalent was 2670 mg pot^{-1} (485 kg ha^{-1}) for the first and 1850 mg pot^{-1} for the second agroecological treatment. Fertilizer N equivalent values exceed net amounts of N mineralized by a factor of 4. Recovery by the barley crop of ^{15}N added at 55 mg pot^{-1} was more efficient in the agroecological treatments (45%–51%) than in the continuous grain or classical Breton treatments (35%–37%). It was concluded (1) that past soil history may be associated more with the ability of barley plants to compete for available N, and hence the use of N, than with net soil N mineralization; and (2) an increased supply of N to crops following the incorporation of fababean residues, manure application, and the soil N-conserving effect of growing legumes were all partly responsible for the observed differences in soil fertility.

Key words: Agroecological rotation – *Hordeum vulgare* – Microbial biomass – ^{15}N – Rotation effects – Pot experiment – Soil nitrogen

A goal of sustainable agricultural systems is to maintain or improve the quality of land resources, the environment, and the human livelihood, including economic resources, derived from them (Weil 1990). To achieve this goal, traditional and modern technologies are combined with an increased reliance on renewable resources in a shift from a substance-based to a knowledge-based paradigm. One approach involves complex cropping systems, characterized in part by diverse crops grown as intercrops or in rotation, additional N supplied by legumes, and the return of crop residues, manures, or other organic materials to the soil.

Terms like "N residual effect" (De et al. 1983) and "fertilizer N replacement value" or N equivalent (Hesterman et al. 1987) are used to describe the role of legumes in crop rotations. They refer to the amount of inorganic N required following a non-legume crop to produce another non-legume crop with an equivalent yield to that obtained following a legume. This concept does not distinguish between biological N_2 fixation and the "N-conserving effect" which results from substitution by legumes of biologically fixed N for soil N. Recently, ^{15}N methodology has been used to measure the residual effects of legumes to circumvent problems with non-isotopic methods (Senaratne and Hardarson 1988).

Recent reports (Cook 1988; Bezdicek and Granatstein 1989; Lee and Wani 1989; Fyson and Oaks 1990) have confirmed the positive nature of "rotation effects" reported since the beginning of this century. The effects have been attributed to numerous biological and physical factors.

Comprehensive examination of these possibilities at a common site is required. Accordingly, we have undertak-

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en a study in three cropping systems on a Gray Luvisol in central Alberta. Mineralizable soil N following one cycle of an 8-year rotation using fababeans as green manure (agroecological rotation) was about double that following 60 years of a 5-year rotation involving forage and cereal crops but without returning the crop residues to the soil (Wani et al., unpublished results 1990). Although there is a rapid and substantial increase in N availability associated with the agroecological system, further evidence is required in order to test the hypothesis that differences in soil quality between the agroecological system and the continuous grain and classical Breton rotation systems are restricted to N availability.

The objectives of the present investigation on a Gray Luvisol under three cropping systems, over periods from 9 to 60 years, were (1) to test the hypothesis that barley yields, under greenhouse conditions, were greater when the soil was from a rotation including fababeans with residues returned to the soil (agroecological) than from cropping systems on the same soil using mineral N fertilizers (continuous grain) or containing forage but with no residues returned to the soil (classical Breton rotation); and if true, (2) to compare N dynamics by (a) determining, for soil from a control treatment, how much added mineral N would be necessary to achieve yields equal to those observed on samples of soil from the agroecological treatment; (b) comparing amounts and availability of N, as expressed by the "A" and "A_N" in the soils from the three rotations; and (c) recording the distribution of native soil N and of fertilizer N among biomass, mineral, and organic moieties for soils from the three cropping systems.

Materials and methods

Site description and cropping systems

The soil samples were taken from the long-term University of Alberta plots near the town of Breton, Alberta (53° 07′ N, 114° 28′ W), 110 km southwest of Edmonton. The dominant soils in the region are Orthic Gray Luvisols (Lindsay et al. 1968). Three cropping systems were compared (1) an agroecological 8-year rotation [barley, fababeans, barley, fababeans, barley underseeded to red clover (*Trifolium pratense* L.) and brome grass (*Bromus inermis* Leyss.), forage, forage, forage] and (2) a continuous grain system, both first seeded in 1980, and considered established in 1981; and (3) a classical Breton 5-year rotation [wheat (*Triticum aestivum* L.), oats, barley underseeded to alfalfa (*Medicago sativa* L.) and brome grass, forage, forage] established in 1930. The area containing the agroecological and the continuous grain plots had been in a crop rotation from 1940 to 1964, after which it was used for general annual grain production with little or no added fertilizer until 1980.

In the continuous grain system, barley had been grown annually since 1981 and NPKS fertilizer at 90:22:46:5.5 kg ha^{-1} year^{-1} had been applied. All crop residues had been returned to the soil except in the years when barley was underseeded to red clover and brome grass. The agroecological rotation was designed to be self-sufficient in N as part of an integrated grain-forage-livestock agricultural ecosystem. No N was applied as chemical fertilizer but PKS had been added annually at 22:46:5.5 kg ha^{-1} year^{-1}. Integration with livestock production and return of manure after feeding the barley, forage, and fababeans to livestock was simulated to two ways. First, the fababeans were ploughed down as green manure after removing 6 m^2 for yield determinations. Second, manure equivalent to 70% of the N removed as forage was returned in the autumn (normally, but occasionally the next spring) to the plots that had been broken from forage, so that each plot was manured once in every cycle of the rotation. On completion of the rotation the forage stubble was ploughed into the soil.

Two treatments were selected from the agroecological rotation (1) following fababeans and (2) following 3 years of forage. Two fertilizer treatments (following oats) were selected from the classical 5-year Breton rotation, one fertilized with PKS and the other as a control, both following oats. The PKS treatment plots had been fertilized with P at 9 kg ha^{-1} year^{-1} between 1930 and 1979; from 1980 on, PKS was applied at 22:46:5.5 kg ha^{-1} year^{-1}. The control plot had not been fertilized since 1930. In the classical Breton rotation, crop residues were removed from the plots.

Surface soil samples were collected in early October 1989 (Table 1). Four replicated samples were obtained from each plot by splitting a well mixed bulk sample obtained by pooling several subsamples. The soil samples were air-dried and undecomposed coarse plant residues were removed.

Barley growth and ^{15}N redistribution under greenhouse conditions

The five treatments (two agroecological, two from the classical Breton rotation, and one continuous grain were replicated four times in a completely randomized design, using plastic pots (22 cm inner diameter) without drainage holes, each containing 5.5 kg soil from the treatments described above. Plant residues, equivalent to the quantity removed, were weighed and mixed with the soil in each pot. Before the barley was sown, superphosphate and K_2SO_4 were applied to provide P at 55 mg pot^{-1}, and S at 22 mg pot^{-1} (10 and 4 kg ha^{-1}, respectively). Barley (cv. Heartland) was seeded on 5th December, 1989, and thinned to four plants per pot 7 days after emergence.

At the time of thinning, N as ^{15}N $(NH_4)_2SO_4$ (25.19 atom% excess) was applied in solution at 55 mg pot^{-1} (10 kg ha^{-1} equivalent) to the pots to be sampled at maturity. In the remaining treatments an equal amount of N was applied as unlabelled $(NH_4)_2SO_4$.

Table 1. Properties of soil samples collected before sowing from long-term plots under different cropping systems

Treatment	pH	Moisture content (g 100 g^{-1} soil)		Total C (g kg^{-1} soil)	Total N (g kg^{-1} soil)	Mineral N (mg kg^{-1} soil)	Clay (g kg^{-1} soil)	Silt (g kg^{-1} soil)	Cation exchange capacity (cmol kg^{-1})
		Field capacity	Wilting point						
AER-1	6.91^{a}	36.20^{a}	11.90^{a}	30.9^{a}	2.5^{a}	66.6^{a}	191^{a}	385^{b}	19.4^{a}
AER-2	6.30^{c}	35.30^{a}	11.05^{a}	24.1^{b}	2.1^{b}	34.7^{b}	198^{a}	$397^{a,b}$	16.8^{b}
CBR-1	6.15^{d}	$30.65^{b,c}$	8.05^{b}	18.9^{c}	1.6^{c}	$15.4^{c,d}$	160^{b}	$386^{a,b}$	11.9^{d}
CBR-2	6.45^{b}	31.80^{b}	8.30^{b}	16.9^{d}	1.4^{d}	12.0^{d}	161^{b}	411^{a}	13.3^{e}
CG	6.34^{c}	20.20^{c}	8.85^{b}	19.4^{c}	1.6^{c}	18.3^{c}	$183^{a,b}$	$396^{a,b}$	14.5^{c}

Means of two replicates; figures with different letters within a column varied significantly ($P \leq 0.05$)

AER, agroecosystem rotation: 1, following fababeans ; 2, following 3 years of forage; CBR, classical Breton rotation; 1, PKS treatment following oats; 2, no fertilizer following oats; CG, continuous grain system

The moisture content of the pots was maintained at 70% water-holding capacity by adding distilled water every 2nd day to return the pots to their prescribed weight. The temperature in the greenhouse was $21 \pm 1\,^{\circ}$C throughout the plant growth period. The plants were grown with a 12-h day and night cycle. Supplementary light was provided by 400 W Son/T high-pressure sodium lamps. The photon flux density (PAR) in the greenhouse varied from 500 to 1680 μmol m^{-2} s^{-1} depending on cloud cover.

Soil from the Breton control treatment was used separately to determine the N equivalent of the four remaining treatments. A completely randomized design was used with four replicates of five N rates: 55, 275, 550, 825, and 1100 mg pot^{-1} as $(NH_4)_2SO_4$. For the treatments given N at 275 to 1100 mg pot^{-1}, half the N was applied 8 days after emergence; the remainder was applied 12 days after emergence.

All treatments were sampled four times (22, 50, 74, and 102 days after emergence). The plants were cut at the soil surface, and the roots were hand-picked from the pots and washed free of soil. On the last sampling date the plants were mature and the ears were separated from the shoots.

Analyses

The grains were separated from the ears and cleaned. All plant materials were dried at 70 °C then weighed.

Microbial biomass C was measured by the chloroform-fumigation and incubation method (Jenkinson and Powlson 1976) on sieved (10 mesh) soil from the greenhouse pots, adjusted to 55% water-holding capacity. Microbial biomass C was calculated as C mineralized from fumigated soil incubated for 10 days minus C mineralized from non-fumigated control soil incubated for 10 days, and Kc was taken as 0.411 (Anderson and Domsch 1978).

Microbial biomass N was calculated as mineral N ($NH4^{+} + NO3^{-}$) in fumigated soil incubated for 10 days minus mineral N in non-fumigated soil incubated for 10 days, with Kn at 0.57 (Jenkinson 1988). Non-microbial organic ^{15}N was calculated by subtracting microbial ^{15}N and mineral ^{15}N from total soil ^{15}N.

The non-labelled, dried plant material was ground, digested in concentrated H_2SO_4 and H_2O_2, and analyzed for total N content using a Technicon Autoanalyser (Technicon 1977a). For ^{15}N determinations, plant material and air-dried soil subsamples were further ground in a Brinkmann ultra high speed ball mill.

The total N content and atom% ^{15}N abundance were determined in finely powdered, labelled, plant and soil samples using a Carlo Erba NA-1500 Nitrogen Carbon Sulphur Analyzer and a Micromass triple collector mass spectrometer (SIRA, Series II, VG Isogas, Cheshire, England) connected by a continuous-flow interface.

Mineral N was extracted from the soil samples into 2 M KCl (25 g soil to 125 ml solution) for 1 h and then filtered through Whatman No. 42 filter paper. The extracts were stored frozen prior to analysis for concentration of NO_3^- and NH_4^+-N using automated cadmium reduction (Technicon 1977b) and indophenol (Technicon 1973) procedures, respectively.

The ^{15}N atom% abundance was measured on NH_3 collected by diffusion from KCl extracts of soil as described by Brooks et al. (1989).

Calculations

The ^{15}N:^{14}N ratio of plants grown in pots with ^{15}N labelled mineral N would be the same for the rotation treatments and their respective controls if there was no soil accumulation of available N from the treatments. A dilution of ^{15}N in plants grown in soil from these treatments would be evidence, therefore, that residual available N was accumulated. A ^{15}N isotope dilution was used to estimate the extent of N accumulation in the two agroecological and the fertilized Breton treatments, with the continuous grain and the unfertilized Breton treatments as the respective controls, using the following:

$$\%\mathrm{Ndfu} = [1 - (\%\mathrm{Ex}_T / \%\mathrm{Ex}_C)] \times 100$$

where %Ndfu is the percentage of total plant N derived from unlabelled source, $\%\mathrm{Ex}_T$ is the atom% ^{15}N excess in treatment plants, and $\%\mathrm{Ex}_C$ is the atom% ^{15}N excess in control plants.

The A_N value (Jansson 1975) was used to calculate the amount of soil N equal in availability to recently immobilized ^{15}N as follows:

$$A_N = B(1-y)/y$$

where B is the amount of organic ^{15}N (recently immobilized) and y is the proportion of labelled N in the total N mineralized.

The A value (Fried and Dean 1952) is formally identical to A_N, but B is replaced by the amount of fertilizer ^{15}N added (55 mg pot^{-1}).

A harvest index was calculated as grain mass × 100/total dry matter.

N-use efficiency was defined as the grain mass produced per unit mass of N in dry matter (non-dimensional).

The N equivalent was defined as the amount of fertilizer N required to obtain, in the control treatment, a yield equal to the yield of the specified treatment. It was calculated by regressing the yield in control pots on added mineral N.

Statistical analysis

The data were analyzed using the General Linear Model procedure of SAS (1987). Analysis of variance was used to test the significance of cropping systems and sampling dates; treatment means were compared using the least significant difference procedure. Linear regression models were fitted to the data for plant dry matter production and total N uptake as a function of added N. Grain, total plant dry matter, and total plant N yields were regressed against plant age (SAS 1987). The regressions of shoot biomass, total plant biomass, and total plant N yield on plant age were compared between treatments using the F statistic (Steel and Torrie 1980).

Results

Properties of the pre-sowing soil samples varied significantly between cropping systems (Table 1). Although characteristics such as the clay content and the cation exchange capacity were variable, the greatest differences were observed in mineral N, which varied by a factor of 5, and in total C and N.

Plant height, tillers, and shoot:root ratios

By 22 and 50 days after emergence the height of the barley varied significantly among the cropping systems. At 22 days after emergence, the tallest plants (42 cm) were in the agroecological plots, followed by those in the control Breton plot (37 cm). Similar trends were observed 50 days after emergence (results not shown) but by 74 and 102 days after emergence the plant height did not differ among treatments.

The greatest number of productive tillers plant^{-1} was observed in agroecological 1 (4.5) = agroecological 2 (3.6) > continuous grain (2.1). At 22 days after emergence the shoot:ratio (w:w) of plants in treatment agroecological 1 (6.2) was marginally, but not significantly, higher than in the continuous grain treatment (4.5). By 50 days after emergence the shoot:root ratios in both agroecological treatments had decreased, but thereafter increased until maturity. By 102 days after emergence the plants in treatment agroecological 1 had the lowest shoot:root ratio (results not shown).

Barley growth patterns and biomass production

Mean production across the cropping systems increased significantly ($P \leq 0.001$) with plant age, from 1.4 g pot^{-1} at 22 days after emergence to 34.2 g pot^{-1} at 102 days after emergence. Similarly, mean plant biomass production across the sampling dates varied significantly ($P \leq 0.001$) amongst the treatments with 34.4 g pot^{-1} in agroecological 1 followed by agroecological 2 > continuous grain and Breton 1 > control Breton. Total plant biomass production in agroecological 1 exceeded that of the continuous grain treatment by a factor of 1.5–2.5 depending on date (Fig. 1). Similar results for mean shoot and root mass were observed amongst the treatments and sampling dates except that the highest mean shoot mass was recorded 74 days after emergence and the highest root mass was recorded 50 days after emergence (data not shown). Simple linear regressions on time accounted for 88%–99% of the variation in total plant mass, but only 56%–76% of the variability in shoot mass. The slopes of the linear regressions of shoot mass and plant biomass on plant age varied significantly among the cropping systems. The highest rate of increase in plant mass was in the first agroecological treatment > agroecological 2 > fertilized Breton and continuous grain > control Breton.

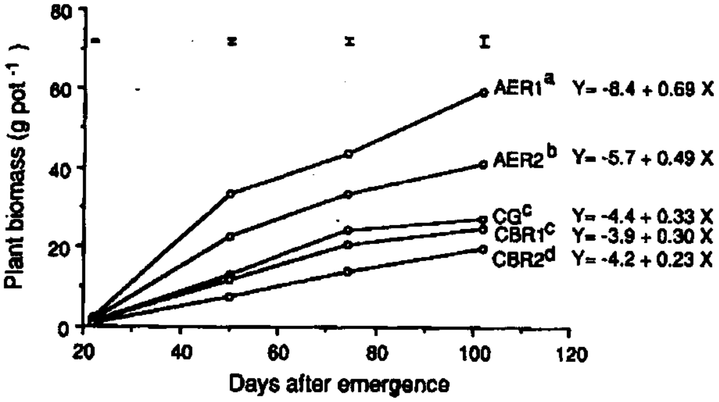

Fig. 1. Barley plant biomass (shoot + root) during growth in the greenhouse in surface soil from five cropping systems. Slopes of regression lines for treatments followed by different lower case letters varied significantly ($P \leq 0.05$). AER 1, following fababeans in an 8-year agroecological rotation; AER 2, following 3 years of forage in an 8-year agroecological rotation; CG, continuous grain; CBR 1, classical 5-year Breton rotation fertilized with PKS, following oats; CBR 2, classical 5-year Breton rotation, unfertilized, following oats

Total plant N accumulation

The mean plant N yield increased ($P \leq 0.05$) with plant age, and varied among the treatments. From the beginning, plant N yield was greatest in the two agroecological treatments > continuous grain and fertilized Breton > control Breton (Fig. 2). At maturity, the total N yield in the plants of the two agroecological treatments 822 and 623 mg pot^{-1}, respectively was more than double that observed in plants grown in soil from the continuous grain plots (308 mg pot^{-1}). Simple linear regression on time accounted for 86%–96% of the variation in plant N. The slowest rate of plant N accumulation was in the control Breton treatment; the fertilized Breton and continuous grain treatments were intermediate in plant N uptake.

Grain N concentration and content, atom% ^{15}N excess, and ^{15}N fertilizer recovery

As with other growth parameters and with the total plant N yield, grain N concentrations and quantities of N in grain, shoots, and roots at harvest time were significantly higher in the agroecological treatments than in the others. N concentrations observed in shoots and roots rarely differed between treatments (Table 2).

The atom% ^{15}N excess in grain, shoots, and roots from the two agroecological treatments was significantly

Table 2. Dry matter, N concentration and content, atom % ^{15}N excess, and fertilizer recovery in grain, shoots, and roots of barley

Variable	Treatment				
	AER-1	AER-2	CBR-1	CBR-2	CG
Grain					
Mass (g pot^{-1})	25.63^{a}	17.87^{b}	11.08^{c}	7.31^{c}	11.82^{c}
N (mg 100 mg^{-1} grain)	2.31^{a}	2.46^{a}	1.65^{b}	1.81^{b}	1.81^{b}
N content (mg pot^{-1})	593.5^{a}	419.4^{b}	182.7^{c}	130.9^{c}	208.5^{c}
Atom % ^{15}N excess	0.3840^{c}	0.4449^{c}	0.7590^{b}	0.9763^{a}	0.7394^{b}
^{15}N fertilizer recovery (%)	37.1^{a}	29.3^{b}	22.5^{c}	20.8^{c}	24.6^{b,c}
Shoots					
Mass (g pot^{-1})	25.63^{a}	18.92^{b}	10.99^{c}	10.34^{c}	12.67^{c}
N (mg 100 mg^{-1} shoot)	0.65^{b}	0.86^{a}	0.62^{b}	0.61^{b}	0.59^{b}
N content (mg pot^{-1})	171.1^{a}	162.0^{a}	68.6^{b}	62.8^{b}	74.3^{b}
Atom % ^{15}N excess	0.3855^{d}	0.4731^{d}	0.9051^{b}	1.1186^{a}	0.7068^{c}
^{15}N fertilizer recovery (%)	11.1^{a,b}	12.7^{a}	10.3^{a,b}	12.9^{a}	8.7^{b}
Roots					
Mass (g pot^{-1})	7.22^{a}	4.21^{b}	2.46^{b,c}	1.80^{c}	2.50^{b,c}
N (mg 100 mg^{-1} root)	1.00^{a}	1.34^{a}	0.92^{a}	0.92^{a}	1.21^{a}
N content (mg pot^{-1})	70.3^{a}	49.8^{b}	22.3^{c,d}	16.4^{d}	28.5^{c}
Atom % ^{15}N excess	0.2724^{d}	0.4292^{c}	0.6296^{b}	1.0977^{a}	0.6516^{b}
^{15}N fertilizer recovery (%)	3.2^{a,b}	3.3^{a}	2.3^{b}	2.9^{a,b}	3.0^{a,b}

Means of four replicates; means with different letters in the same row varied significantly ($P \leq 0.05$) from each other
For explanation of abbreviations, see Table 1

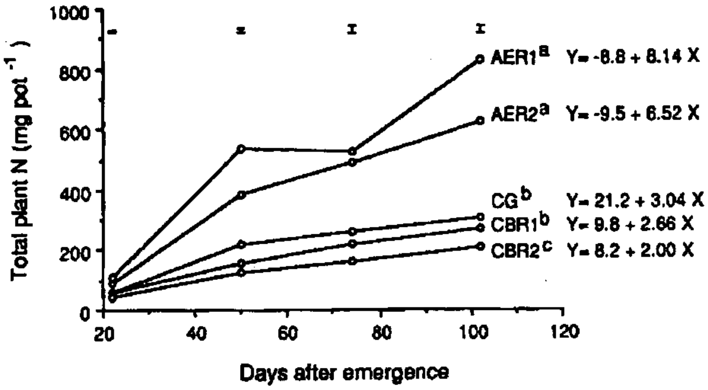

Fig. 2. Total plant N uptake by barley grown in surface soil from five cropping systems. Slopes of regression lines for treatments followed by different lower case letters varied significantly ($P \leq 0.05$). For explanation of abbreviations, see Fig. 1

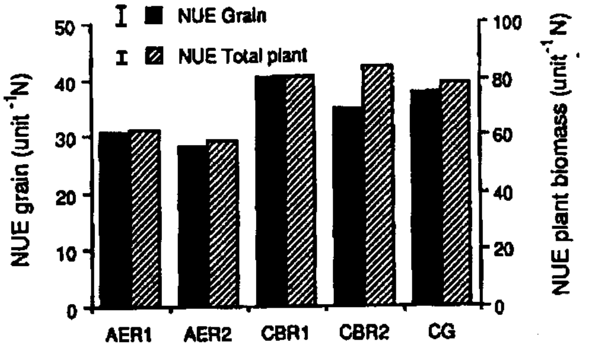

Fig. 3. N-use efficiency (NUE) for grain and total plant biomass production of barley grown in soil from five cropping systems. For other explanations, see Fig. 1

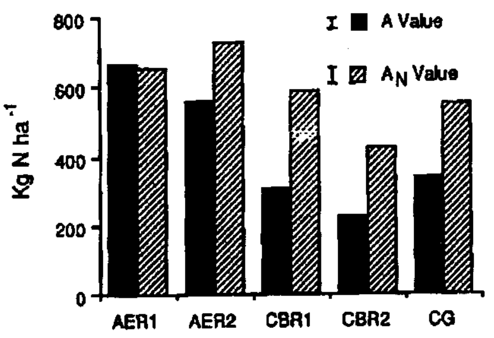

Fig. 4. A and A_N values of the soils from five cropping systems, measured 102 days after emergence. For explanation of treatments, see Fig. 1

lower compared with the other treatments (Table 2). In barley grain, shoots, and roots from the first agroecological treatment (following faba beans), the % ^{15}N excess was only about half that observed in the respective plant parts in the continuous grain treatment. Similarly, within the 5-year rotation, a significantly lower atom% ^{15}N excess was observed in plant parts of the fertilized Breton treatment (PKS) than in those of the control Breton. The recovery of ^{15}N fertilizer in barley grain was significantly higher in agroecological 2 (following forage), than in the continuous grain treatment. The recovery of fertilizer ^{15}N did not differ between treatments in the 5-year rotation. The total ^{15}N fertilizer recovery in plants was 51.4% (agroecological 1), 45.3% (agroecological 2), 35.1% (fertilized Breton), 36.6% (control Breton), and 36.3% (continuous grain). The amount of ^{15}N translocated to grain varied from 57% (control Breton) to 72% (agroecological 1) of total plant ^{15}N.

N-use efficiency and harvest index

The harvest index was similar in all the treatments except the fertilized Breton, in which a significantly higher harvest index (50%) was observed than in the control Breton treatment (41%; results not shown). The N-use efficiency, either for grain (28.1–40.6) or total plant biomass (58.4–84.1), varied significantly ($P \leq 0.05$) between treatments (Fig. 3). The lowest N-use efficiency for total plant biomass production was recorded in the two agroecological systems, with greater efficiency in the Breton rotation and continuous grain systems. A similar trend was also recorded for grain mass.

Residual N in barley and A_N value of soil

The proportion of N derived from unlabelled sources in the grain, shoots, and roots of plants grown in soil from the agroecosystem plots, using the continuous grain treatment as a control, varied from 33.1% to 58.2% of total N. In the 5-year, fertilized, Breton rotation treatment, the proportion of unlabelled N varied from 22.3% to 42.6% among plant parts, with 25% for the complete plant, using the unfertilized Breton plot as a control (Table 3). Whereas the proportion of unlabelled N varied significantly between the two rotations, the absolute amounts of unlabelled N in the plants differed significantly both within and between rotations.

The A values varied from 226 to 666 kg ha^{-1} (Fig. 4). There was significantly more available N in soil from the

Table 3. N derived from an unlabelled source in excess of that present in the respective controls for barley grown in soil from three cropping systems

Treatment	N derived from an unlabelled source							
	Per cent				Amount (mg pot^{-1})			
	Grain	Shoots	Roots	Total	Grain	Shoots	Roots	Total
AER 1	48.1^a	45.5^a	58.2^a	48.5^a	285.5^a	78.3^a	40.9^a	404.7^a
AER 2	39.8^a	33.1^a	34.1^b	37.8^{a,b}	166.9^b	53.6^a	17.0^b	237.5^b
CBR 1	22.3^b	25.7^a	42.6^{a,b}	25.0^b	40.7^c	17.6^b	9.5^c	67.8^c

For explanation of abbreviations, see Table 1; in calculating the N dilution in the two agroecological treatments, the continuous grain treatment was used as a control; for the classical Breton rotation, the unfertilized treatment was used as a control agroecological plots (characterized by the application of animal manure and green manure) than in the continuous grain or classical Breton treatments. Although A_N values were greatest in the agroecological treatments, the treatment differences were not significant.

Fertilizer N equivalent and response to added N

The grain yield and total plant N uptake 102 days after emergence increased consistently with increasing rates of additional N in the control Breton treatment. The mean plant biomass increased ($P \leq 0.01$) by 20.6 g pot^{-1} with N additions of 825 or 1100 mg pot^{-1}. At harvest, the maximum plant biomass was 39.25 g pot^{-1}, obtained with additional N at 1100 mg pot^{-1}, and this value did not differ from that observed with 825 mg N pot^{-1}. The plant biomass value obtained 102 days after emergence and the level of additional N were linearly related ($r^2 = 0.81$, $n = 20$). Similarly, grain yield was related to added N ($r^2 = 0.77$, $n = 20$).

The amount of fertilizer N required for the control treatment to achieve grain yields comparable with those of a specified treatment varied significantly among treatments, with the continuous grain and the fertilized Breton plots providing less N than did the two agroecological plots.

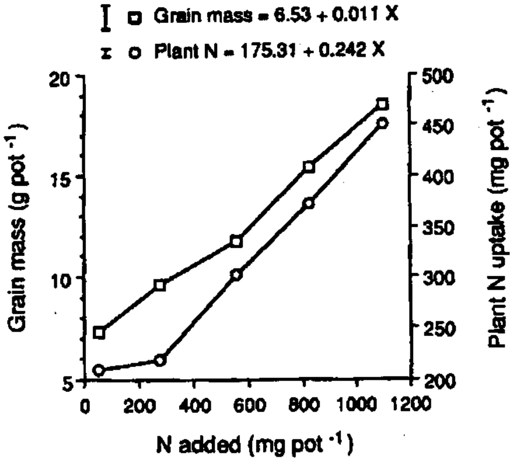

Fig. 6. Microbial biomass C in soil samples collected during the growth of barley in surface soil from five cropping systems. For explanation of treatments, see Fig. 1

Table 4. Amount of fertilizer N equivalent required to obtain barley grain yield and total plant N uptake in unfertilized Breton rotation equal to that in the specified treatments

Treatment	Fertilizer N (mg pot^{-1})	
	Grain	Total plant N uptake
AER-1	1785^{a}	2676.2^{a}
AER-2	1060^{b}	1854.4^{b}
CBR-1	425^{c}	547.8^{c}
CG	$636^{b,c}$	394.4^{c}

Figures within a column with different letters varied significantly ($P \leq 0.05$)
For explanation of abbreviations, see Table 1

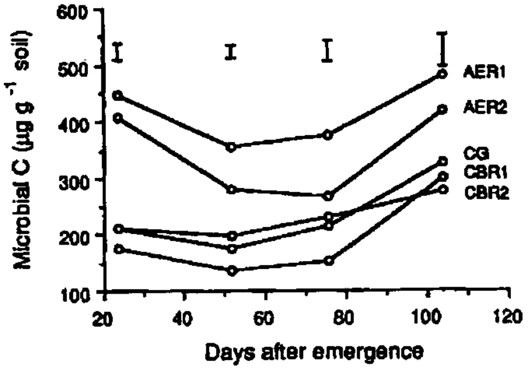

Fig. 5. Grain yield and total plant N uptake at maturity by barley grown in soil from the unfertilized Breton rotation treatment in response to applied N. Slopes of regression lines for treatments followed by different lower case letters varied significantly ($P \leq 0.05$)

Microbial biomass and respiration

Mean microbial C did not differ among the continuous grain and the two Breton rotation plots but was significantly lower ($P \leq 0.0$) in these treatments than in the two agroecological plots. The mean microbial biomass declined significantly with increasing plant age up to 50 days after emergence, and then increased for the duration of the growth period (Fig. 6). There was no significant interaction between treatments and sampling dates. The mean microbial respiration in non-fumigated soil varied significantly over 10 days, among treatments. The C respired over 10 days in agroecological plot 1 (209 μg g^{-1} soil) and agroecological plot 2 (162 μg g^{-1} soil) was significantly higher than that in the fertilized Breton treatment, which did not differ from the C respiration from the control Breton rotation or the continuous grain treatment. Similar trends were observed for microbial respiration at all times (Table 5).

Soil N during crop growth

Mean mineral N decreased from 35 mg kg^{-1} 22 days after emergence to 4 mg kg^{-1} soil 74 days after emergence, with a small increase to 7 mg kg^{-1} soil by 102 days after emergence (Table 5). The mineral N content was highest, by a factor close to 2, in the agroecosystem rotation, and lowest in the 5-year rotation.

The quantity of microbial N varied significantly among treatments, when averaged across sampling dates, with the highest value in the two agroecological treatments and the lowest value in the control 5-year rotation. With increasing plant age, microbial N also increased significantly: $22 < 50$ and $74 << 102$ days after emergence (Table 5). The mean net mineralization of N over 10 days varied significantly among treatments, with agroecological $2 >>$ agroecological $1 >$ continuous grain and fertilized Breton rotation $>$ control Breton rotation. In contrast to microbial N, the size of this N component was greater 22 days after emergence than 74 or 102 days after emergence.

Proportional N pool sizes, net N mineralization, and ^{15}N recovery in soil samples

A greater proportion of soil N was present in mineral and microbial froms in soil from the agroecosystem than from the 5-year rotation or the continuous grain system. Although greater proportions of ^{15}N than of soil N were found in mineral and microbial forms, the rotational relationships were less pronounced with ^{15}N (Table 6). ^{15}N fertilizer recovery as microbial biomass in the unfertilized Breton rotation was significantly lower than in the rest of the treatments. The recovery of ^{15}N fertilizer as non-microbial organic N was lower in agroecological treatment 1 than in any other treatment. Net N mineralization 102 days after emergence did not exceed 0.66% of total soil N but approached 7.85% of recovered ^{15}N.

Discussion

The results of this study are consistent with the initial hypothesis that the barley yield under controlled growth conditions, and by that criterion, soil fertility, was greater when the soil was from a rotation including fababeans with residues returned (agroecosystem) than from cropping systems on the same soil based on mineral fertilizers (continuous grain) or containing forage but with no residues returned (classical 5-year Breton rotation). Further, soil from the unfertilized Breton treatment that included

Table 5. Mineral N, microbial N, net mineralized N content, and microbial respiration in soil at different stages of barley growth

Variable	Treatment				
	AER-1	AER-2	CBR-1	CBR-2	CG
22 days after emergence					
Mineral N ($\mu g\ g^{-1}$ soil)	64.8^{a}	58.5^{a}	13.1^{c}	17.7^{c}	27.7^{b}
Microbial N ($\mu g\ g^{-1}$ soil)	33.6^{b}	40.5^{a}	22.4^{c}	15.1^{d}	24.5^{c}
Net N mineralized ($\mu g\ g^{-1}$ soil 10 days^{-1})	20.9^{b}	26.5^{a}	10.6^{c}	11.0^{c}	13.8^{c}
Microbial respiration (μg C g^{-1} soil 10 days^{-1})	131.7^{a}	178.4^{a}	82.3^{a,b}	75.6^{b}	97.3^{a,b}
50 days after emergence					
Mineral N ($\mu g\ g^{-1}$ soil)	5.8^{a}	13.3^{a}	2.9^{a}	3.6^{a}	4.7^{a}
Microbial N ($\mu g\ g^{-1}$ soil)	54.0^{a}	49.1^{b}	21.9^{d}	20.6^{d}	28.1^{c}
Net N mineralized ($\mu g\ g^{-1}$ soil 10 days^{-1})	22.8^{a}	23.5^{a}	10.7^{b,c}	8.4^{c}	12.2^{b}
Microbial respiration (μg C g^{-1} soil 10 days^{-1}	207.6^{a}	230.4^{a}	112.2^{b}	85.1^{b}	119.5^{b}
74 days after emergence					
Mineral N ($\mu g\ g^{-1}$ soil)	6.1^{a}	8.6^{a}	2.7^{a}	3.4^{a}	3.0^{a}
Microbial N ($\mu g\ g^{-1}$ soil)	56.0^{a}	50.6^{a}	24.4^{b}	23.7^{b}	27.8^{b}
Net N mineralized ($\mu g\ g^{-1}$ soil 10 days^{-1})	19.8^{b}	26.2^{a}	9.3^{c}	6.2^{d}	10.5^{c}
Microbial respiration (μg C g^{-1} soil 10 days^{-1})	182.5^{b}	239.4^{a}	105.9^{c}	63.6^{c}	116.4^{c}
102 days after emergence					
Mineral N ($\mu g\ g^{-1}$ soil)	10.6^{a}	12.4^{a}	3.8^{b}	2.0^{b}	5.8^{b}
Microbial N ($\mu g\ g^{-1}$ soil)	63.1^{a}	55.6^{b}	29.9^{c,d}	23.8^{d}	30.2^{c}
Net N mineralized ($\mu g\ g^{-1}$ soil 10 days^{-1})	14.7^{a}	16.4^{a}	10.0^{b}	5.3^{c}	8.3^{b}
Microbial respiration (μg C g^{-1} soil 10 days^{-1})	126.9^{b}	188.0^{a}	94.8^{c}	94.1^{c}	57.8^{c}

Means of four replicates; figures with different letters within a row varied significantly ($P \leq 0.05$)

Table 6. Amounts of N and ^{15}N expressed as a proportion of soil N, and soil ^{15}N and ^{15}N fertilizer recovery (%) 102 days after emergence

N pool	Treatment				
	AER 1	AER 2	CBR 1	CBR 2	CG
Soil N (%)					
Mineral N	0.43^{a}	0.50^{a}	0.22^{a,b}	0.13^{b}	0.32^{a,b}
Microbial N	3.60^{a}	3.16^{b}	2.46^{c}	2.15^{c}	2.40^{c}
Net N mineralized in 10 days	0.60^{a}	0.66^{a}	0.58^{a,b}	0.34^{c}	0.46^{b}
Soil ^{15}N (%)					
Mineral ^{15}N	9.54^{a}	6.43^{a}	1.93^{a}	[illegible].55^{a}	4.74^{a}
Microbial ^{15}N	20.62^{a}	14.06^{a,b}	11.14^{a,b}	10.30^{b}	14.06^{a,b}
Net ^{15}N mineralized in 10 days	7.85^{a}	5.62^{a}	3.88^{a}	3.11^{a}	7.75^{a}
^{15}N fertilizer recovery (%)					
Mineral N	5.04^{a}	5.16^{a}	0.84^{a}	0.55^{a}	2.32^{a}
Microbial N	12.09^{a,b}	15.71^{a}	6.83^{a,b}	5.13^{b}	9.60^{a,b}
Non-microbial organic N	20.00^{c}	57.90^{a}	35.36^{b}	30.02^{b}	34.09^{b}

Means of four replicates; figures with different letters within a row varied significantly ($P \leq 0.05$)
For explanation of abbreviations, see Table 1

alfalfa in the rotation was as fertile, even during the third cereal crop in a 5-year rotation, as soil from the continuous grain system. They are also consistent with the results of Senaratne and Hardarson (1988) who reported benefits to soil fertility from fababeans in rotations even when grain and straw were both harvested. Residual benefits from legumes, particularly alfalfa, on succeeding cereal crops have been observed to extend to the 7th (Australia; Holford 1980) or 10th crop (Canada; Hoyt 1990), indicating that in the rotations with fertilized legumes and green manure the soil is more fertile.

The observation that up to 48.5% of barley N in the first agroecological plot was derived from N that was either fixed previously and had accumulated, or soil N that was made more available, due to the presence of legumes in the rotation, is evidence of greater N availability. The observation that the A values of soils from the agroecological treatments were significantly greater than those in soil from the continuous grain system is consistent with the results for unlabelled N, with the higher N mineralization rates observed in these soils, and the lower N-use efficiency, and with published reports of increases in A values following fababeans (Senaratne and Hardarson 1988). It is concluded that the soil N availability to plants contributed significantly to the higher soil fertility in the legume-based systems.

The N-equivalent estimates were obtained to test the hypothesis that differences in cereal yields from different cropping systems are solely due to the legume N addition and that fertilizer N is just as available as legume N (Hesterman et al. 1987). A linear response function was used to relate the observed yield to the expected N requirement, based on the assumption that the N supply alone causes the differences in yields observed between cropping systems. This generates a conservative estimate of the N equivalent because normally more N is needed per unit of yield increase as yields approach their maximum. Using the unfertilized Breton rotation as a control, the values calculated for the N fertilizer equivalent were 2670 mg pot^{-1} (485 kg ha^{-1}) in agroecological treatment 1 and 1850 mg pot^{-1} in agroecological treatment 2.

The N equivalent values are unreasonably high estimates of N mineralization, even in soils from the agroecological system. As confirmation, the N equivalent values can be compared to net N mineralization by these soils, calculated from the sum of total plant N plus mineral N 102 days after emergence minus added N. If N were the sole contributor, then the amount of N mineralized in the two agroecological treatments in excess of that mineralized in the unfertilized Breton rotation plot would equal or exceed the N equivalent. The excess was 657 mg pot^{-1} (119.5 kg ha^{-1} equivalent) for agroecological plot 1 and 468.2 mg pot^{-1} for plot 2. Since the net N mineralization was only 1/4 of the calculated N-equivalent values, the higher N mineralization was not the sole cause of the difference in yield.

More rapid denitrification in the continuous grain pots (without drainage) is unlikely because all pots were watered to a predetermined weight to prevent waterlogging, and the soil mineral N contents were not statistically different among treatments at 50 and 74 days after emergence, the period of rapid plant growth. The hypothesis that N supply is the sole contributor to differences in soil fertility between these cropping systems is inconsistent with the results of this study.

It is possible to examine N use in addition to supply. The application of N to soil from the classical Breton rotation at 1100 mg pot^{-1} resulted in $<$500 mg being incorporated into the barley crop. Recovery by the barley crop of ^{15}N added at 55 mg pot^{-1} was more efficient in the agroecological treatments (45%–51%) than in the continuous grain or classical Breton treatments (35%–37%). It is inferred that, in addition to a variable N supply, the ability of barley plants to compete for available N, and hence the N use, varied among treatments and must be included.

The supply of nutrients such as P, K, and S or minor elements may also have been altered by these rotations, and this cannot be excluded as a cause of the observed increase in soil fertility.

Microorganisms contribute to soil fertility and this may have been a factor in the present study. The concentration of microbial N g^{-1} soil; the proportions of soil N, or soil ^{15}N present as microbial N, or microbial ^{15}N; and microbial activity, as indicated by the respiration rate, were all greater in the agroecosystem than in the continuous grain system, as were the soil C and N contents.

Conclusions

In conclusion, the yields of barley plant material and plant N accumulation in a pot experiment, and by those criteria, soil fertility, were higher in the agroecosystem than in the continuous grain system. Higher amounts of available N were observed following the incorporation of fababean residues and manure applications, and due to the soil N-conserving effect of legumes in the rotation, and are concluded to be partly responsible for the differences in yield. It is inferred that, in addition to a variable N supply, the ability of barley plants to compete for available N, and hence N use, varied among treatments and must be included. The contributions from other nutrients and soil biological properties to soil fertility in rotational cropping systems require further research.

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