Improved soil quality and barley yields with fababeans, manure, forages and crop rotation on a Gray Luvisol

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Wani, S P , McGill, W B , Haugen-Kozyra, K L , Robertson, J A and Thurston, J J 1994 Improved soil quality and barley yields with fababeans, manure, forages and crop rotation on a Gray Luvisol. Can J Soil Sci 74 75-84 There exists a need (i) to test, whether equal or better cereal yields could be obtained using cropping systems which rely on renewable resources rather than on fertilizer nitrogen, and (ii) to discover the condition of the soil resource under these systems

The long-term cropping systems on a Gray Luvisol at Breton were studied They included (i) an **agro-ecological 8-yr rotation** (AER), established in 1981, which involved addition of both fababean green manure and manure from livestock fed with forages and fababeans grown in the rotation (ii) a **continuous grain** (barley) system (CG), with fertilizer N at 90 kg ha^{-1} y^{-1}, established in 1981, (iii) a **classical Breton 5-yr rotation** (CBR) involving forages and cereals, with no return of crop residues or manure, established in 1930 Mean barley yields were 16-19% higher in the AER ($P \leq 0.05$) than in the CG system, and yield on either was about double that of the CBR Within 9 yr, there was evidence of increased total C, N, and P, available N, P and K, CEC, microbial biomass, microbial respiration, and counts of bacteria fungi and mycorrhizae in the AER compared with the CG system

We conclude that biological fixation of N by legumes can be used as the sole source of N for barley production on Luvisolic soils of low fertility such as the Breton loam, without sacrificing yield or soil quality Barley yields in the AER (38% of the rotation time) exceeded those of barley grown under continuous cereal cropping The soil resource was maintained or improved during a 10-yr period under AER compared to the CG or CBR systems Further research is needed to discover the mechanisms involved in regulating biological activity and availability of plant nutrients other than N in the AER system

Key words: Barley, Breton loam, cropping systems, Gray Luvisol soil quality, fababeans

Wani, S P McGill W B , Haugen Kozyra K L Robertson J A et Thurston J J 1994 Amélioration de la qualité du sol et du rendement de l'orge dans une rotation féverole, orge et cultures fourragères avec apport d'engrais vert et de fumier. Can J Sol Sci 74 75-84 Il existe un besoin 1) de vérifier si on pourrait obtenir des rendements de céréales équivalents ou meilleurs en pratiquant des assolements n'utilisant que des ressources renouvelables plutôt que des engrais azotés chimiques et 2) d'évaluer l'état du sol dans ces systèmes culturaux Nous avons utilisé pour cette étude les assais de rotations de longue durées conduits sur luvisols gris à Breton (Alberta) Les assolements comparés étaient (1) une rotation agroécologique de 8 ans (RAE) installée en 1981, qui comportait l'apport d'un engrais vert de féverole et de fumier de bétail nourri de fourrages et de féverole produits dans la rotation, (2) un assolement de céréales en continu (CC), recevant une fumure chimique de 90 kg N ha^{-1} par année, démarrée en 1981 et une rotation classique Breton (RBC) de 5 ans établie en 1930, comportant des cultures fourragères et des céréales, sans restitution de fumier ou de restes de cultures Le rendement moyen de l orge était de 16 à 19% plus élevé dans RAE ($P \leq 0,05$) que dans CC et, dans ces deux assolements, il était pratiquement le double de celui obtenu dans RBC Au bout de 9 ans, on constatait une accumulation du C, du N et du P totaux, de N, P et K assimilables, de la CEC, de la biomasse et de la respiration bactérienne ainsi que des numérations bactériennes, cyrptogamiques et mycorhiziennes dans RAE par rapport à CC Ces résultats nous portent à conclure que le N fixé par les légumineuses peut être utilisé comme seule source de N pour la culture de l'orge dans les sols luvisoliques peu fertiles, comme c'est le cas du loam Breton, sans compromettre le rendement de l'orge ni la qualité du sol Le rendement de l'orge dans RAE (38% de la durées de la rotation) dépassait celui obtenu dans CC La qualité du sol s'est maintenue ou même améliorée sur une période de 10 ans dans RAE par comparaison avec CC ou avec RBC Il reste à élucider les mécanismes en jeu dans la régualtion de l'activité biologique et de la biodisponibilité des autres éléments nutritifs dans l'assolement RAE

Mots clés: Orge, loam Breton, assolements, luvisol gris, qualité du sol, féverole

Maintaining the soil resource is an important part of sustainable agriculture (Weil 1990). Sustainable agriculture relies increasingly on renewable resources and on-farm

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nitrogen contributions are achieved through crop rotations that include legumes Inclusion of deep-rooted crops in rotations brings subsoil nutrients to the surface for utilization by subsequent crops. Another feature of sustainable farming is return of crop residues, manures and other organic materials to the soil to close or tighten nutrient cycles.

Long-term experiments conducted at the University of Alberta Breton plots have shown increased levels of organic matter and soil nitrogen in a 5-yr crop rotation including forage legume compared with a wheat-fallow system (Newton et al. 1959).

Further studies showed the 5-yr rotation was associated with more soil microbial N with a slower turnover rate than the 2-yr rotation (McGill et al. 1986). In addition to these improved soil properties, higher cereal yields may be observed in a rotational system compared with a monoculture cropping system (Nambiar et al. 1982; Hoyt and Leitch 1983; Hoyt 1990; Wani et al. 1991a).

Such increased cereal yields are usually attributed to enrichment of soil with nitrogen due to N_2 fixation by legumes or their effect in conserving soil N resulting in increased N mineralization and increased proportion of active N fraction (Nambiar et al. · 1982; De et al. 1983; Senaratne and Hardarson 1988; Wani et al. 1994). Evidence is increasing that legumes in a rotation are associated with more than just their N effect (Bezdicek and Granatstein 1989; Wani et al. 1991a). Such "rotation effects" are usually positive and are attributed to numerous factors, some of which include: a reduction in disease (Cook et al. 1987; Cook 1988), reduced weed and insect problems (Olkowski 1986; Bezdicek and Granatstein 1989), improved soil physical conditions (Goldstein 1989; Kirschenmann 1989), improved soil biological properties through increased population of favorable microorganisms for crop growth (Fyson and Oaks 1990; Wani et al. 1991a) and

increased phosphorus availability through acidification of the rhizosphere by the legumes (Aguilar and van Diest 1981).

An 8-yr agro–ecological rotation (AER) was initiated in 1980, and considered established in 1981, at the University of Alberta Breton plots. It was based on theoretical considerations of amounts of N fixed, organic N turnover rates, the fraction of N returned via manure, and crop demands. One cycle was completed in 1988. A continuous grain (CG) cropping system was also started in 1980, and at the same time fertilizer treatments were updated (normally to increase rates) on the classical Breton rotation plots (CBR). Earlier publications have documented conditions during the period prior to (Newton et al. 1959), or immediately after (McGill et al. 1986) the revision of fertilizer treatments. Soil sampling and a comprehensive study of barley growth, soil N status, nutrient supply, crop residue decomposition cytokinins, and mycorrhizae were undertaken on these systems in 1989 (Wani et al. 1991a,b; 1994). Laboratory and greenhouse studies provided evidence that mineralizable soil N, following one cycle of the AER, was about double that following 60 yr of a 5-yr rotation (CBR). The active N fraction was least in soil under the CG system (Wani et al. 1993). Increased supply of N following incorporation of fababean green
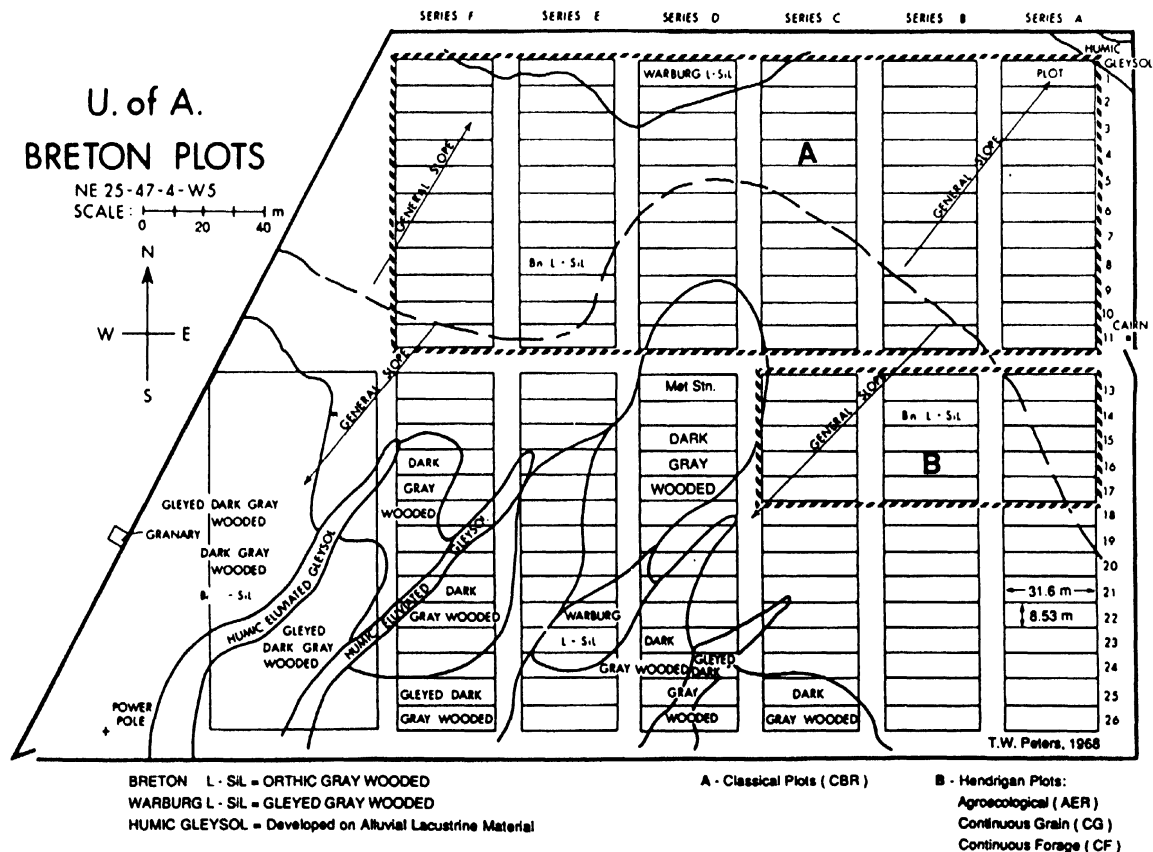

Fig. 1. Soil map and plot layout for three cropping systems at the Breton Plots, University of Alberta.

manure and livestock manure and the soil N-conserving effect of legumes in the AER rotation were only partly responsible for the observed changes in soil fertility (Wani et al. 1991a). The AER was associated with increased vesicular–arbuscular mycorrhizae (VAM) colonization and greater accumulation and translocation to grains, but not with reduced incidence of root rot when compared with the CG system (Wani et al. 1991b).

This paper extends the above work to field conditions and the earlier work by McGill et al. (1986) to an examination of the CBR after 9 yr in comparison with the CG and the AER systems under conditions of the same P-K-S additions. It reports on trends in soil properties and barley yields in the three selected cropping systems over the 9-yr period. Specific objectives were to test the hypotheses (i) that under field conditions, barley yields are higher in a rotation including faba-bean green manure and livestock manure (AER) than in cropping systems based either on mineral N fertilizer (CG), or containing forages but with no residues or manure returned (CBR); and (ii) that the AER rotation is associated with more microbial biomass, and greater availability of nutrients, compared to the systems based on mineral N fertilizer.

MATERIALS AND METHODS

Site Description and Cropping Systems

The results reported here are from the long-term experiments at the 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). The mean annual precipitation is 547 mm, and the mean maximum and minimum July temperatures are 21.2 and 8.8°C, respectively; there is a mean of 80 frost-free days, and 1060 degree-days >5°C (Canadian Climate Program 1982).

Three cropping systems were compared: (i) an agro-ecological (AER) 8-yr rotation [barley, fababean, barley, fababean, barley under-seeded to red clover and bromegrass, forage (red clover and bromegrass), forage, forage], (ii) continuous grain system (CG), both seeded in 1980 as described below and considered established in 1981; and (iii) a classical Breton (CBR) 5-yr rotation (wheat, oat, barley under-seeded to forage, forage, forage) established in 1930. The original forage in the CBR was legumes alone (sweet clover and red clover, or alfalfa and red clover). From 1956 to 1966, the forage mixture consisted of alfalfa, red clover, creeping red fescue, bromegrass, and either timothy or alsike clover. After 1966 the forage mixture was alfalfa and bromegrass.

The Breton plots are set out in series: A–F, running east to west; and ranges: 1–26, running north to south (Fig. 1). Plot size for each treatment was 269.5 m² (31.6 × 8.53 m). The AER is within the Hendrigan Plot area (Fig. 1) and comprises plots: A-14, A-16, A-17, B-13, B-16, C-13, C-15, and C-16. Crops rotated according to Table 1. The CG system comprises plots A-13, B-15, and C-17 of the Hendrigan Plot area (Fig. 1). The remainder of the Hendrigan Plot area is a set of continuous forage plots. The AER and CG plot area was 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. The CBR plots are A-1 to D-11, and F-1 to F-11. Crops rotate across series (Table 1); fertilizer treatments vary with range. Slope varies from 0 to 3% over the plot area used for

Table 1. Crop × year grid for two crop rotations at the Breton Plots											
		Agro-ecosystem rotation (general grain prior to 1981)									
Year	Crop[z]	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
						Plot					
1	Brly	C-15	C-16	B-13	A-17	A-16	C-13	B-16	A-14	C-15	C-16[y]
2	Fb	A-14	C-15	C-16	B-13	A-17	A-16	C-13	B-16	A-14	C-15
3	Brly	B-16	A-14	C-15	C-16	B-13	A-17	A-16	C-13	B-16	A-14
4	Fb	C-13	B-16	A-14	C-15	C-16	B-13	A-17	A-16	C-13	B-16
5	Brly_u	A-16	C-13	B-16	A-14	C-15	C-16	B-13	A-17	A-16	C-13
6	RcBr	A-17	A-16	C-13	B-16	A-14	C-15	C-16	B-13	A-17	A-16
7	RcBr	B-13	A-17	A-16	C-13	B-16	A-14	C-15	C-16	B-13	A-17
8	RcBr[x]	C-16	B-13	A-17	A-16	C-13	B-16	A-14	C-15	C-16	B-13
		Classical Breton rotation (Range 8 = PKS (−N); Range 1,5,11 = control)									
Crop	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
						Series					
Wht	A	B	C	D	F	A	B	C	D	F	A
Oats	F	A	B	C	D	F	A	B	C	D	F
Brly_u	D	F	A	B	C	D	F	A	B	C	D
AlBr	C	D	F	A	B	C	D	F	A	B	C
AlBr[w]	B	C	D	F	A	B	C	D	F	A	B

[z] Brly, barley; Brly_u, barley underseeded; Fb, fababeans; RcBr, red clover and bromegrass; Wht, wheat; AlBr, alfalfa and bromegrass.
[y] Underlined plots or series were sampled for soil analyses (Spring 1985, 1990) (August 1984) presented here; and for greenhouse and laboratory studies (October 1989) (Wani et al. 1991a, 1991b, 1994).
[x] Forage ploughed down in July; manure added in late fall and tilled in.
[w] Forage ploughed down in late July.

Table 2. Nutrients returned in manure to the agro-ecological rotation (AER) plots at Breton

Year	Plot	Manure wet mass (Mg ha⁻¹)	Manure dry matter (fraction)	Nutrients (kg ha⁻¹) N	P	K	S
1981	C-16	15.0	0.52	209	184	167	46
1982	B-13	38.2	0.26	238	154	205	83
1983	A-17	48.0	0.39	446	350	285	122
1984	A-16	72.6	0.29	504	320	234	172
1985	C-13	94.5	0.23	495	NA^t	1000	120
1986	B-16	90.0	0.29	524	167	547	123
1987	A-14	60.5	0.25	401	97	NA	NA
1988	C-15	76.4	0.21	338	84	63	NA
1989	C-16	31.2	0.23	190	46	NA	NA

^{t}NA = not analyzed.

this study. The aspect is southwest for the AER, CG, and much of the CBR plot area; otherwise it is northeast (Fig. 1).

In the CG system, barley was grown annually since 1980 and received N-P-K-S at 90-22-46-5.5 kg ha⁻¹ yr⁻¹. All crop residues from each plot were returned to the soil.

The 8-yr AER was designed to be self-sufficient in N, and received no N as commercial fertilizer but P-K-S were added at 22-46-5.5 kg ha⁻¹ yr⁻¹. On completion of the rotation cycle, the forage stubble was ploughed into the soil. Crop production in the AER was integrated with livestock production by returning manure resulting from the feeding of the produced forages and fababeans. This is simulated in two ways. First, the fababeans are ploughed down as green manure after removing 6 m² for yield determination. Second, manure equivalent to 70% of the N removed as straw from year 5 and forages from years 6 through 8 is returned in autumn (normally, but occasionally the next spring) to the plots that have been broken from forage, such that each plot receives manure once per cycle of the rotation. The quantity of manure applied to the AER plots and nutrients returned as manure during each year are given in Table 2. Cereal straw is returned to the plots with the exception of year 5 when barley is under-seeded to forage. There are eight plots, which provide each phase in the rotation every year.

In the CBR, straw is not returned to the plots. Forage stubble is ploughed down after the first cut in the second year of forage. Series E, and the east half of each of series, A, B, C, D, and F, with the exception of ranges 6 and 7, were limed to pH 6.5 in 1972. No commercial N was added to the plots used in this study. Nitrogen was supplied by biological fixation and atmospheric deposition only. The P-K-S treatment plots received P at 9 kg ha⁻¹ yr⁻¹ between 1930 and 1979; from 1980 on they received P-K-S at 22-46-5.5 kg ha⁻¹ yr⁻¹. The control plot has received no amendments other than lime since 1930.

Two treatments were selected from the AER rotation: (i) barley following fababean in 1990 (rotation-year 3) was on plot A-14 and designated AER-1; and (ii) barley following 3-yr of forage in 1990 (rotation-year 1) occupied plot C-16, and was designated AER-2. Two treatments were selected from the classical 5-yr Breton rotation (CBR): (i) barley following oats in 1990 (series D) of the P-K-S

treatment (range 8), was designated CBR-1; and (ii) barley following oats in 1990 (series D) of the control (ranges 1, 5, 6 lime), and 11) was designated CBR-2.

The only replicated plots were those of the CG system (three replicates). In all cropping systems barley (*Hodeum vulgare* L.) Galt (1980, 1981, and 1983), Klondike (1982 and 1984), Empress (1985-1988), Heartland (1989), and Leduc (1990) cultivars were seeded at 90 kg ha⁻¹ using a double-disc seeder with 0.15-m spacing between rows. Fababeans (*Vicia faba* L.) Diana (1980-1983), and Ackerperle (1984-1990) were inoculated and seeded at 200 kg ha⁻¹. Forage varieties were: alfalfa (*Medicago sativa* L.) Rambler (1980-1982), and Peace (1983-1990); red clover (*Trifolium pratense* L.) Altaswede (1981-1990); bromegrass (*Bromus inermis* Leyss.) Carlton (1980-1990). Fertilizers as per the treatments were applied at seeding: P with the seed; N, K, and the elemental S are broadcast and incorporated. Herbicides were used for weed control in all the plots.

Only barley yields are reported here. For yields of AER-1 treatment (barley following fababeans) the mean was taken of whichever two plots contained years 3 and 5 in the rotation during the current year (e.g., plots A-16 and B-16 in 1981, etc., Table 1). Barley yields for AER-2 were from the plot occupied by rotation-year 1 in the current year (e.g., plot C-15 in 1981, C-16 in 1982, etc., Table 1). The mean of the same three replicated plots (A-13, B-15, and C-17) was used for CG throughout. Aboveground barley was harvested from six 1-m² areas in each plot. Grains were separated, and straw and grain mass recorded. Straw and grain samples from AER and CG plots were processed for chemical analysis.

Several calculations were made based on the plant yield data. The harvest index (HI) was calculated as

$$HI\ (\%) = grain\ mass \times 100\,/\,total\ plant\ dry\ matter \quad (1)$$

The N use efficiency (NUE) for grain production was defined as

$$NUE = grain\ mass\,/\,mass\ of\ total\ plant\ N \quad (2)$$

The N translocation index (NTI) was calculated as

$$NTI\ (\%) = grain\ N\ content \times 100\,/\,total\ N\ content \quad (3)$$

Soil Sampling and Analysis

In 1990, soil samples were collected in May, prior to seeding and fertilization. Plots which were sampled for this paper are underlined in Table 1. Each plot was divided into quadrants and 10 cores (5 cm diameter) 15 cm deep were taken from each quadrant and pooled to form a composite sample (plot A-14 for AER-1; C-16 for AER-2; and A-13 for CG). For the CBR-2 treatment, samples from plots D-1E, D-5E, D-6E, D-6W and D-11E (E = east half) were likewise pooled to constitute one bulk sample; samples from the CBR-1 treatment were pooled from plot D-8E. Four bulk samples were collected from each plot, transported to the laboratory, and stored at 4°C. All biological analyses were performed within 24 h after collection of the samples. Chemical analyses were performed on samples that had been

air-dried and ground < 100 mesh. Soil samples that were previously collected from the same plots in 1980 and in 1984-1985 (refer to Table 1 for sampling schedule) were analyzed for chemical properties along with the 1990 samples.

Microbial biomass-C and biomass-N were measured by the chloroform-fumigation and incubation method (Jenkinson and Powlson 1976) on sieved (10 mesh) soil as described in detail by Wani et al. (1991a); a Kn factor of 0.57 was used to calculate biomass-N, after Jenkinson (1988). Soil respiration data were obtained from the non-fumigated control samples during biomass-C measurements. Soil samples were incubated in sealed 2-L jars in the presence of NaOH to adsorb evolved CO_2. The quantity of evolved CO_2 was calculated following back-titration of the NaOH with HCl. The numbers of colony-forming units were estimated after 7 d of incubation at $21°C$ following dilution and plating on plate bacto agar (Difco) for bacteria, and rose bengal medium with streptomycin for fungi (Wollum 1982). A second, confirmatory, count was taken after 12 d.

Sieved, air-dried soil samples were used to estimate the moisture content at "field capacity" using the "tube" method, and at wilting point (-1.5 MPa potential) using a pressure plate apparatus. In the tube method, soil was placed in a glass tube (32 cm long $\times$ 4.5 cm i.d.; 20 cm column of soil) closed with four layers of cheesecloth, packed to field density, saturated from the top, and allowed to drain for 24 h. The gravimetric water content of the central portion of the tube, measured by drying at $105°C$ for 24 h, was designated as field capacity. Particle size analysis was performed on 40 g of soil sieved to 2 mm, soaked for 24 h in 0.1 L of 5% sodium hexametaphosphate, dispersed for 5 min with a blender, and made to 1 L. Particle size calculations were based on hydrometer readings (McKeague 1978).

Total carbon was determined on ground soil samples (< 100 mesh) by dry combustion using a Leco Carbon Determinator CR-12. Total soil N and P were measured using semi-micro Kjeldahl digestion (McKeague 1978) followed by an autoanalyser method to measure NH_4^+ and P (Technicon 1979). Mineral N concentration was measured on 2 M KCl extracts of sieved (2 mm) soil (McKeague 1978) using an automated indophenol blue method (Technicon 1973) for NH_4^+, and cadmium reduction (Technicon 1977) for NO_3^-. Methods for available P (Bray's method), exchangeable K, soil pH (1:2 soil-water ratio) and cation exchange capacity (CEC) are described in McKeague (1978).

Statistical Analysis

Analysis of variance, General Linear Model procedure of Statistical Analysis System Institute (1987), was used to test for significant treatment effects in barley yields, using years as replications. The sources of variation in the barley yield model included treatments (the five rotations), year (1981-1990), year-by-treatment interaction and error. Because field replication was absent in the long-term plots studied, the year and year-by-treatment interaction terms for barley yields were grouped with experimental error and used as a substitute for a true error term; this appeared logical on the basis of the lack of a strong year or year-by-treatment effect in yields.

Due to the lack of field replication of the rotation, the data of the 1980, 1984/1985 and 1989/1990 soil samples could not be subjected to statistical analysis. Instead, we have included comprehensive information regarding the plot layout, spatial distribution of soil types (Fig. 1), past cropping history and current cropping systems. Although we do not claim to have applied statistical analyses to data on soil properties, long-term plots such as these yield other valuable insights. In contrast to plots set out on landscapes of unknown history, studies on these plots benefit from accumulated background information, in this case knowledge of soil treatment, cropping history, and system performance since 1930. Hence, although their lack of field replication precludes some analyses, the background knowledge of these plots as cropping systems opens alternative avenues of inquiry. We have attempted to pursue those avenues while being diligent to avoid reaching unwarranted conclusions.

RESULTS

Properties of 1980 Soil Samples

Selected soil chemical properties of the 1980 soil samples were characterized by the following mean values (Fig. 2): total C = 15.7 g kg^{-1}; total N = 1.28 g kg^{-1}; total P = 0.53 g kg^{-1}; pH = 6.2; and CEC = 147 mmol (+) kg^{-1}. These data represent the soil status before the agro-ecological rotation was established. The control plots, (CBR-2: D-1E, D-5E, D-6E, D-6W, and D-11E), received no added fertilizer since 1930, and were characterized by extractable P values at about half those of the other soils.

Barley Grain Yield

Barley grain yields fell into two groups: one group (AER and CG) with 9-yr means (Mg ha^{-1}) of 4.2, AER-1; 4.3, AER-2; and 3.6, CG; in contrast to 1.9, CBR-1; and 1.4, CBR-2. The LSD ($P = 0.05$) was 0.5, with a standard error of the mean of 0.3 (Fig. 3). Barley yields tended to be higher in AER-2 and AER-1 than in the CG system (Fig. 3). Both the CBR plots produced significantly lower barley yields than did either CG or AER.

Straw yield in AER-1 and AER-2 tended to be higher (11-12%) than that in CG; the harvest index was similar among all cropping systems (results not shown) and varied from 51.5% in CG to 56.7% in CBR-1.

Mean grain N concentrations were similar among the AER and CG treatments: CG = 18.7 g kg^{-1}, AER-2 = 18.6 g kg^{-1}, and AER-1 = 18.2 g kg^{-1}. Mean annual grain N contents over the 9 yr in AER-2 (80 kg ha^{-1}) and in AER-1 (77 kg ha^{-1}) were marginally higher than in CG (72 kg ha^{-1}). Similarly, the N translocation index (NTI) and N-use efficiency (NUE) for grain production was marginally higher in AER-2 (73.6%, NTI; 40 kg grain kg^{-1} N, NUE) and AER-1 (72.8%, NTI; 39.8 kg grain kg^{-1} N, NUE) than in CG treatment (69.5%, NTI; 37.8 kg grain kg^{-1} N, NUE).

Properties of 1990 Soil Samples

All plots were characterized by 16-20% clay, and 41-45% sand (see Wani et al. 1991a). The mean available water-holding
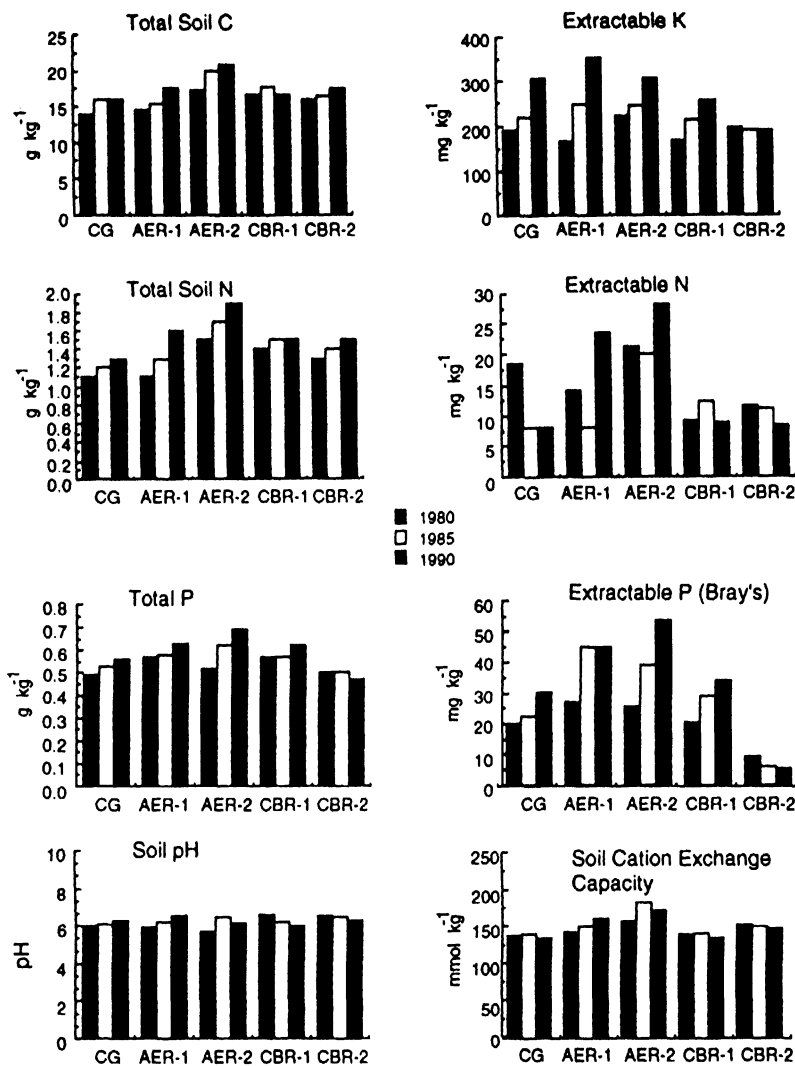
Fig. 2. Soil chemical properties of Ap horizon samples of three cropping systems: AER-1 = agro-ecological 8-yr rotation — year 3 in 1990 (plot A-14); AER-2 = agro-ecological 8-yr rotation — year 1 in 1990 (plot C-16); CG = continuous barley (plot A-13); CBR-1 = classical Breton 5-yr rotation, PKS treatment — year 3 in 1990 (plot D-8E); CBR-2 = classical Breton 5-yr rotation, control treatment — year 3 in 1990 (plots D-1E, -5E, -6E, -6W, -11E). Extractable N = NH_4^+-N + NO_3^--N.

capacity (percent water at field capacity - percent water at wilting point) was 23% (gravimetric). Soil moisture content at field capacity and at the wilting point for AER soils was higher than for the CG soil; however, the CBR and CG plots showed similar moisture contents at field capacity and at the wilting point (see Wani et al. 1991a).

(i) pH AND CEC. Soil samples taken in May 1990 from the AER-1 plot (A-14) were observed to have the highest pH (6.55) among the samples (Fig. 2). The same plot had a pH of 6.22 in 1985, and 5.95 in 1980. In contrast, the lowest pH, 6.0, was recorded in CBR-1 (D-8E) samples which

were at pH 6.24 in 1985, and 6.6 in 1980. A positive trend was exhibited in CEC values from 1980 to 1990 for the AER soils, which was not evident in the other soils (Fig. 2).

(ii) SOIL C, N, P AND K. Data for samples from 1980, 1985, and 1990 provide a form of replication over time and show trends in nutrient concentration and availability over the 10 yr period (Fig. 2). The 1985 data normally fell between the 1980 and 1990 data, with the exception of available N. The trend was toward increased total C and N concentration in all systems, and increased total P in AER, CG, and CBR-1; however, a possible decline in total P was seen in the

control (CBR-2). Available N showed greater variability with no apparent trend. Extractable P and K either declined or remained constant in CBR-2, but tended to increase in the other treatments.

In the spring of 1990, total C concentration of AER-2 (C-16) was higher than the other treatments (Fig. 2). Among treatments, the lowest total P concentration was observed in CBR-2. By 1990, AER-2 soils had approximately 10 times as much extractable P as CBR-2 soils. The AER and CG soil samples contained similar amounts of extractable K, followed by CBR-1 and then CBR-2 soils.

(iii) AMOUNT AND PROPORTION OF N IN SOIL FRACTIONS. The total N concentration was highest in the AER-2 soil, and lowest in soil from the CG system (Table 3). Mineral N as a proportion of total N in AER-1 and AER-2 was twice that of the CG treatment. Microbial N in AER-2 and AER-1 was 90 and 30% greater than that of the CG treatment. Microbial N constituted 1.8-2.7% of total soil N with the highest proportion in AER-2. More N tended to be mineralized over the 10 d incubation from AER soils than from the others.

(iv) BIOLOGICAL PROPERTIES. Microbial biomass measured by the chloroform fumigation-incubation method varied among the treatments with threefold more biomass-C and twofold more biomass-N, per gram of soil from AER-2 than from CG (Tables 3 and 4). Lowest biomass among the treatments was recorded in CG. Soil respiration tended to be highest in AER soil and lowest in CBR-2 (Table 4). Although biomass-C in AER-2 was threefold greater than in CG, respiration was similar, suggesting greater activity per unit biomass in CG. The C:N ratio of the flush following fumigation varied beween 2.98 in CG and 4.92 in AER-2 soil samples. The counts of colony-forming units of bacteria and fungi were higher in samples from AER-1 than from CG; lowest counts were recorded from CBR-2 soil, although it tended to have the most vesicular-arbuscular mycorrhizae (VAM) propagules.

DISCUSSION

This paper deals with two issues. First: are yields of barley obtained on a soil with initially low total N (i.e., low capacity to supply N), and grown in crop rotations without added commercial N (AER or CBR), similar to yields from a continuous grain system based on added mineral N (CG)? Second: what

is the condition of the soil resoruce after 9 yr under these contrasting cropping systems?

Yields

The CG system is the base for comparison, with the 9-yr mean yield (3.62 Mg ha^{-1}) exceeding the provincial mean (2 Mg ha^{-1}; McLelland 1982). Consistently higher barley
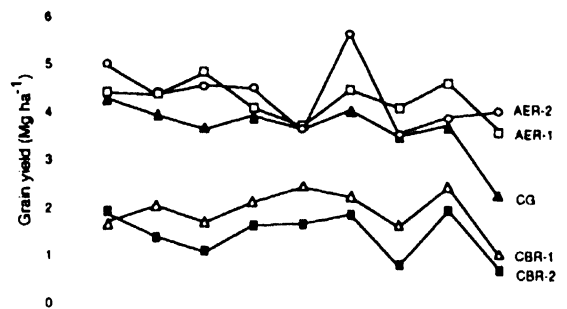
Fig. 3. Annual barley grain yield for three cropping systems on a Gray Luvisol at Breton during 1981-1989.

Table 3. Amounts and proportions of N in fractions of Ap horizon samples collected in May 1990 from long-term plots on a Gray Luvisol at Breton, Alberta under three cropping systems

N fraction	Treatment				
	AER-1	AER-2	CBR-1	CBR-2	CG
Mineral N ($\mu g\ g^{-1}$ soil)	23.6	28.2	8.8	8.5	8.1
Microbial N ($\mu g\ g^{-1}$ soil)	34.9	51.4	26.8	32.2	26.8
Net N mineralized ($\mu g\ g^{-1}$ soil (10 d)$^{-1}$)	12.2	9.5	9.1	7.0	6.4
Total N (mg g^{-1} soil)	1.55	1.87	1.50	1.47	1.32
	(% of total N in soil)				
Mineral N	1.5	1.5	0.6	0.6	0.6
Microbial N	2.3	2.7	1.8	2.2	2.0
Net N mineralized (10 d)$^{-1}$	0.8	0.5	0.6	0.5	0.5

Table 4. Selected biological properties of Ap horizon samples collected in May 1990 from long-term plots on Gray Luvisol at Breton, Alberta under three cropping systems

Treatment	Microbial biomass C ($\mu g\ g^{-1}$ soil)	Respiration ($\mu g\ C\ g^{-1}$ soil (10 d)$^{-1}$)	Flush[z] C:N ratio	Bacteria ($\times\ 10^7\ g^{-1}$ soil)	Fungi ($\times\ 10^4\ g^{-1}$ soil)	MPN-VAM[y] ($\times\ 10^2\ g^{-1}$ soil)
AER-1	175.0	89.6	3.26	26.35	21.95	2.30
AER-2	330.5	73.5	4.92	4.81	15.30	21.50
CBR-1	162.5	66.3	4.08	3.05	10.33	2.70
CBR-2	188.3	59.3	4.28	2.58	2.93	23.00
CG	109.0	73.0	2.98	2.95	16.30	1.58

[z]Calculated as Fc/Fn, where Fc is [(C mineralized from fumigated soil incubated for 10 d) - (C mineralized from non-fumigated control incubated for 10 d)], and Fn is [(mineral N (NH$_4^+$ + NO$_3^-$) in fumigated soil incubated for 10 d) - (mineral N in non-fumigated soil incubated for 10 d)].
[y]MPN-VAM data were originally reported by Wani et al. (1991b), and are the average of duplicates.

yields were observed over 9 yr in AER plots than CG plots, and yields in either system exceeded those of the CBR plots; however, it should be noted that the barley crop sampled for the CBR treatments was underseeded with alfalfa-bromegrass, which may have contributed to lower barley yields. The mean barley yield in AER-2 (following 3 yr of forages) was 18.7% higher, and in AER-1 (following faba-beans) 15.7% higher, than were CG barley yields. Each year the CG system produced barley on 100% of the land area, whereas, the cereal production area was 38% in the AER, and 60% in the CBR. These findings establish that the AER has the potential for yield superiority in barley production over the CG system, on those plots where barley is grown in the AER. We conclude that the biological fixation of N by legumes and return of that N through manure can be used as the sole source of N for barley production on Luvisolic soils of low fertility, such as the Breton loam, in an integrated system involving cereals, forages, and livestock. However, despite the higher barley yields observed in the AER system, only 38% of the land is devoted to cereal production at any given time, and noncereal crops in the rotation are crucial to adequate N supply. Consequently, the amount of barley harvested from comparable land areas is lower, and the amount of alternative product greater, in the AER than in the CG system. Ultimately, the choice of cropping system depends on the goals of the land manager within the economic climate of the industry.

The CBR-1 and CBR-2 treatments produced an annual mean of 1.9 and 1.4 Mg ha^{-1} barley grain, respectively, demonstrating that although P, K and S application in the 5-yr rotation increased barley yields over the control, the CBR-1 treatment (1.9 Mg ha^{-1}) was only 44% as productive as AER-2 (4.3 Mg ha^{-1}). There is an N-P-K-S treatment in the CBR that differs from CBR-1 only in the annual application of N at 50 kg ha^{-1} to wheat, 75 kg ha^{-1} to oats, and 50 kg ha^{-1} to the barley crops. Mean barley grain yield from that treatment during 1981–1989 was 3.46 Mg ha^{-1} yr^{-1}. Consequently, although this rotation contains a productive legume (alfalfa) it is not self-sufficient in N throughout the rotation. Further, even with commercial N added at 175 kg ha^{-1} in each 5-yr cycle (280 kg ha^{-1} in 8 yr), barley yields did not equal those observed in the AER. Due to the underseeded barley crop sampled in CBR, however, a more appropriate comparison may have been to examine yields of barley underseeded to forage in the AER system. These long-term results demonstrate that the relation between cereal yields from continuous cereal cropping, and cereal yields from crop rotations including legumes, may favor either continuous cereal production, or a legume-based rotation, depending on the nature of the rotation.

These field results are supported by observations of N dynamics made under greenhouse conditions. Under controlled conditions, without N application, barley growth in soil from CBR and CG treatments were similar, and barley yields in soil from AER were 218% of those in soil from the CG system (Wani et al. 1991a). Increased cereal yields following legumes in rotation are not uncommon (Nambiar et al. 1982; Senaratne and Hardarson 1988; Cook 1988). Residual benefits of legumes, particularly alfalfa,

to succeeding cereal crops have been observed to extend to the 7th (Australia; Holford 1980) or 10th crop (Canada; Hoyt 1990).

The differences between these three cropping systems relate not only to the presence of legumes, but also to return of crop residues and manures and/or to the lower proportion of time in cereal production in AER. The mechanisms through which these differences are manifested cannot be resolved from data presented here. Hypotheses relating to disease, VAM infection, or cytokinin production warrant testing. Results presented elsewhere (Wani et al. 1991a) suggest that although N economy is superior in the AER system, N supply alone cannot account for the differences in field and laboratory observations. Evidence has been presented for contributions from VAM, involvement of other major nutrients and minor elements, and perhaps direct physiological effects (via hormonal interactions) by the preceding forage on sequent cereal crops (Wani et al. 1991a,b).

Soil Quality

In 1980, prior to the establishment of the AER and CG systems, the soils in these plots were similar. Soil density was not measured on these plots at the time of sampling. McGill et al. (1986) reported densities ranging from 1.30 to 1.37 Mg m^{-3} for Ap horizons of the CBR system. Bulk densities in the top 15 cm of tillage plots (11 yr old) adjacent to the AER and CG plots, calculated from data of Nyborg et al. (1994), are 1.4 Mg m^{-3} in tilled plots, and 1.5 Mg m^{-3} in nontilled plots. A set of plots immediately west of the tillage plots has bulk densities in the top 7.6 cm ranging from 1.25 to 1.4 Mg m^{-3} depending on tillage and cropping system (Haderlein et al. 1993). Consequently, although densities may not be identical in all plots, the differences are not expected to mask observations based on concentration data.

The inclusion of manure in a crop rotation either reduces the rate of soil N or organic matter loss (Hass et al. 1957) or increases the total amount present (Ridley and Hedlin 1968). The outcome depends upon the initial quantity of soil organic matter, its specific decay rate, and rate of organic matter addition (McGill 1983). The original soil organic matter content was low enough, and there was sufficient return of crop residues and manure to show an increasing trend in soil organic matter over the past 10 yr. The CBR plots received low fertilizer additions prior to 1980; the increased additions after that time also increased yields.

Although soil N tended to increase in the CG system, it consistently had less available N at seeding time (by about threefold) than was observed in the AER treatments. There is no evidence that dependence of the CG system on fertilizer N has been diminished by accumulation of soil organic N. In vitro incubation and leaching studies with CG soil showed that 10.6 wk was required for 50 mg kg^{-1} of N to be mineralized, whereas the corresponding value for AER-1 soil was only 4.2 wk, and for AER-2 soil 4.5 wk (Wani et al. 1994).

Phosphate availability showed a positive trend between 1980 and 1990 in AER-1 and -2, CBR-1, and CG plots, but its extent was greater in rotations with legumes (AER and CBR).

Further inquiry into the relation between legume-based rotations and the dynamics of active P is warranted. There is evidence that in 1990, even total P concentrations in AER and CBR-1 systems were higher than in CG, although the rate of P application was similar. The possible exploration of subsoil P supplies by legume roots deserves further study.

When considered together, these findings indicate the ability of the AER to meet the N requirement of barley crops. Our findings suggest that return of crop residues and use of mineral N as practiced in the CG system is associated with some increase in quantity of soil organic matter. Use of crop rotations involving legume green manuring coupled with forages and manure application was found both to improve the quality of this soil, and to maintain productivity with reduced off-farm inputs.

CONCLUSIONS

We conclude that biological fixation of N by legumes can be used as the sole source of N for barley production on Luvisolic soils of low fertility such as the Breton loam, without sacrificing yield or soil quality. A workable rotation involves integrating cereals, forages, and livestock. Barley yields in the AER (38% of the rotation time) exceeded those of barley grown under continuous cereal cropping. The soil resource was maintained or improved during a 10-yr period under AER compared to the CG or CBR systems. Further research is needed to discover the mechanisms involved in regulating biological activity and availability of plant nutrients other than N in the AER system.

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