Intercropping wheat and barley with N-fixing legume species: a method for improving ground cover, N-use efficiency and productivity in low input systems

M. P. REYNOLDS[1], K. D. SAYRE[1] AND H. E. VIVAR[2]

[1] *Wheat Program CIMMYT*

[2] *Barley Program ICARDA/CIMMYT, Lisboa 27, Apdo Postal 6-641, 06600 Mexico, D.F., Mexico*

(Revised MS received 16 November 1993)

SUMMARY

Two cereal cropping systems are described which, through the introduction of a leguminous intercrop, increased productivity, nitrogen output and ground cover of the systems in the absence of added nitrogen fertilizer. Nitrogen-fixing legumes were cultivated between rows of wheat or barley grown at low levels of soil nitrogen, and mostly under rainfed conditions, in Mexico between 1989 and 1992. None of the legumes tested reduced yields of the cereal crop in comparison to controls where cereal yields were in the range of 1–4 t/ha, while the extra total biomass from legumes in some cases more than doubled productivity. Different legume crops were tested to demonstrate the adaptability of the system to the varying needs of farmers. The intercropped legumes achieved dry biomass yields as high as 6·5 t/ha in the case of a sequentially cropped forage crop of hairy vetch, or 1·4 t/ha of dry beans plus 3·5 t/ha of green residue in the case of *Vicia faba*. Total biomass in the intercropped situation gave land equivalent ratios as high as 1·54. Light measurements inside the crop canopies indicated that the intercropped systems intercepted a higher proportion of the incident solar radiation than the cereal monocrop, presumably accounting for the large differences in total biomass produced. In addition, with leaf nitrogen levels of 3·8%, it is assumed that the intercropped legumes fixed considerably more nitrogen than was removed by the wheat crop. The potential of the system to stabilize erodible soils by increasing ground cover as well as by raising inputs of soil organic matter is discussed.

INTRODUCTION

The attrition of natural resources that has often accompanied agricultural intensification in the developed world is now recognized as a serious threat globally. A major resource under threat is the topsoil. Small amounts of soil organic matter and the incomplete ground cover commonly associated with intensive cultivation are two of the major factors leading to accelerated soil erosion (Brady 1974). In the medium-term, soil fertility may be maintained with the application of inorganic nutrients. Intercropping with species which can help to control soil erosion (Langdale *et al.* 1992) and/or utilize symbiotically fixed nitrogen instead of inorganic sources (Tomar *et al.* 1988; Danso & Papastylianou 1992), may be a more sustainable approach to maintaining soil fertility.

In this study, the benefits of intercropping wheat and barley with N-fixing legumes were examined at low levels of N input to the soil. High altitude, rainfed environments such as subsistence communities in countries of the high Andes or the Himalayas (Weismantel 1992) are frequently characterized by erodible, highly leached soils and a lack of infrastructure which precludes the use of external inputs. Most of the current work was conducted on the central altiplano of Mexico, where wheat and barley are grown with relatively low inputs, under rainfed conditions, at a mean altitude of 2250 m (Byerlee & Longmire 1986).

When two crops are grown together as intercrops, both crops generally yield less than they do in monoculture, although the land equivalent ratio (LER) is often larger in comparison to that with the monocrops (Papadakis 1941; Ofori & Stern 1987). The hypothesis to be tested was that, for barley and wheat growing at suboptimal levels of N fertility, unused radiation can be absorbed by an N-fixing intercrop without detriment to the main crop. The intention was also to investigate whether this legume could also provide other benefits such as extra ground cover, a source of animal forage, a source of grain legume for human consumption and/or a substantial input of organic matter and N to the soil, either as a green manure or indirectly in the form of crop residues.

MATERIALS AND METHODS

For all experiments, the planting method involved leaving wide spaces (skip rows) between paired (or triple) rows of the cereal so as to accommodate the intercropped legumes. The exact spacing arrangements varied between experiments and details are given for each. Experiment 1 examined the association of six legume species intercropped with wheat (*Triticum aestivum* L.) with or without added N fertilizer. The legumes were common vetch (*Vicia sativa* L.), hairy vetch (*Vicia villosa* Roth), berseem clover (*Trifolium alexandrium* L.), crimson clover (*Trifolium incarnatum* L.), New Zealand white clover (*Trifolium repens* L. New Zealand) and Ladino white clover (*T. repens* L. Ladino) and there was also a control plot containing wheat without any legume. The legumes were chosen for their potential for rapid establishment, and a relatively short growth habit, after consultation with the Rodale Research Center, Kutztown, PA, USA (M. Sarrantonio, personal communication), and seeds were supplied by Kaufman Seeds Inc. (Ashdown, Arkansas, USA). The N fertilizer treatment of 50 kg N/ha was banded on wheat rows at planting in the form of granular urea. The same wheat cultivar (Opata 85) was used in all plots and sown at a standard seed rate of 120 kg/ha. Legumes were sown at the same time as the wheat, with standard seed rates (for monocropped legumes) of between 15 and 20 kg/ha. All legume seed was inoculated before sowing with the appropriate rhizobial strains (Nitragin Inoculants, Liphatech Inc, Milwaukee, Wisconsin, USA). The design was a 2 × 7 factorial with treatments laid out in a randomized complete block design with four replicates. Wheat seeds were sown in paired rows, 20 cm apart, on top of 75 cm beds; legumes were sown in the furrows between beds. Plots were 5 m long and six beds wide, while the harvested area consisted of the inner four beds with a 50 cm border removed from each end. The first experiment was conducted in a typical spring wheat growing environment at a Mexican government experimental station, Centro de Investigaciones Agricolas del Nor Oeste (CIANO; 27° 20′ N, 109° 54′ W; 38 m above sea level (ASL)) in northwestern Mexico, on a heavy clay soil (mixed montmorillonitic typic caliciorthid). Phosphate fertilizer was applied to the experimental site during land preparation at the rate of 50 kg P_2O_5/ha as triple superphosphate. The land had previously supported a maize crop grown without N fertilizer in order to deplete and homogenize soil N. The trial was grown during the spring wheat cycle, from December 1989 to April 1990. After the seeding irrigation, five more irrigations were applied during the cycle whenever soil moisture reached *c.* 50% depletion of available moisture in the 0–60 cm profile, as determined by gravimetric sampling. At the flag leaf stage of the crop (stage 40 of Zadoks *et al.* 1974), the fastest growing legumes, common vetch, hairy vetch and berseem clover, had accumulated *c.* 500 kg/ha of above-ground biomass (estimated by oven-drying subsamples) and were incorporated with spades into the soil between beds as a green manure. The remaining three legumes were left undisturbed until harvest of the wheat crop, at which stage, still green and in flower, subsamples were harvested for dry biomass estimates. The wheat was machine-harvested, yield was measured directly and later adjusted to 0% moisture content after oven-drying subsamples for 48 h at 70 °C. Grain protein content was also estimated as described in the Approved Methods of the American Association of Geochemists (1983). One ancillary trial (Expt 1*b*) was sown at the same time and adjacent to the main experiment to test the response of monocropped wheat yields to N. It consisted of a series of replicated nitrogen treatments, in increments of 25 kg N/ha from 0 to 150 kg/ha, applied at planting as urea.

All subsequent experiments were conducted between 1990 and 1992 at the CIMMYT El Batan experiment station in Central Mexico (19° 31′ N, 98° 50′ W; 2249 m ASL) on a sandy, clay loam vertisol. Experiment 2 included wheat in association with two legume species, berseem clover and hairy vetch. For each legume there were two methods of utilization; the legume was either incorporated at the flag leaf stage of the wheat crop as a green manure, or it was harvested sequentially during the season as a forage crop. Wheat seeds were sown in paired rows, 20 cm apart, with a 60 cm space between paired rows. Legumes were sown in the spaces between paired rows. Plots were 5 m long and four paired rows wide, while the harvested area consisted of the inner two paired rows with a 50 cm border removed from each end. Two controls were included in the experiment: Control 1, where the wheat was sown at a 20 cm row spacing throughout, with no skip rows (a conventional spacing arrangement for wheat) and Control 2 where, although not intercropped, the wheat was sown at the same row spacings as when associated with the legume. The experiment had a randomized complete block design with four replicates. The wheat cultivar Bacanora was sown in all plots at the standard seed rate of 120 kg/ha. Where legumes were harvested sequentially as a forage crop, the entire above-ground biomass was cut and removed from the plots, except for 1–2 cm of stem tissue, which remained for regrowth. Harvests were made when the legume had attained approximately maximum ground cover. Above-ground biomass was estimated at harvest by

Table 1. *Soil pH, exchangeable cations (Ca, Mg, K; mmol/kg), cation exchange capacity (CEC; mmol/kg) and levels of organic matter (OM; %), total N (Kjeldahl; %) and available P (Olsen or Bray-1; mg/kg) for bulked soil samples taken from unfertilized experimental plots, at the two sites used for Expt 1 (CIANO) and Expts 2–5 (El Batan) respectively*

Location	pH	Ca	Mg	K	CEC	OM (%)	P* (mg/kg)	N (Kjeldahl) (%)
		(mmol/kg)						
CIANO	8·3	265	49·1	12·8	341	1·3	8·7	—
El Batan	7·0	94·8	59·6	10·7	167	1·6	56·7	0·07

* Available P (Olsen) estimated for CIANO, available P (Bray-1) estimated for El Batan.

oven-drying the legumes from a subsampled area of each plot. Immediately prior to the forage harvests, the ground cover of the wheat control and intercropped plots was estimated visually. No fertilizer was applied to any of the treatments before or during the trial, residual soil P levels not being limiting (Table 1). The crop was not irrigated and received 480 mm of rain during the season. The experiment was sown in early June 1990, at the beginning of the traditional rainfed wheat cycle in the region, and was harvested in early October 1990. Wheat was hand-harvested and threshed for yield, while biomass was estimated from subsamples. The N contents of grain, straw and legume samples were measured as described in the Approved Methods of the American Association of Geochemists (1983).

Two ancillary experiments (2*b* and 2*c*) were planted at the same time as and adjacent to Expt 2. Experiment 2*b* was a series of replicated N treatments on plots with monocropped wheat, planted in the same arrangement as for the intercropped treatments. Nitrogen treatments were applied in increments of 50 kg N/ha from 0 to 250 kg/ha applied at planting in the form of urea. In Expt 2*c*, forage production of sole crops of berseem and hairy vetch was measured in replicated plots, harvested at the same time as the intercropped legumes. These plots were broadcast-sown at standard seed rates.

Experiments 3, 4 and 5 constituted a longer term trial in which a barley (*Hordeum vulgare* L.)–faba bean (*Vicia faba* L.) intercrop was compared with two barley monocrop planting methods, with or without N fertilizer at a rate of 50 kg/ha. Treatments were grown on the same plots in consecutive cycles. Intercropped barley was sown in three rows 15 cm apart on top of 90 cm beds at a seed rate of 75 kg/ha. Faba beans were sown as a single row between the beds at a seed rate of 60 kg/ha, but later thinned to one plant per 50 cm. In both monocrop controls, barley was sown in the same arrangement as for the intercrop treatment. However, in one of the controls, an additional 50 kg/ha of barley seed was sown broadcast between the beds. Experiment 3 had a randomized complete block design with six replications of the three barley cultivation treatments, without added N fertilizer. The design for Expts 4 and 5 consisted of a 3 × 2 factorial with three replications, the N treatments as a split-plot factor, and the barley treatments randomized within blocks. Plots were 9 m long and four beds wide, while the harvested area consisted of the inner two beds with a 50 cm border removed from each end. Experiments 3 and 5 were rainfed, with precipitation totalling 450 and 540 mm, respectively. Experiment 4 coincided with the dry winter season and was irrigated. Previous to planting, the land had supported a crop of oats, grown without N fertilizer, in order to deplete and homogenize soil N levels. During grain-filling, interception of photosynthetically active radiation (PAR) at midday was calculated from measurement of PAR above the crop and at ground level using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA). At maturity of the barley, the grain was hand-harvested, threshed and weighed, and the yield components were estimated from subsamples. The faba beans were left for about 1 week before harvesting. Crop residues were left *in situ* and incorporated at land preparation of the subsequent cycle.

In all experiments, diseases and pests were controlled chemically, and weeds were controlled by hand cultivation. Mean temperatures for the growth cycle for Expts 1–5 were 17·8, 16·6, 17·3, 13·6 and 17·0 °C respectively, while average numbers of sun hours per day were 8·7, 6·0, 5·8, 6·4 and 5·6 respectively for the five experiments. Results of the soil analyses for the two experimental locations are given in Table 1. Soil pH was measured at a 1:2 soil:water ratio; exchangeable cations Ca, Mg, K, and cation exchange capacity as described by Gillman & Sumpter (1986); organic matter as described by Walkey (1947); total N (Kjeldahl) as described by Bremner (1960); available P (Bray-1) as described by Bray & Kurtz (1945); and available P (Olsen) as described by Watanabe & Olsen (1965).

RESULTS

In the first experiment, none of the legume intercrops had any statistically significant effect on wheat yields

Table 2. *Grain yield (t/ha) and percentage grain protein for wheat intercropped with six different N-fixing legume species, and as a monocrop with and without 50 kg/ha applied N, at CIANO, Obregon, NW Mexico, 1989/90 (Expt 1)*

	Wheat yield (t/ha)			Grain protein (%)		
	Applied N			Applied N		
Legume treatment	Zero	50 kg/ha	Mean	Zero	50 kg/ha	Mean
(*a*) Legume incorporated at booting as green manure						
Berseem clover (*T. alexandrium*)	3·8	4·5	4·2	10·1	9·5	9·8
Common vetch (*V. sativa*)	3·7	4·3	4·0	9·4	8·9	9·1
Hairy vetch (*V. villosa*)	3·5	4·2	3·9	9·2	9·1	9·2
(*b*) Legume cut for forage after maturity of wheat						
Crimson clover (*T. incarnatum*)	3·5	4·1	3·8	8·8	9·1	8·9
Ladino white clover (*T. repens*)	3·2	4·2	3·7	8·7	9·1	8·9
NZ white clover (*T. repens*)	3·8	4·5	4·2	9·5	8·6	9·0
Control (monocrop wheat)	3·3	4·2	3·8	9·5	9·0	9·3
Mean	3·5	4·3	3·9	9·3	9·0	9·2
S.E.	0·21	0·20	0·20	0·38	0·24	0·31
D.F.	18	18	39	18	18	39

Table 3. *Grain yield (t/ha), straw biomass (t/ha) and nitrogen distribution for wheat intercropped with two N-fixing legume species for forage or green manure, and as a monocrop without applied N, at CIMMYT, El Batan, Mexico 1990 (Expt 2)*

Treatment	Grain yield (t/ha)	Straw biomass (t/ha)	Grain protein (%)	Straw nitrogen (%)
Berseem clover (*T. alexandrium*)				
Green manure	2·6	4·1	11·5	0·73
Forage	2·5	4·6	10·7	0·68
Common vetch (*V. villosa*)				
Green manure	2·4	3·6	12·3	0·71
Forage	2·3	4·0	10·6	0·65
Control (wheat monocrop)				
2 skip rows	2·3	3·9	10·9	0·61
No skip rows	2·1	3·4	10·4	0·59
S.E.	0·16	0·29	0·15	0·44
D.F.	15	15	15	15

in comparison to the monocropped control. Yields averaged 3·5 t/ha without applied N, and 4·3 t/ha with 50 kg N/ha, with no significant interaction between legume treatment and nitrogen rates (Table 2). Legumes in association with the wheat varied in their productivity. Berseem clover and the two vetch species were the fastest growing, but biomass was only measured prior to their incorporation as green manure, and was *c.* 0·5 t/ha dry weight at both N levels. The biomass of the other legumes was estimated at the time of wheat harvest to be 1·8 t/ha for crimson clover and 0·75 t/ha for the two white clover species, and did not differ significantly between N levels. The protein content of the wheat grain was not statistically different from the control in any treatment (Table 2), including those with the highest applied N levels. Although there was no statistically significant effect of the green manure treatments, both wheat yield and wheat grain protein content tended to be higher with the berseem green manure treatment (Table 2). In Expt 1 *b*, the analysis of response to applied nitrogen suggested an approximately linear response up to levels of 100 kg/ha, with a predicted yield at zero applied N of 3·4 t/ha, and a yield response of 19·5 kg of extra yield per kg of N applied. The maximum yield, at 150 kg N/ha was 5·4 t/ha, and the yield with 100 kg N/ha was 5·3 t/ha.

In the second experiment, only one of the intercropping treatments affected wheat yield significantly; berseem clover incorporated as a green manure increased the wheat yield by 24% over the control without skip rows (Table 3). Both green manure treatments increased wheat grain protein significantly by 18 and 11% over the control treatment, with the incorporation of vetch and berseem, respectively (Table 3). Like the wheat yields, grain protein was not affected by the intercropped forage treatments. However, the sequentially-harvested forage intercrop treatments had a considerable impact on total productivity giving *c.* 2·4 times as much dry biomass as the control without skip rows (Table 4). Nitrogen content of the forage cuts remained relatively constant, averaging 3·8%, and did not differ significantly between treatments. Ground cover, estimated visually immediately prior to forage harvests, was consistently higher for

Table 4. *Total biomass (t/ha), total crop N (kg/ha), land equivalent ratio (LER) and ground cover estimate (%), for wheat and forage legumes intercropped or monocropped at CIMMYT, El Batan, Mexico, 1990 (Expt 2)*

Cropping system	Biomass (t/ha)	Total crop N (kg/ha)	Land equivalent ratio	Ground cover (%)
Intercropping				
Berseem clover	5·6	214	—	—
Wheat	7·1	79	—	—
Total	12·7	293	1·5	85
Common vetch	6·7	263	—	—
Wheat	6·4	71	—	—
Total	13·0	334	1·4	90
S.E. total (3 D.F.)	0·71	17·5	0·08	—
S.E. legume (3 D.F.)	0·35	13·5	—	—
Monocropped legume				
Berseem clover	14·9	566	1·0	100
Common vetch	18·7	643	1·0	100
S.E. (3 D.F.)	0·68	24·2	—	—
Monocropped wheat				
2 skip rows	6·1	69	1·0	60
No skip rows	5·4	59	1·0	70
S.E. wheat (9 D.F.)	0·41	4·6	—	—
S.E. all cropping systems (15 D.F.)	—	—	—	3·3

both intercropped forage treatments than either monocrop (Table 4). In Expt 2*b*, the response of monocropped wheat yields to nitrogen rate was linear in the range 0–200 kg N/ha, the yields being *c*. 2·3, 2·9, 3·8, 4·8, and 5·4 t/ha at 0, 50, 100, 150 and 200 kg N/ha respectively. The predicted yield at the zero N level was 2·2 t/ha and the yield response to application was 16·6 kg/ha per kg N. The yield with 250 kg/ha of applied N was 5·5 t/ha. In Expt 2*c*, the monocropped vetch and berseem plots, harvested sequentially at the same dates as the intercropped legumes in Expt 2, yielded an overall total of 18·7 and 14·9 t/ha dry weight, respectively. These values were used to calculate land equivalent ratios (Table 4), as defined by Willey & Osiru (1972).

In Expts 3, 4 and 5, where barley was intercropped with faba bean, barley yield was not significantly different in the intercropped situation to the wide-spaced control (with skip rows). Although there were no significant interactions between sowing dates and treatments, there were significant differences between sowing dates in terms of the productivity of barley and faba beans. Experiment 3 suffered from waterlogging until heading of the barley, which resulted in yields which averaged only 0·8 t/ha, while the faba bean attained a biomass of 1·7 t/ha. In Expt 4, when yields were averaged across the three treatments,

Table 5. *Grain yield (t/ha), yield components and midday light interception (%) for barley cropping systems involving barley in two spacing arrangements, or intercropped with faba bean, without applied N after the second cycle of continuous cropping at El Batan, Mexico 1991/92 (Expt 4)*

Cropping system	Yield (t/ha)	Biomass (t/ha)	Light interception (%)	Spikes/ m^2	Grains/ Spike
Barley sole crop					
Solid stand	2·6	9·1	55	777	8·1
90 cm rows	3·1	7·5	43	521	14·4
Mixed crop					
Barley	3·0	7·4	—	522	15·2
Faba bean	1·4	4·9	—	—	—
Total	4·5	12·3	75	—	—
S.E.*	0·29	0·43	2·8	19·1	0·88
D.F.	4	4	4	4	4

* For comparison of the three barley means for each parameter, and all means for light interception.

barley yielded 2·9 t/ha without added N (Table 5), and 3·4 t/ha with 50 kg/ha of applied N. The applied N did not affect the yield (1·4 t/ha) of faba beans in comparison to the faba bean yield without applied N (Table 5), but faba bean total biomass was reduced by 0·5 t/ha. Interception of PAR measured at midday during grain-filling was on average 36% higher for the intercrop system than for the solid stand monocrop (Table 5). There was no significant interaction of N levels and intercropping treatments on barley yield for Expts 4 and 5. In Expt 5, barley yields averaged 1·9 t/ha without N and 2·5 t/ha with N, across all planting arrangements. Faba bean yield and biomass were less than half that of the previous experiment, probably due to a seed-borne *Fusarium* infection. When comparing the monocrop treatments, the control in which barley had been sown in the skip rows showed a significant (12%) yield depression in comparison to the control with skip rows left unsown, when averaged over all experiments.

DISCUSSION

These experiments were designed with three main objectives: (i) to test the hypothesis that for wheat growing at suboptimal levels of N fertility, light is not a limiting factor and can be used by an N-fixing intercrop without detriment to the main crop; (ii) to evaluate the performance of different N-fixing legumes when intercropped with wheat in alternate rows; and (iii) to test an improved barley cropping system that, by including a leguminous intercrop, could benefit resource-poor farmers in one or more ways. The benefits might be direct, such as extra yield of beans/forage, and by adding nitrogen to the system in the form of crop residues. Indirect benefits potentially include soil stabilization by increasing organic matter input into the soil with extra crop or animal residues, and increasing crop cover of the soil during the growing cycle. In the first experiment, in northwestern Mexico, there were two important findings. The first was that N-fixing legumes could be successfully intercropped with wheat at suboptimal levels of N without apparent detriment to wheat yields or quality (Table 2). The second was that, of the six legumes tested, berseem clover and the two vetch species seemed to be the best adapted to growth in association with wheat under these conditions. The utility of such a system in an irrigated environment is debatable and is discussed below.

Subsequent experiments were conducted at the CIMMYT El Batan station in the moderate-high rainfall, temperate environment of the central highlands of Mexico. While this is a potential target environment in itself, it also serves as a model environment for other rainfed, high altitude zones. Experiment 2 established that by intercropping wheat with vetch and berseem clover, the total productivity of the system could be more than doubled over wheat controls (Table 4) where the legume was harvested sequentially as a forage. Taking into consideration the biomass produced by monocropped legumes, favourable values for land equivalent ratio (LER) of the intercrops were found (Table 4). Based on the favourable LERs observed when intercropping forage legumes with wheat, another experiment was initiated to test the compatibility of intercropping an N-fixing grain legume (faba bean) with barley. Barley was chosen as it is a commonly grown cereal in many marginal environments, and faba bean since the beans provide an extra food source for human consumption. In the most productive of the three barley–faba bean experiments (Expt 4) the system gave, in addition to 3 t/ha of barley, 1·4 t/ha of grain legume in dry weight and 3·5 t/ha of green aboveground residues.

It was important to answer the question as to whether the use of skip rows in the planting of wheat, a prerequisite of this method of intercropping with legumes, was in itself detrimental to wheat yields at low N levels in comparison to closer spacing arrangements. In none of the trials was there any evidence that a closer planting arrangement gave any benefit to the wheat crop (Tables 3 and 5). On the contrary, when data were combined in an analysis of all experiments, the treatments without skip rows yielded significantly less grain. In Expt 4, the fact that yield and grains/spike were lower but total biomass and spikes/m^2 were higher in the solid stand barley in comparison to the wider spacing (Table 5) indicated a more favourable partitioning of assimilates to yield in the latter, and suggests that perhaps the wider spacing resulted in a more conservative use of soil N early in the growth of the crop.

The hypothesis that the light not intercepted by wheat growing at suboptimal levels of N fertility can be used by an N-fixing intercrop was supported by the light interception values in the barley–faba bean intercrop experiment (Table 5), as well as the ground cover estimates in the wheat forage trial (Table 4). This result is in contrast to other studies (Sivakumar & Virmani 1980; Reddy & Willey 1981), where it was concluded that higher productivity of the intercrop system was achieved by an increased efficiency in converting light energy into dry matter, and not by an increase in the amount of light energy absorbed. However, those studies were not specifically examining low N fertility environments. Most studies have demonstrated that cereals show reduced yields when intercropped, in comparison to the monocrop (see Ofori & Stern 1987; Table III) even though land equivalent ratios may be higher. Surprisingly, few data are available for low N fertility environments, where one might expect to see a greater degree of synergy between a cereal and an intercrop which fixes its own nitrogen. There is evidence that N-fixing legumes intercropped with cereals increased the availability of soil N to the subsequent wheat crop (Singh 1983; Izaurralde *et al.* 1990; Danso & Papastylianou 1992). There is also evidence that the intercropping of a cereal with an N-fixing legume, in this case pearl millet with groundnut, permits the lateral movement of fixed N from the legume to the cereal (Willey & Reddy 1981). One possible mechanism for the movement of N from soyabean to maize has been demonstrated using ^{15}N tracers, where the transfer took place via mycorrhizal connections between the two species (van Kessel *et al.* 1985).

The data presented in this study show an increase in the N output of the intercropped system coming largely from the N content of the legumes, although in one treatment in Expt 2 there was evidence for increased N output from the cereal crop (Table 4). Two mechanisms are known which can improve the N status of a cereal in association with a legume; nitrogen transfer and the sparing effect (Giller & Wilson 1991). In Expt 2, the N contents of the intercropped wheats were not higher than those of the controls (Table 3) but, since the wheat biomass was increased over controls when intercropped with berseem forage, there was a net increase in N output of the wheat in this treatment (Table 4). The increased N output of the intercropped wheat in this case was presumably due to N transfer, since the sparing effect would only be possible if the intercropped wheat yielded equal or less N than the monocropped wheat, on a total area basis. The sequential harvests of the intercropped forage legumes during the wheat cycle may have catalysed the N transfer, since removal of the legume above-ground biomass would most likely have resulted in some turnover of N from the roots and nodules. The relatively large N content of the legume crops (Table 4) presumably originated from both the soil and the atmosphere via biological N-fixation. While it is known that intercrops can extract more N from the soil than sole crops (Mason *et al.* 1986) the data presented here indicate that biologically fixed N made a significant contribution to the N budget of the legumes. Since the systems were N limited, as indicated by the response of sole cropped wheat to applied N, it is improbable that the legumes derived virtually their entire N content, which exceeded 200 kg/ha (Table 4), from a source in the soil that was unavailable to the wheat, especially given the relatively low soil N and organic matter contents (Table 1).

Crop N data were not collected in Expts 3, 4 or 5. However, since the treatments were repeated on the same plots consecutively, carry-over effects might have been expected if the treatments had resulted in a differential effect on the N budgets of the cropping systems. Despite the fact that the intercropped faba bean residues from Expts 3 and 4 were incorporated, no statistically significant carry-over effects were apparent in Expts 4 or 5. The apparent lack of a response to the incorporation of faba bean residues from one cycle to the next is not unexpected. Firstly, if the faba bean intercrop derived a significant part of its N from the soil, the return of its residues would not necessarily make a net contribution to soil N. Secondly, given the turnaround time of *c.* 6–8 weeks between incorporation of residues and germination of the subsequent crop, it is possible that some of the organic N might have been lost or rendered unavailable. Since the residues were still green at incorporation, their relatively low C:N ratio would encourage rapid mineralization of organic N (Giller & Wilson 1991), which in turn would lead to N losses via leaching in such a high rainfall environment. The apparent lack of a carry-over effect implies that the intercropped system did not cause a net reduction in the N fertility of the soil in comparison to control plots, despite the fact that productivity was significantly higher for the intercropped system (Table 5). These observations suggest that the faba bean crop fixed some of its N biologically, and that the return of the crop residues as a green manure helped to maintain soil fertility levels. In circumstances where the bulk of the N of an intercrop is fixed biologically, its use as a green manure would be expected to contribute significantly to the N status of the subsequent crop.

Without conducting a further, longer term experiment, it is not possible to say that the intercropping of wheat with legumes would be more productive than a more traditional wheat–legume rotation. The issue is, in fact, not simple, since a greater land area is generally used for cultivating cereals than legumes in the target environments, and rotations in marginal areas tend to be quite complex. In the Andean countries, for example, the rotations may include maize, potatoes, other vegetables and herbs apart from barley and legumes (Weismantel 1992). Furthermore, there are additional benefits of intercropping irrespective of productivity, such as reducing the spread of insect pests and some diseases (Trenbath 1976). Since leaf diseases such as scald and net blotch are common problems of barley in many marginal environments, intercropping may well provide some protection by providing a physical barrier to the movement of spores via rain splash. Weed control is another potential benefit of intercropping (Gliessman 1986; White & Scott 1991). In our studies, although no formal measurements were made, it was clear that the increased early ground cover of the intercropped systems, especially those containing vetch and clover, had a substantial effect in suppressing a broad spectrum of weed species. It is important to remember that, in any attempt to introduce such a system to a community, the potential dangers of the legume itself becoming a weed should be considered. In this regard, it is worth noting that the vetches, with their climbing habit, tended to interfere more with wheat growth in these studies than the clovers. Although important in terms of extrapolating results, the issue of water-use efficiency in the intercropped situation is not addressed in this report since the immediate target environments for this type of system typically have $>$ 500 mm of rainfall during the year.

Marginal agricultural lands are a logical target environment for this type of cropping system for three reasons: firstly, cereals, especially barley, are a staple food; secondly, farmers in such areas are generally resource-poor and have limited access to inorganic N fertilizers and therefore a system that utilizes the fixation of atmospheric N is likely to improve total productivity; and thirdly, many such environments are prone to soil erosion and degradation. Erosion can be combated to some extent by improving spatial and temporal ground cover with a crop, thus protecting the soil. Increased levels of soil organic matter can also stabilize soils by improving their physical properties, as well as by improving water infiltration rates (Brady 1974). In our experiments, the cereal–legume intercrop system not only improved ground cover (Table 4), which in Expt 4 was indicated by increased light interception values (Table 5), but also substantially raised total crop productivity, potentially allowing a greater return of organic matter to the soil in the form of increased crop residues, or possibly animal wastes at a later stage (Cornick & Kirby 1981). In addition to this, the total N output of the system was raised, an important aspect of sustainability in a nitrogen-deficient system.

While intercropping is currently of major interest in marginal environments, the potential for intercropping cereals with legumes has also been demonstrated in high yielding environments such as the UK (Martin & Snaydon 1982; Jones & Clements 1993), and the US (Singh 1983; Tomar *et al.* 1988; Grubinger & Minotti 1990; Izaurralde *et al.* 1990). In our first experiment, it was shown that a wheat yield of > 4 t/ha was achieved without detriment from the intercropped legumes. This is higher than the average yield of spring wheat for the developing world and indicates the potential of intercropping to provide agricultural soils with a restitutive green manure crop without taking main crops out of production. The use of alternate row cropping, in particular, is a system of intercropping that is highly amenable to mechanized management (Ofori & Stern 1987). Such systems allow the intercrop to utilize the available resources of light, nutrients and possibly water, at stages of development when they are not limiting to the main crop (Trenbath 1976; Gliessman 1986). Our increased understanding and subsequent exploitation of such interactions in plant communities are potentially important in solving the problem of meeting the world's growing demand for agricultural products without further erosion of our natural resource base.

REFERENCES

APPROVED METHODS OF THE AMERICAN ASSOCIATION OF CEREAL CHEMISTS (1983). Methods 46-10 & 46-11 in *Approved Methods of the American Association of Cereal Chemists*, 7th edn. St Paul, Minnesota: AACC.

BRADY, N. C. (1974). *The Nature and Properties of Soils*, 8th edn. New York: Macmillan Publishing Co.

BRAY, R. H. & KURTZ, L. T. (1945). Determination of total organic and available forms of phosphorus in soils. *Soil Science* **59**, 39–45.

BREMNER, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *Journal of Agricultural Science, Cambridge* **55**, 11–33.

BYERLEE, D. & LONGMIRE, J. (1986). Comparative advantage and policy incentives for wheat production in rainfed and irrigated areas of Mexico. *CIMMYT Economics Program, Working Paper No. 01/86.*

CORNICK, T. R. & KIRBY, R. A. (1981). Interaction of crops and livestock production in the generation of technology in sloped areas. *Publication of New York State College of Agriculture of Life Science.* Ithaca, NY: Cornell University.

DANSO, S. K. A. & PAPASTYLIANOU, I. (1992). Evaluation of the nitrogen contribution of legumes to subsequent cereals. *Journal of Agricultural Science, Cambridge* **119**, 13–18.

GILLER, K. E. & WILSON, K. J. (1991). *Nitrogen Fixation in Tropical Cropping Systems.* Wallingford: CAB International.

GILLMAN, G. P. & SUMPTER, E. A. (1986). Modification to the compulsive exchange method for measuring exchange characteristics of soils. *Australian Journal of Soil Research* **24**, 61–66.

GLIESSMAN, S. R. (1986). Plant interactions in multiple cropping systems. In *Multiple Cropping Systems* (Ed. C. A. Francis), pp. 82–95. New York: Macmillan Publishing Company.

GRUBINGER, V. P. & MINOTTI, P. L. (1990). Managing white clover living mulch for sweet corn production with partial rototilling. *American Journal of Alternative Agriculture* **5**, 4–12.

IZAURRALDE, R. C., JUMA, N. G. & MCGILL, W. B. (1990). Plant and nitrogen yield of barley-field pea intercrop in cryoboreal-subhumid central Alberta. *Agronomy Journal* **82**, 295–301.

JONES, L. & CLEMENTS, R. O. (1993). Development of a low input system for growing wheat (*Triticum vulgare*) in a permanent understorey of white clover (*Trifolium repens*). *Annals of Applied Biology* **123**, 109–119.

LANGDALE, G. W., CLARK, R. L. & BRUCE, R. R. (1992). The role of legumes in sustaining soil productivity and controlling soil erosion. In *Biological Nitrogen Fixation and Sustainability in Tropical Agriculture* (Eds K. Mulongoy, M. Gueye & D. S. C. Spencer), pp. 361–366. Chichester: John Wiley and Sons.

MASON, S. C., LEIHNER, D. E. & VORST, J. J. (1986). Cassava-cowpea and cassava-peanut intercropping. III. Nutrient concentrations and removal. *Agronomy Journal* **78**, 441–444.

MARTIN, M. P. L. D. & SNAYDON, R. W. (1982). Intercropping barley and beans. I. Effects of planting pattern. *Experimental Agriculture* **18**, 139–148

OFORI, F. & STERN, W. R. (1987). Cereal–legume intercropping systems. *Advances in Agronomy* **41**, 41–90.

PAPADAKIS, J. S. (1941). Small grains and winter legumes grown mixed for grain production. *Journal of the American Society of Agronomy* **33**, 504–511.

REDDY, M. S. & WILLEY, R. W. (1981). Growth and resource use studies in an intercrop of pearl millet/groundnut. *Field Crops Research* **4**, 13–24.

SINGH, S. P. (1983). Summer legume intercrop effects on yield and nitrogen economy of wheat in the succeeding season. *Journal of Agricultural Science, Cambridge* **101**, 401–405.

SIVAKUMAR, M. V. K. & VIRMANI, S. M. (1980). Growth and resource use of maize, pigeonpea and maize/pigeonpea intercrop in an operational research watershed. *Experimental Agriculture* **16**, 377–386.

TOMAR, J. S., MACKENZIE, A. F., MEHUYS, G. R. & ALLI, I. (1988). Corn growth with foliar nitrogen, soil-applied nitrogen, and legume intercrops. *Agronomy Journal* **80**, 802–807.

TRENBATH, B. R. (1976). Plant interactions in mixed crop communities. In *Multiple Cropping* (Eds R. I. Papendick, P. A. Sanchez & G. B. Triplett), pp. 129–169. Special Publication No. 27. Madison, Wisconsin: American Society of Agronomy.

VAN KESSEL, C., SINGLETON, P. W. & HOBEN, H. J. (1985). Enhanced N-transfer from a soybean to maize by vesicular arbuscular mycorrhizal (VAM) fungi. *Plant Physiology* **79**, 562–563.

WALKLEY, A. (1947). A critical examination of a rapid method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* **63**, 251–263.

WATANABE, F. S. & OLSEN, S. R. (1965). Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. *Soil Science Society of America Proceedings* **29**, 677–678.

WEISMANTEL, M. J. (1992) *Food, Gender and Poverty in the Ecuadorian Andes*. Philadelphia: University of Pennsylvania Press.

WILLEY, R. W. & OSIRU, D. S. O. (1972). Studies on mixtures of maize and beans (*Phaseolus vulgaris*) with particular reference to plant population. *Journal of Agricultural Science, Cambridge* **79**, 517–529.

WILLEY, R. W. & REDDY, M. S. (1981). A field technique for separating above- and below-ground interactions in intercropping: an experiment with pearl millet/groundnut. *Experimental Agriculture* **17**, 257–264.

WHITE, J. G. & SCOTT, T. W. (1991). Effects of perennial forage-legume living mulches on no-till winter wheat and rye. *Field Crops Research* **28**, 135–148.

ZADOKS, J. C., CHANG, T. T. & KONZAK, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research* **14**, 415–421.