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Intercropping Cereals with N-Fixing Legume Species:

A Method for Conserving Soil Resources in Low-Input Systems

M.P. Reynolds, K.D. Sayre, and H.E. Vivar

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Preface

Low-input, high-efficiency cereal crop production contributes to poverty alleviation, increases agricultural revenues, and enhances environmental (soils and water) conservation. This Wheat Special Report discusses results of 4 years of work on intercropping barley and wheat with various N-fixing legumes. The results are highly encouraging in as much as barley and wheat were grown at suboptimal levels of nitrogen in rainfed environments (around 500 mm/season) and the yields of the intercrops did not decrease. The land equivalent ratio was increased to as much as 1.54.

This model aims at helping the poor to obtain adequate agricultural output while conserving their natural resources, even in the most difficult situations. Crop management practices discussed are the basis for the implementation of sustainable agricultural systems. We encourage national agricultural research programs to try models similar to the one presented here.

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Leader
Crop Management and Physiology Subprogram
CIMMYT Wheat Program
Introduction

The natural resources of the developing world are becoming increasingly threatened as the agricultural sector intensifies. A major resource being lost is the topsoil. Low levels 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 that 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 and Papastylianou 1992), may be a more sustainable approach to the problem.

This study examined the benefits of intercropping wheat and barley with N-fixing legume when soil resources are both scarce and unstable. High altitude, rainfed environments, such as subsistence communities in countries of the high Andes or the Himalayas (Weismantel 1992), are frequently characterized by fragile, highly leached soils and a lack of infrastructure precluding 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, and at a mean altitude of 2250 masl (Byerlee and Longmire 1986).

When intercropped, both crops generally yield lower than they do in monoculture, although the land equivalent ratio is often higher in comparison to the monocrop (Papadakis 1941, Ofori and Stern 1987). We tested the hypothesis that, for barley and wheat growing at suboptimal levels of nitrogen fertility, unused radiation can be absorbed by an N-fixing intercrop without detriment to the main crop. Furthermore, we wished to demonstrate that the legume could provide a number of alternative benefits: 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 nitrogen to the soil, either as a green manure crop or indirectly in the form of crop residues or animal wastes.

Materials and Methods

The first experiment involved the association of six legume species intercropped with wheat (*Triticum aestivum* L.) at two nitrogen levels. The legume treatments included *Vicia sativa* L. (common vetch), *Vicia villosa* Roth (hairy vetch), *Trifolium alexandrium* L. (berseem clover), *Trifolium incarnatum* L. (crimson clover), *Trifolium repens* L. New Zealand (NZ clover), *T. repens* L. Ladino (Ladino clover), and a control without any legume in association with the wheat. 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, pers. comm.), and seed were supplied by Kaufman Seeds, Inc. (Ashdown, Arkansas, USA). The nitrogen fertilizer treatments, 0 and 50 kg N/ha, were banded on wheat rows at planting in the form of granular urea. The wheat variety 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 15-20 kg/ha. All legume seed was inoculated before sowing with appropriate rhizobial strains, (Nitragin Inoculants, Liphatech, Inc. Milwaukee, Wisconsin, USA). For design of experiments, row spacing, plot size, and environmental data see Table 1. The first experiment was conducted in northwestern Mexico, a typical spring wheat growing environment, at a Mexican government experimental station, Centro de Investigaciones Agricolas del Nor Oeste (CIANO), at 27°20'N; 109°54'W; and 38 masl. Soil type was a heavy clay. Phosphate fertilizer was applied to the trial during land preparation at the rate of 50 kg P2O5/ha as triple superphosphate. Prior to planting, the land had supported a maize crop grown
Table 1. Summary of treatments, and design for five experiments involving the intercropping of cereals with legume species.

<table>
<thead>
<tr>
<th>Methods</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design:a</td>
<td>RCB</td>
<td>RCB</td>
<td>RCB</td>
<td>SP(F1)</td>
<td>SP(F1)</td>
</tr>
<tr>
<td>Reps:</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Factor 1: legume</td>
<td>7d</td>
<td>2(2+2c)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Factor 2b: management</td>
<td>N</td>
<td>GM/FOR</td>
<td>-</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Land preparation:</td>
<td>Beds</td>
<td>Flat</td>
<td>Beds</td>
<td>Beds</td>
<td>Beds</td>
</tr>
<tr>
<td>Plot length:</td>
<td>5 m</td>
<td>5 m</td>
<td>9 m</td>
<td>9 m</td>
<td>9 m</td>
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<tr>
<td>Plot width:</td>
<td>4.8 m</td>
<td>3.2 m</td>
<td>3.6 m</td>
<td>3.6 m</td>
<td>3.6 m</td>
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<tr>
<td>Row space:</td>
<td>20 cm</td>
<td>20 cm</td>
<td>15 cm</td>
<td>15 cm</td>
<td>15 cm</td>
</tr>
<tr>
<td># Rows:e</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td># Skip rows:</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Narrow-spaced control?:f</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Av. temp. for cycle C:</td>
<td>17.8</td>
<td>16.6</td>
<td>17.3</td>
<td>13.6</td>
<td>17.0</td>
</tr>
<tr>
<td>Av. Sun hours/D. for cycle:</td>
<td>8.7</td>
<td>6.0</td>
<td>5.8</td>
<td>6.4</td>
<td>5.6</td>
</tr>
</tbody>
</table>

a Parentheses indicate split plot factor (Fn).
b Number of treatments including the no legume control(s).
c The 2 controls (+2) could not be incorporated into the factorial structure of the experiment since factor 1, use of legume, is mutually exclusive to control treatments.
d Of the six legumes grown three were incorporated as a green manure during the wheat cycle, and three harvested as forage at the end of the cycle (see materials and methods).
e Number of planted rows between groups of skip rows.
f See materials & methods for details of narrow spaced controls.

RCB, randomized complete block; SP, split-plot; N, nitrogen fertilizer; GM, green manure incorporation; FOR, legume harvested sequentially as forage; FABA, faba bean.
without nitrogen fertilizer in order to deplete and homogenize soil nitrogen. 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 when soil moisture
reached approximately 50% depletion of available moisture in the 0-60 cm profile, as
determined by gravimetric sampling. At the flag leaf stage of the crop (Zadok's stage 40)
the fastest growing legumes, vetch, hairy vetch, and berseem clover, had accumulated
approximately 500 kg/ha of above-ground biomass 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 hours at 70°C. Grain protein content was also estimated
(AACC 1983). One ancillary trial was sown at the same time and adjacent to the main
trial. It consisted of a series of replicated nitrogen treatments on plots with monocropped
wheat. Treatments, in increments of 50 kg N/ha from 0 to 150 kg/ha, were applied as
urea at planting.

All subsequent experiments were conducted between 1990 and 1992 at CIMMYT's El
Batan experiment station, which is situated in Central Mexico, at 19°31'N, 98°50'W, and
2249 masl. The second experiment 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 incorporated at the flag leaf stage of the wheat crop as a green
  manure.

• The legume was harvested sequentially during the season as a forage crop.

The planting arrangement is described in Table 1. Two controls were included in the
trial: Control 1, where the wheat was sown at a 20 cm row spacing, 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 spacing as when associated with a
legume (Table 1). The wheat variety Bacanora was sown in all plots at the standard seed
rate of 120 kg/ha, except where stated otherwise. Where legumes were harvested
sequentially as a forage crop, the entire above-ground biomass was cut and removed from
the plots, except for 1 or 2 cm of stem tissue, which remained for regrowth. Harvests
were made when the legume attained approximately maximum ground cover. Above-
ground biomass was estimated at harvest by oven drying the legumes from a subsampled
area of each plot. Immediately prior to the forage harvests, light interception of the wheat
control and intercropped plots were estimated visually by approximating the percentage
of sun flecks visible at soil level at solar noon. No fertilizer was applied to any of the
treatments before or during the trial, residual soil P levels not being limiting. The crop
was not irrigated and received 480 mm of rain during the season. The trial was sown in
early June 1990, at the beginning of the traditional rainfed wheat cycle in the region, and
harvested in early October 1990. Wheat was hand-harvested and yield components were
estimated from subsamples. The nitrogen content of grain, straw and legume samples was
measured (AACC 1983).

Two ancillary trials were planted at the same time and adjacent to the main trial. One was
a series of replicated nitrogen treatments on plots with monocropped wheat, planted in
the same arrangement as for intercropped treatments (Table 1). Treatments ran in
increments of 50 kg N/ha from 0 to 250 kg/ha applied at planting in the form of urea. In
the other ancillary trial, forage production was measured in replicated plots of sole crops
of berseem and hairy vetch, harvested at the same time as the intercropped legumes. These plots were broadcast-sown at standard seed rates.

The third, fourth, and fifth experiments 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. 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 (Table 1), at a seed rate of 75 kg/ha. Faba beans were sown in one row between the beds at a seed rate of 60 kg/ha, but later thinned to one plant every 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. The third and fifth experiments were rainfed with precipitation totaling 450 and 540 mm, respectively. The fourth experiment coincided with the dry winter season and was irrigated. Previous to planting the trial, the land had supported a crop of oats, grown without nitrogen fertilizer, in order to deplete and homogenize soil nitrogen levels. During grain-filling, interception of photosynthetically active radiation (PAR) at mid-day 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 approximately 1 week before harvesting. Crop residues were left in situ and incorporated at land preparation of the subsequent cycle. In all trials, diseases and pests were controlled chemically. Weeds were controlled by hand cultivation.

Results

In the first experiment, none of the legume intercrops had any statistically significant effect on wheat yields in comparison to the monocropped control. Yields averaged 3.5 t/ha without applied N (Table 2), and 4.3 t/ha with 50 kg N/ha, with no significant interaction between legume treatment and nitrogen level. 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 approximately 0.5 t/ha dry weight at both N levels. 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 was not significantly different 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 highest applied N levels. Although there was no statistically significant effect of the green manure treatments, both grain yield and protein content tended to be higher with green manuring in the zero applied N treatments, for the berseem clover (Table 2). 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.

In the second experiment, only one of the intercropping treatments affected wheat yield significantly; berseem incorporated as a green manure increased the wheat yield by 36% 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 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 approximately 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 among treatments. Light interception,
Table 2. Grain yield and percent grain protein for wheat intercropped with six different N-fixing legume species without applied N; CIANO, Obregon, northwestern Mexico, 1989-90 (Experiment 1).

<table>
<thead>
<tr>
<th>Legume species</th>
<th>Wheat yield (t/ha)</th>
<th>Grain protein (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Legume incorporated at booting as green manure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berseem clover</td>
<td>3.8</td>
<td>10.1</td>
</tr>
<tr>
<td>Vetch</td>
<td>3.7</td>
<td>9.4</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td>3.5</td>
<td>9.2</td>
</tr>
<tr>
<td><strong>Legume cut for forage after maturity of wheat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crimson clover</td>
<td>3.5</td>
<td>8.8</td>
</tr>
<tr>
<td>Ladino white clover</td>
<td>3.2</td>
<td>8.7</td>
</tr>
<tr>
<td>NZ white clover</td>
<td>3.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Control 0 kg N/ha</td>
<td>3.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Control 50 kg N/ha</td>
<td>4.2</td>
<td>9.4</td>
</tr>
<tr>
<td>S.E.</td>
<td>0.21</td>
<td>0.38</td>
</tr>
<tr>
<td>D.F.</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3. Grain yield, straw biomass, and nitrogen distribution for wheat intercropped with 2 N-fixing legume species for forage or green manure, without applied N; CIMMYT, El Batan, Mexico 1990 (Experiment 2).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grain Yield (t/ha)</th>
<th>Straw Biomass (t/ha)</th>
<th>Grain Protein (%)</th>
<th>Straw Nitrogen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Berseem</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green manure</td>
<td>2.6</td>
<td>4.1</td>
<td>11.5</td>
<td>0.73</td>
</tr>
<tr>
<td>Forage</td>
<td>2.5</td>
<td>4.6</td>
<td>10.7</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>Vetch</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green manure</td>
<td>2.4</td>
<td>3.6</td>
<td>12.3</td>
<td>0.71</td>
</tr>
<tr>
<td>Forage</td>
<td>2.3</td>
<td>4.0</td>
<td>10.6</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 skip rows</td>
<td>2.3</td>
<td>3.9</td>
<td>10.9</td>
<td>0.61</td>
</tr>
<tr>
<td>No skip rows</td>
<td>2.1</td>
<td>3.4</td>
<td>10.4</td>
<td>0.59</td>
</tr>
<tr>
<td>S.E.</td>
<td>0.16</td>
<td>0.29</td>
<td>0.15</td>
<td>0.44</td>
</tr>
<tr>
<td>D.F.</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 4. Total biomass, total crop N, land equivalent ratio, and noon light interception estimate, for wheat and forage legumes intercropped or monocropped. CIMMYT, El Batan, Mexico, 1990 (Experiment 2).

<table>
<thead>
<tr>
<th>System</th>
<th>Biomass (t/ha)</th>
<th>Total crop N (kg/ha)</th>
<th>Land equivalent ratio</th>
<th>Light interception (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercrop</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Berseem w/wheat</td>
<td>5.6</td>
<td>214</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>12.7</td>
<td>293</td>
<td>1.54</td>
<td>85</td>
</tr>
<tr>
<td>Vetch w/wheat</td>
<td>6.7</td>
<td>263</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>13.1</td>
<td>334</td>
<td>1.4</td>
<td>90</td>
</tr>
<tr>
<td>Monocrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berseem</td>
<td>14.9</td>
<td>566</td>
<td>1.0</td>
<td>100</td>
</tr>
<tr>
<td>Vetch</td>
<td>18.7</td>
<td>643</td>
<td>1.0</td>
<td>100</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-skip rows</td>
<td>6.1</td>
<td>69</td>
<td>1.0</td>
<td>60</td>
</tr>
<tr>
<td>No-skip rows</td>
<td>5.4</td>
<td>59</td>
<td>1.0</td>
<td>70</td>
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</table>

estimated visually immediately prior to forage harvests, was consistently higher for both intercropped forage treatments than either monocrop (Table 4). In the ancillary trials, the monocropped vetch and berseem plots, harvested sequentially at the same dates as the intercropped legumes (Table 4), yielded a total of 18.7 and 14.9 t/ha dry weight, respectively, for the cycle. These values were used to calculate land-equivalent ratios (Table 4) as defined by Willey and Osiru (1972). The response to nitrogen treatments was approximately linear in the range of 0 to 200 kg N/ha. The predicted yield at the 0 N level was 2.2 t/ha and the yield response to application was 16.6 kg/ha per kg N. There was little yield response to the application of N rate above 200 kg/ha.

In the third, fourth, and fifth experiments, where barley was intercropped with faba bean, barley yields were not statistically significantly different in the intercropped situation to the control with skip rows unsown. Although there were no significant interactions among sowing dates and treatments, there were significant differences among sowing dates in terms of the productivity of barley and faba. The third experiment suffered from waterlogging up until heading of the barley, which resulted in yields that averaged only 0.8 t/ha, while the faba bean attained a biomass of 1.7 t/ha. In the fourth experiment, when yields were averaged across the three treatments, 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 yield without applied N (Table 5), but faba total biomass was reduced by 0.5 t/ha. Interception of photosynthetically active radiation measured at mid-day during grain-filling was on average 45% higher for the intercrop system than for the solid stand monocrop situation (Table 5). There was no significant interaction of N levels and intercropping treatments.
Table 5. Grain yield, yield components, and noon 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, El Batan, Mexico 1991-92 (Experiment 4).

<table>
<thead>
<tr>
<th>System</th>
<th>Yield (t/ha)</th>
<th>Biomass (t/ha)</th>
<th>Light Interception (%)</th>
<th>Spikes/m²</th>
<th>Grains/Spike</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley Sole Crop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Solid Stand</td>
<td>2.6</td>
<td>9.1</td>
<td>55</td>
<td>777</td>
<td>8.1</td>
</tr>
<tr>
<td>2) 90-cm rows</td>
<td>3.1</td>
<td>7.5</td>
<td>43</td>
<td>521</td>
<td>14.4</td>
</tr>
<tr>
<td>Mixed Crop:</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>3.0</td>
<td>7.4</td>
<td>--</td>
<td>522</td>
<td>15.2</td>
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<tr>
<td>Faba</td>
<td>1.4</td>
<td>4.9</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3) Total</td>
<td>4.5</td>
<td>12.3</td>
<td>75</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

S.E. a .29 .43 2.8 19.1 .88
D.F. 4 4 4 4 4

a For comparison of barley means only.

on barley yield for experiments 4 and 5. In the fifth experiment, 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 seedborne 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 unsown, when averaged over all experiments.

Discussion

These experiments were designed with three main objectives:

• To test the hypothesis that, for wheat growing at suboptimal levels of nitrogen fertility, light is not a limiting factor and can be used by an N-fixing intercrop without detriment to the main crop;

• To evaluate the performance of different N-fixing legumes when intercropped with wheat in alternate rows; and

• To demonstrate an improved barley cropping system that, by including a leguminous intercrop, could benefit resource-poor farmers in one or more of the following ways: directly, with extra yield in the form of beans/forage, and by adding nitrogen to the system in the form of crop residues and indirectly through 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 trial in northwestern Mexico, there were two important findings. One was that N fixing legumes could be successfully intercropped with wheat at suboptimal levels of N without apparent detriment to wheat yields or grain quality (Table 2). The second was that, of the six legumes tested, berseem clover and the two vetch species seemed to be best adapted to growth in association with wheat under these conditions. The utility of such a system in the irrigated environment is debatable and is discussed later.

Subsequent experiments were conducted at CIMMYT's 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. The second trial 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, we see favorable values for land equivalent ratio of the intercrops (Table 4). With the view to assessing the flexibility and sustainability of the system, a longer term trial was initiated in which wheat was replaced by barley since it is a commonly grown cereal in many marginal environments. In addition, the forage intercrop was replaced by faba bean to assess the productivity of a grain legume in the system. In the most productive of the three barley/faba experiments (experiment 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 above-ground residues. The yield of barley in experiment 5 in plots where faba residues from experiment 4 had been incorporated was 10% higher than the control, but only at the 10% level of statistical significance. The poor response to the incorporation of faba residues from one cycle to the next may have been due to the effect of soil movement at land preparation, since plot sizes were relatively small, (9 m * 3.6 m).

It was important to answer the question as to whether the use of skip rows in the planting of wheat (Table 1), a prerequisite to this method of intercropping with legumes, was in itself detrimental to wheat yields at low N levels in comparison to a closer spacing arrangement. 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 experiment 4, the fact that yield and grains/spike were lower but total biomass and spike/m² were higher in the solid stand barley in comparison to the wider spacing (Table 5), indicated a more favorable 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 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 intercrop experiment (Table 5), as well as the light interception estimates in the wheat forage trial (Table 4). This result is in contrast to other studies (Sivakumar and Virmani 1980, Reddy and 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 any increase in the amount of light energy absorbed. However, those studies were not looking specifically at the low nitrogen fertility scenario. Most studies demonstrate that cereals generally show reduced yields when intercropped, in comparison to the monocrop (see Ofori and Stern 1987, Table III) even though land equivalent ratios may be higher. Surprisingly, few data are available for the low nitrogen fertility scenario, where one might expect to see a greater degree of synergy between a cereal and an intercrop that fixes its own nitrogen. There is evidence that N-fixing legumes intercropped with cereals increased the availability of
soil nitrogen to the subsequent wheat crop (Singh 1983, Izaurralde et al. 1990, Danso and 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 nitrogen from the legume to the cereal (Willey and Reddy 1981). One possible mechanism for the movement of nitrogen from soybean to maize has been demonstrated using N15 tracers, where the transfer took place via mycorrhizal connections between the two species (van Kesse et al. 1985). In our experiment, the extra radiation intercepted by the intercropped system presumably provided sufficient assimilates to sustain symbiotic N fixation to the level of well over 200 kg N/ha (Table 4). Unlike in previous studies (Willey and Reddy 1981), there was no direct evidence of a transfer of nitrogen from legume to cereal. If this occurred, it was masked perhaps by the shading effects of the legume.

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 this simple since: 1) a greater land area is generally used for cultivating cereal than legumes in the target environments, and 2) 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 the productivity issue, such as reducing the rate of 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, the intercropped situation may well provide some protection by providing a physical barrier to the movement of spores via rain splashing. Weed control is another potential benefit of intercropping (Gliessman 1986, White and Scott 1991). In our studies, although no formal data were taken, it was clear that the increased early ground cover of the intercropped systems, especially those with vetch and clover, had a substantial effect in suppressing a broad spectrum of weed species. Parenthetically, 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 more than 500 mm of rainfall during the year.

Marginal agricultural lands are a logical target environment for this type of cropping system for three reasons:

- Cereals, especially barley, are a staple food;
- Farmers in such areas are generally resource poor and have limited access to inorganic N fertilizer and therefore a system that utilizes the fixation of atmospheric N is likely to improve total productivity; and
- Many such environments are prone to soil erosion and degradation.

Erosion can be combatted 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 soil 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, as indicated by light interception values (Tables 4 and 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 and Kirby 1981). In addition to this, the total nitrogen 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 and Snaydon 1982, Jones and Clements 1993), and the U.S. (Singh 1983; Tomar et al. 1988, Izaurralde et al. 1990, Grubinger and Minotti 1990). In our first experiment, it was shown that a wheat yield of over 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 and 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 nonlimiting to the main crop (Trenbath 1976, Gliessman 1986). Our increased understanding and subsequent exploitation of such interactions in plant communities are perhaps important prerequisites to meeting the world’s growing demand for agricultural products, without further erosion of our natural resource base.

Summary

In the interests of preserving our global natural resource base, agricultural research, which integrates ecological as well as agronomic principles, must be conducted with the view to meeting the developing world’s food requirements. This report describes a model cropping system that raises productivity and increases organic matter and nitrogen inputs to the soil in rainfed regions where farmers have limited access to external sources. The work was conducted in two wheat growing environments in Mexico between 1989 and 1992. Nitrogen fixing legumes were cultivated between rows of wheat or barley grown at low levels of soil nitrogen. None of the legumes tested reduced yields of the cereal crop in comparison to controls where cereal yields were in the range of 1 to 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 V. 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 as was removed by the wheat crop. The potential of the system to stabilize fragile soils by increasing ground cover as well as by raising inputs of soil organic matter is discussed.

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