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Soil fertility effects on yield, pests, weeds and symbionts of fababean (*Vicia faba* L.) in ecological farming systems

by

Chengzhi Yang

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

at

Dalhousie University
Halifax, Nova Scotia
August, 1996

DALHOUSIE UNIVERSITY

FACULTY OF GRADUATE STUDIES

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "Soil fertility effects on yield, pests, weeds, and symbionts of fababean (*Vicia faba* L.) in ecological farming systems"

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ABSTRACT

Yield instability in fababean is a limitation to more widespread use of this potentially high yielding, N_2-fixing crop. I hypothesized that high levels of residual N and P from other crops could reduce yields by stimulating pests, diseases, and weeds, and by suppressing rhizobial and mycorrhizal symbionts; also that deficiencies of K would increase susceptibility to pests and diseases. There were three components to the research: 1. A correlational study involving observations of soil and plant variables (yields, roots, symbionts, leaf nutrients) on manually weeded plots and unweeded plots was conducted on farmer-grown crops on 8 farms in Prince Edward Island (PEI). These farmers had eliminated or were reducing use of synthetic fertilizers and chemical controls of weeds, pests and diseases. 2. Prior to seeding fababean, N, P, K and Ca fertilizers were added to replicated plots on two farms in PEI (except for Ca) and two in Nova Scotia (NS) and to large concrete cylinders containing soils of low (LF) and high (HF) background fertility. All plots were weeded manually except at NS1 where non-weeded treatments were also included. Rock-P was included as an additional treatment in the cylinders. 3. Rhizobial and mycorrhizal isolates from each of two farms were inoculated individually and in different combinations onto plants grown on artificial medium in a growth chamber. Plant variables were observed in (2) and (3).

Grain yields varied widely in the 8-farm study, and were highly correlated with leaf K, but not with nodulation, mycorrhizal levels or weeds. Positive responses to K were observed in the fertilizer experiments. Adding N suppressed nodulation, but not yields. All fertilizers suppressed mycorrhizae at all sites except for N, P and K in the LF cylinders. Super-P increased nodulation and yield in the LF cylinders, but rock-P did not. At farm NS1, adding N increased losses of yield due to weeds. N increased levels of an insect pest in the HF but not in the LF cylinders. In the growth chamber experiments, inoculants that included mycorrhizae effected increases in grain+pod yield at levels of infection below those observed in the field. It is concluded that variation in soil K is a major factor in yield variation of fababean in PEI and NS. The critical and maximum normal leaf K levels appear to be higher than in other grain legumes. It is suggested that the high requirement for K is related to high yield and drought susceptibility of fababean. Nutrient suppression of mycorrhizal infection appears not to have negative effects on the crop, however complete elimination of mycorrhizae could have negative effects.

ABBREVIATIONS (not including abbreviations used with SI units)

ANOVA	analysis of variance
BS%	percentage of base saturation
CEC	cation exchange capacity
CV%	coefficient of variation
F	F value calculated from ANOVA
HF cyl.	high fertility cylinders
LF cyl.	low fertility cylinders
M1	mycorrhizae isolated from PEI Farm 8
M2	mycorrhizae isolated from NS 1
Myc	% or Myc.: percent of roots with mycorrhizal arbuscules
NS 1	farm at Lawrencetown in Nova Scotia
NS 2	farm at Shinimicas in Nova Scotia
p	probability
PC	principal component
PCA	principal component analysis
PEI	Prince Edward Island
pl	plant
R1	*Rhizobium* isolated from PEI Farm 8
R2	*Rhizobium* isolated from NS 1
R^2	coefficient of determination
R^2_L	coefficient of determination for linear regression
R^2_Q	coefficient of determination for quadratic regression
r	correlation coefficient
RCB	randomized complete block
SOM	soil organic matter
t	t value caculated from t-test
+w	plus weed plots
-w	minus weed plots

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1. Introduction

The fababean is a cool season legume grown for grain or silage that has potentially exceptionally high yields (to over 9 t ha^{-1} grain and over 3% efficiency in conversion of incoming solar radiation: Sprent and Bradford, 1977; Fasheun and Dennett, 1982; Austin et al., 1986), and ranks highly amongst grain legumes in N_2 fixation (LaRue and Patterson, 1981; Bremer et al., 1988; Townley-Smith et al., 1993). It was the major grain legume in Europe until this century, when production declined sharply because of availability of cheap imported protein for livestock, superior feeding quality of soybean (mostly imported) and apparent instability of yields (Lawes, 1978; Hawtin and Hebblethwaite, 1983). It has long been and remains an important crop in the cooler regions or in cooler seasons in many developing countries (Table 1.1). Fababean has been grown on a significant scale commercially in Canada only since the 1970s. In both Europe and Canada, there have been serious efforts in the last 20 years to improve the crop for modern farming systems (Rowland, 1978; Picard et al., 1988). In Canada, five new fababean varieties were developed and registered between 1981 and 1987 (McVetty et al., 1981, 1985; Rowland et al. 1982, 1986; Berkenkamp and Meeres, 1988). In spite of these efforts, acreage peaked in the early 80s at about 6,000 ha, and in 1993, only 3,549 ha were recorded (Canada Grains Council, 1977; Statistics Canada data 1976-1995) the last year for which data are available). Reasons for the very limited success include continuing yield instability and simple market dominance by soybean; however there is reportedly renewed interest in the crop in the west recently (Dr. K. Vessey, Dr. D. Burton, University of Manitoba, personal communication).

The fababean's reputation for "unstable yields" is commonly cited as a principal limitation to its more widespread use. This instability has been attributed to its indeterminate growth habit, failure of pollination, sensitivity to heat and water stress, and

Table 1.1. Area and yield of fababean in various regions in 1972, 1982, and 1992. (FAO, 1972, 1982, and 1992).

Region	Area harvested (thousands of hectares)			Yield (kg ha^{-1})		
	1972	1982	1992	1972	1982	1992
World	4683	3699	3005	1137	1142	1353
Africa	614	750	764	1267	1157	1122
North & Central America	72	77	64	595	1078	903
South America	244	229	149	548	520	558
Asia	3171	2308	1752	1115	1166	1480
Europe	582	318	194	1436	1408	1935
Oceania	no record	16	82	976	950	1220

to pests and diseases, most notably black bean aphids (*Aphis fabae* Scop.) and chocolate spot (*Botrytis fabae* Sard.) (Lawes, 1978; Thompson and Taylor, 1982; Austin et al., 1986; Picard et al., 1988; Silim and Saxena, 1992). In a Canadian study, yield stability in the moister regions of the prairies was equivalent to that of wheat; however it was less than that of wheat in the drier regions of the prairies, and in the eastern provinces (Seitzer and Evans, 1976). The authors noted that pests and diseases were not a factor in those trials, and that much greater yield variability might have resulted if they had been factors. Pests and diseases have been cited as factors affecting yield in eastern Canada (Langille and Hough, 1981).

Variation in soil fertility has not been cited as a factor contributing to the exceptional yield variability of fababean. This research began as an investigation of the proposition that variation in soil fertility factors contributes to the high yield variability of fababean. The research followed up on studies by Patriquin et al. (1988, 1995) which had suggested that black bean aphids outbreaks in fababean - a major factor in yield variation - are related to excess plant N. The first year of field work was conducted in collaboration with a group of farmers in Prince Edward Island (PEI) who were conducting field scale trials with fababean as part of overall efforts to increase self reliance in feed for livestock, and in nutrients. Fababean is of particular interest to ecological farmers [a] in temperate

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[a] Ecological farming or ecofarming (Kotschi et al., 1989) places priority on reducing external inputs to farms by maximizing use of on-farm resources. Farmers calling themselves "ecological farmers" sometime use small amounts of conventional fertilizers, pesticides etc. "Organic" farming is now defined by certification codes (Lampkin, 1990) These codes, while encouraging self reliance, place greater emphasis on the form of any imported materials, which cannot include synthetic or secondarily processed chemicals or biochemicals. All of the farmers in the PEI group would be described as ecological. None were certified organic but some were following organic regulations in their field operations. All of the farmers were attempting to reduce herbicide, pesticide and fungicide use to a minimum.

regions as an on-farm source of protein for livestock because of the paucity of soybean varieties that can be grown in cooler regions, its frost resistance and high N_2 fixing capabilities, the fact that it can be managed with the same equipment used for cereal grains, high yields, and because it can be used as feed without the need for a heat treatment as required for soybean (Patriquin and Burton, 1982; Lampkin, 1990).
In 1988 when fababean was grown on two farms in PEI, one farmer obtained a good yield on an unfertilized, organically managed field, while a second farmer had a poor yield on a field to which some fertilizers had been added. Six additional farmers were proposing to try the crop in 1989, and invited my participation in their efforts to identify factors influencing the success of fababean on their farms.

Initial hypotheses

I hypothesized that variation in N, P, and K status of soils, and in particular high levels of N and P that may occur when fababean follows intensively fertilized crops, can have pronounced effects on yields through their effects on susceptibility of the crop to black bean aphids and other pests and diseases, on the establishment and functioning of rhizobial and mycorrhizal symbioses in fababean, and on weed-crop interactions. Following are the mechanisms that I postulated could generate yield variability between these farms, and possibly more generally in fababean.

(i) An excess of N at the beginning of the season could reduce nodulation but not provide enough N to make up for the loss of N_2 fixed. Nitrate levels above about 2 mM, which is equivalent to only 5.6 μg N g soil^{-1} assuming 20% moisture, are reported to suppress nodulation in legumes (Streeter, 1988) and could be present as residual N from previous crops or result from mineralization of organic N after previous crops are harvested (Addiscott et al., 1991). Herridge and Brockwell (1988) reported that intermediate levels of fertilizer N (100 kg ha^{-1}) applied to soybean suppressed nodulation

but did not supply enough N to make up for N lost as a result of reduced N_2 fixation, and consequently, the yield was reduced compared to unfertilized soybean. Similar but more pronounced effects might be expected in fababean because it nodulates earlier than soybean and is not dependent on small amounts of starter N as is soybean (Patriquin and Burton, 1982; Sprent and Thomas, 1984).

(ii) An excess of N could stimulate weeds. Patriquin et al. (1981, 1988) documented a shift in the weed crop balance in favor of weeds when plots of fababean on soils with low levels of inorganic N were fertilized with N; such an effect is presumably due to the added N detracting from the competitive advantage of the N_2-fixing fababean under low N conditions.

(iii) An excess of N could stimulate aphids and possibly other pests and diseases. Many studies have shown that high levels of plant N can stimulate certain pests and diseases (reviewed by Mattson, 1980; Marschner, 1986). Aphids in particular respond to increases in certain amino acids in the phloem, which can be induced by N fertilization (Leckstein and Llwellyn, 1974; McNeill and Soutwood, 1978). The black bean aphid, (*Aphis fabae* Scop.) is a serious pests of fababean in temperate regions, and it is considered that chemical control is essential to avoid periodic serious losses (Cammel and Way, 1983). Patriquin et al. (1988) found marked increases in numbers of black bean aphid-infested plants in plots of fababean on an organic farm from which weeds had been removed, compared to numbers in the crop with normal weed levels, and related these differences to differences in leaf N. N fertilization also increased numbers of aphid-infested plants. They suggested that weeds can reduce the susceptibility of the host to pests by consuming soil N and restricting luxury uptake of N by the plants. Hainsworth (1954) remarked that there seems to be a strong connection between fertilizer use and chocolate spot diseases in fababean, a disease which caused many farmers to give up the crop in the UK. He commented that fababeans do particularly well in organic farming

systems. Other studies have provided some evidence to suggest that overall, organic methods of fertilization may be less conducive to pests than conventional methods, however, excessive levels of organic fertilizers can also increase pests and diseases (reviewed in Hodges and Scofield, 1983; Patriquin et al., 1995)

(iv) A deficiency of K relative to N could stimulate diseases and pests. It is well documented that deficiencies of K relative to N can stimulate pests and diseases (Marschner, 1986). For example, severity of stalk rot in corn was increased with increasing rates of N application and decreased with higher rates of applied K. Where N and K applications were balanced, the severity was much lower (Murphy, 1980). In studies of the interaction of N and K fertilization on peach aphid populations on brussels sprouts, van Emden (1966) reported that increases in aphid number and soluble N in the leaf tissue resulted from deficiencies in K.

The PEI farms were considered to be prone to K deficiencies because they occur in a high rainfall region and possess sandy loam soils, thus K might be lost readily by leaching. Also, nutrient budgets suggest that inputs of K on some organic farms are inadequate to balance losses (Patriquin et al., 1986; Nolte and Werner, 1994). Legumes generally have a high requirement for K (Hunt and Wagner, 1963), and do not compete well with grasses for K (Mengel and Kirkby, 1982). Fababean is reported to respond to K fertilization (Boyd et al., 1952; Moffatt, 1960; Mahler et al., 1988).

(v) An excess of P could suppress mycorrhizal infection and its various benefits other than provision of P. Mycorrhizal infection is well known to be suppressed by high soil P (Mosse, 1986). There is a tendency for excessive levels of P to build up in soils receiving regular applications of P fertilizer, as P is not very mobile (McCollum, 1991; Pierzynski, 1991). I speculated that high residual P on farms making the transition from conventional to organic or ecological management could be sufficient to suppress mycorrhizal infection and in turn result in loss of benefits from mycorrhizae other than

those related to provision of P. While improved P nutrition on P-poor soils is generally recognized as the major benefit of mycorrhizae (Robson et al., 1981) other benefits have been demonstrated or inferred under certain conditions. Those include increased nodulation and N_2 fixation, and photosynthetic rate (Linderman, 1992), protection of crop roots from pathogens (Graham and Menge, 1982; Caron et al., 1986) and nematodes (Pinochet et al., 1993), enhanced crop drought tolerance (Sanchez-Diaz et al., 1990), and increased Ca, Zn, Cu, and Fe uptake (Kucey and Janzen, 1987; Hamel and Smith, 1991). Lambert et al. (1979) reported that P fertilization significantly reduced Zn and Cu concentrations in mycorrhizal soybean, but concentrations in nonmycorrhizal treatments were not affected.

In general, legumes are considered to benefit more from mycorrhizae than cereals or other grass crops because the legumes have coarse roots with fewer root hairs than the grasses (Manjunath and Habte, 1990; Khalil et al., 1994). Kucey and Paul (1983) reported that nodulated root systems of mycorrhizal fababean fixed more N than nodulated root systems of non-mycorrhizal plants. An increase in nodule biomass for plants infected with both rhizobia and mycorrhizal fungi was considered to be the major factor increasing N_2 fixation rates. Inoculation of fababean with mycorrhizae increased dry matter production under growth chamber and field conditions even in the presence of indigenous mycorrhizae.

It was considered possible as well that mycorrhizae could be more important to fababean than to other modern crops, because of the relative lack of intensive breeding of fababean for modern conditions (Lawes, 1978). There is evidence in cereals that mycorrhizae are detrimental to modern cultivars but not to traditional cultivars (Hetrick et al., 1993). Further, there is evidence that mycorrhizae can be detrimental to the host under high levels of soluble nutrients (Johnson, 1993).

The primary objective of the research was to determine if there is any evidence for variations in yield of fababean under field conditions in the Maritimes being related to variation in soil fertility status through the mechanisms above or others. There were three components to the research. The first was a correlational study involving observations of soil and plant variables on fababean on eight farms located within a 70 km radius in PEI. Previous management of the farms ranged from moderately intensive use of synthetic fertilizers and pesticides to no use of pesticides and reliance mostly on on-farm sources of nutrients. The fababean was grown following different types of crops. Thus a wide range of background fertility conditions was presented. The second involved experimental additions of N, P and K to plots superimposed on fababean fields on two farms in PEI and with addition Ca on two farms in Nova Scotia. An additional N, P, K and Ca experiment was conducted in large concrete cylinders which had two levels of background fertility established by addition of compost to half of the cylinders three years prior the experiment. This facility allowed me to examine interactive effects of low and high of background fertility and added nutrients. The third component of the research involved isolation of mycorrhizae and rhizobia from fababean on two of the farms, and testing the effects of different combinations of the isolates on levels of symbionts, yield and nutrient variables of fababean grown under controlled conditions.

This combination of research methodologies or levels of abstraction - between farm comparisons on farmer-grown crops, superimposed fertilizer experiments on four farms, fertilizer experiments under more controlled conditions in cylinder out of doors, and highly controlled experiments in a growth chamber - also permitted some assessment to be made of the efficacy of the different approaches in answering questions posed by farmers.

2. Materials and methods

2.1. Field studies on 8 farms on Prince Edward Island (PEI) in 1989

Studies were conducted in fababean fields on eight farms in PEI in 1989. Fields were of 0.5 ha or greater in area. On each farm, manually weeded plots ("minus weeds") and unweeded plots ("plus weeds") except as conducted by the farmer (Table 3.1) were established. These were sampled early in the season for soil nutrients, at mid-season for fababean root biomass, nodules, mycorrhizal infection, top biomass, and at the silage harvest stage for pod, grain, stem, and weed biomass. At the combine harvest stage, samples for grain, pods, and stem biomass were taken from 5 of the 8 farms.

2.1.1. Plots

Minus and plus weed plots were set up in each field in a Randomized Complete Block (RCB) design with 6 replicates. Plots were 1.5 x 1.5 m with 3 m between plots. The plot areas were at least 5 m away from the edge of the fields; plots were arranged in a single row parallel to the field edge. The plots were established June 13 - 15 after fababean had been seeded and all of the farmers' operations had been completed. In the minus weed plots, weeds were removed initially by hand-hoeing; subsequently, they were hoed at biweekly intervals until canopy closure.

2.1.2. Sampling

On June 13-15, 60 soil cores were taken from each site with a standard 1.8 cm internal diameter soil corer inserted to 15 cm depth. Samples were taken adjacent to the individual plots, but not in the plots themselves.

Between June 29 and July 10, at the 100% flowering stage, 5 of the youngest fully-expanded compound leaves were taken from each of 5 plants in each plot. The leaves were combined by treatment, and dried in a solar dryer at approximately 60 °C. The samples were later analyzed for nutrients.

Between July 24 and 31, numbers of fababean plants were counted within a 1 x 1 meter quadrat placed in the center of each of three plots in the minus weed treatment and three in the plus weed treatment. There were no significant differences of stem densities between minus and plus weed plots for any of the farms (Appendix Table 4), and hence the average values for plus and minus weed plots together were used in making calculations on a square meter basis for both plus and minus weed treatments. Three fababean plants in a corner of each plot were collected for determination of mid-season root biomass, nodule weight, top biomass, and mycorrhizal infection. The plants were carefully dug out using a fork; it was attempted to keep the lateral roots intact. The tops were cut from the roots and dried in a solar dryer. The roots were washed free of soil. Roots were taken from one of the three plants in each sample area, and combined by treatment. The lateral roots were cut off, pressed into plastic cages (40 x 28 x 7 mm), and stored in FAA (900 mL 95% ethanol + 55 mL glacial acetic acid + 55 mL formalin) solution for subsequent examination of mycorrhizal infection. Roots from one of the remaining two plants were selected, combined by treatment, and nodules removed, and weighed. Selected samples were dried and reweighed. Roots from the third plant were combined by treatment, dried in a solar-dryer, and weighed.

At the silage harvest stage (August 24 and 25), when most pods in most of the fields had turned black, six fababean plants and all weeds were cut at ground level within a 35 x 35 centimeter quadrat placed in the center of the plot. If there were less than six fababean plants in the quadrat, additional plants located near the quadrat were taken to make a total of six. The pods, stems, and weeds were placed in separate paper bags, and dried in a dryer. When plant biomass was being sampled, the relative abundance of weeds in the weed biomass was ranked by visual estimation after the crop had been removed from the quadrat. Weed species were ranked 1 for most abundant, 2 second in

abundance and so on until an estimated 80% of the biomass were accounted for. Ranking for each site was derived by averaging rank values for all individual plots.

On October 3, at the combine harvest stage, five plants were taken from each of five fields. They were separated into grains, pods, stem+leaves, dried and weighed.

2.2. Fertilizer addition experiments

These experiments were conducted on 4 separate farms and in large concrete cylinders located out of doors at Dalhousie University. The general format for the farm experiments was to set up plots just after farmers had completed all spring operations except for planting. Details for each site are given in Table 2.1. Plots were sited in from the edges of the fields, fertilizers broadcast, and then dug in to approximately 20 cm soil depth using a shovel. The farmers planted and weeded crops in the normal fashion. Weeding of plots was conducted as described above for the 8-farm study.

At the Dalhousie site, twelve large concrete cylinders (1.2 m in diameter x 0.6 m in depth) were filled with ordinary grade topsoil in July 1987. To six of the cylinders (one in each pair of two), farm compost (10 kg cylinder^{-1}) was mixed into the top 30 cm of soil in 1987 to give a high fertility (HF) treatment; the soil without compost was designated as a low fertility (LF) treatment. The cylinders were located in a linear sequence, with 0.7 m between cylinders. Each cylinder was used as a main plot in a split plot design with HF & LF treatments as the main plot variables. Prior crops included oil radish in 1987, oats in 1988, fababean in 1989, crimson clover in 1990. On May 1, 1991, the soil in the cylinders was mixed to depth of 40 cm using a shovel. Open-bottom plastic buckets (0.31 m in diameter x 0.27 m in depth) were pressed 22 cm into the soil at 6 positions, located around the perimeter of the cylinders. The area enclosed within each bucket constituted a subplot. The fertilizers were applied to the subplots and worked into the top 20 cm of soil. Six fababean seeds were sown in each subplot on May 1. On May

Table 2.1. Site conditions and experimental design of fertilizer addition experiments.

	Experiments				
Feature	PEI Farm 7	PEI Farm 8	NS 1	NS 2	HF/LF Cylinders
Location:	Stanley Bridge, PEI	Winsloe, PEI	Lawrencetown, NS	Shinimecas, NS	Dalhousie Univ., Halifax, NS.
Year:	1989	1989	1990	1990	1991
Soil texture:	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam
Previous crop & tillage:	oats, straw removed, fall plowed	winter wheat, straw removed, fall plowed	winter wheat straw incorporated in spring	oats / alsike clover, spring plowed	-Windsor bean in spring/summer of 1989 -crimson clover in 1990
Fertilizers applied to previous crop:	44,800 kg ha^{-1} manure. Manured regularly before.	13,400 kg ha^{-1} fish-manure compost.	5,600 kg ha^{-1} hen manure.	224 kg ha^{-1} 17-17-17.	no fertilizer.
Experimental design:	RCB	RCB	split-plot	RCB	split-plot
Plot size: [a]	3 x 4 m	2 x 2 or 3 x 3 m[b]	-6 x 4 m main plot -6 x 2 m subplots	3 x 3 m	-Main plot: 1.2 m diam.x 0.6 m depth cylinders -Subplot: 0.31 m diam. open bottomed buckets x 0.27 m in depth

Table 2.1 (concluded).

Feature	PEI Farm 7	PEI Farm 8	NS 1	NS 2	Cyl. HF/LF
Replicates of each treatment	6	6	6	5	6
Treatments:[c]	-control -100 kg N ha^{-1} -100 kg P_2O_5 ha^{-1} -60 kg K_2O ha^{-1}	-control -100 kg N ha^{-1} -100 kg P_2O_5 ha^{-1} -60 kg K_2O ha^{-1}	main plots: -control -152 kg N ha^{-1} -166 kg P_2O_5 ha^{-1} -100 kg $K_2O$$ha^{-1}$ -104 kg $CaSO_4$ ha^{-1} subplots: -minus weeds -plus weeds	-control -152 kg N ha^{-1} -166 kg P_2O_5 ha^{-1} -100 kg $K_2O$$ha^{-1}$ -186 kg $CaSO_4$ ha^{-1}	main plots: -HF and LF soil subplots: -control -152 kg N ha^{-1} -166 kg P_2O_5 ha^{-1} -166 kg P_2O_5 ha^{-1} as rock-P [d] -100 kg K_2O ha^{-1} -104 kg $CaSO_4$ ha^{-1}
Date of fertilizing:	May 17, 1989	May 16, 1989	April 25, 1990	May 28, 1990	May 1, 1991
Date of seeding:	May 19, 1989	May 17, 1989	May 4, 1990	June 5, 1990	May 1, 1991
Weeding:	-blind harrowed on June 5 -manually hoed biweekly until canopy closure	-blind harrowed on June 5 -manually hoed biweekly until canopy closure	-harrowed after emergence -manually hoed biweekly until canopy closure	-harrowed after emergence	-manually weeded biweekly until canopy closure

[a] Distance between the plots was 2 or 3 meters.

[b] 4 blocks were 2 x 2 m and 2 blocks were 3 x 3 m plots.

[c] N as urea, P_2O_5 as superphosphate, K_2O as potassium sulfate, $CaSO_4$ as commercial gypsum.

[d] Rock phosphate: Zorafos soft rock phosphate with colloidal clay, available phosphoric acid 2%, total phosphoric acid 18%.

23, plants were thinned to 3 in each subplot. Weeds were removed initially on June 1 by hand-hoeing, and were subsequently hoed at biweekly intervals until canopy closure. The cylinders were exposed to rain, water was applied from a hose 5 times, during periods of infrequent rainfall in June and July.

2.2.1. Sampling fertilizer experiments on farms

For soil samples taken in the early season, sixty soil cores were taken in each of the experimental fields with a standard 1.8 cm inter diameter soil corer inserted to a depth of 15 cm. Samples were taken throughout the plot areas, but not in the plots themselves.

At the 100% flowering stage (July 13 -14), the youngest fully-expanded compound leaves were taken from five plants in each plot, and dried in a solar dryer. At the same time, 6 fababean plants were taken from one side of each plot for determination of mid-season root biomass, nodule weight, nitrogenase activity, top biomass, and mycorrhizal infection. Three of the six plants were used in acetylene reduction assays (see section 2.4). Tops were separated from the roots of all six plants and dried in a solar dryer. Roots of the three plants not used in acetylene reduction assays were washed, dried and weighed. Roots from the acetylene reduction assays were washed, and nodules removed and weighed. Nodule subsamples were dried to determine dry-to-fresh weights. Three laterals from each of the 3 plants were cut off and pressed into plastic cages (40 x 28 x 7 mm), and stored in FAA solution for subsequent examination of mycorrhizal infection. Sampling at the silage harvest stage was conducted as described in 2.1.2.

2.2.2. Sampling of fertilizer experiment in cylinders

On April 14, 1991, before different subplot treatments were established, six soil cores of 15 cm in depth were taken from each of the main plots and combined by main plot treatment.

On June 25, five fully expanded compound leaves from one of the three plants in each subplot were taken and dried at 80 °C. The same plant was taken for determination of mid-season root biomass, nodule weight, top biomass, and mycorrhizal infection. The top was separated from the roots, dried in the oven, and weighed. The roots were washed, dried and weighed. At the same time, nodules on the fresh roots were removed, and weighed. The lateral roots on the plant were cut off and pressed into plastic cages (40 x 28 x 7 mm), and stored in FAA solution for subsequent examination of mycorrhizal infection. The roots were dried and weighed.

On September 2, the remaining two fababean plants and weeds in each subplot were cut at ground level, separated, dried and weighed as described in 2.1.2.

2.2.3. Observations on pests and diseases

Plots were examined for pests and diseases during manual weeding operations, (prior to canopy closure), and during the mid-season (100% flowering) and during the silage stage sampling.

To document levels of chocolate spot disease (*Botrytis fabae* Sard.), the 5th to 8th oldest leaf was taken from 3 separate plants in each plot at mid-season and assigned a rating of 1 (no infection) to 5 (highest level for the particular site).

I regularly examined the tops of plants during flowering for black been aphids by turning over the leaves. Numbers of aphid plants (more than one black bean aphid per plant) in plots were noted. For observation of the plant bug (*Calocoris norvegicus* Fieber) in the cylinder system, I examined the whole plants by turning them slightly so that leaves and stems in each plot (bucket) were exposed. The number of bugs on each plant was recorded.

2.3. Inoculation experiments

Two experiments were conducted in a walk-in growth chamber maintained at 23 °C for 18 hours of each day with light and at 18 °C for 6 hours of each day without light. Light intensity was 100 W m^{-2} (or approximately 440 umol m^{-2} s^{-1}). Humidity was not controlled, and was mostly between 35 and 50%.

Plants were grown in potting mix in standard six-inch plastic pots of 183 cm^3 volume. Pots were set up in a RCB design with 7 replicates. The potting mix consisted by volume of 42% Turface (montmorillonite clay from Applied Industrial Materials Corporation, Illinois U.S.A.), 42% silica sand #4 mesh (Nova Scotia Sand & Gravel, Shubenacadie, N.S. Canada), 2% Jersey Green Sand (glauconite from Zook & Ranck, Inc. Pennsylvania U.S.A.), 2% rock phosphate (ZO-RA-FOS, described as soft phosphate with colloidal clay; available phosphoric acid = 2%; total phosphoric acid = 18%; Zook & Ranck, Inc. Pennsylvania, U.S.A.), 2% $CaCO_3$ (Calcium carbonate, 95% $CaCO_3$ C-CAL Zook & Ranck, Inc. Pennsylvania, U.S.A.), and 10% peat moss (Fisons Westen Coorparation, B.C.). The mix was leached with distilled water until electrical conductivity, measured in a 1:1 water to mix extract, stabilized at about 150 μS cm^{-1}. The mixture was steamed in an autoclave at 121 °C, 18 lbs in^{-2} for 2 hours for the first experiment and for 4 hours for the second experiment. The medium was placed in the pots which had been surface sterilized by cleaning with 90% ethanol.

Rhizobia and mycorrhizae were isolated from fababean fields on two farms (PEI F8 and NS 1). The method of isolation of rhizobia was that of Vincent (1970): (1) soil pieces were placed on yeast extract mannitol agar medium containing 0.002% actidione in Petri dishes; (2) five *Rhizobium*-like colonies (similar sized, gummy colonies) were streaked to separate agar plates; (3) three well isolated colonies from three of the five

dishes were picked and inoculated onto sterilized fababean seeds on agar slant in test tubes; (4) nodules from plants grown in tubes were crushed aseptically over the surface of two agar dishes; (5) colonies were re-streaked on another dish and an isolated colony picked, and streaked onto a storage medium in screw-capped tubes. Paraffin was added to the storage tubes after growth had occurred.

The mycorrhizal inoculants were supplied by Endgro System Corporation, Dalhousie University. They isolated mycorrhizal spores from the same soils by a wet sieving method, and inoculated them onto leeks cultured in Turface medium. After the leeks were well developed, the roots and the growth medium were collected and used as inoculants.

Fababean seeds were rinsed in 90% ethanol and suspended for 5 minutes in acidified 0.2% $HgCl_2$, and then washed 3 times with sterilized water and seeded directly into the pots. Four seeds were planted in each pot. The seedlings were thinned to 2 plants per pot a few days after emergence.

Five grams of well mixed mycorrhizal inoculant containing an average of 5.8 spores (+ hyphae) per gram were placed at about 2 cm below the seeds. The rhizobia were cultured in test tubes on yeast extract mannitol agar medium containing 0.002% actidione. About 5 mL sterilized water was used to wash rhizobia colonies from the agar slope surface. The suspension was transferred to a 250 mL flask containing 50 mL water, and a series of 10-fold dilutions in distilled water prepared. Rhizobia in suspension were counted by using a bacterial counting chamber observed under 400 x magnification. Finally a suspension with 2×10^6 rhizobia mL^{-1} was prepared. Five mL of the suspension were pipetted onto each seed.

Inoculation treatments were:

Control (5 mL sterilized water)
M1 = mycorrhizae from PEI 8
M2 = mycorrhizae from NS 1

R1 = *Rhizobium* from PEI 8
R2 = *Rhizobium* from NS 1
M1R1 = M1 + R1
M2R2 = M2 + R2
M1R2 = M1 + R2 (2nd experiment only)
M2R1 = M2 + R1 (2nd experiment only)

Plants were watered daily with distilled water. When fababeans were in the 100% flowering stage, the 3 youngest fully expanded leaves from each plant of every pot in blocks 1, 3, and 5 were taken, combined by pot, and dried at 80 °C. Whole plants were removed, the tops separated from roots, and dried. The roots were washed, and the nodules removed, weighed fresh, dried and weighed again. The lateral roots were removed and stored in FAA solution for later determination of mycorrhizal infection. The roots were dried and weighed.

At the final harvest stage, the plants in the four remaining blocks were harvested when most of the pods had turned black. The pods, stems, and roots were separated into different bags and dried at 80 °C.

When experiment I was conducted, growth chamber power failed when plants were 3 weeks old. The plants in pots were removed for three days and then moved back into the growth chamber.

2.4. Analytical procedures

The soil samples were spread out on plastic and allowed to air dry. Soil nitrate was determined on 100 g subsamples of the fresh soil using Merckoquant nitrate test strips, following the procedure of Patriquin et al. (1993).

Two-hundred gram samples of air dried soil were sent to A & L Laboratories East, London, Ontario, for determination of soil organic matter, pH, cation exchange capacity, percent base saturation, P, S, K, Ca, Mg, Zn, Mn, Fe, Cu, and B. The Mehlich III extraction was used for all elements.

Sand, silt and clay composition of the subsamples was determined by the hydrometer method according to Day (1956).

For measuring N mineralization and soil respiration, the air dried soils were passed through a 1 mm sieve. One hundred g subsamples were weighed and thoroughly mixed with 300 g coarse silica sand in plastic bags. The whole mixture was then transferred into a 1000 mL Mason jar to which 60 mL of deionized water had been added. The tops of the jars were closed with polyethylene film to allow aeration but restrict water loss (Bremner, 1965). The jars were incubated at 30 °C. Forty gram subsamples of the mixture were removed with a spoon on the 1st, 7th, and 17th incubation days respectively, mixed with 40 mL of deionized water in 250 mL flasks and shaken for 15 minutes by an electric shaker at 200 r. p. m. Electrical conductivity and pH of the mixture solution were measured (Patriquin et al., 1993). The solution was centrifuged for 10 minutes, passed through #1 filter paper, and 20 mL of the filtered solution was frozen and sent to the Nova Scotia Environmental Chemistry Laboratory in Halifax for analysis of nitrate and other major anions and cations (Patriquin et al., 1993).

After 17 days of incubation, the jars were opened, flushed with a stream of fresh air, closed with a metal cover containing a serum stopper, and then put back into the incubator for one half hour. One-half mL gas phase samples were removed from the jars with a syringe at 0.5 and 4 hours, and injected into an infrared gas analyzer (Analytical Development Co. Ltd., Hoddesdon, U. K., Model 225 mk2-3028) using a closed recirculating system. CO_2 concentrations were calculated by reference to a CO_2 gas standard.

For acetylene reduction assays of nitrogenase activity, fababean roots (plus nodules) were excised from 3 plants taken within each of experimental plots and were placed in 1.5 liter jars. Assays were conducted in the two PEI Farm fields on July 15 -16,

1989. Acetylene, freshly generated from calcium carbide and water was added to give approximately 10% v/v acetylene in the jars, and the jars were buried in the soil. Gas samples for analysis of ethylene by gas chromatography (Hardy et al., 1967) were taken after 60 minutes and stored in tubes closed with serum stoppers.

Roots were stained for mycorrhizal infection using the procedure of Brundrett et al. (1984). One modification was introduced: the entire process of clarifying, washing and staining the roots was carried on with the roots kept in the plastic cages (40 x 28 x 7 mm). The infection estimation procedure used was that of McGonigle et al. (1990). After staining root samples, the roots were cut into pieces about 1 cm in length, and more than 100 pieces of the roots were spread on a microscope slide in parallel orientation, and covered with a microscope cover slip. At least 100 intersections between the microscope eyepiece cross hair and roots at 200-fold magnification were examined for arbuscules, hyphae and vesicles (McGonigle et al., 1990). The mycorrhizal infection was calculated by % occurrence of arbuscules in the per plant roots.

Leaf samples from the 1989 8-farm study were sent to the Soil & Feed Testing Laboratory, PEI Department of Agriculture, Charlottetown, Canada, for determination of N, P, K, Ca, Mg, S, B, Cu, Zn, Mn, and Fe. Leaf samples from other experiments were ground to pass through a 20 μm mesh sieve, and stored in vacutainers until analysis. The ground samples were digested using concentrated H_2SO_4 and 30% H_2O_2 (Thomas et al., 1967). The digested samples were diluted and sent to the Nova Scotia Environmental Chemistry Laboratory in Halifax for analysis of N, P, K, Ca, Mg.

2.5. Statistical analyses

For analyses of the data from 8 farms, the following statistical procedures were employed. (i) One and two tail t-tests were performed using the StatView II software (Abacus Concepts, Inc., Berkeley, California, USA, 1987). (ii) Univariate correlations

and univariate linear and quadratic regressions were examined using the StatView II software. (iii) Principal components analyses (PCA) were performed using Systat II software (SYSTAT, Inc., Evanston, Illinois, USA, 1989); a common factor model was used to reduce the multivariate nature of the correlation matrix to a few interpretable dimensions; loading data were rotated or not as indicated in results to give the highest eigenvalues; factor scores for each farm were used as new variables in multivariate correlations examined using the StatView II software. (iv) Stepwise regressions were conducted using the StatView II software; initial F to enter and remove values (5.99 and 6.00) were set to correspond to $\alpha = 0.05$.

ANOVAs of the experimental data were performed using Super-ANOVA (Abacus Concepts, Inc., Berkeley, California, USA, 1989). Because there were some significant interactions between the main plot treatments and subplot treatments for many of the variables in the split-plot design experiments, these data were further subjected to analysis using a RCB model applied to the main plot treatments separately.

The Bonferroni comparison test was used to compare selected treatments in the inoculation experiments using the Super-ANOVA software.

The Bonferroni/Dunn (Control) and Bonferroni/Dunn (All Means) tests were used to compare means with control values or means with each other using the Super-ANOVA software. Differences that are significant at $\alpha = 0.1$ are referred to as "trends".

Coefficients of variation were calculated as:

CV= 100 x sq rt (Error Mean Square)/mean.

3. Results I. Identification of factors responsible for variation in yield of fababean between 8 farms in Prince Edward Island

This thesis is an investigation of the proposition that the reported high variation in fababean yield could be related in part to variation in nutrient status of the soil, particularly through negative effects of high levels of N and P on symbionts, effects of N and K on pests, and effects of N on weeds. In this first phase of the study, I tested this proposition by correlation analysis, that is by determining how much of the yield variation under real farm conditions could be related to variation in soil and plant nutrient status. By also examining levels of symbionts, weeds and pests, I attempted to determine if any of the mechanisms referred to above could be involved.

The observations were conducted on eight farms with different histories of fertilizer input (Table 3.1) to maximize potential difference in soil nutrient status, also to represent a range of soil management going from conventional to organic. Variation in climatic factors was minimized by conducting the study in one season on farms located within a radius of approximately 70 km, and within a region of relatively uniform topography (gently rolling land). Temperature and rainfall in 1989 were close to long term averages (Agriculture Canada, Research Summary, 1990; Appendix Table 1).

Fababean is considered to be very non-competitive with weeds (Wilson and Cussans, 1970; Evans and Rogalsky, 1975; Canada Grains Council, 1977; Dyke and Prew, 1983; Hebblethwaite et al., 1983). As these farms varied in the intensity and mechanisms of weed control, I wished to examine the relationship of yield to weeds and nutrient variables under both existing weeds levels, and under conditions of minimal weed interference. Hence, on each farm, plots with and without manual weed control were

Table 3.1. Farm products, general practices and details of the fields where fababean was grown in 1989.

No	•FARM •LOCATION •PRODUCTS •FERTILIZERS /PESTICIDES [a] •PREVIOUS CROP •FIELD PREPARATION & WEEDING	FERTILIZERS APPLIED TO FABABEAN: •IN 1989 TO FABABEANS •TO PREVIOUS CROP IN 1988	SEEDING: •DATE •METHODS •RATE •CULTIVAR •INOCUL-ATION	•PREDOMINANT WEEDS, [b] •PESTS [c]	•COMMENTS
1	-Howatt Family -Hunter River -hogs, dairy, beef -S3, P0, F0, H2 -hay -no post seeding-weeding	-1989: 150 kg ha^{-1} 20-20-20 -1988: no fertilizers applied	-May 20 -broadcast -120 kg ha^{-1} -unknown -inoculated	-grasses, mustard -4 patches of aphids; 2 in plots, 2 across borders, light chocolate spot.	-fababean stayed green later in the season than at other farms. -first trial with fababean.
2	-Doran Family -Vernon River -beef, dairy, chickens -S1, P0, F0, H1 -timothy / clover hay previous 3 years -no post-seeding weeding	-1989: 1,170 kg ha^{-1} 5-20-20 -1988: 4,500 kg ha^{-1} lime	-May 20 -broadcast -210 kg ha^{-1} -unknown -inoculated	-grasses, mustard, horsetail, hemp-nettle. -3 patches aphids in plots heavy chocolate spot reduced pod set	-first trial with fababean.

Table 3.1. (continued).

3	-MacKinnon Family -New Argyle -dairy, beef, rabbits -S2, P0, F0, H0 -hay previous 6 years -plowed 1988 fall; no post-seeding weeding	-1989: no fertilizer applied -1988: 112 kg ha^{-1} 15-5-7	-May 20 -broadcast -224 kg ha^{-1} -Herz Freya & Pegasis mixture -inoculated	-grasses, mustard, lambsquarter, vetch, hemp-nettle -4 patches aphids; 2 in plots, 2 across borders more chocolate spot	-first trial with fababean.
4	-Turner Family -Winsloe -beef -S2, P2, F0, H2 -oat / pea -harrowed 2 times before seeding no post-seeding weeding	-1989: no fertilizers applied -1988: 25,700 kg ha^{-1} compost in fall -Prio to 1988 intensive fertilizer, pesticides	-May 12 -drilled -112 kg ha^{-1} -Encore -inoculated	-grasses, mustard, wild radish, vetch, cudweed -2 patches aphids across borders light chocolate spot	-fababean stayed green late in the season, and combining was difficult. -farmer had grown fababean in previous years.
5	-McCallum Family -Brackley Beach -dairy, hogs -S2, P2, F0, H2 -mixed grain -disced fall 1988, harrowed in spring1989; no post-seeding weeding	-1989: no fertilizers applied -1988: 225 kg ha^{-1} rock P, & 349 kg ha^{-1} crab meal	-May 2 -broadcast -182 kg ha^{-1} -Hertz Freya & Pegasis -inoculated	-grasses, horsetail, lambsquarter, wild carrot, clover, corn spurry -no pests	-the crop was generally very weedy. -first trial with fababean.

Table 3.1. (concluded).

6	-McFayden Family -Hunter River -dairy -S2, P2, F0, H2 -barley -chisel plowed in fall 1988; no post-seeding cultivation	-1989: no fertilizers applied -1988: 269 kg ha^{-1} 17-17-17	-May 5 -harrowed drilled -202 kg ha^{-1} -Hertz Freya -inoculated	-mustard, lambsquarter -no pests	-first trial with fababean.
7	-Fyfe Family -Stanley Bridge -dairy -S2, P0, F0, H0 -oats -plowed fall 1988; one light harrowing on June 5	-1989: no fertilizers applied -1988: 44800 kg ha^{-1} manure, manured regularly before	-May 19 -drilled -179 kg ha^{-1} -Hertz Freya & Pegasis -inoculated	-wormseed mustard, lambsquarter, grasses, horsetail -2 patches aphids; 1 in plot, 1 across border light chocolate spot	-one year organic management, pods matured well and crop combined easily. -first trial with fababean.
8	-Ling Family -Winsloe -hogs, beef, dairy -S0, P0, F0, H0 -winter wheat 1988 -harrowed twice before planting; blind harrowed on June 5	-1989: no fertilizers applied 13,400 kg ha^{-1} fish manure compost applied to winter wheat in 1987	-May 17 -drilled -213 kg ha^{-1} -Hertz Freya & Pegasis -inoculated	-grasses, horsetail, lambsquarter, hemp-nettle, lady's-thumb, corn spurry, wild buckwheat -light chocolate spot	-organic management for 3 years. -farmer had grown fababean previously.

Footnotes to Table 3.1

[a] Designated S,P,F,H to refer to use of synthetic fertilizer, pesticides, fungicides, herbicides respectively. Numbers refer to intensity of use: 0: none, 1: very reduced, 2: reduced, 3: at conventionally recommended levels.

[b] Weeds are given in order of abundance, based on average ranking values. Latin names corresponding to the common names are as follows

clover: *Trifolium repens* L.
corn spurry: *Spergula arvenis* L.
cudweed:*Gnaphalium uliginosum* L.
grasses: *Agropyron repens* [L.] Beauv, *Avena fatua* L.
hemp-nettle:*Galeopsis tetrahit* L.
horsetail:*Equisetum arvense* L.
lady's-thumb: *Polygonum persicaria* L.
lambsquarter: *Chenopodium album* L.
mustard: *Sinapis arvensis* L.
vetch:*Vicia angustifolia* Reichard
wild buckwheat: *Polygonum convolvulus* L.
wild radish: *Raphanus raphanistrum* L.
wormseed mustard: *Erysimum cheiranthoides* L.

[c] Pests and diseases common and latin names are as follows:

aphids: *Aphis fabae* Scop.
chocolate spot: *Botrytis fabae* Sard.

established. Observations were conducted on both sets of plots and each data set was examined separately.

Grain crops go through five more or less distinct physiological stages: germination, seedling growth, vegetative growth, and reproductive growth and storage. Limiting factors may operate and be expressed at each of these stages, and/or events at an earlier stage may prove limiting to yield at later stages (Brown, 1984). In order to provide some indication of when factors controlling crop yield are operative, and also because farmers may harvest crops early for silage or later for grain, I obtained measures of vegetative growth (referred to as "mid-season crop yield", obtained when fababean just reached 100% flowering, i.e., all plants had flowers), vegetative and early reproductive growth (referred to as "crop yield"; crop sampled on August 24-25 at or slightly past the stage when whole plants would be taken for silage) and storage in grain (referred to as "grain yield"). Grain yield was inferred from yields of seeds on August 24-25 when seeds were still green. Final grain yields measured in October in unweeded parts of the fababean fields on five farms were highly correlated with the yields in the August in the plus weed plots ($R^2 = 0.912$, $p = 0.012$), and averaged 1.76-fold higher (Appendix Table 2). Thus the grain yield measured in August is considered to be a good indicator of the final grain yield.

To facilitate description and because grain yield was of most interest to the PEI farmers, the farms are designated by numbers from 1 to 8, in order of increasing grain yield in the minus weed plots.

A conceptual model of how the variables included in this study are related is given in Figure 3.1. Yield variables are the dependent variables, and independent variables are those over which the farmers have some control (stem density, weeds, soil physical and chemical variables, and to some extent, pests and diseases). The effects of these independent variables are in some cases direct and in other cases affect other

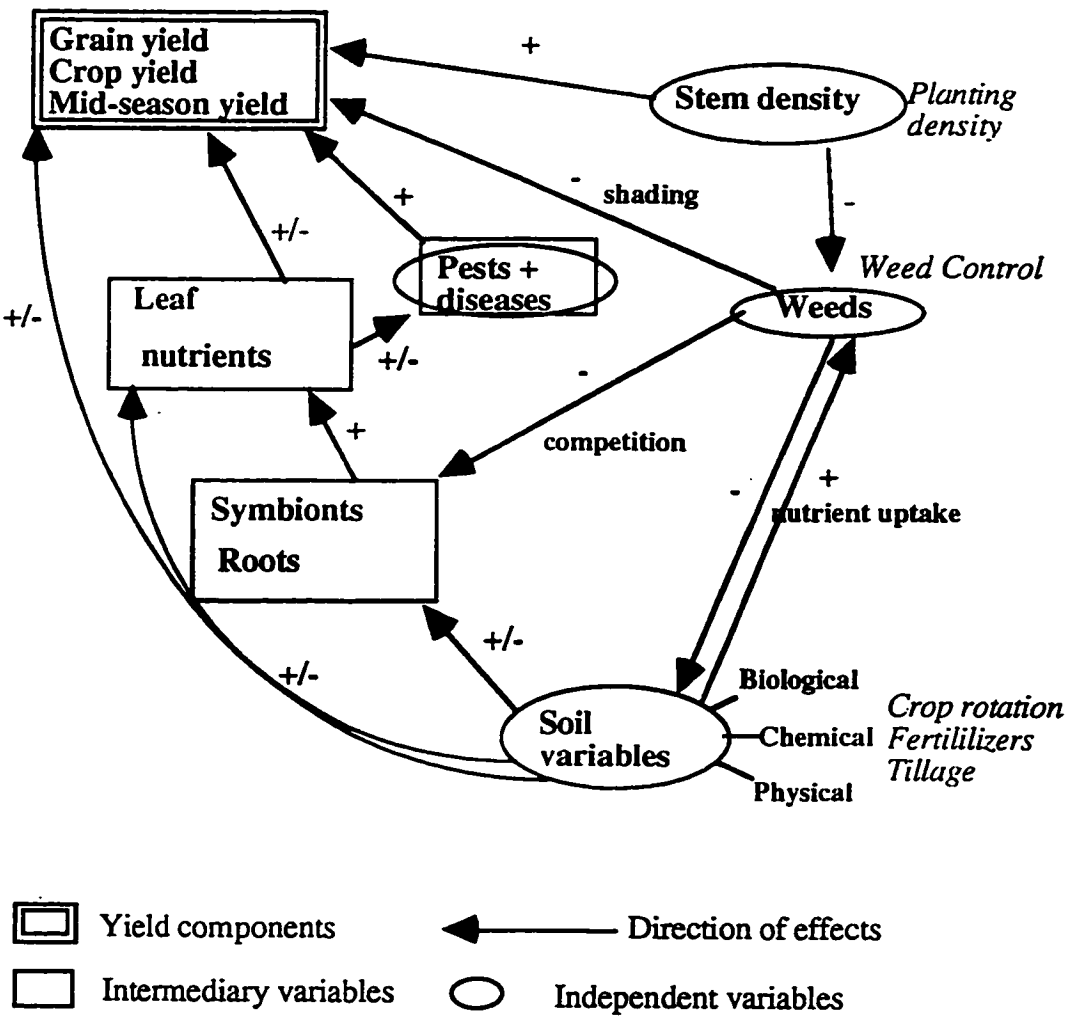

Figure 3.1. Postulated directional relationships between yield (dependent variables) and independent variables over which the farmers have some control (as indicated in italics). In some cases the relationships are direct, and in others are indirect or act through "intermediary variables". A plus sign indicates that an increase in one variable effects an increase in the affected variable. A negative sign indicates that an increase in one variable effects a decrease in the affected variable.

biological variables, which I call "intermediary variables," which in turn affect yields or other intermediary variables.

The intermediary variables are leaf nutrients, pests and diseases, roots, and symbionts. For the purposes of this analysis, roots are considered an intermediary variable in the same category as symbionts (rhizobia and mycorrhizae), since both affect levels of leaf nutrients which, in turn, affect yield components. Soil variables might affect roots, symbiont status, or plant nutritional status, or have other unidentified effects on crop growth and grain yield (Figure 3.1). Crops and weeds affect soil variables via nutrient uptake, but as the soil observations were made early in the season, it is assumed that the soil variables measured in the early season are not affected by the crop or by weeds. However, subsequent weed growth could affect the crop leaf nutrient status measured at mid-season via effects on soil nutrients, hence an effect of weeds on soil nutrients is indicated in the conceptual model.

Weeds are regarded as an independent variable. Crops affect weeds, but differences in levels of weeds between farms were probably largely independent of the crop, being due mainly to the history of the field and the early season management. Weeds might have a direct negative effect on the crop, on symbionts or root biomass, or have indirect effects through competition for soil nutrients. Soil variables could affect the roots, symbionts, plant nutritional status, or have other unidentified pathways by which they affect crop yields.

Relationships within and between sets of variables were examined initially by constructing matrices of univariate correlation coefficients. Larger sets of variables were characterized further by Principal Components Analysis (PCA). I also examined multivariate correlations between sets of variables, using stepwise regression, and regressions of yield on factors scores for farms obtained from PCA.

3.1. Significance level for univariate correlations

There are 8 pairs of variables for each correlation. If a relationship were considered in isolation, then r values of 0.71 and 0.62 would be significant at the 0.05 and 0.1 probability levels respectively. As I am examining sets of correlations, there is an additional family-wise error introduced, which depends on the number of correlations being considered. To minimize this family-wise error, correlations were examined only where some relationship might be suspected (i.e., be explainable) a priori. As the number of correlations examined in each case varied, the significance level, in principle, would vary accordingly. However, a single value, $r = 0.75$ ($R^2 = 0.56$), was selected for the following reasons: (i) to simplify the analysis because the selection of the number of correlations to be used in calculating the family-wise error is to some degree arbitrary and is a function of how the variables in total are partitioned into groups for analysis; (ii) it corresponds roughly to an alpha value of 0.1 or less when the family-wise error is calculated for data sets of 5 to 10 (Howell, 1982; Appendix Table 3), which is usually the maximum alpha value considered worthy of any consideration; (iii) when I examined correlations that had lower r values, there were many that seemed non-sensible, and therefore spurious, whereas at this level, most could be explained and were probably not spurious.

3.2. Correcting for autocorrelation

The yield (dependent) and root biomass (intermediary) variables were calculated on a unit area basis by multiplying per plant values by stem densities. As stem density varied between farms, this could result in spurious correlations where two such variables are being compared. The per plant values exhibited negative relationships with stem density (Table 3.2). Negative relationships would be expected due to intraspecific competition (Loomis and Connor, 1992) and the occurrence of negative relationships is evidence that such competition was occurring. However, as expected, when densities are

Table 3.2 Correlations of yield and intermediary variables (except leaf nutrients) with stem density expressed on a per plant &/or per m^2 basis. r values of 0.75 or greater are underlined.

VARIABLE	MINUS WEEDS		PLUS WEEDS	
	per plant values versus stem density	per m2 values (per plant values x no. stems/m2) versus stem density	per plant values versus stem density	per m2 values (per plant values x no. stems/m2) versus stem density
Grain	-.578	-.088	-.176	.242
Crop	-.569	.437	-.040	.522
Mid-season crop	-.779	-.182	-.884	-.511
Roots	-.928	-.527	-.776	-.277
Myc.	.172		-.462	
Nodules	-.280	.679	-.323	.097
Weeds		-0.447		-.240

near optimal, there are low correlations with stem density for the variables expressed on a unit area basis and they are not consistently negative or positive - this is expected because above a certain density, the addition of more biomass resulting from addition of more plants is roughly compensated for by loss of biomass per plant, and the yield per unit area (or values of other variables related to photosynthetic capacity expressed on a unit area basis) do not increase with increasing density (Loomis and Conner, 1992). Thus it appears likely that there would not be significant autocorrelation between variables expressed on a unit area basis. As a further check, I examined the correlations where autocorrelation might be suspected and is a matter of concern, by examining the correlation of the residuals from the regression of dependent variables on stem density with the residuals from the regression of the independent variables on stem density. If the correlation is still high, that is considered evidence that the correlation between the two variables was not due to autocorrelation. The leaf nutrient values which are expressed as g kg^{-1} or mg kg^{-1} could be expected to increase with decreasing stem density in the absence of other differences. Nodules, expressed on a weight per plant basis, and mycorrhizal infection expressed on a percent basis might also be expected to change with stem density. Hence, significant correlations between these variables or of these variables with yield variables were also examined for autocorrelation by examining correlations of residuals from regressions of each variable on the stem density.

3.3. Range of variation between farms and relationships within sets of variables

3.3.1. Yield variables and weeds

There was large variation in yield variables between farms (Figure 3.2, Table 3.3, Appendix Table 4). Mid-season crop yield varied by 2.1- and 3.6-fold (maximum value divided by minimum value) between farms, crop yield by 2.2- and 5.0-fold, and grain yield by 3.4- and 6.8-fold in the minus and the plus weed plots respectively (Table 3.3).

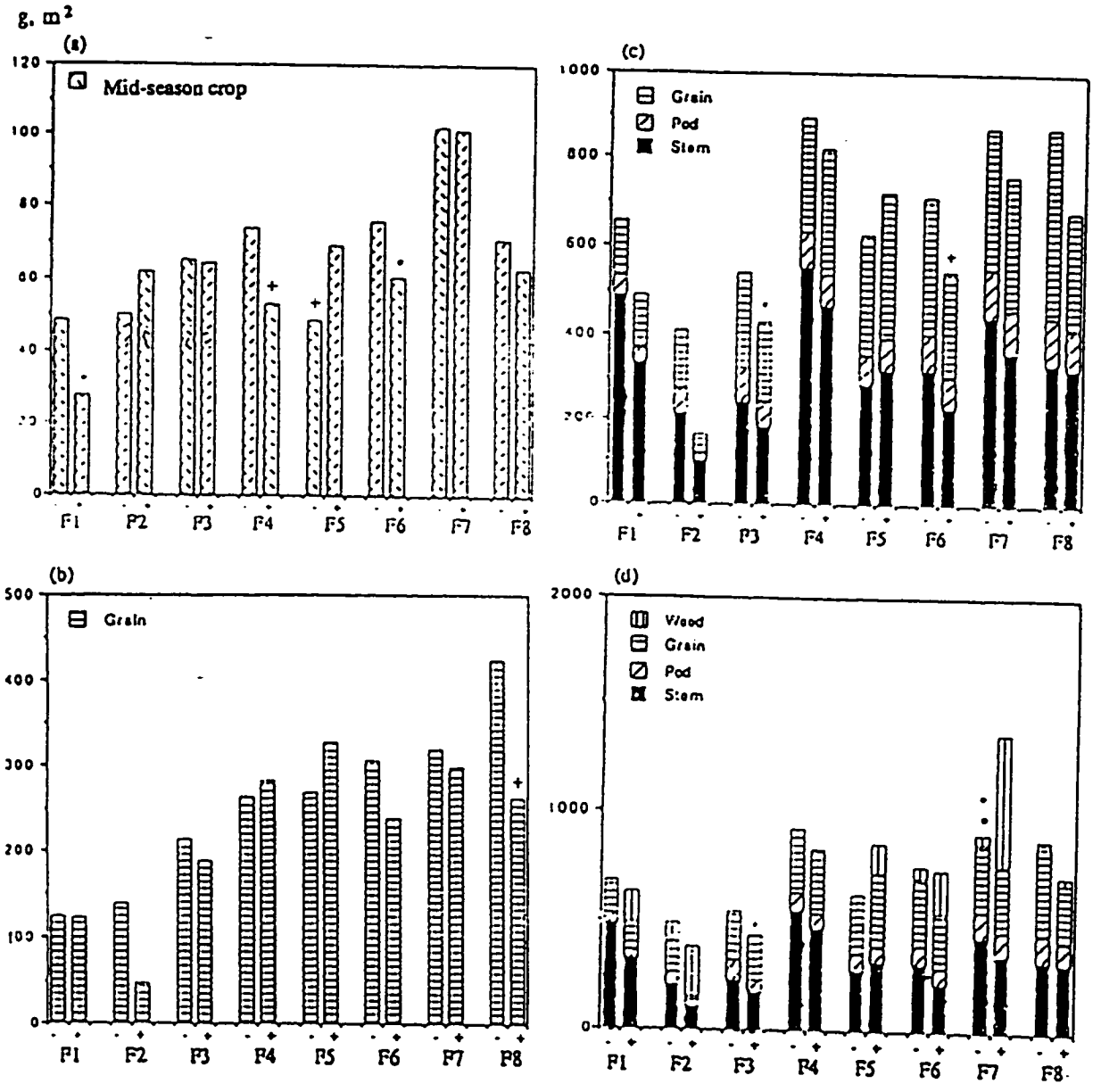

Figure 3.2. Fababean yield variables in the minus (-) and plus (+) weed plots. (a) mid-season crop biomass, (b) grain yield only, (c) crop yield (grain + pod + stem), (d) weed + crop. Significant differences between minus and plus weed plots are indicated above the bars (+, *, ** correspond to a = 0.1, 0.05, 0.01)

Table 3.3. Average values of yield variables, symbionts, and leaf and soil variables in minus and plus weed plots for the eight farms considered together. t test refers to the difference and r to the correlation between minus and plus weed variables for the 8 farms. Variances compared by F test. r values of 0.75 or greater are underlined.

VARIABLE	MINUS WEEDS	PLUS WEEDS	t-test prob.	CV%	r	r-prob.	Ratio of variance +w /-w
YIELD VARIABLE							
Grain g m^{-2}	257	221	0.093(1)[b]	20.2	<u>.749</u>	0.016	0.944
range	125-423	48.1-327					
Grain+pods g m^{-2}	335	283	0.049(1)	17.6	<u>.795</u>	0.018	1.05
range	166-529	61.8-397					
Stem+leaves g m^{-2}	364	294	0.006(1)	25.1	<u>.879</u>	0.004	0.901
range	217-556	102-471					
Crop[a] g m^{-2}	698	577	0.006(1)	11.4	<u>.882</u>	0.004	1.53
range	412-894	164-818					
Weeds g m^{-2}	30.2	171	0.031(1)	12.6	.448	0.27	58.7**[c]
range	2.2-75.1	11-593					
Crop+weeds g m^{-2}	728	747	0.806(2)	19.9	.736	0.037	3.12+
range	487-927	388-135					
Stem density m^{-2}	29.9	29.7	0.938(2)	17.8	.699	0.054	1.58
range	19-41	16-48					
Pods $plant^{-1}$	9.57	9.20	0.005(1)	36.4	<u>.918</u>	0.001	1.12
range	3.7-13.9	2.7-12.9					

Table 3.3. (continued)

VARIABLE	MINUS WEEDS	PLUS WEEDS	t-test prob.	CV%	r	r-prob.	Ratio of variance +w/-w
Ratio of grain+pods to crop	0.479	0.490	0.483(1)	52.4	.849	0.008	0.769
range	0.25-0.61	0.31-0.57					
Mid-season crop g m^{-2}	66.8	62.4	0.218(1)	16.2	.705	0.051	1.22
range	48.5-102	27.9-101					
Ratio of roots to mid-season crop	1.124	1.060	0.209(1)	20.7	.35	0.401	0.361
range	0.757-1.78	0.814-1.38					
SYMBIONTS & ROOTS							
Roots g m^{-2}	75.1	66.2	0.016(1)	9.5	.919	0.001	1.47
range	36.7-105	26.1-96.9					
Myc. %	23.3	26.9	0.415(2)	33.2	.588	0.125	3.42+
range	14.5-33.3	9.12-56.6					
Nodules, g $plant^{-1}$	1.3	1.25	0.847(2)	29.3	.627	0.096	4.55*
range	0.78-1.80	0.63-2.50					
LEAF NUTRIENTS							
leaf N g kg^{-1}	.566	.569	0.459(1)	8.26	.010	0.981	0.911
range	.49-.63	.51-.65					
leaf P g kg^{-1}	.0485	.0523	0.216(1)	19.8	.080	0.851	1.83
range	.034-.056	.034-.068					

Table 3.3. (continued)

VARIABLE	MINUS WEEDS	PLUS WEEDS	t-test prob.	CV%	r	r-prob.	Ratio of variance +w/-w
leaf K g kg^{-1}	.256	.218	0.050(1)	17.4	.873	0.005	0.456
range	.11-.42	.11-.34					
leaf Ca g kg^{-1}	.120	.109	0.267(1)	27.5	.687	0.059	0.432
range	.04-.207	.036-.167					
leaf Mg g kg^{-1}	.0421	.0391	0.231(1)	24.6	.835	0.010	0.382
range	.019-.070	.017-.051					
leaf S g kg^{-1}	.0156	.0151	0.401(1)	24.5	.434	0.283	0.667
range	.01-.023	.009-.022					
leaf Zn mg kg^{-1}	43.3	49.6	0.104(1)	19.7	.776	0.024	0.816
range	21-79	27-88					
leaf Mn mg kg^{-1}	92.1	102	0.190(1)	20.6	.779	0.023	0.523
range	37-164	64-156					
leaf Fe mg kg^{-1}	88.6	97.4	0.173(1)	18.6	.262	0.530	0.334
range	43-106	72-119					
leaf Cu mg kg^{-1}	8.00	9.75	0.177(1)	39.6	.661	0.075	1.29
range	3-20	3-20					
leaf B mg kg^{-1}	38.6	39.4	0.448(1)	28.4	.492	0.216	1.34
range	23-64	23-73					

Table 3.3. (continued)

VARIABLE	PLUS WEEDS
SOIL VARIABLES	Plus and minus weeds
CO_2-C $\mu g\ g^{-1}h^{-1}$	0.726
range	0.27-1.23
SNO_3^- -N $\mu g\ g\ soil^{-1}$	23.1
range	15.8-30.4
SOM %	2.96
range	2.4-3.5
Clay %	6.83
range	0-11
Sand %	61.5
range	49-74
Silt %	31.7
range	20-41
CEC meq. $100\ g^{-1}$	6.2
range	4.2-8.8
pH	6.06
range	5.6-6.4

Table 3.3. (continued)

VARIABLE	PLUS WEEDS
BS %	92.6
range	76.1-100
Total + Mg + Ca + Mg meq. $100g^{-1}$	5.65
range	4.2-6.8
P mg kg^{-1}	75.6
range	54-106
K mg kg^{-1}	91.8
range	57-174
Ca mg kg^{-1}	935
range	689-1213
Mg mg kg^{-1}	90.1
range	51-142
S mg kg^{-1}	12.9
range	11-14
Zn mg kg^{-1}	2.8
range	1.2-10.2
Mn mg kg^{-1}	36.9
range	26-58
Fe mg kg^{-1}	45.9
range	26-61

Table 3.3. (concluded)

VARIABLE	PLUS WEEDS
Cu mg kg^{-1}	1.59
range	1-2.2
B mg kg^{-1}	0.5
range	0.4-0.6

[a] Crop = grain + pods + stems + leaves.

[b] (1) and (2) refer to 1 tail and 2 tail t test.

[c] +, *, **, variances differ (F test) at $\alpha = 0.1, 0.05$, and 0.01 respectively.

Weed biomass, measured at the silage harvest stage varied from 2.2 to 75.1 g m^{-2} in the minus weed plots, and 11 to 593 g m^{-2} in the plus weed plots (Table 3.3).

Grain and crop yields were highly correlated with each other in the plus weed plots ($r = 0.923$); the correlation was high but not significant ($r = 0.724$) in the minus weed plots (Table 3.4). These variables were poorly correlated with mid-season crop yield ($r = 0.295$ to 0.696), suggesting that processes taking place after mid-season have as much influence on the final grain or silage yields as processes occurring before the mid-season.

Stem density varied from 19 to 41 stems m^{-2} in the minus weed plots and from 16 to 48 stems m^{-2} in the plus weed plots (Table 3.3.).

3.3.2. Pests

Crops were examined for pests and diseases. Although there was some disease (chocolate spot) and minor pest infestations (black bean aphids) at some sites, these were no serious pest or disease problems except at Farm 2 where chocolate spot was abundant and appeared to damage plants to the extent that yield was reduced (Table 3.1).

3.3.3. Leaf nutrients

The analyses of leaf nutrients were conducted on uppermost leaves at the flowering stage to give indications of their adequacy for plant growth (rather than on whole plants at later stages to give the total amounts accumulated). Literature searches and consultation with European and North American researchers (Dr. K. Clark, University of Manitoba; Dr. J. Sprent, University of Dundee) failed to reveal data on critical concentrations of nutrients in fababean crops. Plants were sampled at stages recommended for soybeans. Critical concentrations cited for dry beans (*Phaseoulus vulgaris L.*) and soybeans (*Glycine max* L.) are similar (Riddell and Switzer, 1987), and were used as presumptive values for fababean. For S, a value for whole peas grown in PEI was used (Gupta and MacLeod, 1984; Table 3.5).

Table 3.4. Correlation matrices for yield variables, weeds, and stem density in the minus and plus weed plots. r values of 0.75 or greater are underlined.

VARIABLE	Grain	Crop	Weeds	Crop +weeds	Mid-season crop	Stem density
MINUS WEEDS						
Grain						
Crop	.724					
Weeds	-.364	-.251				
Crop + weeds	.691	.990	.112			
Mid-season crop	.599	.696	.078	.726		
Stem density	-.088	.437	-.447	.384	-.182	
PLUS WEEDS						
Grain						
Crop	.923					
Weeds	.104	.089				
Crop + weeds	.731	.777	.696			
Mid-season crop	.486	.295	.683	.644		
Stem density	.242	.522	-.240	.225	-.511	

Table 3.5. Critical and maximum normal levels of leaf nutrients for reference legumes, observed ranges of leaf nutrient values for fababean. Yield loss due to nutrient deficiency is expected when nutrient concentrations are at or below the "critical"concentration; maximum normal concentrations are more than adequate but do not necessarily cause toxicities.

	Literature values [a] dry beans / soybeans		Observed fababean ranges	
Nutrient	Critical level	Maximum normal	Minus weeds	Plus weeds
N g kg^{-1}	.40/.40	.55/.60	.49-.63	.51-.65
P g kg^{-1}	.015/.015	.05/.05	.034-.056	.034-.068
K g kg^{-1}	.12/.12	.25/.25	.11-.42	.11-.34
Ca g kg^{-1}	-/.036	.50/.30	.04-.207	.036-.167
Mg g kg^{-1}	.01/.01	.10/.10	.019-.07	.017-.051
S g kg^{-1}	-/.012	-/-	.01-.023	.009-.022
Zn mg kg^{-1}	14/12	50/80	21-79	27-88
Mn mg kg^{-1}	14/14	100/100	37-164	64-156
Fe mg kg^{-1}	-/-	-/-	43-106	72-119
Cu mg kg^{-1}	4/4	30/30	3-20	3-20
B mg kg^{-1}	10/20	55/55	23-64	23-73

[a] Values apply to the top fully developed leaf of dry beans (*Phaseolus vulgaris* L.) and soybean (*Glycine max* L.) at first flowering except for the S value which is for whole pea plants. Data from Riddell and Switzer, 1987, except for the critical level for Ca in soybean which is taken from Small and Ohlrogge, 1973, and S value which is from Gupta and MacLeod, 1984.

Based on these values, K varied between farms from inadequate (below critical level) to excessive (above maximum normal level), P and N from normal to excessive, and Mg values were all within the normal level. Ca values were all below maximum normal values; the lowest values were close to critical values inferred for Ca. Lowest S values were close to or below the critical value inferred for S (Table 3.5).

A correlation matrix for the 6 macronutrients is given in Table 3.6 and PCA results in Table 3.7. The first two components account for 89.9% and 66.1% of the total variance in the minus and the plus weed plots respectively. The correlation matrix and PCAs illustrate strong associations between leaf Mg and leaf Ca in the minus and the plus weed plots, between leaf K and leaf N in the minus weed plots, and overall negative relationships of leaf K and leaf N with leaf Ca and leaf Mg, these being stronger in the minus weed than in the plus weed plots. The relationship of leaf P to other macronutrients appears to differ between the minus and the plus weed plots; P is highly associated with leaf Ca and leaf Mg in the minus weed plots but not in the plus weed plots (Table 3.7). This difference is probably related to weed uptake of P; there was a significant negative correlation between leaf P and weed biomass in the plus weed plots, but not in the minus weed plots (section 3.4.3).

Farms 4, 6, and 7 had the highest leaf K values (except for Farm 4 in the plus weed plots), and Farm 4 and 6 had very low leaf Ca and Mg values compared to other farms (Figure 3.3; Appendix Table 5). There were significant negative correlations of leaf K with leaf Mg and leaf Ca in the minus weed plots (Table 3.6).

Leaf micronutrient values, excluding Fe for which the critical levels are not cited, were mostly within the adequate but not excessive range (Table 3.5) with the exception of leaf Mn values which were well above the suggested maximum (100 mg kg^{-1}) at Farm 1 and Farm 2 (Appendix Table 5).

Table 3.6. Correlation matrices for all leaf nutrients. r values of 0.75 or greater are underlined.

	N	P	K	Ca	Mg	S	B	Cu	Zn	Mn	Fe
MINUS WEEDS											
Leaf N											
Leaf P	-.506										
Leaf K	.750. (.969)[a]	-.835 (.984)									
Leaf Ca	-.734	.752 (.973)	-.775 (.986)								
Leaf Mg	-.789 (.964)	.798 (.980)	-.824 (.991)	.965 (.997)							
Leaf S	.016	.363	.116	.325	.281						
Leaf B	.254	.583	-.262	.067	.082	.186					
Leaf Cu	-.372	.457	-.726	.555	.570	-.480	.250				
Leaf Zn	.075	.549	-.271	.387	.304	.438	.645	.208			
Leaf Mn	-.622	.605	-.814 (.991)	.766 (.983)	.679	-.105	.141	.673	.507		
Leaf Fe	-.420	.814 (.990)	-.575	.797 (.936)	.719	.588	.516	.285	.674	.614	

Table 3.6. (concluded).

	N	P	K	Ca	Mg	S	B	Cu	Zn	Mn	Fe
PLUS WEEDS											
Leaf N											
Leaf P	.279										
Leaf K	.007	- .434									
Leaf Ca	- .395	- .175	- .098								
Leaf Mg	- .357	.098	- .412	.899 (.982)							
Leaf S	.335	.178	.391	.481	.371						
Leaf B	- .504	.485	- .122	.327	.420	.220					
Leaf Cu	.197	.574	- .628	.283	.402	.231	.467				
Leaf Zn	- .205	- .403	.304	.750 (.946)	.464	.582	.079	.142			
Leaf Mn	- .172	- .463	- .439	.324	.214	- .374	- .210	.338	.302		
Leaf Fe	- .350	.421	- .072	.647	.705	.606	.821 (.886)	.480	.471	- .240	

[a] Number in brackets is r value between residuals from regressions of each of the two variables on stem density.

Table 3.7. Loadings, eigenvalues, and variance from PCA (quartimax rotation) of leaf nutrient data.

VARIABLE	LOADINGS					
	MINUS WEEDS			PLUS WEEDS		
	PC1	PC2	PC3	PC1	PC2	PC3
MACRONUTRIENTS						
Mg	.982	.055	.041	.986	-.096	.027
Ca	.951	.134	.046	.970	-.170	.003
P	.892	.195	-.364	.059	.694	.527
S	.279	.944	-.146	.425	-.487	.755
N	-.800	.328	-.473	-.444	.143	.765
K	-.890	.400	.201	-.339	-.882	.125
Eigenvalues	4.17	1.22	0.42	2.41	1.56	1.45
%Variance described	69.6	20.3	7.03	40.2	25.9	24.2
MICRONUTRIENTS						
B	.659	.054	.710	.865	-.102	-.047
Cu	.212	.894	.084	.609	.486	-.046
Zn	.848	.023	.118	.172	.176	.963
Mn	.636	.638	-.435	-.141	.887	.171
Fe	.801	.135	-.031	.924	-.174	.339
Eigenvalues	2.67	1.05	0.48	2.18	1.28	0.76
%Variance described	44.9	24.6	14.3	40.5	21.9	21.6

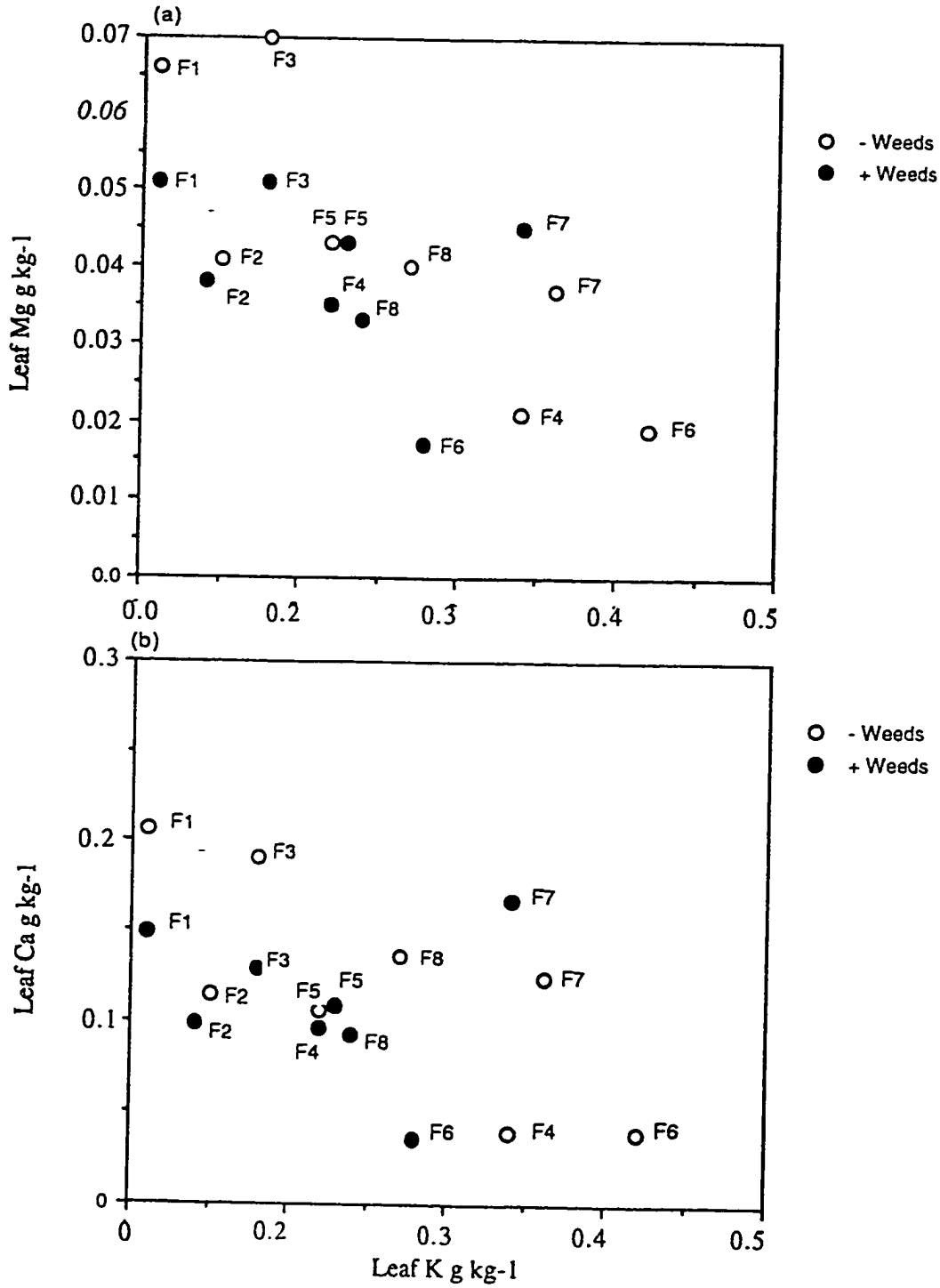

Figure 3.3. Relationships of leaf K with leaf Mg (a) and leaf Ca (b).

For the five micronutrients, the correlation matrix and PCA are given in Tables 3.6. and Table 3.7. The first two components accounted for 69.5% and 62.4% of the variances between farms for micronutrients for the minus weed and the plus weed plots respectively. There were no significant correlations between the micronutrients except for that between leaf B and leaf Fe in the plus weed plots (Table 3.6). There was a significant negative correlation between leaf K and leaf Mn in the minus weed plots (Figure 3.4; Table 3.6).

Nine out of ten of the correlations of individual leaf micronutrients with leaf K were negative (Table 3.6), which has a probability of 0.01 of occurring if there is a 50-50 chance of being negative. A plot of total leaf micronutrients versus leaf K is shown in Figure 3.5. Farm 7 appears to be deviant in having high leaf micronutrients with high leaf K. When Farm 7 is removed, the negative correlation between leaf K and the total micronutrients is significant for both the minus and the plus weed plots ($r = -0.939$ and $= -0.800$ respectively). Overall, there were higher levels of leaf micronutrients in the plus weed plots compared to those in the minus weed plots (Table 3.3) and lower levels of leaf K in the plus weed plots compared to those in the minus weed plots (Table 3.3), suggesting that uptake of K by weeds reduced antagonistic effects of K on uptake of micronutrients by the crop.

3.3.4. Roots, mycorrhizae, and nodules

Roots, mycorrhizae, and nodules all varied by more than 2-fold between farms (Table 3.3). There were no significant correlations between roots, mycorrhizae and nodules (Table 3.8).

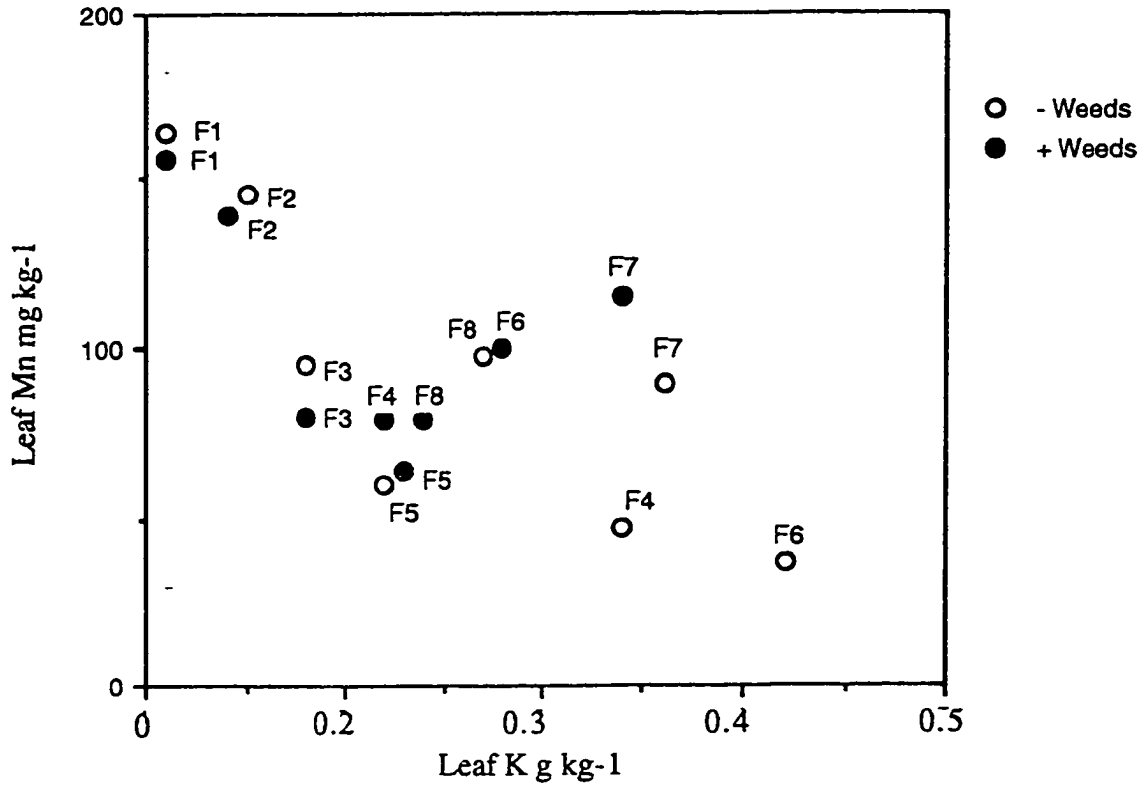

Figure 3.4. Relationships of leaf K with leaf Mn.

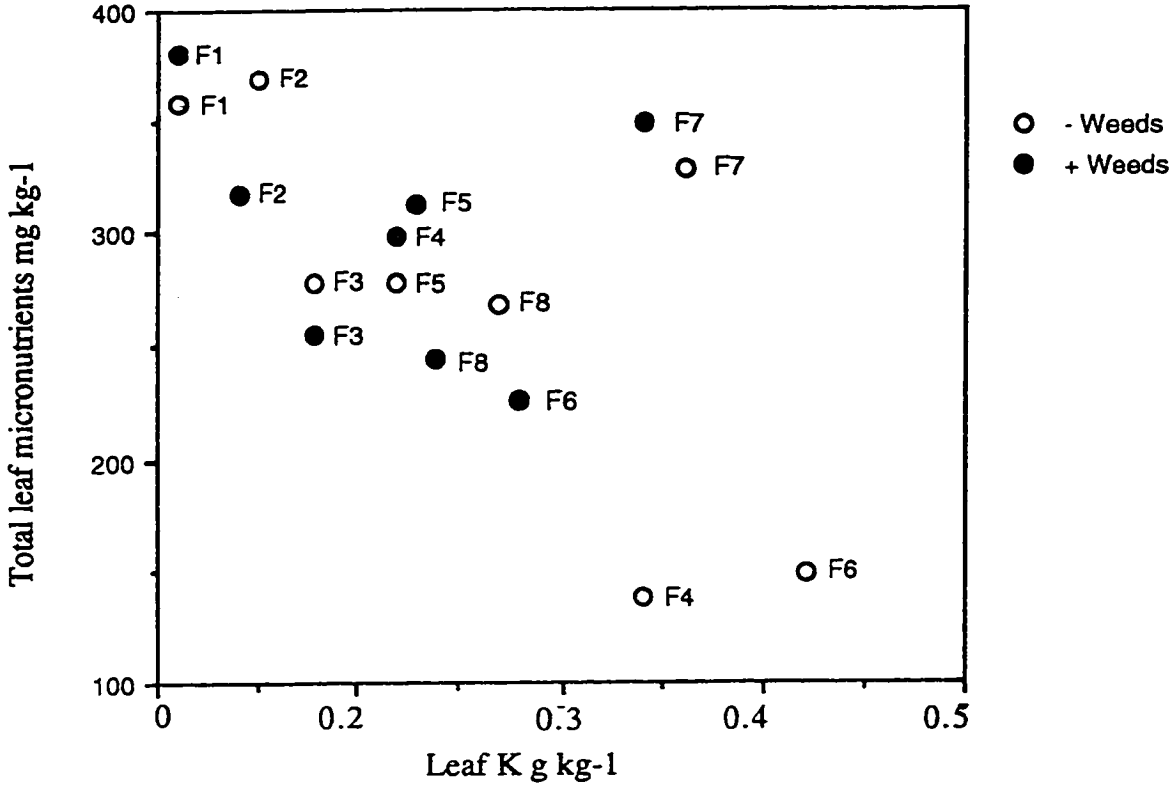

Figure 3.5. Relationships of leaf K with total leaf micronutrients.

Table 3.8. Correlation matrices for roots, mycorrhizae, and nodules.

VARIABLES	Roots	Myc.	Nodules
MINUS WEEDS			
Roots			
Myc.	.326		
Nodules	-.099	-.217	
PLUS WEEDS			
Roots			
Myc.	.554		
Nodules	.509	.58	

3.3.5. Soil variables

Soil variables that reflect primarily the chemical environment (pH, exchangeable bases, P, micronutrients, cation exchange capacity), biological environment (respiration, nitrate production), and physical environment (texture), and organic matter which impacts on all 3 categories, were measured early in the growing season (Table 3.9). Soil samples were taken throughout the plot area, but not in the plots themselves. They are considered representative of initial soil conditions for both the minus and the plus weed plots, as there had been little growth of weeds or crops at the time they were sampled (June 14).

Between farms, soils did not vary greatly in texture: all farms would be classified (Brady, 1974) as sandy loam except for Farm 2 which was classified as loam. Soil organic matter values varied from 2.4 to 3.5%, CEC by more than 2-fold, nitrate production by approximately 2-fold and CO_2-C production over the range from 0.27 to 1.23 $\mu g\ g^{-1}\ h^{-1}$. Soil macronutrient values were all classified as very high for P; for K, they varied from very low to high; for Ca from medium to high; for Mg from very low to high; and for S from medium to high (Table 3.9). For the micronutrients, all levels were categorized as medium or above, except for B and Zn which were classified as low for most farms (Table 3.9).

For soil variables that are independent of each other, there was significant correlation only between soil K and soil NO_3^- (Table 3.10); (by independent, I mean in this case, variables that are not numerically dependent on each other such as the percent of sand, silt and clay).

Table 3.11 gives results of principal component analysis of seven soil variables selected to represent soil biological, physical, and chemical conditions (a maximum of 7 could be selected because of the restrictions due to the number of farms sampled). Three of 7 components have eigenvalues greater than or equal to 1.0 and accounted for 82.4% of the variance of the original variables. The first PC has high positive loading for soil K

Table 3.9. Values of soil variables for the 8 farms.

SOIL VARIABLE	F1	F2	F3	F4	F5	F6	F7	F8
CO_2-C $\mu g\ g^{-1}h^{-1}$	0.58	0.61	0.31	0.27	0.73	1.03	1.23	1.06
NO_3^--N [a] μg g soil^{-1}	16.2	15.8	18.9	26.9	25.6	27.2	30.4	23.9
SOM %	2.8	2.4	3.2	2.9	3.5	2.8	3.0	3.1
Clay %	3.5	11.0	4.75	0	9.0	9.35	11.0	6.0
Sand %	71.5	49.0	56.5	59.0	61.5	64.0	56.5	74.0
Silt %	25.0	40.0	38.8	41.0	29.5	26.7	32.5	20.0
CEC meq. $100g^{-1}$	4.3	6.1	5.8	6.8	6.2	8.8	7.5	4.2
pH	6.3	5.6	6.1	6.0	6.2	6.4	5.9	6.0
BS%	100	80.5	100	100	100	76.1	83.9	100
Total K+ Mg + Ca meq. $100g^{-1}$	4.3	4.9	5.8	6.8	6.2	6.7	6.3	4.2
P mg kg^{-1}	65 (VH)[b]	58 (VH)	54 (VH)	106 (VH)	75 (VH)	61 (VH)	87 (VH)	99 (VH)
K mg kg^{-1}	57 (VL)	64 (VL)	65 (VL)	115 (M)	89 (L)	76 (L)	174 (H)	94 (L)
Ca mg kg^{-1}	718 (H)	832 (M)	893 (H)	1136(H)	974 (H)	1213(M)	1024(M)	689 (H)
Mg mg kg^{-1}	73 (M)	74 (M)	142 (H)	98 (M)	135 (H)	51 (VL)	85 (L)	63 (M)
S mg kg^{-1}	11 (M)	13 (H)	12 (M)	13 (H)	14 (H)	13 (H)	14 (H)	13 (H)
Zn mg kg^{-1}	10.2(VH)	1.8 (L)	1.2 (L)	2.0 (L)	1.5 (L)	2.4 (L)	1.9 (L)	1.5 (L)
Mn mg kg^{-1}	52 (VH)	58 (VH)	29 (M)	37 (H)	26 (M)	27 (M)	32 (H)	34 (H)
Fe mg kg^{-1}	46 (H)	61 (VH)	46 (H)	57 (VH)	40 (H)	26 (H)	43 (H)	48 (H)
Cu mg kg^{-1}	2.2 (H)	1.6 (H)	1.1 (M)	2.2 (H)	2.1 (H)	1.4 (H)	1.1 (M)	1.0 (M)
B mg kg^{-1}	0.6 (M)	0.5 (L)	0.4 (L)	0.5 (L)	0.6 (M)	0.4 (L)	0.4 (L)	0.6 (M)

[a] NO_3^--N = nitrate relased during incubation plus field nitrate.

[b] Commercial lab's rating: VL, L, M, H, VH refer to very low, low, medium, high, very high.

Table 3.10. Correlation matrix for soil variables. r values of 0.75 or greater are underlined except when they are not independent.

VARIABLE	CO_2	NO_3	OM	Clay	Sand	Silt	CEC	pH	BS	Tot.K MgCa	P	K	Ca	Mg	S
CO_2-C															
NO_3^--N	.521														
SOM	.046	.419													
Clay	.677	.138	-.137												
Sand	.274	.055	.310	-.365											
Silt	-.637	-.129	-.261	-.121	-.889										
CEC	.253	.615	-.116	.384	-.476	.313									
pH	.050	.191	.433	-.268	.623	-.527	.124								
BS	-.506	-.178	.601	-.724	.438	-.099	-.712	.194							
Total K+Mg+Ca	-.054	.694	.237	.033	-.439	.452	.864	.205	-.273						
P	.159	.596	.243	-.389	.304	-.128	-.100	-.157	.354	.118					
K	.488	.801	.217	.182	-.157	.074	.376	-.254	-.145	.438	.639				
Ca	.037	.677	.043	.071	-.369	.358	.934	.249	-.441	.962	.089	.368			
Mg	-.548	-.047	.656	-.189	-.347	.467	-.108	.009	.555	.291	-.128	-.022	.043		
S	.495	.734	.283	.552	-.350	.091	.516	-.309	-.324	.517	.393	.661	.463	.097	

Table 3.11. Loadings, eigenvalues, and variance from PCA (non rotated) of selected soil variables.

VARIABLE	LOADINGS		
	PC1	PC2	PC3
SOM	.480	.404	.476
K	.827	-.168	-.430
NO_3^--N	.972	.098	-.093
CO_2-C	.590	-.703	.292
pH	.187	.502	.745
Total K+Mg+Ca	.663	.446	-.236
Clay	.157	-.797	.399
Eigenvalues	2.71	1.78	1.28
% Variance described	38.7	25.5	18.2

and soil NO_3^-; the second PC has high negative loading for soil CO_2-C production and clay, and the third PC has high positive loading for soil pH (Table 3.11).

3.4. Relationships between variables in different sets of variables

Significant univariate regressions and multivariate regressions (based on stepwise selection) are given in Table 3.12. All values are given in Appendix Tables (6, 7, 8, 9, 10, and 11).

3.4.1. Relationships of yield variables with stem density

There is very little correlation of grain or crop yields with stem density (Table 3.2). Patriquin et al. (1986) observed the ratio of crop-to-(crop + weed) biomass to increase as density of fababean increased up to 25 plants per square meter. Day et al. (1979) observed that yields of fababean per hectare were unaffected by plant density above 18 plants per square meter. All densities were close to or higher than 25 plants per square meter except for Farm 2 (19.0 stems m^{-2} in the minus weed plots and 16.3 stems m^{-2} in the plus weed plots; Appendix Table 4). Thus low stem density was likely an important factor in the low yields on the plus weed plots at Farm 2. This site exhibited the greatest reduction in yield due to weeds. The effect was pronounced at harvest, but was not evident at mid-season (Figure 3.2; Appendix Table 4).

3.4.2. Relationships of yield variables with weeds

There is very little correlation of the grain or crop yield with weeds in the plus weed plots (Table 3.4).

3.4.3. Relationships of yield variables and weed biomass with leaf and soil nutrients

In this study, leaf nutrients were examined partially as an intermediary variable and partially as a proxy indicator of soil nutrient status. Hence the relationship of yield variables to leaf and soil nutrients are considered together.

Table 3.12. Significant relationships between dependent, intermediary, and independent variables.

FOR SIGNIFICANT UNIVARIATE REGRESSIONS

Dep. Var	-/+w	Ind Var	R^2	*p*	Estimating Equation [a]
Yield & weeds with leaf nutrients					
Grain	+	K	0.604	.0249	6.13 + 98.7 x K
Mid-season crop	-	K	0.613	.0216	33.4 - 13.02 x K
Mid-season crop	+	K	0.645	.0164	15.0 + 21.8 x K
Weeds	+	P	0.702	.0090	948 - 1489 x P
Yield and weeds with symbionts and roots					
Grain	+	Roots	0.646	.0162	4.72 + 3.26 x Roots
Mid-season crop	+	Roots	0.704	.0092	14.5 + 0.72 x Roots
Mid-season crop	+	Myc.	0.705	.0091	30.8 + 1.18 x Myc.
Yield and weeds with soil variables					
Grain	+	NO_3	0.787	.0033	-134 + 15.4 x NO_3
Crop	-	NO_3	0.577	.0288	142 + 24.1 x NO_3
Crop	-	P	0.747	.0056	121 + 7.62 x P
Crop	+	NO_3	0.679	.0119	-172 + 32.3 x NO_3
Crop	+	P	0.631	.0185	-81.2 + 8.69 x P
Mid-season crop	-	NO_3	0.584	.0273	7.84 + 2.55 x NO_3
Mid-season crop	-	K	0.713	.0084	29.8 + 0.40 x K
Mid-season crop	+	K	0.598	.0244	25.1 + 0.41 x K
Mid-season crop	+	S	0.649	.0157	-149 + 16.4 x S
Weeds	-	SOM	0.858	.0009	444 - 241 x SOM
Weeds	-	BS%	0.633	.0182	204 - 1.88 x BS%

Table 3.12. (concluded)

Dep. Var	-/+w	Ind Var	R^2	*p*	Estimating Equation
Leaf nutrients with roots and symbionts					
Leaf S	-	Myc.	0.672	.01271	0.01 + 0.01 x Myc.
Leaf K	∓	Roots	0.767	.00443	0.33 + 0.03 x Roots.
Leaf K	+	Myc.	0.618	.02010	1.08 + 0.04 x Myc.
Leaf K	+	Nodules	0.610	.02212	1.07 + 0.87 x Nodules
Leaf nutrients with corresponding soil nutrients					
Leaf N	-	NO_3	0.764	0.0048	3.87 + 0.08 x NO_3
Leaf Ca	-	Ca	0.631	0.0185	3.59 - 0.003 x Ca
Leaf K	+	K	0.652	0.0154	0.74 + 0.02 x K
Roots and symbionts with soil variables					
Roots	-	NO_3	0.574	0.0295	13.5 + 2.67 x NO_3
Roots	-	S	0.88	0.0006	-160 + 18.3 x S
Roots	+	NO_3	0.716	0.0081	-17.2 + 3.61 x NO_3
Roots	+	S	0.859	0.0009	-215 + 21.9 x S
Myc.	∓	K	0.596	0.0248	0.268 + 0.29 x K
FOR SIGNIFICANT MULTIVARIATE REGRESSIONS					
Dep. Var	-/+w	Ind Var	R^2	*p*	Estimating Equation
Grain	+	Leaf K & Leaf P	0.912	0.0023	-361 + 133 x Leaf K + 558 x Leaf P
Mid-season crop	+	Myc. Roots, & nodules	0.963	0.0026	13.3 + 0.94 x Myc. + 0.54 x Roots + (-9.16 x Nodules)
Grain	+	NO_3, SOM, & BS%	0.994	0.0001	-817 + 13.5 x NO_3 + 333 x SOM + 1.66 x BS%
Crop	+	NO_3 &BS%	0.956	0.0004	-1277 + 36.1 x NO_3 + 10.9 x BS%
Leaf K	+	Roots & Nodules	0.919	0.0019	0.18 + 0.02 x Roots + 0.506 x Nodules
Roots	+	S, K, SOM, of soil	0.951	0.004	-294 + 17.8 x S + 0.08 x K + 72.2 x SOM

Footnotes to Table 3.12

[a] Units are:

grain, crop, mid-season crop, weeds, and roots: g (dry weight) m^{-2}.
leaf nutrients: g kg^{-1}.
myc. : % roots infected by mycorrhizal arbuscules.
nodules: g (fresh weight) $plant^{-1}$.
NO_3^-: µg N g $soil^{-1}$.
SOM: % of soil by weight.
BS%: % of CEC.
soil K, S, P, Ca: mg kg^{-1}.

Univariate correlation coefficients of 0.75 ($R^2 = 0.562$) or higher between crop yield variables or weed biomass with leaf nutrients were found for grain yield with leaf K in the plus weed plots (Figure 3.6 c; Table 3.12), for mid-season crop yield with leaf K in the minus and the plus weed plots (Figure 3.6 a) and for the weed biomass with crop leaf P in the plus weed plots (Table 3.12). All r values of crop yield variables with leaf K were above 0.64 (Appendix Table 6).

A plot of grain yield versus leaf K illustrates a pattern of continuous increase with increasing leaf K to values of leaf K between 0.25 g kg^{-1} and 0.30 g kg^{-1}, and then a leveling off or a decline (Figure 3.6 c). Similar but less pronounced trends are evident for the crop and mid-season yields versus leaf K (Figure 3.6 b, a). For the minus and the plus weed data considered together, the relationship of crop and mid-season yields with leaf K are equally well described by linear and quadratic regressions ($R^2_L = 0.595$, $p = 0.0005$; $R^2_Q = 0.605$, $p = 0.002$ for mid-season crop yield, $R^2_L = 0.426$, $p = 0.006$; $R^2_Q = 0.464$, $p = 0.017$ for crop yield); for grain yield, the quadratic regression significantly improved the relationship ($R^2_L = 0.518$, $p = 0.002$; $R^2_Q = 0.698$, $p = 0.0004$).

Significant univariate correlations were found for several yield variables with soil $NO3^-$ production (Table 3.12). Mid-season crop yields in the minus and the plus weed plots were significantly correlated with soil K (Table 3.12). Other significant correlations of yield variables with soil variables were with soil P and soil S (Table 3.12). Weed biomass exhibited a significant negative correlation with soil organic matter and soil BS%, in contrast to crop yield variables which were only positively related to soil variables (Table 3.12).

Stepwise regression analysis was used to determine if yield was better correlated with leaf nutrient or soil variables when more than one independent variable is considered. It substantially improved the correlations compared to univariate

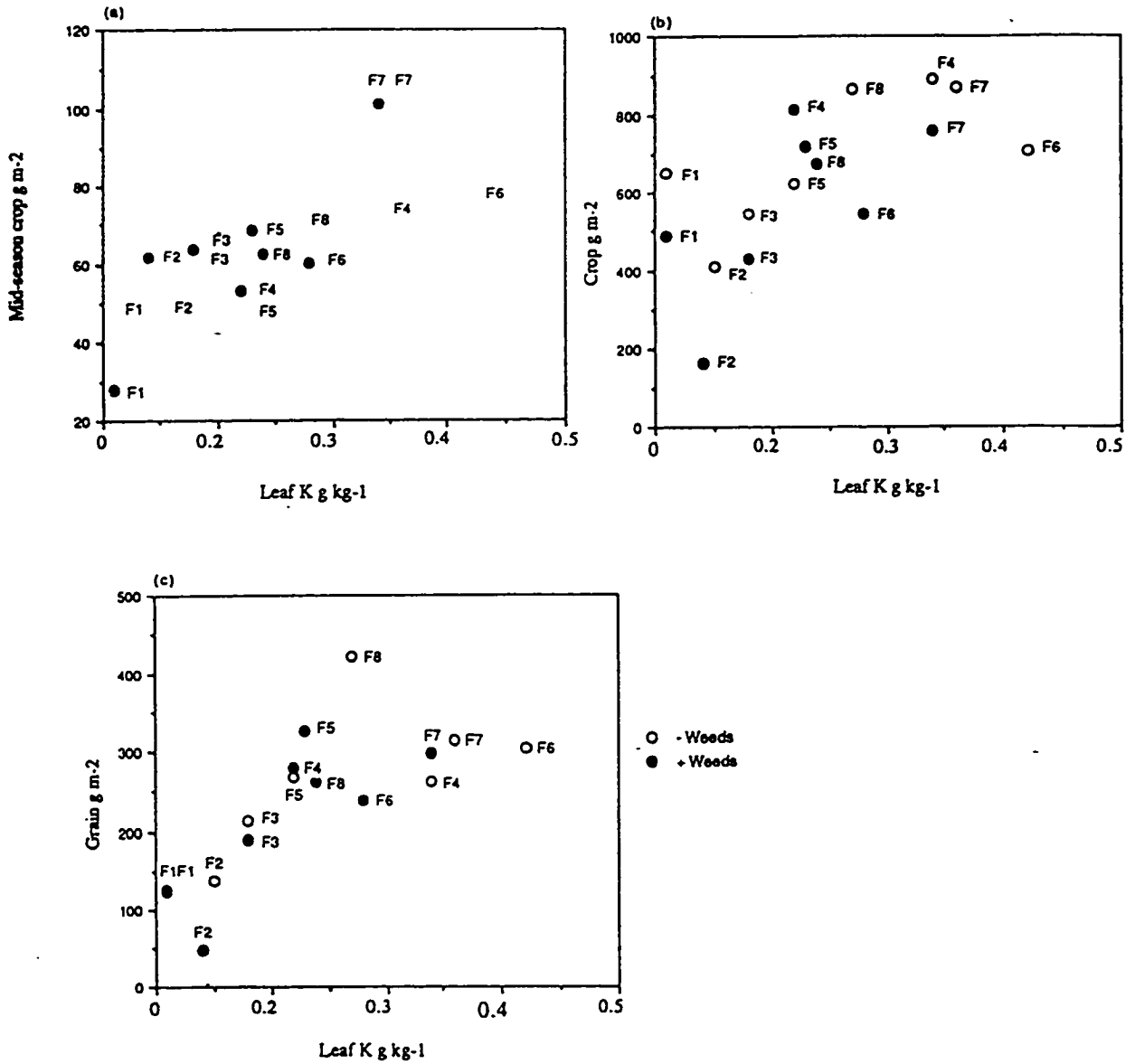

Figure 3.6. Relationships of mid-season yield (a), crop yield (b), and grain yield (c) with leaf K.

correlations, only for plus weed data, giving high R^2 values for grain yield as a function of leaf K and P, grain yield as a function of soil NO_3, SOM and BS%, and crop yield as a function of soil NO_3 and BS% (Table 3.12).

PCA also illustrated a close relationship of grain yield with leaf K in the plus weed plots (Figure 3.7). A PCA of grain yield and soil variables that correlated significantly with yield variables individually (Table 3.12) shows grain yield more closely related to soil P than to other variables, but also closely related to NO_3 and K (Figure 3.8).

Multivariate correlations of yield on leaf nutrients or soil variables using the first 3 factor scores for nutrients from each farm (from PCA) as predictor variables (Iezzoni and Pritts, 1991) did not give better or more significant correlations than the univariate correlations.

3.4.4. Relationships of leaf nutrients with soil nutrients

Correlations between leaf and soil nutrients were examined to determine to what extent the leaf values are predicted by the corresponding soil values for individual nutrients. There were significant correlations between leaf N and soil N in the minus weed plots ($R^2 = 0.764$), for leaf K and soil K in the plus weed plots ($R^2 = 0.652$), and for leaf Ca and soil Ca in the minus weed plots ($R^2 = 0.631$; Table 3.12).

For micronutrients, there were significant positive correlations for leaf Mn with soil Mn in both the minus and the plus weed plots, and for leaf Cu with soil Cu in the plus weed plots (there was a similar trend for leaf Cu with soil Cu in the minus weed plots) (Appendix Table 12).

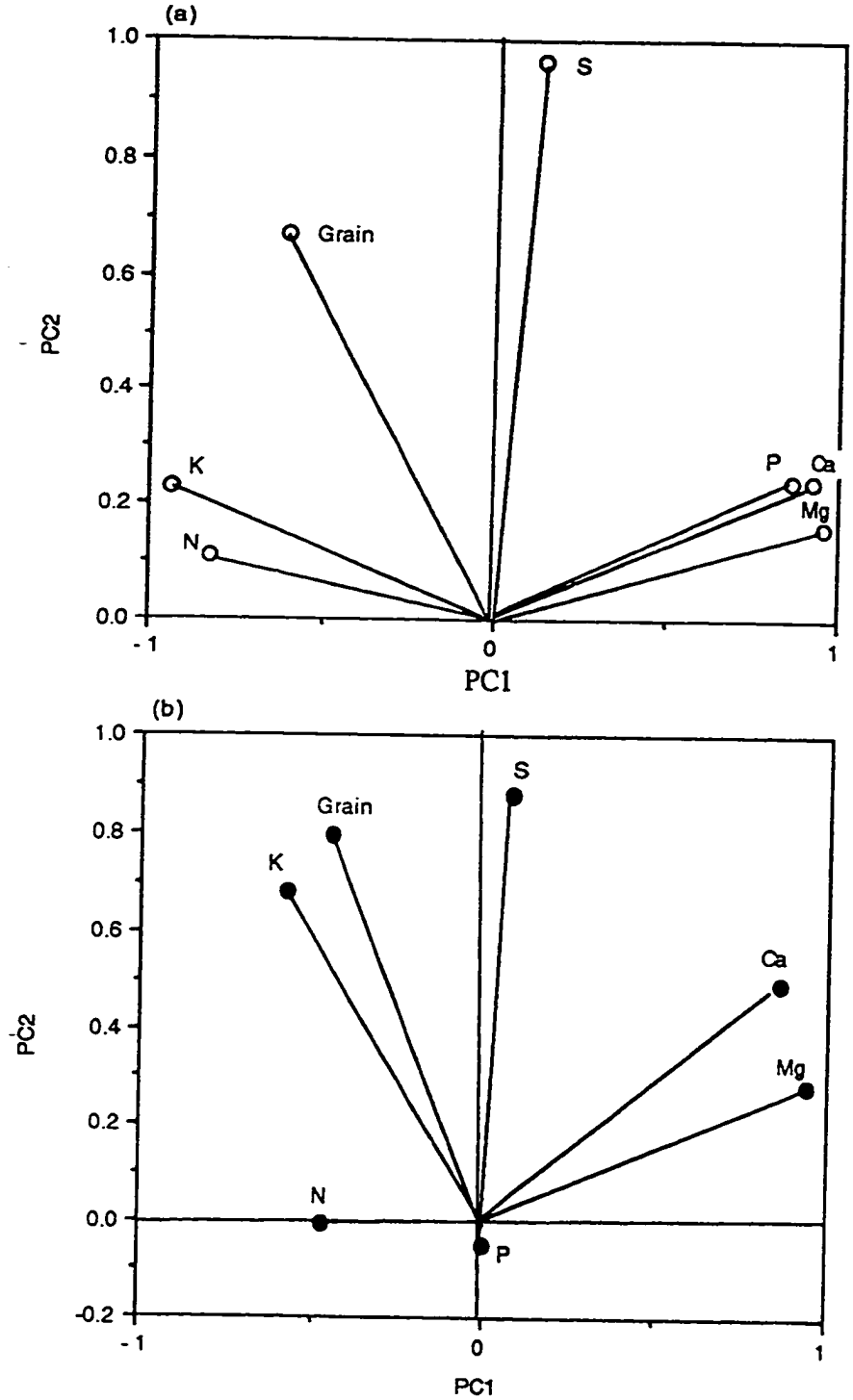

Figure 3.7. Plot of PC1 and PC2 loadings of leaf nutrients and grain yield for the minus weed (a) and the plus weed (b) plots.

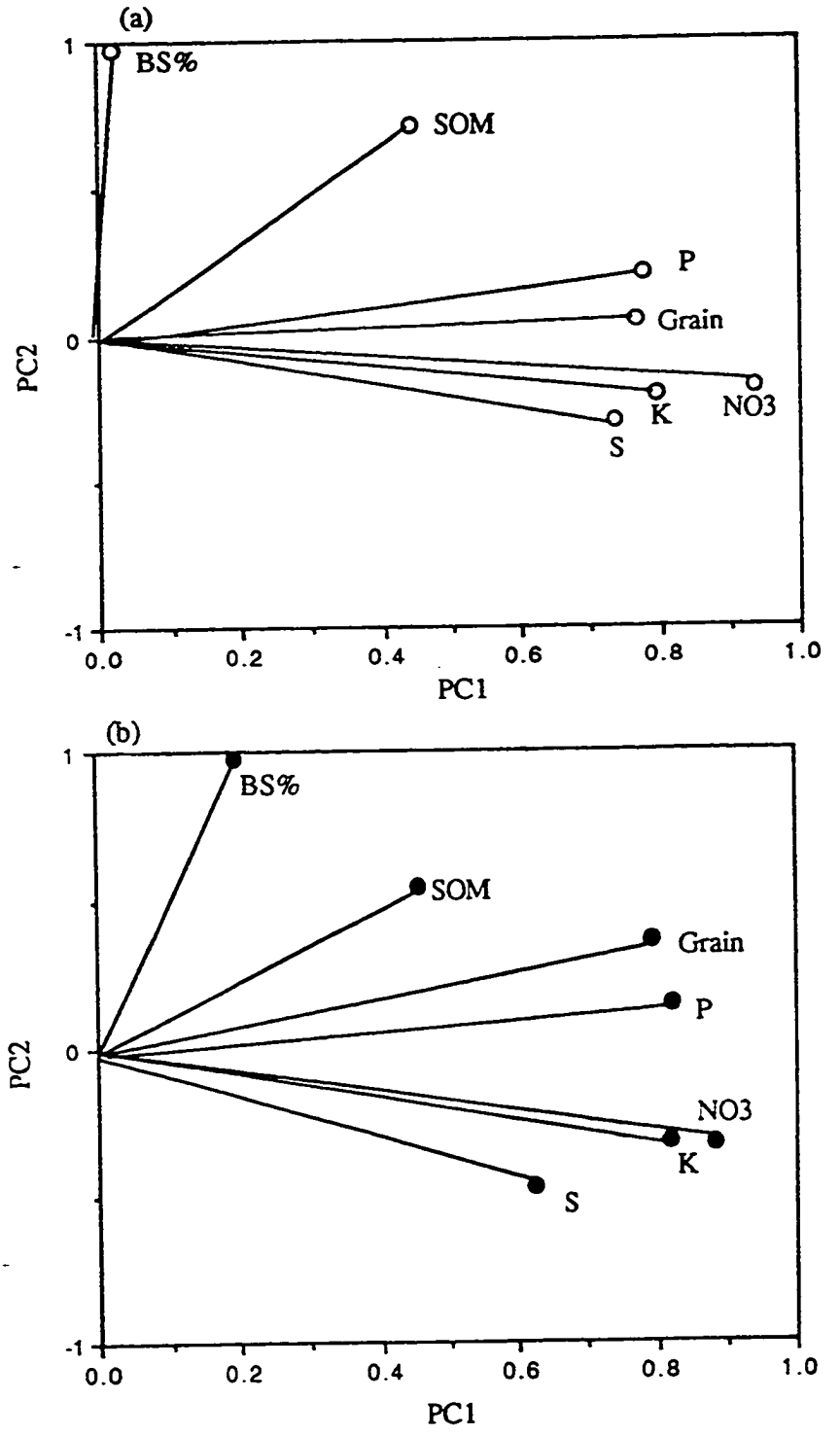

Figure 3.8. Plot of PC1 and PC2 loadings of soil nutrients and grain yield for the minus weed (a) and for the plus weed (b) plots.

3.4.5. Relationships of yield variables and weed biomass with roots, mycorrhizae, and nodules

Significant positive correlations of yield variables with roots and symbionts were found for the plus weed plots, but not for the minus weed plots; in the former, the grain yield and the mid-season crop yield were significantly correlated with roots (Table 3.12), also mid-season crop yield was significantly correlated with mycorrhizal infection (Table 3.12).

Multiple regression substantially improved the prediction of the mid-season crop yield in the plus weed plot with both symbionts and roots selected as predictor variables (Table 3.12).

3.4.6. Relationships of roots and symbionts with leaf and soil nutrients

Significant positive correlations of leaf nutrients with roots and symbionts were found for leaf K with roots, mycorrhizae and nodules in the plus weed plots; the only other significant correlation was between leaf S and mycorrhizae in the minus weed plots (Table 3.12). Significant positive correlations were found for roots with soil NO_3^- in both the minus and the plus weed plots. A significant positive correlation of mycorrhizal infection and soil K was found in the plus weed plots (Table 3.12).

A negative relationship between mycorrhizae and leaf P might be expected (Braunberger et al., 1991). There is a suggestion of negative relationship ($r = -0.721$) in the plus weed plots (Appendix Table 9). A significant negative relationship between leaf P and weeds was observed in the plus weed plots (Appendix Table 6). Thus it could be postulated that in the plus weed plots, weeds encourage mycorrhizae by reducing levels of soil P. However, when the difference in mycorrhizal infection between the plus and the minus weed plots is plotted against the difference between leaf P in the minus and the plus weed plots, this plot did not exhibit, as would be expected, a significant positive relationship between the two different variables, nor was there any evidence of a trend for

such a relationship (Figure 3.9). On only three of the farms was the relationship that which might be expected, i.e., with higher mycorrhizal infection and lower leaf P in the plus weed plots than in the minus weed plots. They were Farms 2, 3, 7. Farm 7 had the highest weed biomass of all farms, which might be significant, but there is no way to assess that from this data set, and there is no simple overall relationship between weeds, mycorrhizae and leaf P, nor was there a negative relationship of mycorrhizal infection with soil P ($r = 0.59$ in the minus weed plots and $r = 0.196$ in the plus weed plots; Appendix Table 11).

There were not, as might be anticipated, significant negative relationships of nodule weight with soil NO_3^- ($r = -0.048$ in the minus weed plots and $r = 0.674$ in the plus weed plots; Appendix Table 11).

3.5. Comparisons of crop yield variables between the minus and the plus weed plots

Crop variables were measured in plots with weeds at levels occurring in the field at large (plots not manually weeded) and in plots in which weeds were manually removed until canopy closure. Thus I was able to examine the effects of weeds (at levels maintained by farmers) on crop yield by experiment as well as by correlation.

For individual farms, differences in crop yield between the minus and the plus weed plots were significant for mid-season crop yield on Farm 1 and Farm 6 ($\alpha = 0.05$); there was a trend ($\alpha = 0.1$) for a difference on Farm 4; for crop yield, differences were significant on Farm 3 while there was a trend of difference for Farm 6; there were no differences at $\alpha = 0.05$ for grain yield, but there was a trend on Farm 8 (Appendix Table 4). For all farms considered together, there were significant differences between the minus and the plus weed treatments for the crop yield, but not for the mid-season crop yield (Table 3.3). The difference between grain yields was significant at $\alpha = 0.1$. The average grain and crop yields in the plus weed plots were 86% and 83%, respectively, of

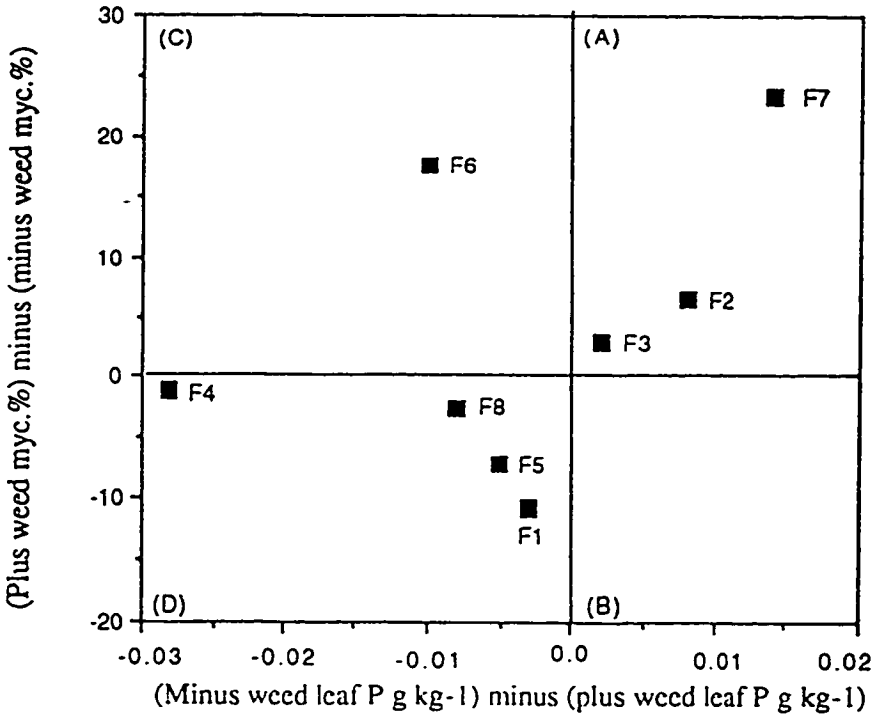

Figure 3.9. Plot of difference in mycorrhizal infection between the minus and the plus weed plots versus difference in leaf P between the minus and the plus weed plots. Sector A includes farms where mycorrhizal infection was higher and leaf P was lower in the plus weed plots compared to the minus weed plots; Sector C includes farm where mycorrhizal infection was higher and leaf P was higher in the plus weed plots compared to the minus weed plots; Sector D includes farms where mycorrhizal infection was lower and leaf P was higher in the plus weed plots compared to the minus weed plots.

those in the minus weed plots; the average value for the mid-season crop yield in the plus weed plots was 93% of that in the minus weed plots (Table 3.3).

The average crop + weed yield was slightly higher in the plus weed plots (747 g m^{-2}) than in the minus weed plots (728 g m^{-2}). The highest weed biomass was recorded at Farm 7; the grain yield in the plus weed plots at that farm was 93% of that in the minus weed plots; while crop+weed yield in the plus weed plots was 1.49 times that in the minus weed plots (Appendix Table 4). The predominant weeds at Farm 7 were wormseed mustard and lambsquarter (Table 3.1).

If weeds have a large effect on yields, one would expect yields on different farms in minus weed to be poorly correlated with yields in plus weed plots. However, grain and crop yields in the minus weed plots were well correlated with those in the plus weed plots (Table 3.3).

The variation in yield variables between farms was not significantly greater in the presence of weeds than in their absence for most yield variables (excluding weeds), except for the symbionts (Table 3.3).

For the other variables (roots, symbionts, and leaf nutrients), composite samples were taken for each of the minus weed and the plus weed treatments on each farm, so statistical comparisons of the minus weed and the plus weed effects can be made only for all farms considered together. Paired t-tests were conducted to test the hypothesis that there were real differences in mean values between the minus and the plus weed treatments for all farms considered together. For the symbionts, there were no significant differences at $\alpha = 0.1$ or $\alpha = 0.05$. However, variances were greater in the presence of weeds. For the roots, the value of the root biomass in the minus weed plots was significantly higher than that in the plus weed plots ($p = 0.016$). For leaf nutrients, only leaf K in the minus weed plots was significantly higher than the value for the plus weed plots ($p = 0.05$). There were significant positive correlations for leaf K, Mg, Zn, and Mn

between the minus and the plus weed plots, but not for leaf N, P, S, Fe, and B. Correlations for leaf Ca and Cu between the minus and the plus weed plots were also high ($p < 0.1$) (Table 3.3).

3.6. Discussion

A major goal of this research was to determine to what extent variation in soil fertility factors contribute to the apparently large yield variation in fababean. Such variation has been most commonly attributed to failure of pollination, sensitivity to heat and water stress, pest and disease problems (notably black bean aphids and chocolate spot) and genetic variation (Kambal, 1969; Sprent, 1977; Lawes, 1978; Salem, 1982; Austin et al., 1986; Picard et al., 1988).

Variation in soil fertility factors has not been cited as a major factor relating to fababean yield variation. I postulated five mechanisms by which variation in soil N, P, and K could affect yields. For four of these, low yields would result from an excess of N or P relative to crop needs and consequent deleterious effects on symbionts, or positive effects on weeds or pests; such excesses could result inadvertently from high residual levels of nutrients after heavily fertilized cereal crops. In the case of the fifth mechanism, it was proposed that a deficiency of K relative to N could cause low yields by stimulating pests and diseases. Fababean grown in conventional farming systems might be affected by the first four factors which might account for some of the high yield variability of fababean under modern farm conditions. Organic farming systems might be particularly prone to K deficiencies (Patriquin et al., 1986; Nolte and Werner, 1994).

In this study, I observed yields, leaf nutrients, roots and symbionts, and soil variables for fababean grown on eight farms at various stages in a transition to organic farming techniques. It was expected that there would be a wide range of soil nutrient conditions going from deficient to excess. The intention was to assess the significance of soil fertility factors under real farm conditions by determining the degree of correlation of

yield variables with leaf and/or soil nutrients, while correlations with symbionts, weeds and pests would give some indication of the mechanisms. Total crop yield was measured at mid-season, and at the silage stage; grain yield measured at the silage stage was shown to be a good indicator of final grain yield. Correlations can only suggest causal relationships. In complex systems where many variables are changing simultaneously, there may be confounding effects which make even simple interpretations of correlations problematic. Most of those logical difficulties can be overcome by experimental approaches in which all variables except a few test variables are controlled or vary minimally, however, often while this increases the logical power or "internal; validity", it usually results also in loss of realism or "external validity" (Phillips, 1988). Thus, complementing the observational, multifarm approach, which had a high degree of real world validity, were the experimental data obtained from the minus and the plus weed plots on each of the 8 farms, and as described in the next chapter, data from fertilizer addition experiments which were conducted on two of the farms.

It turned out that there was large variation in yield between the farms. Harvest yields estimated by multiplying August seed yields by 1.76 (Appendix Table 2) x 0.75 (a correction factor to applied to estimate combine yields from quadrat data: Patriquin et al., 1986) vary from 1650 to 5500 kg ha^{-1} in the minus weed plots, and from 625 to 4250 kg ha^{-1} in the plus weed plots. These may be compared to average yields for fababean in Europe of 1935 kg ha^{-1} in 1992 (Table 1.1), i.e., the variation under real farm conditions (represented by plus weed plots) was from poor to very good.

3.6.1. Possible effects of non-nutrient factors on yields

Variation in non-nutrient factors known to affect fababean yields could complicate attempts to explore yield/nutrient relationships. These were taken into account as much as possible in the initial design.

None of the farmers used pesticides or herbicides on the fababean crop, which was an important aspect of the design as some of postulated mechanisms involved pests or weeds and these effects would be masked by use of pesticides.

The farms were located on similar topographies (gently rolling land) within a 70 km radius. Thus I expected that macro-climatic factors would not contribute substantially to yield variability, although undoubtedly there were some differences in microclimatic factors.

Variation in grower competence could be another confounding factor. Although 6 of the 8 farmers had not grown the crop before, all had grown cereal grains routinely. Generally it is considered that farmers growing cereals can readily adapt to fababean (Presber, 1972), hence, variation in "grower competence" was not likely to be a complicating factor in the study.

Variation in time of planting could be a confounding factors. Fababean is a long season crop that tolerates early frosts and grows quickly under cool spring conditions; it is generally planted as early as possible, and the yield declines with late planting (Massey and McKnight, 1975; McVetty et al., 1986). The crops in this study were planted between May 2 and May 20. The highest yielding sites (Farms 7, 8) were seeded at the same time, May 17-20 as the lowest yielding sites (Farms 1, 2) indicating variation in planting time was not a significant factor in yield variation between farms.

A factor not controlled for was differences in cultivars. At least 3 different cultivars were used (Table 3.1). To the extent these or other factors not related to nutrients affected yields, correlations of yield with nutrient variables would be lowered.

3.6.2. Effects of weeds

One of the postulated mechanisms involved effects of N on weeds. Variation in other factors that affect weed pressure such as size and nature of the seedbank or the efficacy of weed control could mask the operation of the hypothesized mechanisms by

which soil nutrients affect yields. It was anticipated that there would be some variation in the efficacy of weed control, as the farmers were in the process of reducing herbicide use and were still experimenting with non-chemical methods of control. To assess and control this factor, observations were made on the crop as managed by the farmer ("plus weeds" or "normal farm conditions"), and on plots in which weeds were manually weeded until canopy closure ("minus weeds").

Weed control practiced by the farmers was not intensive: it consisted mainly of ensuring there was a clean seedbed through mechanical means (Table 3.1). Six of the eight farmers (nos. 1-6) conducted no weed control after seeding. At Farm 7, one light harrowing was conducted after plants were up, and at Farm 8, the field was "blind harrowed" (harrowed after seeding but before emergence). None of the farmers used herbicides. My manual (experimental) control consisted of weeding until canopy closure. After canopy closure, it would have been difficult to remove weeds without damaging the crop. In any case, the "critical period" for weed control in fababean occurs before canopy closure (Hewson et al., 1973; Glascow et al., 1976), thus there should not have been any significant effects of weeds that emerged later on yields.

The variance in yields for the 8 farms in the plus weed plots was not significantly larger than that of the minus weed plots, suggesting that weeds were not a major factor in yield variation between the farms under normal farm conditions. This interpretation is supported further by the fact that the yield variables in the plus weed plots were highly correlated with those in the minus weed plots ($r = 0.749$ for grain yield; $r = 0.882$ for crop yield; $r = 0.705$ for mid-season crop), and there were no significant correlations of the yield variables with weed biomass in the plus weed plots.

There could have been confounding factors that make interpretations of correlations or lack of correlations between crop yield and weeds difficult. However, the experimental data from the minus and the plus weed plots supports the general

conclusions based on correlations. On only one or two farms were there significant negative effects or trends for effects of weeds on mid-season, crop and grain yield. For all farms considered together, mid-season crop yield, crop yield, and grain yield in the plus weed plots averaged 93%, 83%, and 86% of yields in the minus weed plots respectively. The reductions in yields due to weeds within individual farms were not large compared to the variation in yield between farms which where high even in the absence weeds. Thus, I conclude that, overall, the large variation in yield between farms was not attributable to weeds.

3.6.3. The initial hypotheses as explanations for yield variation

Below, the results are considered in relation to the 5 proposed mechanisms by which it was postulated that soil fertility factors might contribute to yield variation.

(i) Nitrogen and nodulation

It was hypothesized that excess N could reduce yields by reducing nodulation, without providing enough combined N to compensate for loss in N_2 fixation. If such a mechanism contributed significantly to yield variation in this study, I would expect yield to be positively correlated with nodulation, and yield and nodulation to be negatively correlated with soil N. The data are not consistent with this prediction, the only significant correlations being positive correlations of yields with soil N.

Soil was sampled on June 13 -15, which was 26 to 41 days after planting (May 2 -20), well before canopy closure and at a time before there would have been intensive uptake of soil N. The *in situ* nitrate-N values were in the range 6.7-11.3 $\mu g\ NO_3\text{-}N\ g\ soil^{-1}$. Additional nitrate released by one week incubation of the soil varied from 7.6 to 19.1 $\mu g\ NO_3\text{-}N\ g\ soil^{-1}$, suggesting there was significant variation in soil N supply between the farms. According to Streeter (1988), legume nodule development and activity are suppressed when nitrate goes above about 2 mM, which corresponds to 5.6 $\mu g\ N\ g\ soil^{-1}$ assuming 20% moisture. Thus the *in situ* values - which were possibly

higher earlier in the season - may have been sufficient to cause some suppression of nodulation. Nodule weights varied by almost 4-fold; the higher values are close to highest values reported in the literature (Appendix Table 14). Thus it appears that there was considerable variation in the amount of N supplied by N_2 fixation on the different farms. Nevertheless, leaf N was in the adequate to excess range on all farms. Hence it appears that yield was not correlated with nodule weight because where nodulation was suppressed by N, the supply of soil N was adequate to make up the difference.

Comparisons of soil N supply estimated for the PEI farms by multiplying one week incubation values by 4, which should be conservative, with estimated total N accumulation in crop+weeds in minus weed plots suggest that soil N should have been sufficient to supply 42 to 68% of fababean N in the minus weed plots (Appendix Table 13). Those numbers lie within in a range (15 to 85% of total N derived from soil) indicated by other studies (Patriquin et al., 1986; Chalifour and Nelson, 1987; Hardarson et al., 1991). Thus it appears that these soils were not unusually deficient or excessive in regard to soil N supply for fababean.

Several studies have concluded that fababean yield is relatively insensitive to combined N. N fertilization reduces nodulation (McEwen, 1970; Table 32), and percent N derived from N_2 fixation (Hardarson et al., 1991; Chalifour and Nelson, 1987; Table 32), but has little effect on yield (McEwen, 1970; Chalifour and Nelson, 1987; Hardarson et al., 1991); at low N, N_2 fixation appears to be sufficient to provide all N. Only exceptionally high N application (560 kg N ha^{-1}) has been found to increase yields (Sorwli and Mytton, 1986).

Overall, my results support the generalization that yield of fababean in PEI is relatively insensitive to combined N, and there is no evidence to support the hypothesis that variation in yield would be related to effects of soil N on nodulation.

(ii) and (iii) Nitrogen, weeds, and pests

For the plus weed plots, there is no correlation between yield and weeds (discussed above), or between soil N and weeds, suggesting that overall, N-weed-crop interactions did not contribute significantly to yield variation between the farms. There were few pests except on Farm 2, so it appears that, overall, N - pest - crop interactions did not contribute significantly to yield variation between the farms.

(iv) Phosphorus and mycorrhizal infection

It was hypothesized that excess P could reduce yields by suppressing mycorrhizal infection and its related benefits. Soil P values (Mehlich 3 extraction) varied between the farms from 54 to 106 mg kg^{-1}; all values were ranked "Very High". Leaf P values were all well above the critical value (0.015 g kg^{-1}), and higher than the maximum normal value (0.05 g kg^{-1}) for all farms except Farm 6 and Farm 7 in both the minus and the plus weed plots and Farm 4 in the minus weed plots. Thus, the ratings for soil P and leaf P rating agree in a general way to indicate that the P supply was adequate to excessive and therefore suppressive effects might be expected.

Overall the results were not consistent with the predictions that mycorrhizal infection and yield would be positively correlated and each would be negatively correlated with leaf P. There was a significant negative correlation of weed biomass with leaf P and a suggestive negative correlation ($r = -0.721$) of leaf P with mycorrhizal infection in the plus weed plots. These data suggested that under actual farm conditions (represented by plus weed plots), weed growth reduces the supply of P to the crop, resulting in turn in increased infection by mycorrhizae; that would be consistent with the prediction that high soil P is suppressing mycorrhizal infection on these farms. However, in this case, comparison of data from plus and minus weed plots allowed an experimental test of this explanation for the correlations, and the test results did not support that explanation. The only other significant correlations involving P are positive correlations for crop yield and soil P, which are clearly not consistent with the "P hypothesis".

(v) Potassium /nitrogen and diseases and pests

It was postulated that K/N imbalances could result in reduced yields via effects on N metabolism and susceptibility to pests. As these are sandy soils subject to leaching, it was considered possible that K would be deficient on some soils, also K inputs on organic farms are sometimes limited (Patriquin et al., 1986; MacRae et al., 1990; Nolte and Werner, 1994). Varying levels of K might also affect yield by direct effects on plant metabolism, or in a legume, through effects on nodules (Mengel et al., 1974; Premaratne and Oertli, 1994).

Soil K values varied from 57 to 174 mg kg^{-1} and were ranked from very low to high. Leaf K values varied from below the critical level to above the maximum normal level. There was a significant correlation of soil K with leaf K in the plus weed plots ($r = 0.791$); in minus weed plots ($r = 0.615$). As could be expected given this range of leaf values, there were significant correlations of yield with soil K and leaf K.

There were few pest and disease problems on most farms; thus overall, K effects could not have been due to effects on pests. Farm 2 which was the only farm with heavy chocolate spot, had the second lowest leaf K value and the 2nd lowest ratio of leaf K to leaf N (Appendix Table 5). In addition, this site was the lowest lying and flattest of all, was perceived to be more moist than other sites, and had heaviest soil (loam vs sandy loam of all other farms). Thus it is possible that low K in combination with the higher moisture was a factor in the heavy chocolate spot on Farm 2.

3.6.4. Yield variation related to nutrients, other than by the initially hypothesized mechanisms

The high variation in yield between sites in this study is strongly correlated with leaf and soil nutrient factors, particularly K. All of the significant univariate correlations with leaf nutrients are with K, and were found for both minus and plus weed plots; these values suggest that 61 to 65% of the variation in mid-season yield is associated with

difference in leaf K in both minus and plus weed plots, and similar figures were observed for soil K. For crop and grain yields, only grain yield in the plus weed plots showed a significant correlation with leaf K ($r = 0.777$; Table 3.12); all r values for yield variables with leaf K in minus and plus weed plots were above 0.645 (Appendix Table 6). Evidence that this is a causal relationship is given by the absolute leaf K values; K was the only nutrient for which there were values below critical levels (as assessed for dry bean and soybean). K fertilization at Farms 7 and 8 produced a marginally positive result at Farm 8, but not at Farm 7 which had very high leaf K (next chapter). Overall, leaf K values but not values for other nutrients were significantly lower in the plus weed plots than in the minus weed plots (0.218 g kg^{-1} in plus weed plots versus 0.256 g kg^{-1} in minus weed plots), which might account for some of the negative effects of weeds that were observed.

Of the leaf nutrients, K was the only one showing significant correlations with yields. For soil nutrients, significant correlations of yield variables with soil nutrients were observed also with soil N, P and S. Given the close covariation of N, K, and S revealed by PCA, it seems probable that the relationships of yields with soil N and S are correlative rather than a reflection of real limiting factor, which is probably K. The crop yield in both the minus and the plus weed plots was positively correlated with soil P, and the regression of grain yield in the plus weed plots on leaf nutrients was significantly better with leaf K and P as independent variables than with K alone. However, there is no evidence from leaf data to indicate P was actually limiting, nor did P fertilization produce responses or suggestions of responses (next chapter). Hence a role for P in yield variation on the PEI farms is suggested by the correlations, but remains unexplained and was not confirmed by experiment (next chapter).

There are a number of possible mechanisms by which K could affect yield, other than by effects on pests and diseases. K has a number of roles in plant metabolism,

notably activation of more than 60 enzymes, stimulation of transport, neutralization of acids, nitrogen uptake and protein metabolism, starch synthesis and in turgor regulation and movement of stomata (Tisdale et al., 1985). In legumes, K has been reported to increase leaf area and photosynthetic efficiency, and to increase root growth and nodulation (Duke and Collins, 1985). K is well known to have important effects on drought tolerance at the whole plant level. Studies of Johnson and Wallingford (1983) for example illustrated that soybean yields were much less reduced by drought when soil K was high that when it was low. Fababean has an exceptionally high growth potential, exhibiting amongst the largest values for conversion of solar energy amongst C3 crops (Fasheun and Dennett, 1982), thus its absolute water requirement is high, which is reflected in its high susceptibility to drought stress (Sprent, 1972; Gallacher and Sprent, 1978; Husain et al., 1990). Thus it could be expected to have an exceptionally high requirement for K; this could be particularly critical on the sandy soils of PEI. The plots of grain yield versus leaf K (Figure 3.6; 3.10) suggest that fababean responded to K at leaf tissue K levels above those cited for dry bean and soybean for which the critical level is 0.12 g kg^{-1}; for fababean there appeared to be a positive response up to about 0.25 g kg^{-1} (Figure 3.10).

Nodulation is known to be affected by K status, but the effect is believed to be indirect and by effects on photosynthesis, rather than directly on nodules (Duke and Collins, 1985). Roots, nodules, and mycorrhizae all exhibited significant positive relationships with leaf K in the plus weed plots. It seems likely that this reflected overall greater photosynthesis, and higher supply of carbon substrates to roots at higher levels of K. Yields were correlated with roots, but not with nodules in the plus weed plots, and there were no significant correlations of yield with roots or symbionts in the minus weed plots. Thus effects of K on root growth appear to have been more critical in the presence of weeds than in the absence, possibly by affecting competition with weeds.

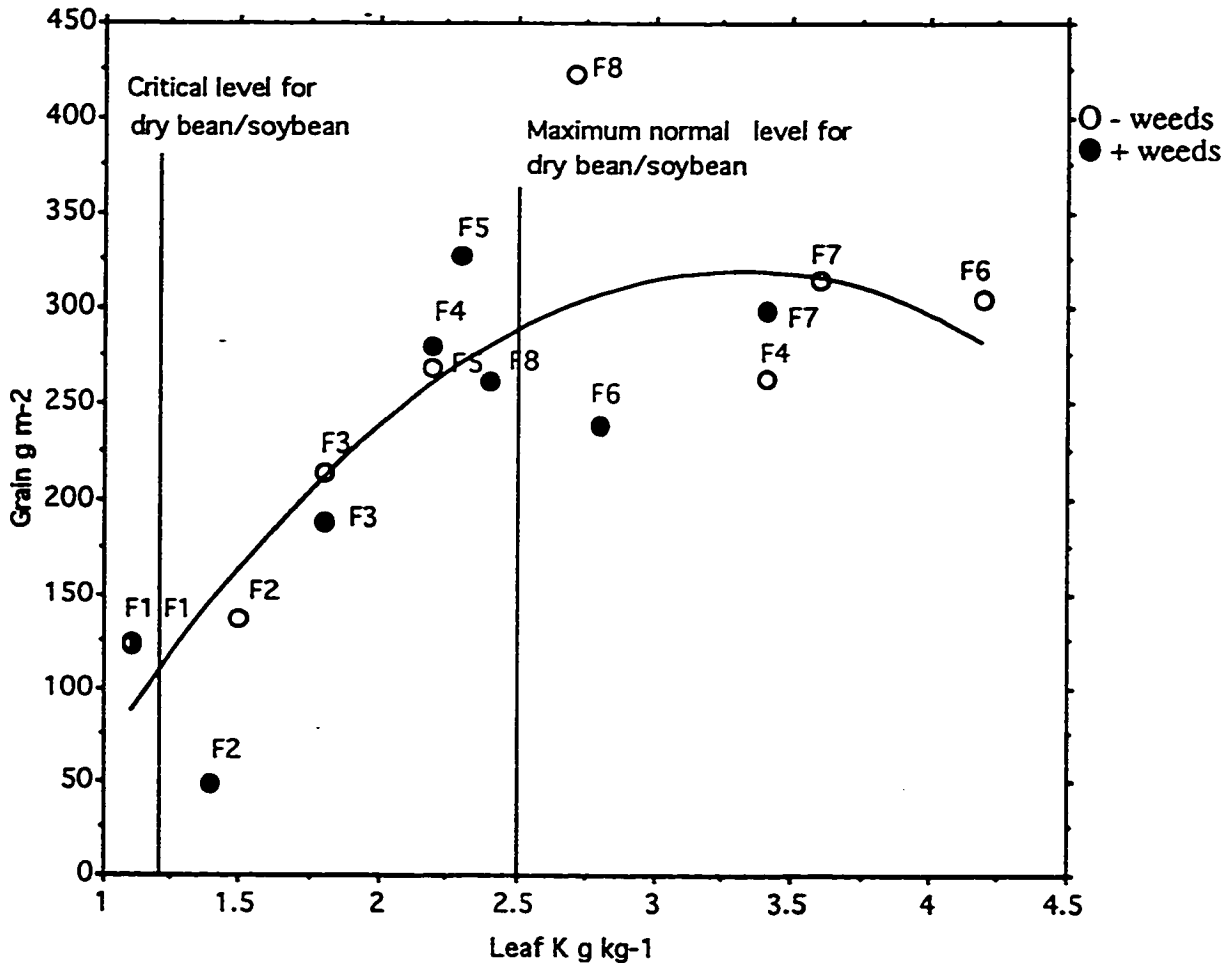

Figure 3.10. Relationship of grain yield to leaf K, with critical level and maximum normal level for dry bean and soybean indicated.
The curve is that of a 2nd order polynormial (see page 60) fitted to both minus and plus weed data.

Stepwise regression improved relationships of yield with soil nutrients for the plus weed plots, but not for the minus weed plots; perhaps in the presence of weeds, more variables affect yield. The relationships to the variables selected are sensible, i.e., positive relationships to nitrate (which could reflect a causal relationship to K), and of residuals from the regressions on nitrate showing positive relationships to SOM and/or BS%. R^2 values for the stepwise regressions of yield variables on soil variables were in the range of 0.994 to 0.956, suggesting that the soil variables accounted for most of the variation in yields in PEI under real farm conditions in 1989.

Significant effects of K addition on fababean yields have been reported in the literature (Boyd et al., 1952; Moffatt, 1960; Mahler et al., 1988); however, this appears to be the first study to document K as a major factor in the large variations in fababean yield between farms under real farm conditions.

Farms 1, 2, and 3 had lower soil K than the other farms (Table 3.9) and leaf K values were low or below critical levels (Table 3.5 and Appendix Table 5). Each of these farm fields but none of the others had been in sod (hay) in previous years (Table 3.1). It is well known that hay crops remove a lot of soil K (Wild, 1988; Plamondon et al., 1991). Thus it seems likely that this was a factor in the low K status, and low yields of fababean following hay.

There was some suggestion of suppression of yield at the highest leaf K value, as indicated by the better fit of a quadratic regression than of a linear regression for the grain yield - leaf K data. This is possibly associated with suppression of Ca and Mg uptake at high K. Even the lowest values of leaf Mg were above the critical level for Mg (inferred data from soybean). However the lowest value for Ca was close to the critical value (inferred from soybean).

There were significant negative relationships of K with Ca and Mg. High K is well known to suppress uptake of Ca (DeKock, 1964) and Mg (Mengel and Kirkby,

1980). High K has also been reported to suppress uptake of some micronutrients (Daliparthy et al., 1994). A significant negative relationship of leaf K with leaf Mn was observed. Also, overall, micronutrients were lower in the minus weed plots that in the plus weed plots, which might be attributable to weed uptake of K. However, none of the micronutrients were assessed as limiting based on leaf data.

4. Results II. Effects of added fertilizers on fababean yields

Results from the 8-farm experiments provide important information on factors that might influence fababean yields, but they do not on their own provide conclusive evidence for causal relationships. To test the hypothesis that variation in N, P, K status of soils, and in particular, high levels of N and P can have pronounced effects on yields through their effects on susceptibility of the crop to insect pests and diseases, on the establishment and functioning of rhizobial and mycorrhizal symbioses with fababean, and on weed-crop interaction, N, P, K fertilizer addition experiments were conducted. Two experiments were conducted in 1989 on two of the farms in PEI at the same time that the 8-farm study was conducted. The farms were chosen to represent a farm with a history of organic management (PEI F8), and one which up until 1989, had been managed conventionally although not intensively (PEI F7). It turned out that they were also the farms with the highest fababean grain yields, but this was not anticipated. Similar experiments, but with the addition of a Ca fertilizer, were conducted at 2 farms in Nova Scotia in 1990 to provide data from a wider range of conditions. Ca was added because the results of the 8 farm study suggested that Ca might be close to limiting at some sites.

In 1991, an experiment was conducted in large concrete cylinders containing high fertility and low fertility soils which allowed me to test the interactive effects of background fertility and additional fertilizer (N, P, K, and Ca) on fababean yields, symbionts and nutrient status. Rock-P was added as an additional fertilizer treatment in this experiment because the low fertility soil was known to be deficient in P, and this allowed me to test efficacy of rock-P as a fertilizer for fababean. Organic farmers utilize rock-P to provide net inputs of P to farms (Lampkin, 1990), sometimes adding it to barn gutters to absorb odor and activate the P (Brian Turner, PEI farmer personal communication; Lampkin 1990) or to manure piles or during composting to activate the P

(Mishra and Bangar, 1986). I wished to test whether adding rock-P to fababean might be another means to mobilize some of the rock-P. Legumes acidify the rhizosphere when fixing N_2, which can increase the release of P from rock-P (Aguilar and van Diest, 1981).

Weeds in the experiments were controlled manually until canopy closure. The interaction between fertilizers (N, P, K and Ca) and weeds on fababean yields was examined at Farm NS1 by including minus weed and plus weed subplots.

Details of experiment design and site conditions are given in Table 2.1. The rates of application were increased at the Nova Scotia farms and in the cylinder systems compared to the PEI sites as the former were more finely textured soils and would be expected to have higher nutrient-holding capacities.

For the purposes of distinguishing different soil fertility regions, the LF and HF cylinder systems are referred to below as different sites. The "NS1 site" refers to the manually weeded plots. Comparison of weeded and not weeded plots at this site is conducted separately from data for other sites.

4.1. Comparisons of the measured variables in control plots between sites.

The effects of adding fertilizers on fababean yield variables can be expected to vary according to the background conditions of the sites. Soil organic matter values were in the range characteristic of "good crop land" (2.5 to 4.0%; Koepf et al., 1976) and above the minimum value (3%) suggested for structural stability in English soils (Greenland et al., 1975) except at the LF cyl. site where it was 1.8% (Table 4.1). Soil NO_3^- measured in the early season stage (Table 4.1) was correlated with soil organic matter ($r = 0.82$, $p = 0.046$). Values of soil NO_3^-, P, K, Ca, and Mg varied between the sites by factors of 5.0-, 15.0-, 3.9-, 2.2-, and 2.9-fold respectively. The LF cyl. site had the lowest values for each of these nutrients (Table 4.1).

Table 4.1. Soil analysis data for control plots before application of fertilizers.

Site[a]	SOM	pH	NO_3^-	P	K	Ca	Mg	CEC	BS	Clay	Sand	Silt
	%		----------mg kg^{-1}----------					meq/ 100g	%	%	%	%
PEI F7	3.9	6.0	20	73 (VH)[b]	44 (VL)	1082 (H)	98 (M)	8.7	72.5	11.0	56.0	33.0
PEI F8	3.9	5.5	25	130 (VH)	115 (M)	747 (H)	86 (L)	9.6	50.2	6.5	73.5	20.0
NS 1	3.5	6.4	20	228 (VH)	155 (H)	1187 (H)	221 (H)	11	76.6	15.0	71.1	13.9
NS 2	3.1	6.2	10	47 (M)	68 (L)	893 (H)	159 (H)	6.0	100	12.0	73.0	15.0
HFcyl.	3.1	6.5	5	75 (VH)	60 (VL)	1246 (H)	125 (H)	9.5	78.0	16.0	72.4	11.6
LFcyl.	1.8	6.3	5	15 (VL)	40 (VL)	569 (M)	75 (M)	4.8	74.9	16.0	72.4	11.6

[a] SOM:soil organic matter, CEC:cation exchange capacity, BS:base saturation, HFcyl and LFcyl.: high fertility cylinder and low fertility cylinders.

[b] Commercial lab's rating: H:high, VH:very high, L:low, VL:very low, M:medium.

Grain+pod yield varied from 48.8 to 376 g m^{-2}, crop yield (grain+pod + stems + leaves) from 112 to 680 g m^{-2}, nodule weight from 0.25 to 1.92 g $plant^{-1}$, and mycorrhizal infection from 17.8 to 52.5% (Table 4.2). Values of leaf nutrients in the control plots (Table 4.3) were within the adequate to maximum normal ranges for the reference legume crops (Table 3.5) except for

Leaf N at the LF cyl. site (< critical value)
Leaf K at the LF cyl. site (< critical value)
Leaf K at the HF cyl. site (< critical value)
Leaf K at the PEI F7 site (>maximum normal value)
Leaf P at the PEI F8 site (>maximum normal value)

Between control plots in the different experiments, there were no significant correlations between mycorrhizal infection and nodule weight ($r = -0.472, p = 0.285$), between the symbionts and crop variables ($r < 0.501, p > 0.312$), between nodule weight and soil nitrate ($r = 0.605, p = 0.203$) or between mycorrhizal infection and soil P ($r = -0.458, p = 0.361$) or leaf P ($r = 0.131, p = 0.804$).

Plants in the HF cyl. site had the highest mycorrhizal infection (Table 4.2) at a comparatively low soil P value (Table 4.1), however the NS2 site had relatively low mycorrhizal infection (Table 4.2) at a lower soil P value (Table 4.1). Soil Ca levels affect P concentration in the soil solution, P varying inversely with Ca (Russell, 1973); thus it was suspected that different levels of Ca between sites might explain some of the deviation from the inverse relationship between mycorrhizal infection and soil P. Leaf nutrient levels might be expected to give a better indication of availability of nutrients than the soil data. Leaf Ca in the control plots was lowest at the NS2 site and highest at the HF cyl. site (Table 4.3). For soil Ca, the NS2 site ranked third lowest and the HF cyl. was highest (Table 4.1). In other studies, there was evidence that forage legume production at the NS2 site was Ca limited (Patriquin et al., 1993b). There was a strong positive correlation ($r = 0.94, p$

Table 4.2. Fababean yields, mid-season crop, roots, mycorrhizae, nodules, and C_2H_2 reduction in control plots at different sites.

Site	Grain + pods	Crop	Mid-crop	Roots	Myc.	Nodules	AR[a] per plant (AR per g nodule)
	----------g m^{-2}----------				%	g $plant^{-1}$	
PEI F7	376	680	458	394	44.7	1.18	39.3 (34.7)
PEI F8	245	489	278	163	34.9	1.03	22.5 (22.1)
NS 1	212	284	205	120	17.8	1.92	
NS 2	65.6	408	234	57.0	17.9	1.04	
HFcyl.	144	265	138	72.7	52.5	0.95	
LFcyl.	48.8	112	70.5	53.6	40.4	0.25	

[a] Acetylene reduction.

Table 4.3. Leaf nutrients in control plots at different sites.

Site	N	P	K	Ca	Mg	N:P	Ca:P	K:N
	----------g kg^{-1}----------					----------ratios----------		
PEI F7	.560	.042	.343	.138	.041	13.3	3.3	0.61
PEI F8	.50	.059	.260	.140	.046	9.0	2.4	0.52
NS 1	.478	.045	.222	.085	.041	10.6	2.0	0.46
NS 2	.482	.030	.234	.062	.033	15.9	2.1	0.49
HFcyl.	.438	.042	.071	.161	.069	10.4	3.8	0.16
LFcyl.	.366	.032	.069	.099	.045	11.4	3.1	0.18

< 0.01) between mycorrhizal infection and leaf Ca:P (Figure 4.1). This suggests that high soil Ca in the HF cyl. and at PEI F7 made soil P less available, stimulating mycorrhizal infection compared to other sites.

4.2. Effects of fertilizers

Results of the different experiments are summarized in Tables 4.4 to Table 4.8 except for the comparisons with rock-P in the cylinder system and the comparisons between minus and plus weed plots at the NS1 site which are described separately. In these tables the values of different variables are expressed as percentages of the control values at each site. The control values are given in Table 4.2 and Table 4.3. The details of ANOVAS for each site are given in Appendix Tables 15-44. Effects of each nutrient are highlighted below.

Nitrogen N fertilizer was applied at higher levels (100-152 kg ha^{-1}: Table 2.1) than typically applied in "starter fertilizer" applications (20-80 N kg ha^{-1}: Boyd et al., 1952; Richards and Soper, 1982), but not at levels that would be sufficient to supply all N (>300 kg ha^{-1}: Richard and Soper, 1982). Thus negative effects of N fertilizer on fababean yields were anticipated.

Leaf N values in control plots at all sites were in the adequate range except for that at the LF cyl. site where it was below the critical level (Table 4.3: Table 3.5).

The LF cyl. site was also the only site where leaf N was significantly increased by N fertilizer (Table 4.4).

Root weights did not respond significantly to N fertilizer at any site (Table 4.5)

Nodulation in N-fertilized plots was 40 to 74% of control values; the effects were statistically significant only at the two PEI sites (Table 4.6). Acetylene-reducing activity was measured at those two sites at mid-season when nitrogenase activity is near the maximum (Sprent et al., 1977). The activity expressed on a per gram basis (specific

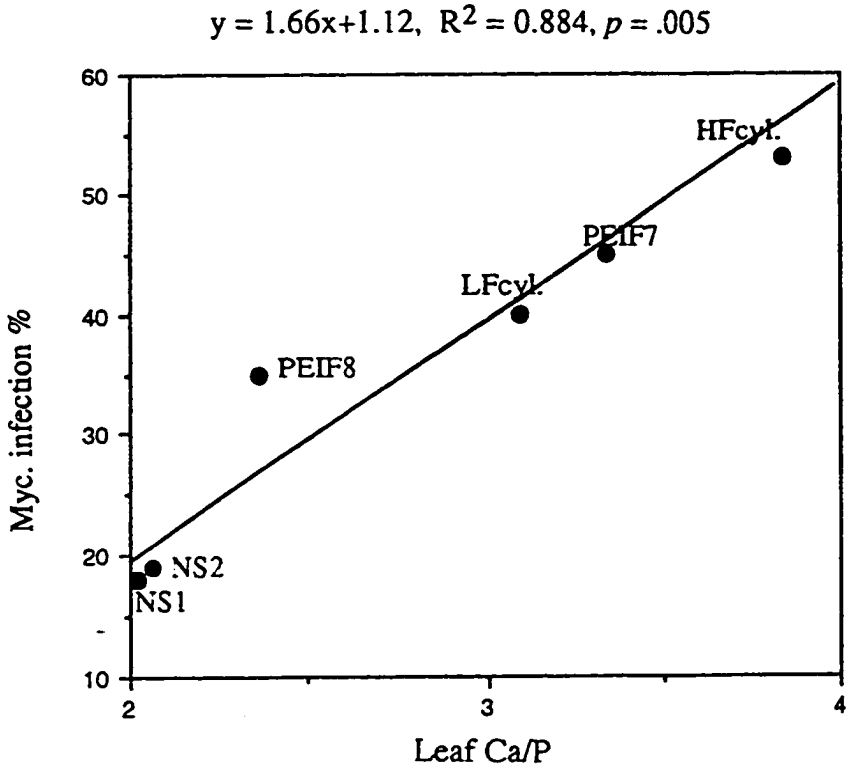

Figure 4.1 Relationship of mycorrhizal infection with leaf Ca and P ratio within control plots at the different experiment sites.

Table 4.4. Responses of leaf nutrients to fertilizers at different sites.

Site	Leaf N				Leaf P				Leaf K			
Fertilizer	N	P	K	Ca	N	P	K	Ca	N	P	K	Ca
	(Percent of values in control plots)				(Percent of values in control plots)				(Percent of values in control plots)			
PEI F7	101	101	105+[a]	---	105	98	105	---	97	99	99	---
PEI F8	98	108	106	---	90	95	86	---	96	89	92	---
NS 1	101	99	99	101	104	93	89	98	99	99	99	86*
NS 2	100	97	108	99	97	93	83*	103	99	94	112*	108
HFcyl.[b]	99	100	98	106	93	100	95	98	115	97	165**	119
LFcyl.	119**	117*	96	98	97	109**	100	97	138+	91	201**	93

Table 4.4. (concluded).

Site	Leaf Mg				Leaf Ca			
Fertilizer	N[a]	P	K	Ca	N	P	K	Ca
	(Percent values in control plots)				(Percent values in control plots)			
PEI F7	100	98	102	---	101	99	101	---
PEI F8	98	93	93	---	114	93	100	---
NS 1	110	98	97	100	113**	99	96	103
NS 2	109+	103	97	100	106	110	92	97
HFcyl.[b]	100	99	75*	99	91	83*	84*	94
LFcyl.	96	127*	87	89	127*	120+	126*	103

[a] +, *, **, significantly different from control value at $\alpha = 0.1, 0.05, 0.01$ respectively.

[b] Probability for interaction term (HF/LF cylinders x added fertilizer): $p = 0.012$, 0.705, 0.182, 0.008, 0.202 for leaf N, P, K, Ca, Mg respectively.

Table 4.5. Responses of roots, mycorrhizae to fertilizers at different sites.

Site	Roots				Myc.			
Fertilizer	N	P	K	Ca	N	P	K	Ca
	(Percent of values in control plots)							
PEI F7	86	104	95	-----	80	62*[a]	78	---
PEI F8	78	114	95	------	47**	45**	81	---
NS 1	91	157**	171**	127	43*	65+	90	66
NS 2	102	89	90	108	34**	58+	52*	89
HFcyl.[b]	115	111	102	105	49**	81	85	49**
LFcyl.	127	132+	141*	113	122	101	113	49+

[a] +, *, **, significantly different from control value at $\alpha = 0.1, 0.05, 0.01$ respectively.
[b] Probability for interaction term (HF/LF cylinders x added fertilizer): $p = 0.639, 0.053$ for roots and mycorrhizal infection respectively.

Table 4.6. Responses of nodules and acetylene reduction to fertilizers at different sites.

Site	Nodule fresh weight				AR[a] per plant (AR per g nodule)			
Fertilizer	N	P	K	Ca	N	P	K	Ca
	(Percent of values in control plots)				(Percent of values in control plots)			
PEI F7	48**[b]	87	84		36.6** (94.0)	83.9 (97.6)	60.8+ (75.4)	
PEI F8	54**	116	109		76.0 (144)	108 (107)	101 (88.6)	
NS 1	65	144	210**	151+				
NS 2	64	139	176*	146				
HFcyl.[c]	74	139+	136	128				
LFcyl.	40	196*	94	104				

[a] Acetylene reduction.

[b] +, *, **, significant different from control value at $\alpha = 0.1, 0.05, 0.01$ respectively.

[c] Probability for interaction term (HF/LF cylinders x added fertilizer): $p = 0.371$ for nodules.

Table 4.7. Responses of chocolate spot (*Botrytis fabae* Sard.) and plant bug (*Calocoris norvegicus* Fieber) to fertilizers at different sites.

Site	Chocolate spot				Plant bug			
Fertilizer	N	P	K	Ca	N	P	K	Ca
	(Percent of values in control plots)				(Percent of values in control plots)			
PEI F7	119	138	104	---	no	no	no	---
PEI F8	152	84	144	---	no	no	no	---
NS 1	103	153	113	130	no	no	no	no
NS 2	81	72	81	83	no	no	no	no
HFcyl.[a]	no[b]	no	no	no	209**[c]	101	72	130+
LFcyl.	no	no	no	no	111	167	166	110

a Probability for interaction term (HF/LF cylinders x added fertilizer): $p = 0.011$ for plant bug.

b Levels of chocolate spot in the sites were very low.

c +, **, significantly different from control value at $\alpha = 0.1, 0.01$ respectively.

Table 4.8. Responses of fababean yield variables to fertilizers at different sites.

Site	Grain+ pods				Crop				Mid-season crop			
Fertilizer	N	P	K	Ca	N	P	K	Ca	N	P	K	Ca
	(Percent of values in control plots)				(Percent of values in control plots)				(Percent of values in control plots)			
PEI F7	96	86	108	---	103	93	112	---	78+	96	86	---
PEI F8	79	85	115	---	84	101	132	---	80	115	114	---
NS1	112	149	184*[a]	115	130	173+	202*	132	101	107	107	98
NS2	117	83	124	172*	89	90	89	104	102	95	84	98
HF cyl.[b]	91	76	92	83	102	81	113	89	103	84	134+	90
LF cyl.	167	211*	176	118	137	177**	149+	112	108	158**	123+	105

[a] +, *, ** significantly different from control value at $\alpha = 0.1, 0.05, 0.01$ respectively.

[b] Probability for interaction term (HF/LF cylinders x added fertilizer): $p = 0.292, 0.083, 0.091$ for grain+pods, crop, and mid-season crop respectively.

nitrogenase activity) was not affected by N fertilizer, while the per plant values were significantly lowered by N fertilizer at PEI F7 (Table 4.6).

Mycorrhizal infection was lowered significantly by N fertilizer at 4 of the 6 sites.

There were no statistically significant responses of chocolate spot disease to N fertilizer. N fertilizer addition caused significant increases in numbers of *Calocoris norvegicus* at the HF cyl. site (Table 4.7).

There were no significant effects of N fertilizer on final yield variables (Table 4.8).

Phosphorus P fertilizer was applied at high rates (100-166 kg P_2O_5 ha^{-1}: Table 2.1). Initial soil P levels were already in the "Very High" category, except at the LF cyl. site and at NS2 for which soil P values were assessed to be "Very Low" and "Medium" respectively (Table 4.1).

Leaf P values in control plots at all sites (Table 4.3) were in the adequate range except at PEI Farm 8 where leaf P was assessed as excessive (Table 3.5).

Leaf P was significantly increased by P fertilizer at the LF cyl. site, but the increase was not large (9%: Table 4.4).

Root weights were increased significantly by P fertilizer at NS1, and there was a similar trend ($\alpha = 0.1$) at the LF cyl. site (Table 4.5).

Mycorrhizal infection was significantly reduced by P fertilizer at 2 of the 6 sites and there were trends for reductions at 2 other sites (Table 4.5). There was no effect in the LF cyl. site, for which soil P was in the Very Low category.

Nodulation was significantly increased by P fertilizer at the LF cyl. site; there was a trend for increase at the HF cyl. site (Table 4.6).

Pests and diseases did not respond significantly to P fertilizer (Table 4.7) .

There were significant effects of P fertilizer on all yield variables at the LF cyl. site, and a trend of response ($p < 0.1$) for crop yield at NS1 (Table 4.8).

Potassium K fertilizer was applied at modest rates (60-100 kg ha^{-1}: Table 2.1) to soils assessed to be "Very Low" (PEI F7, LF cyl. and HF cyl.), "Low" (NS2), "Medium" (PEI F8), and "High" (NS1) in soil K (Table 4.1).

Leaf K values in control plots were assessed as deficient in the cylinder systems, as excessive at PEI F7, and as adequate at other sites (Table 4.3; Table 3.5).

Leaf K values were increased significantly by K fertilizer at NS2 and in the LF and HF cyl. sites (Table 4.4).

Root weights exhibited significant positive responses to K at NS1 and at the LF cyl. site (Table 4.5).

Nodulation was increased significantly by K addition at NS1 and NS2 (Table 4.6).

Mycorrhizal infection was significantly reduced by K fertilizer at NS2 (Table 4.5).

Pests and diseases were not significantly affected by K fertilizer (Table 4.7).

Yield variables responded significantly to K fertilizer or there were trends for increase at NS1, and at the LF and HF cyl. sites (Table 4.8).

Calcium Ca fertilizer was applied as gypsum at modest rates (104-186 kg ha^{-1}) to 4 sites (Table 2.1) at which soil Ca values were assessed to be "High" and one site (LF cyl.) at which it was assessed to be "Medium" (Table 4.1). Leaf Ca values in the control plots at all sites were in the adequate range (Table 4.3; Table 3.5).

Ca fertilizer significantly increased grain+pod and crop yield at NS1 but had no effect on yield at other sites (Table 4.4). There were no other significant effects on the measured variables; there were trends for positive effects on nodule weight at NS1, and on *Calocoris norvegicus* in the HF cyl. site, and a trend for a negative effect on mycorrhizae at the LF cyl. site.

Root weights were numerically larger in the Ca treatments than in controls at all four sites, but differences were not significant (Table 4.5).

Likewise, nodule weights were numerically higher in Ca treatments than in controls; the difference was not significant except for a trend at the NS1(Table 4.6).

Mycorrhizal infection was lowed numerically by Ca fertilizer at all sites; the difference was significant at the HF cyl. site, and there was a trend for a difference at the LF cyl. site (Table 4.5).

There was a trend for a positive effect ($\alpha = 0.1$) of Ca fertilizer on *Calocoris norvegicus* at the HF cyl. site (Table 4.7).

There was a significant positive effect of Ca fertilizer on grain+pods at NS2 (Table 4.8).

Rock-P compared to super-P

Rock-P was included as an additional treatment in the cylinder systems. In contrast to super-P, rock-P did not significantly affect leaf P, roots, symbionts or yield variables except for a trend for an effect on grain+pods at LF cyl. site (Table 4.9).

4.3. Effects of weeds on yield, symbiont and leaf nutrient variables at NS1.

This farm had very high densities of weeds in the seedbank (Hill et al., 1989). In 1985, losses of fababean grain yield due to weeds were estimated as 20% and 0 % in unharrowed and once harrowed fababean respectively. In an experiment in 1986 in which N fertilizer additions and weeding were combined factorially, yields in N fertilized plots were reduced 35% by weeds, while yields were increased by 55% by weeds in the unfertilized plots; the unfertilized/plus weed treatment had the highest yield (Patriquin et al., 1988).

Table 4.9. Responses of fababean yields, roots, symbionts, chocolate spot (*Botrytis fabae* Sard.) and plant bug (*Calocoris norvegicus* Fieber), and leaf nutrients to super-P (P) and rock-p (Rp) fertilizers in cylinder systems

Fertilizer/ Variable	HF/LF cyl.	P	Rp
		(Percent of values in control plots)	
Grain+pods[a]	HF	76	72
	LF	211*[b]	143+
Crop	HF	81	82
	LF	177**	113
Mid-crop	HF	84	95
	LF	158**	129
Roots	HF	111	93
	LF	132**	112
Nodules	HF	139+	122
	LF	202*	75
Myc.	HF	81	80
	LF	101	107
Chocolate spot	HF	no[c]	no
	LF	no	no
Plant bug	HF	101	81
	LF	167	148
Leaf N	HF	100	97
	LF	117*	101
Leaf P	HF	100	90
	LF	109**	94
Leaf K	HF	97	116
	LF	91	118
Leaf Ca	HF	83*	86*
	LF	120+	98
Leaf Mg	HF	99	82*
	LF	127*	88

[a] Probability for interaction term (HF/LF cylinders x added fertilizer): $p = 0.016$, 0.003, 0.0004, 0.021, and 0.009 for grain+pods, crop, mid-season crop, plant bug, and leaf Ca respectively.

[b] +, *, ** significantly different from control value at $\alpha = 0.1, 0.05, 0.01$ respectively.

c Levels of chocolate spot in the sites were very low.

In 1990, a fertilizer addition experiment was conducted on the same field as in 1986, after one complete rotation of crops (fababean / oats / clover / winter wheat). Field preparation procedures differed from those in 1986. In 1990, straw from the preceding crop (winter wheat) was not worked into the soil until spring, while in 1985 and 1986, straw had been rotovated into the soil in the fall. In the 1990 experiment, fertilizer additions to main plots included N as in 1986, plus P, K, and Ca; minus weeds and plus weed treatments were established as subplots.

As described above (section 4.2), fababean final yields in the minus weed plots at NS1 responded significantly to K fertilizer, and there was a trend for response of crop yield to P fertilizer. Nodulation responded positively to K and Ca, and roots to K and P fertilizers. Mycorrhizal infection was reduced by all fertilizers (Table 4.5).

Most yield variables (grain+pods, crop, and mid-season yield) were significantly reduced in the plus weed compared to the minus weed treatments in control, N and K main plots; there were no significant differences in the Ca and P main plots, except for a trend for reduction in mid-season crop yield in the Ca main plots (Table 4.10). Stem density was significantly reduced by weeds in the N fertilizer treatments, but not in others. Roots mass was significantly reduced, or there was a trend for reduction in root mass in plus weed compared to minus weed treatments in all main plots except for Ca. Mycorrhizae and nodules were not significantly affected by weeds in any of the main plots, however in the case of nodules, there was limited sensitivity because of the large variability between plots (see coefficients of variation, Appendix Table 25). There were some significant but not numerically substantial differences for leaf nutrients between the minus and the plus weed plots (Table 4.10).

The interactive effects of fertilizer and weeds on yield, roots and symbionts, and leaf nutrients was examined separately for each fertilizer (Table 4.11). Significant interactions between N fertilizer and weeds were observed for grain and crop yields (α =

Table 4.10. Values of yield, symbionts, and leaf nutrient variables in the plus weed plots expressed as percentages of values in the minus weed plots for each fertilizer treatment considered separately at the NS1 site.

Treats.	Grain+ pods	Crop	Mid-season crop	Stem density	Weeds	Roots	Myc.	Nodules	Leaf N	Leaf P	Leaf K	Leaf Ca	Leaf Mg
	(Percent of values in minus weed plots)												
C	62*[a]	86	54*	85	166+	58+	115	55	99	97	99	112*	115**
N	25**	36**	37**	52**	131+	37**	136	55	98	98	98	93	104+
P	67	78	89	96	123	74+	91	79	106	95+	86*	94+	100
K	51*	58*	62*	73	104	52**	112	72	97	98	92	101	110**
Ca	53	61	82+	84	124	84	79	73	100	91	90	100	112

[a] +, *, ** mean for plus weed treatment is significantly different from mean for minus weed treatment at $\alpha = 0.1, 0.05, 0.01$ respectively for each main plot testament considered separately.

Table 4.11. Probabilities that the response of different variables to weeds is affected by fertilizer at NS1 [a].

Variable	Grain+ pods	Crop	Mid-season crop	Stem density	Weeds	Roots	Myc.	Nodules	Leaf N	Leaf P	Leaf K	Leaf Ca	Leaf Mg
Treats.	(Probability values)												
N	0.036	0.019	0.455	0.062	0.423	0.478	0.995	0.465	0.920	1.000	0.862	0.008	0.012
P	0.734	0.545	0.084	0.548	0.243	0.948	0.665	0.354	0.354	0.836	0.078	0.004	0.001
K	0.081	0.075	0.779	0.351	0.132	0.083	0.948	0.767	0.692	0.817	0.357	0.069	0.102
Ca	0.656	0.278	0.159	0.802	0.442	0.370	0.529	0.819	0.873	0.516	0.271	0.064	0.411

[a] From ANOVA for split plot design in which main plot treatments are plus fertilizer and no fertilizer and subplot treatments are plus weeds and minus weeds. The analysis was conducted separately for each fertilizer.

[a] +, *, ** within rows, mean values differ from control at $\alpha = 0.1, 0.05, 0.01$ respectively.

0.05) and for stem density ($\alpha < 0.1$). There was a trend for interaction ($\alpha < 0.1$) between K fertilizer and weeds on grain+pod and crop yields, and roots (Table 4.11).

All of the significant interactions or trends were for cases in which these variables were reduced more by weeds in the presence of fertilizer than in the unfertilized plots; there was no case in which losses due to weeds were significantly lessened by fertilizers (Table 4.11).

To consider (a) whether fababean responds to fertilizer under weedy conditions, and (b) whether adding fertilizer under very weedy conditions can increase yield to the level achieved under non weedy conditions without fertilizers in Table 4.12, I have compared yields in response to fertilizer for the plus weed plots conducted separately and I have expressed values as percentages of values in minus weed/no fertilizer plots.

In the plus weed plots, P, K, and Ca fertilizer additions effected significant increases in some of the yield components and of roots and nodules, however, N fertilizer had only negative effects, causing significant reductions or trends of reduction for grain+pod and crop yields (Table 4.12). No fertilizer treatment increased grain yield in the presence of weeds above that which occurred in the weeded unfertilized plots.

4.4. Discussion

4.4.1. Nitrogen and nodulation

I had postulated that adding N fertilizer at greater than "starter N " level, but in an amount significantly less than that needed to provide all N, would reduce yields by reducing nodulation or N_2 fixation, and, accordingly, total N intake.

Nodulation was significantly reduced by N fertilizer at the two PEI sites but not at other sites. Nitrogenase activity was measured at the PEI sites in mid-season when it would be expected to be near maximal (Sprent et al., 1977; Patriquin et al., 1981). N fertilizer had no effect on specific nitrogenase activity (activity per gram nodule). These

Table 4.12. Responses of crop variables to fertilizers under minus and plus weed regines. Yields are expressed as percentages of the values in the minus weed/no fertilizer treatment, however statistical comparisons apply only within the minus weed or plus weed treatments examined separately.

Fertilizer/ Variable	+w/-w	C	N	P	K	Ca
		(Values expressed as % of minus weed/no fertilizer treatment)				
Grain+pods	+w	62	28+a	99+	94	61
	-w	100	112	149	184*	115
Crop	+w	86	47*	135*	117	81
	-w	100	130	173+	202*	132
Mid-crop	+w	54	37	95**	66	80*
	-w	100	101	107	107	98
Weeds	+w	166	149	101*	102*	154
	-w	100	114	82	98	124
Roots	+w	58	34	116**	89+	107**
	-w	100	91	157**	171**	127
Nodules	+w	55	36	114*	151**	110+
	-w	100	65	144	210**	151+
Myc.	+w	115	58*	59*	101	52*
	-w	100	43*	65+	90	66
Stem density	+w	85	56*	121*	85	107
	-w	100	108	126+	116	127+
Leaf N	+w	99	99	105	96	101
	-w	100	101	99	99	101
Leaf P	+w	97	102	88	87+	89
	-w	100	104	93	89	98
Leaf K	+w	99	97	85	91	77*
	-w	100	99	99	99	86*
Leaf Ca	+w	112	105	93**	97*	103
	-w	100	113**	99	96	103
Leaf Mg	+w	115	114*	98	107	112
	-w	100	110	98	97	100

observations are consistent with the model of Streeter (1988) indicating that nodule mass is more sensitive to added N than specific nitrogenase activity.

There were no significant reductions in final yields in N fertilized plots compared to controls. At PEI F7, mid-season crop yield was reduced by 22% (significant at $\alpha < 0.1$), but final yields were not suppressed by the added N. At the LF cyl. site, in which leaf N in unfertilized plots was below critical N levels, there was a suggestion of an increase of the grain+pod yield in the N fertilized plots (yield 1.67 x control; $p = 0.153$). Nodule weight in the control plot at the LF cyl. site was approximately half of the lowest values at the Farm sites. Thus, the effects of the adding N fertilizer experimentally appear to concur overall with the interpretation of the field data that differences in nodulation did not greatly affect N supply, i.e., that overall the nodules and soil N acted interactively to satisfy fababean's N requirements except under conditions where there is poor nodulation even in the absence of N.

Other than the data of Patriquin et al. (1988), the only data suggesting a substantial inhibitory effect of N on final yield of a grain legume appears to be that of Herridge and Brockwell (1988) for soybeans. Yields of uninoculated (non-nodulated) soybean responded positively to intermediate and higher levels of the added N fertilizer, while normally inoculated soybean responded negatively to intermediate levels (100 or 200 kg N ha^{-1}) of the added N fertilizer, but not to 300 kg added N. When the inoculation intensity was increased 100-fold, there was a negative response to added N only at the 100 kg N level (and not at 200 or 300 kg N); when inoculation was increased 1000-fold, there was not a negative response to either intermediate or high levels of N. The significant negative responses were in the range at 18 to 26% below control values. The reduction in nodulation in the soybean experiments was close to 100% for normally nodulated soybean fertilized with 100 kg N fertilizer, and was approximately 80% for plants inoculated at the 100-fold level. In my experiments, addition of N at 100 or 152 kg

N ha^{-1} reduced nodulation by only 26-60%. Thus nodulation of soybean appears to be much more sensitive to N fertilizer than fababean, and this difference seems to explain the lack of or lower magnitude of, a negative effect of N fertilizer on fababean compared to soybean.

4.4.2. Nitrogen and diseases and pests

Effects of N fertilizer on pests would only be testable in these experiments if pests and diseases were present, and conditions at least somewhat conducive to their proliferation.

Black bean aphids cited as a major pest of fababean shown in a previous study to be stimulated by N (Patriquin et al., 1988) were present at 2 of the 6 sites in these experiments, but were uncommon at four sites (Appendix Table 44).

Chocolate spot disease was observed on control plants at the 4 field sites, but not on plants in the cylinders. There were no statistically significant effects of the added N fertilizer on the chocolate spot. According to Marschner (1986) obligate but not facultative parasites respond to an excess of N. Chocolate spot can grow saprophytically (Martens et al., 1984), hence its lack of response to N in these experiments is consistent with Marschner's generalization.

Calocoris norvegicus a known phytophagous miridae (Kelton, 1982; Bardner, 1983) occurred in the cylinders and there was a highly significant interaction between background fertility and added fertilizers on plant bug infestation. N fertilizer significantly increased *Calocoris norvegicus* infestation in the HF cylinders, but had no significant effect in the LF cyl. The increased *Calocoris norvegicus* infestation was not sufficient to reduce the yield variables. It seems likely that when conditions except for N are more favorable for pests, that excess N could push the pests and certain diseases over critical levels.

4.4.3. Phosphorus and mycorrhizal infection

It was hypothesized that high levels of soluble P might have negative effects on yields by suppressing mycorrhizal infection, resulting in reduction in or loss of one or more of the potential benefits of mycorrhizal infection. There were significant reductions in mycorrhizae or trends for reduction in mycorrhizae in P fertilized plots compared to controls at all sites except for the HF and LF cyl. sites. However, the added P fertilizers did not have significant negative effects on yield variables. At NS1, P fertilizer increased crop yield ($\alpha = 0.1$). P also significantly increased all yield variables in the LF cyl. sites, which had the lowest soil Mehlich-P. At NS1 and LF cyl. sites, P fertilizer also increased root biomass and nodule weights. Thus it appears overall that the direct beneficial effects of the added P fertilizer on plant nutrition and nodulation countered any negative effects of the added P fertilizer on mycorrhizal infection and its benefits.

The reduction in mycorrhizal infection due to P fertilizer was only partial and was of similar magnitude to reduction in nodulation due to the added N fertilizer. It was also not greater than the reduction due to the added N, K, and Ca fertilizers. In the present experiments, at all sites except for LF cylinders, the reduction of mycorrhizal infection by N, K, and Ca fertilizers was large. According to a recent review by Abbott and Robson (1991), few studies have been made of effects of nutrients, other than P, on abundance and distribution of VAM fungi in the field. They cite literature showing both positive and negative effects of N, but most are negative. A study by Mosse and Bowen (1968) showed that dung addition increased spores of one type of mycorrhizae, while adding inorganic N, P, and K reduced numbers of other types; the reductions seem to result from imbalances created by application of N, or P, or K alone. Johnson and Pfleger (1992) in another review cite papers indicating that imbalanced applications of nutrients tend to reduce infection more than balanced applications of N-P-K or of N and P, or of P and K; thus part of the negative effects observed in the present study may be attributable to the nutrients being applied individually. On a nutrient poor tropical soil, Saif (1986)

observed mycorrhizal infection of legumes to be increased by K and Ca. The only site at which P, K, and N fertilizers appeared not to have a negative effect was in the LF cylinders, where also leaf P, K, N positively responded to the respective fertilizers - hence in these cases, single nutrient addition may have been redressing balances rather than accentuating imbalances.

There appear to be few data in the literature on effects of Ca application or of gypsum on mycorrhizal infection. In these experiments, Ca was suppressive even in the LF cylinders. Saif (1986) reported that Ca fertilizer increased mycorrhizal infection of two type legumes in Ca-poor soil. Gryndler et al. (1991) reported that in an artificial substrate, Mg increased mycorrhizal infection while replacement of Mg with Ca or K had strong negative effects.

4.4.4. Potassium and pests

It was postulated that low K relative to N might restrict yield by stimulating pests and diseases, hence that K fertilization could reduce pests and diseases, and possibly increase yields. There were no statistically significant effects of the added K fertilizers on chocolate spot, which was present in controls at 4 of the 6 sites, or on *Calocoris norvegicus* in the two cylinder systems.

4.4.5. Response to K not related to pests

K fertilizer did have significant positive effects on fababean final yield variables at NS1, on crop yield in the LF cylinders ($\alpha = 0.1$) and on mid-season crop in both the LF and HF cylinders ($\alpha = 0.1$). The leaf K values in control plots in both LF and HF cylinders were below critical levels, and leaf K responded strongly and significantly to K fertilizer.

K fertilizer had a significant positive effect on roots in the LF cylinders, but little effect on nodules or mycorrhizal infection. Lack of effect on nodules was probably because nodulation was strongly limited by P (indicated by 2-fold increase in nodules in

P fertilized plots). There was a slight numerical increase in mycorrhizal infection in K fertilized plots in the LF cylinders while in the HF cylinders, and at all field sites, there were numerical decreases (significant at one site). It thus appears that in the LF systems, positive effects of K on yields could have been related to benefits of K for root mass, but not to any effects on nodulation or mycorrhizae. The effects on roots was much stronger in the LF cylinders than in the HF cylinders.

Leaf K at NS1 was 0.22 g kg^{-1} which is within, or close to the sufficiency range of leaf K and did not respond to the added K fertilizer; however, the added K fertilizer had very strong positive effects on nodules and root mass, while there was weak negative effect on mycorrhizal infection.

In the 8-farm study, a plot of the yield versus leaf K (Figure 3.10) suggests that leaf K levels at PEI F8 (0.27 g kg^{-1} in the minus weed plots and 0.24 g kg^{-1} in the plus weed plots) were near to the value for the maximum yield, while leaf K values at PEI F7 (0.36 g kg^{-1} in the minus weed plots, 0.34 g kg^{-1} in the plus weed plots) appeared to be in the saturation region or inhibitory region. Yield variables did not respond significantly to K fertilizer at theses two sites. There was a strong positive response of yield variables to K fertilizer at NS1 (leaf K was 0.22 g kg^{-1} in control treatment). These three sets of data and the field data taken together suggest that the maximum normal value for leaf K in fababean is approximately 0.30 g kg^{-1} (versus 0.25 K g kg^{-1} cited for soybean and dry bean), while the critical value is close to 0.25 K g kg^{-1} (versus 0.12 K g kg^{-1} cited for soybean and dry bean). Leaf K at NS2 was 0.23 g kg^{-1} in control treatment; grain yield showed a numerically positive response (124%), but not crop or mid-season crop yields (89 and 84%), which does not fit with this interpretation. However, grain+pod yield at this site responded significantly to the added Ca fertilizer; thus, the added K fertilizer alone may not have benefited yield because of Ca limitation.

Fababean seems to have a higher demand for K than dry bean and soybean. This may be related to its exceptionally high energy and dry matter yields (Fasheun and Dennett, 1982), as discussed previously (chapter 3).

4.4.6. Calcium and K/Ca antagonism

Calcium fertilizer (as gypsum) was included in the 1990/1991 experiments because results in the 8-farm study suggested that high levels of K were reducing yields, there was an inverse relationship between K and Ca, and lowest Ca values were close to critical levels (0.036 Ca g kg^{-1} as assessed for soybean). I hypothesized that deficient Ca might have been responsible, i.e., that Ca levels were limiting where there was high K. The soil pH values were in most cases over 6.0 (Table 4.1); thus Ca was applied as gypsum rather than lime to minimize pH changes.

Leaf Ca was significantly reduced by the added K fertilizer at the NS1 site (only in the plus weed subplots), and leaf K was significantly reduced by addition of gypsum at the NS1 site (in both subplots); thus there was definite evidence of mutual K/Ca antagonism. Leaf Mg was not affected by added K fertilizer at the NS1 site. Most crop yield variables at the NS1 site, and nodules and root mass responded positively to both the added K and Ca fertilizers (significantly positive for some variables).

PEI F7 had very high leaf K, but addition of K did not reduce leaf Ca (leaf Ca in K fertilized plot was 1.01 x control). The NS2 site had the lowest leaf Ca (0.062 g kg^{-1}) in the control, and there was evidence for Ca limitation at this site as shown by response to Ca fertilizer and from other studies (Patriquin et al., 1993b); however the added K at the NS2 site did not reduce leaf Ca (value 0.92 x control). The added K fertilizer did not result in any significant reduction in yield variables at these two sites. Thus there is no direct evidence from these experiments of negative effect of the added K fertilizer on yields or intermediary variables through Ca/K antagonism. Likewise in the HF cylinder system which had adequate Ca, but low K as evidenced by soil and leaf analyses, there is

no evidence that added gypsum had detrimental effects on yields through Ca/K antagonism. There was a trend for response of *Calocoris norvegicus* to the Ca fertilizer in the HF cylinders, which could be postulated as due to an effect of Ca on plant K resulting from Ca/K antagonism. However, leaf K was not reduced by the added Ca fertilizer, so the effect on plant bug, if real, is not readily explained as due to Ca/K antagonism. Hence, overall, although the experiment sites included sites of very low K (the cylinders), and very low Ca (NS2), there is no evidence for any significant effects of Ca/K antagonism on crop yields or intermediary variables.

The added Ca fertilizer increased grain+pod yield significantly only at NS2, but it did not give significant increases in crop yield or mid-season crop yield, or in root mass or nodules; thus the benefit of Ca seems to have been mainly on grain filling. In a study of effects of Ca on cereal production, Fenn et al., (1995) reported that Ca can redirect foliar metabolites to the seeds, and increase grain yields. There was a trend for a positive response of nodules to the added Ca fertilizer at the NS1 site. As sulfur was also supplied with the Ca, it is possible that the response was to sulfur; however, it seems more likely that the responses were associated with Ca, as these two sites (NS1 and NS2) had the lowest leaf Ca.

Surprisingly, the gypsum application caused significant reductions in mycorrhizal infection at the NS1 site (only in the plus weed subplots), and in both LF and HF cylinders, where the average reduction was approximately 50%. Only at NS2, which was the site of lowest leaf Ca, was the mycorrhizal infection decline numerically small and non-significant. Gryndler et al. (1991) reported that replacement of $MgSO_4$ by K_2SO_4 and $CaSO_4$ as nutrient solution for maize significantly reduced mycorrhizal infection in hydroponic culture conditions.

4.4.7. Interaction of background fertility and fertilizers

Responses of fababean to the added fertilizers between sites differed, but as the sites themselves were not replicated, it is possible only to speculate on the existence of significant interactions between site fertility and added fertilizers. The cylinder system allowed the interaction between background fertility and added fertilizers to be examined in a replicated plot experiment. The LF cylinders had the lowest values of any sites for organic matter, P, K, Ca, Mg, while values for soil variables for the HF cylinders were within the ranges for the 4 field sites. Estimated yield per unit area was very low in the LF cylinders; in the HF cylinders most yield variables corresponded to the bottom end of the range for the 4 field sites. There were possibly some physical limitations related to the limited depth of the soil in the cylinders that restricted yield compared to the field sites.

For the yield variables, and root mass and nodules, the responses to fertilizers were mostly non significant and not numerically large in the HF cylinders; all yield variables were numerically lower than control values where P was added (76-84% of control) and Ca (83-90% of control). There was a trend for a positive response of mid-season yield to K (134% of control), but not for grain+pod yield (91% of control). In the LF cylinders, there were some large and significant positive responses to the added fertilizers. Hence, in the high fertility cylinder system, the responses overall were lower than in the lower fertility cylinder system which is what would be predicted based on soil data.

In the HF cylinders and at the farm sites, mycorrhizal infection appeared to be suppressed by all nutrients. In the LF cylinders, there was no effect of fertilizer on mycorrhizae except for Ca (strongly negative). Mycorrhizal infection in super-P fertilized plots in the LF cylinders was not affected by P (mycorrhizal infection was 1.01 x control value). This suggests that in the LF cylinders, levels of soil N, P, and K without

fertilizers were optimal or slightly below optimum for mycorrhizal infection, while in the HF cylinders and at other sites, they were above optimum, and these fertilizers substantially reduced infection.

Mycorrhizal infection is reported to respond positively to low levels of applied P on P-poor soils, while high levels still suppress infection (Saif, 1986; Mosse, 1986). The only soil which was ranked very low for P in this study was that in the LF cylinders, and this was the only soil where adding P fertilizer did not suppress infection (mycorrhizal infection in P-fertilized plots was 1.01 x that in unfertilized plots). Leaf P (0.032 g kg^{-1} in the control) was raised significantly by P fertilization, but not substantially (by 1.09-fold). Hence this site was likely one of P stress, and mycorrhizal infection could have been responsible for the fababean in the control having leaf P at an apparently adequate value. Nevertheless, fababean responded strongly to P fertilizer, mid-season, crop and grain+pod yield increasing by 1.58-, 1.77- and 2.11-fold respectively. This response seems to have been associated with P effects on nodules (nodule weight increased 1.96-fold) and possibly on root mass (roots increased 1.32-fold; a trend at $\alpha = 0.1$). There was a suggestion of a response to N fertilizer applied alone (mid-season crop, crop, and grain+pod yields increased 1.08, 1.37 and 1.67-fold respectively; $p = 0.403$, 0.193, and 0.153 respectively), but it was not as large as the response to P. Hence, it appears that in this low P, low N soil, mycorrhizae were not able to overcome significant P limitation, which was related in part and possibly mostly to P limitation of nodule growth. Yield in the absence of P fertilization was exceptionally low, even allowing for some limitations due to physical restriction of the cylinders. With P fertilization, yield approached the control values for the HF cylinders in which soil P was ranked as "Very High".

Many studies have demonstrated a positive effect of mycorrhizal infection on nodulation, and the evidence suggests that it results from improved P nutrition, including fababean (Abbott and Robson, 1977; Ssimi et al., 1980; Barea et al., 1987; Kucey and

Janzen, 1987). However, the results of P fertilization in the LF cylinders suggest that under P and N deficient conditions, while the (indigenous) mycorrhizae may be having some benefits, they cannot compensate for low P sufficiently to increase nodulation to the point that the plants can support economically acceptable yields of grain. Kucey and Paul (1983) reported that inoculation with a selected strain of mycorrhizae even in the presence of indigenous mycorrhizae, increased yields, suggesting that superior strains might be more effective than were the mycorrhizae in the LF cylinders. However the magnitude of the increases cited by Kucey and Janzen (1987; less than 1.5-fold), would still not be sufficient to produce economic yield in a situation similar to that represented by the LF cylinders.

4.4.8. Interactive effects of fertilizers and weeds

It was postulated that high levels of available N could reduce fababean yields by stimulating weeds. The effects of adding N fertilizer on weeds was investigated at the NS1 site where there is a very large weed seedbank (Hill et al., 1989), and previous studies had demonstrated a pronounced effect of N fertilizer on yield losses due to weeds (Patriquin et al., 1988).

In unfertilized main plots, in the 1990 experiment, yields in the minus weed subplots (212 g grain+pods m^{-2}) were considerably lower than those of 1985 and 1986 (341-529 g grain+pods m^{-2}).

I attribute the low yields in 1990 to a very dry growth period (Appendix Table 1), and the high sensitivity of fababean to moisture stress (Sprent et al., 1977; Keatinge and Shaykewich, 1977; Karamanos, 1978). A second factor is that in 1990, straw from the previous winter wheat crop was incorporated in the spring just prior to seeding fababean, while in 1985 and 1986 and most other years it was incorporated in the fall. In 1979, it was incorporated in spring and was followed by excessive weeds and very low yields of

fababean, it is suggested that phytotoxins produced after incorporation are still present in the seedbed when residues are incorporated in spring (Patriquin et al., 1986).

Weeds had a stronger negative effect on yields in unfertilized plots (38% reduction due to weeds) than observed in 1985 and 1986 (20% reduction to 55% stimulation), but the reductions in yields in N fertilized plots in 1990 were also far greater (75%) than reductions in the minus weed plots, and than reduction in the plus-N fertilizer plots in 1985/86 (35% reduction). Thus the results are consistent with the previous study (Patriquin et al., 1988) showing an accentuation of losses due to weeds in the presence of high N. A major part of this effect appeared to be through effects on stem density, which was reduced significantly by weeds in the plus-N fertilizer plots but not in the unfertilized plots.

Effects of high levels of other fertilizer nutrients (K, P, Ca) were also examined in this experiment. The results suggest that high levels of readily available P, K, and Ca fertilizers did not exacerbate weed problems in weedy fields, however, their full fertilizing benefits would not be realized unless weeds were controlled to some extent. In contrast, high levels of available N fertilizer dose exacerbate weed problems in weedy fields.

In summary, the results of these experiments support the 8-farm study in suggesting that high soil N would not reduce yields through effects on nodulation and N_2 fixation, in indicating that variations in mycorrhizal infection on the scale observed in the 8-farm study are probably not of any significance to fababean nutrition, and in suggesting that variation in soil K is likely a major factor affecting yields of fababean, and that fababean has an exceptionally high demand for K. The experiments also support the hypothesis that high levels of N would exacerbate weed and pest problems under circumstances of poor weed control or high background pest levels.

5. Result III. Inoculation experiments

Most legume crops are symbiotic with both *Rhizobium* and mycorrhizae. When legumes are symbiotic with both symbionts, plant growth is generally much better than it is for unfertilized plants or for plants with either symbiont alone (Linderman, 1992). All strains and species of *Rhizobium* and mycorrhizal fungi do not affect their host plant in the same manner or to the same degree (Linderman, 1992). It has been suggested that interendophyte compatibility may play a role in the combined effect on plant growth (Bayne and Bethlenfalvay, 1987). It might be expected that these effects would be most obvious in higher nitrogen-fixing legumes such as fababean.

The results from the 8-farm study suggest that variation in mycorrhizal infection in the range from 9 to 57% (percent of roots with mycorrhizal arbuscules) had little effect on plant nutrition and yields. Likewise, although fertilizers caused large reductions in mycorrhizal infection at all experiment sites, the fertilizers did not cause significant reductions in yield. Those results seem to suggest that variation in mycorrhizal infection in the field does not affect fababean nutrition. It is still possible, however, that there is a threshold effect of mycorrhizal infection. In a review of field inoculation experiments, McGonigle (1988) concluded that size differences between infection levels could not account for mycorrhizal growth responses. He suggested that " there might exist a functional threshold infection level, below which no benefit is possible, but above which facilitation of nutrient uptake is the same for any infection level". To verify (or not) that a benefit can be demonstrated when a comparison is made with non mycorrhizal plants, two inoculation experiments were conducted. Single mycorrhizal and rhizobial isolates were obtained from farms PEI 8 (isolates M1, R1) and NS1 (isolates M2, R2), and inoculated individually and in combination into artificial madia in which fababean was grown subsequently. In the first experiment, treatments were C (uninoculated control),

M1, M2, R1, R2, M1R1, M2R2. In the second experiment, the same treatments were included, plus two additional treatments (M1R2, and M2R1) in order to examine possible interactions between rhizobial and mycorrhizal strains.

5.1. Medium and leaf P levels

The Mehlich P value for the medium used in experiment I was 61 mg P kg^{-1}; this value is ranked as "Very High" (Table 5.1). The same formula was used in preparing the medium for experiment II. The field values for the source farms were 130 mg P kg^{-1} ("Very High") and 228 mg P kg^{-1} ("Very High") for PEI 8 and NS1 respectively. The range of values for the PEI farms in the 8-farm study was 54-106 mg P kg^{-1}; all values were ranked "Very High". The leaf P values in control treatments were 0.034 g kg^{-1} and 0.038 g kg^{-1} in experiments I and II respectively (Table 5.2; Table 5.3), indicating the plants were not growing under P stressed conditions. These values are also within the ranges for field leaf P values (0.034 - 0.068 g kg^{-1}). Thus P status of the experimental systems was similar to that of the field systems.

5.2. Contamination problems

In experiment I, the plants in the control treatment had nodules and were infected with mycorrhizae; rhizobial inoculated plants were infected with mycorrhizae; and mycorrhizal inoculated plants had nodules (Table 5.4). Cross-contamination of pots probably occurred when they had to be moved out quickly following growth chamber failure at the third week. In experiment II, there were no nodules or mycorrhizae in the control plants, and plants inoculated with rhizobia did not exhibit mycorrhizal infection (Table 5.5). However, mycorrhizal inoculated plants were contaminated with rhizobia as indicated by presence of nodules in plants inoculated only with mycorrhizae (Table 5.5). As controls were free of rhizobia, it appears that the contamination by rhizobia was a result of the original mycorrhizal inoculants being impure.

Table 5.1. Soil analysis data for artificial medium used in Experiment I. The medium was sampled after washing to reduce electrical conductivity but before autoclaving.

Variable[a]	OM	pH	P	K	Ca	Mg	CEC	NO_3^-	BS
	%		----------mg kg^{-1}----------				meq. 100 g-1	mg g-1	%
Growth medium	1.1	7.7	61 (VH)b	198 (H)	2204 (VH)	120 (L)	12.5	5	100

[a] OM:soil organic matter, CEC:cation exchange capacity, BS:base saturation.
[b] Commercial lab's rating: H:high, VH:very high, L:low.

Table 5.2. Experiment I: effects of different isolates of *Rhizobium* and mycorrhizae, and their combinations on fababean leaf tissue nutrients. Values are averages of 3 replicates.

Treats	N	P	K	Ca	Mg
	----------	----------	g kg^{-1} ----------	----------	----------
Control	.484	.034	.241	.132	.047
M1.	.507	.031	.295	.130	.047
M2.	.465	.031	.231	.112	.042
R1.	.479	.033	.278	.176+[a]	.055+
R2.	.529	.033	.260	.139	.047
M1R1.	.513	.030	.285	.132	.046
M2R2.	.517	.032	.295	.127	.048
F(6, 12)=	1.312	0.717	0.871	1.218	1.633
Prob. =	.324	.644	.543	.362	.221
CV%	6.94	7.53	17.8	19.6	11.1

[a] +, significantly different from the control values at $\alpha = 0.1$.

Table 5.3. Experiment II: effects of different isolates of *Rhizobium* and mycorrhizae, and their combinations on fababean leaf tissue nutrients. Values are averages of 4 replicates.

Treats	N	P	K	Ca	Mg
	----------g kg^{-1}----------				
Control	.128	.038	.183	.176	.031
M1.	.454**[a]	.016*	.177	.209	.045*
M2.	.462**	.047	.182	.359**	.051**
R1.	.147	.031	.141	.282+	.048**
R2.	.542**	.055+	.170	.383**	.050**
M1R1.	.481**	.027	.138	.368**	.054**
M2R2.	.481**	.038	.175	.309*	.052**
M1R2	.543**	.0375	.186	.364**	.058**
M2R1	.504**	.048	.203	.329*	.047**
F(8, 16)=	16.38	4.65	0.716	3.42	4.46
Prob. =	.000	.004	.675	.017	.005
CV%	16.5	26.6	25.2	22.2	13.1

[a] +, *, ** significantly different from the control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Table 5.4. Experiment I: effects of different isolates of *Rhizobium* and mycorrhizae, and their combinations on fababean biomass, nodules, mycorrhizal infection, pH, electrical conductivity at mid-growth stage. Values are averages of 3 replicates.

Treats	Mid-season crop	Mid-season root	Dry weight nodules	Myc.	pH	Electrical conductivity
	----------g pl^{-1}----------			%		$\mu S\ cm^{-1}$
Control	3.25	4.00	0.15	3.00	5.77	44.3
M1.	3.84	4.45	0.19	23.3**a	5.80	32.3
M2.	3.67	3.49	0.18	18.5*	5.67	37.3
R1.	3.92	5.85*	0.19	7.70	5.63	48.3
R2.	3.92	3.45	0.13	3.20	5.55+	48.7
M1R1.	3.64	3.75	0.19	23.0**	5.70	45.0
M2R2.	3.29	2.85	0.16	13.5	5.50*	43.7
F(6, 12)=	0.336	5.452	1.376	6.34	1.838	0.406
Prob. =	.905	.006	.300	.003	.174	.861
CV%	22.9	17.9	19.5	11.9	2.42	37.8

[a] +, *, ** significantly different from the control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Table 5.5. Experiment II: effects of different isolates of *Rhizobium* and mycorrhizae, and their combinations on fababean biomass, nodules, mycorrhizal infection, growth medium pH, electrical conductivity at mid growth stage. Values are averages of 3 replicates.

Treats	Mid-season crop	Mid-season root	Dry weight nodules	Myc.	pH	Electrical conductivity
	----------g pl^{-1}----------			%		$\mu S\ cm^{-1}$
Control	0.67	1.90	0.00	0.00	6.80	37.3
M1.	2.17**[a]	3.03**	0.052**	14.6**	7.10*	37.7
M2.	2.58**	3.00**	0.073**	12.6**	7.13*	39.0
R1.	0.75	2.37	0.038*	0.00	7.03+	39.3
R2.	2.08**	2.24	0.028	0.00	7.17**	39.3
M1R1.	2.08**	2.38	0.060**	16.0**	7.20**	36.0
M2R2.	2.33**	2.47+	0.048*	10.9**	7.13*	37.7
M1R2	2.17**	2.67*	0.038*	14.3**	7.20**	35.7
M2R1	2.08**	2.23	0.057**	12.6**	7.20**	36.7
F(8, 16)=	8.56	2.595	3.235	12.29	2.39	0.412
Prob. =	.0002	.049	.022	.0001	.066	.897
CV%	21.4	16.0	45.5	37.4	2.01	9.90

[a] +, *, ** significantly different from the control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

5.3. Experiment I

In spite of the mycorrhizal contamination of all treatments in experiment I, there was still a large effect of mycorrhizal inoculation on percent root mycorrhizal infection (Table 5.4). Maximum mycorrhizal infection was 23% (Table 5.4). There were no effect of mycorrhizal infection on leaf P (Table 5.2). In contrast, there was no strong effect of rhizobial inoculation on nodulation (Table 5.4). Nodule weights varied from 0.13 g pl^{-1} to 0.19 g pl^{-1} (Table 5.4). There were no substantial differences in leaf nutrients between any of the inoculated treatments and controls except that there was a trend of higher Ca and Mg in R1 inoculated plants (Table 5.2).

Values for mid-season crop yield in inoculated treatments were not significantly different from the control (Table 5.4).

At the final harvest, M1R1 exhibited a highly significant increase in grain+pod yield over the control (Table 5.6). Grain+pod yield in the R2 treatment exhibited a trend increase compared to control (Table 5.6). The M1R1 treatment also exhibited a more than 2-fold increase in medium electrical conductivity (significant at $\alpha = 0.1$), and the largest reduction in medium pH (significant at $\alpha = 0.01$). Soil electrical conductivity values were all numerically above the control except for those in R1 and R2 treatments and pH values were all significantly less, or there was a trend for them to be less than the control values (Table 5.6).

Bonferroni comparison tests were made to determine whether the combined mycorrhizal/rhizobial inoculant differed in effect from the individual rhizobial or mycorrhizal inoculants and other combined inoculants. The tests indicate significant differences or trends for differences of M1R1 from M1, R1, and M2R2 for grain+pod yield, and of M1R1 from R1 and M2R2 for crop yield (Table 5.7).

Table 5.6. Experiment I: effects of different isolates of *Rhizobium* and mycorrhizae, and their combinations on fababean yields, growth medium pH, and electrical conductivity at final harvest. Values are averages of 4 replicates.

Treats	Grain + pods	Stem + leaves	Roots	Crop	pH	Electrical Conductivity
	g pl^{-1}					$\mu S\ cm^{-1}$
Control	1.31	8.13	5.63	15.1	5.48	37.0
M1.	2.94	9.13	7.57	19.6	5.10+a	46.5
M2.	1.63	9.19	5.88	16.7	4.95*	55.8
R1.	2.25	9.63	6.25	18.1	5.15+	36.3
R2.	3.75+	6.75	6.50	17.0	5.05*	31.5
M1R1.	6.50**	8.57	7.13	22.1+	4.53**	100+
M2R2.	2.19	8.25	6.38	16.8	5.05*	62.3
F(6, 18)=	3.323	0.748	0.532	2.422	4.736	2.31
Prob. =	.022	.619	.777	.068	.005	.079
CV%	65.9	25.7	28.7	16.7	5.14	49.7

[a] +, *, ** significantly different from the control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Table 5.7. Experiment I and II: probabilities that Bonferroni comparisons of combined inoculants with single inoculant and with reciprocal combinations for mid-season and final season yield variables. Probability values less than 0.1 underlined.

Comparisons	Grain+ pods	Stem+ leaves	Roots	Crop	Mid-season crop
Experiment I					
M1R1---M1	0.057	0.692	0.648	0.228	0.775
M1R1---R1	0.030	0.501	0.294	0.073	0.689
M2R2---M2	0.645	0.595	0.810	0.949	0.585
M2R2---R2	0.348	0.248	0.945	0.905	0.372
M1R1---M2R2	0.016	0.817	0.697	0.049	0.618
Experiment II					
M1R1---M1	0.084	0.964	0.042	0.138	0.804
M1R1---R1	0.027	0.009	0.001	0.002	0.001
M2R2---M2	0.641	0.300	0.613	0.983	0.460
M2R2---R2	0.376	0.430	0.303	0.257	0.461
M1R1--M1R2	0.499	0.857	0.207	0.451	0.804
M1R1--M2R1	0.156	0.585	0.317	0.244	1.00
M2R2--M2R1	0.906	0.836	0.501	0.770	0.460
M2R2--M1R2	0.641	0.301	0.712	0.348	0.621
M1R2---M1	0.351	0.823	0.639	0.280	1.00
M1R2---R2	0.137	0.120	0.101	0.002	0.804

5.4. Experiment II

There was no mycorrhizal or rhizobial contamination of the control in this experiment, but there was rhizobial contamination of the mycorrhizal inoculated plants. Mycorrhizal inoculated plants exhibited 10.9 to 16.0% mycorrhizal infection, and mycorrhizal and/or rhizobial inoculated plants had 0.028 to 0.073 g nodules per plant (Table 5.5). There was a large difference between the control and other treatments in leaf N (0.128 g N kg^{-1} in control, versus 0.454 to 0.543 g N kg^{-1} in the inoculated treatments except treatment R1 which had 0.147 g N kg^{-1} (Table 5.3). There also were substantial effects of all inoculation treatments on other leaf nutrients over the control except for leaf K (Table 5.3).

Values for mid-season crop yield in inoculated treatments were all significantly higher than control values except for R1 (Table 5.5). Root mass values were significantly greater than the control in the plants inoculated with mycorrhizae alone (with rhizobial contaminant), but not in those inoculated with rhizobia alone (Table 5.5).

At the final harvest, values for yield variables in all inoculated treatments were numerically higher than those in the control treatment except for roots in R1 (Table 5.8). M1R1 exhibited the highest grain+pod yield and also significant increases for other yield variables (Table 5.8). M1R2 had all yield variables significantly above the control (Table 5.8). M2R1 and M2R2 did not increase grain+pod yield significantly, but did increase stem+leaves and crop yield. Although effects on electrical conductivity were not as large as in experiment I, the differences were significant for M1R1, M1R2 and M2R1 over the control (Table 5.8). There were no significant differences in pH (Table 5.8).

Bonferroni comparison tests were made to determine whether the combined mycorrhizal/rhizobial inoculant differed in effect from the individual rhizobial or mycorrhizal inoculants and whether the combined mycorrhizal/rhizobial inoculant differed in effect according to the precise combinations. The tests indicate significant

Table 5.8. Experiment II: effects of different isolates of *Rhizobium* and mycorrhizae, and their combinations on fababean yields, growth medium pH, electrical conductivity at final harvest. Values are averages of 4 replicates.

Treats	Grain + pods	Stem + leaves	Roots	Crop	pH	Electrical Conductivity
	g pl^{-1}					$\mu S\ cm^{-1}$
Control	0.43	1.5	2.13	4.05	7.00	35.8
M1.	1.57	7.38**[a]	5.88**	14.8**	7.13	39.0
M2.	1.34	7.50**	5.00**	13.8**	7.15	39.5
R1.	0.63	1.78	1.75	4.15	7.05	38.5
R2.	0.79	5.32**	4.13*	10.2+	7.13	39.5
M1R1.	3.78**	7.44**	7.25**	18.5**	7.15	42.3**
M2R2.	2.01	6.00**	5.75**	13.8**	7.15	39.3
M1R2.	2.79*	7.75**	6.25**	16.8**	7.18	41.8*
M2R1	1.84	6.38**	6.63**	14.8**	7.20	42.8**
F(8, 24)=	2.03	6.95	8.18	9.22	0.665	1.904
Prob. =	.084	.0001	.0001	.0001	.717	.106
CV%	89.7	32.4	27.3	27.6	2.15	7.90

[a] +, *, ** significantly different from the control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

differences of M1R1 from M1 for grain+pod and roots, of M1R1 from R1 for all yield variables, and of M1R2 from R2 for crop yield (Table 5.7). Curiously, the R1 inoculant was apparently ineffective as judged from the leaf N (Table 5.3). On the other hand, M1R1 appeared to be the most effective inoculant overall and was numerically more effective than M1 alone (which carried an effective rhizobial contaminant) suggesting that organism R1 did contribute to the effectiveness of this association; M1R1 was significantly more effective than R1 alone for all yield variables (Table 5.8). R2 was an effective N_2 fixer alone, and M1R2 significantly increased the effect on crop yield (Table 5.8) but the difference between M1R1 and R1 was not significant (Table 5.7). All final yield values for M1R1 are numerically greater than those for M2R1 and all for M1R2 are greater than those for M2R2, however none of the individual differences are significant (Table 5.8; Table 5.7). Thus mycorrhizal strain effects appear to be weak compared to the effects of mycorrhizae being present or not.

5.5. Discussion

In experiment II, the controls were not contaminated, nor were *Rhizobium* inoculants contaminated with mycorrhizae. However, the mycorrhizal inoculants were contaminated with rhizobia, and these were effective as judged by effects of M1 and M2 alone on nodules and leaf N. Hence any benefits attributable to a mycorrhizal inoculant, could be wholly or in part due to associated rhizobia or other bacteria (Secilia and Bagyaraj, 1987; Garbaye, 1994), a feature common to most experiments with mycorrhizae (Koide and Li. 1989; Linderman, 1992). Commonly it is recommended that washings from mycorrhizae are added to controls so that the comparisons are between a control with associated bacteria, and a treatment with mycorrhizae and associated bacteria (Linderman and Hendrix, 1982; Talukdare and Germida, 1994), however this is not always the case (e.g. Pacovsky et al., 1991). In my experiments, washings were not added to the control.

In experiment II, all inoculated treatments except for R2 increased leaf N significantly and by a large factor over the control value, indicating effective rhizobia were present in inoculants containing any one or more of R2, M1, M2. Although R1 nodulated roots, it was apparently ineffective or only marginally effective as judged from leaf N. Interestingly, inoculation with R1 and M1 in experiment II appeared to increase yield over inoculation with M1 alone (+contaminant rhizobia), even though R1 by itself was not effective.

In experiment II, all inoculants except R1 had statistically significant positive effects on mid-season crop yield and on all final yield components compared to controls except in some cases for grain+pods. For the grain+pods, the rhizobial inoculants alone had very little numerical effect on yield; all treatments with mycorrhizae increased yield numerically at least 3-fold, but only those treatments with M1 plus either of the rhizobia increased the yield significantly. Mycorrhizal infection levels in experiment II (10.9% to 16.0%) were below those observed in most of the field sites or treatments (chapter 3).

Experiment I was largely invalidated because of rhizobial and mycorrhizal contamination of controls. Nevertheless, like experiment II, it did show a highly significant effect of M1R1 on grain+pod yield, also in both experiments, the largest differences between treatments on yield components were expressed in the grain+pod yield. M1R1 effected a large increase in medium electrical conductivity compared to all other treatments in Experiment I, and effected the largest reduction in pH.

While not conclusive because of methodological limitations, these results are consistent with the hypothesis that there is a threshold effect for mycorrhizal benefits to fababean yield. Comparison of the plants that were inoculated with mycorrhizae (and associated bacteria) with plants inoculated with *Rhizobium* alone or that were not inoculated suggest that there mycorrhizae (and associated bacteria) significantly increased grain yield (and/or shortened time to maturity) but had little effect at earlier

stages or for other yield components such as roots or stems+leaves. Further this benefit occurred in the presence of apparently adequate background P, i.e. it did not appear to be related to improved P nutrition. Other researchers have noted strong effects of mycorrhizae in simplified systems on reproductive components, but these have been correlated with improved P nutrition resulting from mycorrhizal infection, or similar benefits were obtained by applying P fertilizers (Bryla and Koide, 1990; Lu and Koide, 1994; Lau, et al., 1995). However Koide et al. (1988) concluded that the stimulating effect of mycorrhizae on reproductive components in oats may be independent of P supply. In my experiments the background P was high, and M1 in experiment I even significantly reduced leaf P when inoculated alone; P was numerically lower but not significantly when inoculated with M1R1. Interestingly, Kucey and Paul (1983) presented data on inoculation of fababean with mycorrhizae which show a positive effect on seed mass regardless of the level of added P.

Various researchers have demonstrated significant mycorrhizal strain or species effects on host crops (Al-Raddad Al-Momany, 1991; Ames et al., 1991; Azcon et al., 1991; Danields-Hylton and Ahmad, 1994). My experiments provide some suggestion of mycorrhizal strain effects (M1 versus M2), but lack of statistical significance suggests they were not very strong.

6. General discussion

Fababean is a potentially very high yielding crop, with high yield being achieved even under non-chemically intensive conditions. It is an ancient, cool season grain crop which was a major grain in Europe until this century. It is still a major crop in many developing countries. At least under modern farming conditions, the crop has proved to be erratic in performance (reviewed in introduction).

I began this study with the idea that fababean may be particularly dependent on its rhizobial and mycorrhizal symbionts, and that high residual levels of fertilizers in modern farming systems could suppress symbiotic infection and its benefits, also that high levels of residual N could be a factor in the pest problems. This might explain the consistently good yields achieved by some organic farmers (Hainsworth, 1954; Patriquin et al., 1986), in apparent contrast to more general experience. The effects of N on weeds was a factor of particular interest to organic farmers.

The field studies and experimental studies failed to show a general relationship of yield to nodulation, or an inhibitory effect of combined N on yields. This result is in general agreement with results of other studies on fababean showing neither inhibitory nor stimulatory effects of N fertilizer on yields (Dean and Clark, 1980; Hill-Cottingham and Lloyd-Jones, 1980; Roughley et al., 1983) except for stimulation in some systems under exceptionally high N application (Richards and Soper, 1979; Sorwli and Mytton, 1986). In these experiments, N levels were altered by increasing levels above background through use of fertilizers. It remains possible that reducing levels below field levels by immobilization could increase yields. Shivashankar and Vlassak (1978) reported that incorporating straw increased N_2 fixation and yield in soybean. Abboud (1992) found that incorporation of oat hulls before planting vetch lowered soil nitrate (to

<7 from 23 μg N g^{-1}), increased N_2 fixation, and produced higher yields of vetch and fewer weeds than in plots without oat hulls.

Although definite benefits from mycorrhizal infection have been demonstrated for crops growing under P-stressed conditions (Barea and Azcon-Aguilar, 1983; Linderman, 1992), it is not clear whether VA mycorrhizae do have nutritional benefits for crops with high yield potentials under conditions in which those potentials are realized. There is evidence that mycorrhizal dependency has been selected against in modern crops (Hetrick et al., 1993) and that fertilization of soil can select for less mutualistic mycorrhizae (Johnson, 1993). Several studies have demonstrated significant effects of different farming systems (e.g. Douds et al., 1995; Kurle and Pfleger, 1994) and of tillage and cover crops within systems (e.g. McGonigle and Miller, 1993; Johnson and Pfleger, 1992) on mycorrhizal infection. There appears to be an underlying assumption in such studies that the higher the infection level, the better, but there is little if any evidence to support that. In a review of published field trials, McGonicle (1988) remarked "For the present, direct evidence for a mutualistic function of VA mycorrhizal symbioses in the field is scant".

Several factors in my study might be considered to improve the likelihood that a positive relationship between yield and mycorrhizal infection would be found: (i) I looked for evidence of a relationship of this sort in farming systems which had reduced or were reducing fertilizer inputs, and that overall would be expected to be more dependent on mycorrhizae (ii) I was examining a high yielding legume which had been shown in experimental studies to benefit from mycorrhizae (Kucey and Janzen, 1987), and legumes are considered more likely to benefit from mycorrhizae than cereals (Manjunath and Habte, 1991). (iii) I used frequency of roots infected with arbuscules as a measure of

infection, which could be expected to provide a better measure of mycorrhizal activity than hyphae frequency used in many past studies (McGonicle, 1990).

A large range of variation in infection was found in field studies, however there was no evidence for a relationship of mycorrhizal infection with yields, leaf nutrients, or nodules. Infection levels were substantially reduced by all fertilizers, but with no apparent overall detrimental effect. All farms in the 8-farm study and all sites in the fertilization experiment except the LF cylinders had P levels which were rated very high, thus benefits might not be expected. The LF cylinders had a very low level of soil P, but apparently adequate leaf P, which could be a result of mycorrhizal infection. However, as discussed in chapter 4, nodulation was still severely P limited, yields were low and only P fertilization produced yields approaching those that would be commercially acceptable.

Many researchers have shown significant positive effects of mycorrhizae on nodulation and Barea and Azcon-Aguillar (1983) and Linderman (1992) suggest that the two systems need to be "optimized" for maximum benefit. However the results of my study suggest that it is very difficult to simultaneously optimize conditions for both symbionts as levels of P, K required for maximum nodulation inhibited mycorrhizae. Barea and Azcon-Aguillar (1983) suggest that applying P as rock-P is a way to overcome the incompatibility of mycorrhizal infection and nodulation in regard to P supply, and they review studies indicating that mycorrhizae can effect improved P nutrition in the presence of rock-P in acid soils. However the cylinder studies did not demonstrate any benefits from adding rock-P, even though the LF cylinder was P deficient, and the soil pH was at 6.3.

I conclude that under conditions in eastern Canada, variation in mycorrhizal infection at levels above about 10% is not likely to be a factor influencing success of fababean.

On the other hand, the growth chamber experiments suggest there may be benefits to a certain minimum level of mycorrhizal infection which is below that found in most field sites. Thus, while variation in mycorrhizal infection at the levels observed on these farms is not a significant factor, it could be that any practices that interfered with mycorrhizae more extremely (e.g. fungicides), could have significant detrimental effects.

Experimental studies did demonstrate positive effects of high levels of N on pests and weeds, and likely these are factors in some farming systems. However, except at Farm 2, pests were not a factor in yield variation on farms.

I had postulated that low K might be a factor in low yields, and the field studies support that contention. However the mechanism is not through effects on pests and diseases as I had hypothesized, but appear to be related more fundamentally to overall production. The field and experimental studies provide the basis for preliminary estimates of the critical and maximum normal levels of K in fababean leaves, and these appear to be substantially higher than those reported for other legumes. Because of the susceptibility of organic farming systems to K deficiency (Nolte and Werner, 1994; Lampkin, 1990), this factor may be very important for organic farming systems.

This study included both observational (correlational) and experimental approaches to the question of what causes yield variability in fababean. Each approach has its own benefits and drawbacks. Correlational studies deal with real conditions, but it is logically difficult to make confident conclusions about causal relationships. Experimental studies are logically more powerful, however, they alter the real conditions and for practical reasons, often can be conducted at only a few sites. There appear to have been few studies of the multifarm type such as I conducted in PEI. Letourneau et al. (1996) conducted a multifarm study of insect damage to tomatoes in which they planted a single variety of tomato in 20 subplots distributed over 17 commercial farms representing a wide variety of management practices. They had expected to find a relationship

between N level and pest damage as this had been demonstrated repeatedly in experiments. Tissue N and pest damage did vary but they were weakly negatively correlated (rather than positive as predicted), and transplant date was a much better predictor of insect damage. They remarked that those results "do not extend logically from experimental studies with a wide range of herbivorous insects attacking tomato or other solanaceous crops", and comment that " the results of controlled experiments which isolate single variable effects may not provide realistic assessment of process dependent characteristics such as herbivore damage, which are sensitive to complex, interacting factors at the scale of whole-farm management decisions".

Similarly if I relied totally on the experimental studies, I would have concluded that weeds and pests are increased by N as hypothesized, and there is some response to K; the inhibitory effects of fertilizers on mycorrhizae would have confirmed part of my hypothesis concerning myocrrhize, and the growth chamber experiment showed that mycorrhizae do have critical effects on yields. However, only the field study of 8-farms could put these factors in perspective; they showed that variation in K was the major factor in fababean yield variation in practice, and pointed to an explanation not originally hypothesized, i.e., that it was related to an exceptionally high requirement for K. The leaf nutrient data were particularly useful because they served both to indicate variation in soil nutrient status between farms, and the likelihood of nutrient limitation could be inferred from the absolute values. Correlations of yield with leaf K provided independent evidence that K was likely limiting on certain farms. The observations on nodules and mycorrhizae provided further circumstantial evidence regarding the mechanism of K limitation, i.e., that it was not related to nodulation or mycorrhizae. I concluded partially by default, and partially based on general knowledge of K effects on crops, that the K effects on yield are likely related to its overall role in plant growth, especially to leaf expansion and drought tolerance. This would still have to be confirmed by experiments,

such as those of Hanway and Johnson (1985) in which soybean yields were examined under factorial combinations of droughtiness and K. However, the multifarm study was crucial to identify which of many possible mechanisms causing yield variability might be operative, or likely are not operative.

The finding that variation in K was a major factor in variation in yields between farms is of particular relevance to organic farming because of the relatively high amounts of K needed to replace inevitable losses from farms and a general scarcity of acceptable forms of K that can be used as inputs to replace lost K (Lampkin, 1990). By affecting legume function, lack of K might also affect inputs of N by N_2 fixation, or production of leguminous forages. Budgets for mixed organic farms for K indicated net annual losses from whole farms of 7 (Kaffka and Koepf, 1989), 37 (Abboud, 1992), 47 (Patriquin et al., 1986), and 65 (Nolte and Werner, 1994) kg K ha^{-1} yr^{-1} for farms in Germany, Ontario, Nova Scotia, and Germany respectively. At the Ontario farm, soil K was ranked as low and alfalfa leaf tissue K was below the critical level. At the Nova Scotian farm, cereals did not respond to K and soil K actually increased between 1981 and 1985 (Patriquin et al., 1986); however, sampled in 1990 for this study, soil K was found to be low compared to 1985 and fababean responded to K fertilization. K on the German farm where the loss was 7 kg K $ha^{-1}yr^{-1}$ was maintained by importation of straw and compost; at the second German farm (losses 65 kg K ha^{-1} yr^{-1}), it was recognized that K was likely to limit crop growth.

Interestingly on the PEI farms, K was not indicated as limiting for the longest standing organic farm (PEI F8) where compost had been regularly applied; it also had the highest yield for fababean. The fababean field on Farm 7, which had the highest soil K had received the most consistent applications of manure in the past. According to Wild (1988) "large applications of farmyard manure are more valuable than fertilizers for building up the relatively high concentration of potassium ions in the solution", because

of the salt effects of K fertilizers. Interestingly, of the three farms with the highest leaf K, PEI F7 was exceptional in that high K was not associated with low levels of Ca, Mg, and micronutrients. PEI F4 and PEI F6 had more recent histories of intensive use of fertilizers than PEI F7. PEI F7 also had more moderate level of leaf P than most farms, and had the highest mycorrhizal infection.

Thus it seems that the regular applications of manure or compost (produced on the farms) has served to maintain K adequately for fababean on two of the PEI farms. However, as whole systems, they can still be expected to be prone to K deficiencies if K is not imported. The budgets of Nolte and Werner (1994) indicate that the greatest losses of K in mixed organic farms are apt to occur in manure handling; they suggest in the case of a farm losing 65 kg ha^{-1} yr^{-1}, optimizing the composting process could reduce whole farm losses to circa 10 kg ha^{-1} yr^{-1}.

The lowest K levels and lowest yield occurred on the 3 farms where hay had been grown before fababean; as discussed (Section 3.6.4), this makes sense in view of the known high uptake of K by hay crops. Thus either fababean should not be grown after hay, or farmers should ensure that there is adequate K for fababean. There could be other reasons that fababean did not do well following hay as well, which still need to be investigated.

7. Appendix Tables

Appendix Table 1. Seasonal rainfall and temperature data for Charlottetown, PEI in 1989 and for Nappan, N.S. and Kentville, N.S. in 1990.

	Rainfall (mm)					
Months [a]	PEI 1989	PEI Avg. prev. 81 years	Nappan 1990	Nappan Avg.prev. 30 years	Kentville 1990	Kentville Avg. prev. 30 years
May	117.2	81.1	231.5	74.5	198	102.2
June	58.6	78.5	41.4	78.3	31	88.9
July	80.6	77.7	112.4	84.4	79	97.6
August	70.4	87.1	101.1	91.1	32	105.3
Total	326.8	324.4	486.4	328.3	340	394

	Temperature (°C)					
Months	PEI 1989	PEI Avg. prev. 81 years	Nappan 1990	Nappan Avg.prev. 30 years	Kentville 1990	Kentville Avg. prev. 30 years
May	13.3	9.3	8.4	9.2	9.4	10.4
June	15.1	14.8	15.9	14.7	17.3	15.9
July	18.2	19.0	18.8	18.0	20.6	19.2
August	19.2	18.5	19.6	17.4	20.7	18.4
Total	65.8	61.6	62.7	59.3	68	63.9

[a] Rainfall and temperature records for PEI are averages for previous 8 years (1910-1990) and for Nappan and Kentville (Nova Scotia) are averages for previous 30 years (1951-1980). PEI data from Agriculture Canada, Research Summary 1990. Research Station Charlottetown. P.E.I., and NS data from Environment Canada, Atmospheric Environment Service, A Publication of the Canadian Climate Program. UDC: 551.582(715/9).

Appendix Table 2. Comparisons of fababean yields on October 3 with those on August 27 and 28, 1989.

FARM & VARIABLE	October	August
FARM 1		
Grain g m^{-2}	220	124
Pods g m^{-2}	285	151
Stem+leaves g m^{-2}	317	340
ratio Oct./Aug. for Grain	1.774	
FARM 2		
Grain g m^{-2}	127	48.1
Pods g m^{-2}	162	61.7
Stem+leaves g m^{-2}	116	102
ratio Oct./Aug. for Grain	2.640	
FARM 3		
Grain g m^{-2}	306	189
Pods g m^{-2}	381	247
Stem+leaves g m^{-2}	154	185
ratio Oct./Aug. for Grain	1.619	
FARM 4		
Grain g m^{-2}	440	280
Pods g m^{-2}	593	347
Stem+leaves g m^{-2}	353	471
ratio Oct./Aug. for Grain	1.571	
FARM 7		
Grain g m^{-2}	360	298
Pods g m^{-2}	457	397
Stem+leaves g m^{-2}	211	364
ratio Oct./Aug. for Grain	1.208	

Appendix Table 3. Family-wise error rates.

Formula for calculating family-wise error rate: [a]

family-wise error rate: $\alpha = 1 - (1 - \alpha')^c$

α' represents error rate for any one comparison.
c represents the number of comparisons.

Values of the correlation coefficient, r, for different levels of significance at 6 degree of freedom:

r	probability
.622	0.1
.707	0.05
.834	0.01
.925	0.001

Desired error rate	α values to use when considering > 1 correlation (6 degrees of freedom)	
	5 comparisons	10 comparisons
0.05	0.0103	0.0052
0.1	0.069	0.0105

[a] According to Howell, 1982, p 326.

Appendix Table 4. Comparisons of fababean yields, weeds, stem density, and mid-season crop and root variables between the minus and the plus weed plots on 8 individual farms.

FARM & VARIABLE	MINUS WEEDS	PLUS WEEDS	Probability	CV%
FARM 1				
Grain g m^{-2}	125	123	0.482(1)[b]	64.0
Grain+pods g m^{-2}	166	151	0.434(1)	63.0
Stem+leaves g m^{-2}	490	340	0.059(1)	56.7
Crop g m^{-2} a	656	491	0.160(1)	27.8
Weeds g m^{-2}	30.3	146	0.001(1)	38.9
Crop+weeds g m^{-2}	686	637	0.774(2)	23.7
Stem density m^{-2}	40.3	48.3	0.169(2)	10.5
Mid-season crop g m^{-2}	48.5	27.9	0.036(1)	19.7
Roots g m^{-2}	36.7	26.1	0.096(1)	21.2
FARM 2				
Grain g m^{-2}	138	48.1	0.173(1)	86.7
Grain+pods g m^{-2}	195	61.8	0.175(1)	88.9
Stem+leaves g m^{-2}	217	102	0.148(1)	84.4
Crop g m^{-2}	412	164	0.133(1)	84.1
Weeds g m^{-2}	75.1	225	0.011(1)	22.6
Crop+weeds g m^{-2}	487	389	0.217(2)	58.7
Stem density m^{-2}	19.0	16.3	0.631(2)	33.5
Mid-season crop g m^{-2}	49.9	61.7	0.274(1)	16.5
Roots g m^{-2}	75.9	50.2	0.212(1)	25.4
FARM 3				
Grain g m^{-2}	214	189	0.153(1)	21.0
Grain+pods g m^{-2}	301	247	0.058(1)	21.2
Stem+leaves g m^{-2}	243	185	0.032(1)	19.3
Crop g m^{-2}	544	432	0.039(1)	19.1
Weeds g m^{-2}	2.88	11.5	0.001(1)	56.1
Crop+weeds g m^{-2}	547	444	0.099(2)	18.9
Stem density m^{-2}	26.3	23.7	0.604(2)	21.4
Mid-season crop g m^{-2}	64.9	64.0	0.466(1)	26.7
Roots g m^{-2}	67.9	55.4	0.046(1)	30.5

Appendix Table 4. (continued).

FARM & VARIABLE	MINUS WEEDS	PLUS WEEDS	Probability	
FARM 4				
Grain g m^{-2}	264	281	0.357(1)	29.6
Grain+pods g m^{-2}	339	347	0.445(1)	29.7
Stem+leaves g m^{-2}	556	471	0.076(1)	14.8
Crop g m^{-2}	895	818	0.249(1)	20.1
Weeds g m^{-2}	31.9	21.0	0.325(1)	18.0
Crop+weeds g m^{-2}	926	838	0.482(2)	23.0
Stem density m^{-2}	34.7	40.3	0.173(2)	8.9
Mid-season crop g m^{-2}	73.6	52.9	0.054(1)	29.3
Roots g m^{-2}	74.9	63.1	0.105(1)	18.7
FARM 5				
Grain g m^{-2}	268	327	0.169(1)	35.4
Grain+pods g m^{-2}	336	396	0.202(1)	35.3
Weeds g m^{-2}	2.16	135	0.017(1)	36.7
Stem+leaves g m^{-2}	290	327	0.302(1)	36.1
Crop g m^{-2}	626	723	0.240(1)	37.7
Crop+weeds g m^{-2}	628	858	0.162(2)	37.2
Mid-season crop g m^{-2}	48.7	68.7	0.055(1)	21.1
Stem density m^{-2}	41.0	25.3	0.162(2)	26.6
Roots g m^{-2}	86.7	94.8	0.338(1)	19.9
FARM 6				
Grain g m^{-2}	305	239	0.129(1)	36.3
Grain+pods g m^{-2}	385	311	0.179(1)	36.0
Stem+leaves g m^{-2}	325	234	0.030(1)	29.8
Crop g m^{-2}	710	545	0.058(1)	28.9
Weeds g m^{-2}	46.9	194	0.001(1)	27.6
Crop+weeds g m^{-2}	757	739	0.874(2)	26.8
Stem density m^{-2}	20.7	23.7	0.478(2)	19.5
Mid-season crop g m^{-2}	75.7	60.4	0.047(1)	30.7
Roots g m^{-2}	81.6	74.3	0.363(1)	41.2

Appendix Table 4. (concluded).

FARM & VARIABLE	MINUS WEEDS	PLUS WEEDS	Probability	CV%
FARM 7				
Grain g m^{-2}	319	298	0.327(1)	27.5
Grain+pods g m^{-2}	426	397	0.291(1)	27.5
Stem+leaves g m^{-2}	445	364	0.029(1)	21.8
Crop g m^{-2}	871	761	0.117(1)	24.2
Weeds g m^{-2}	40.3	593	0.001(1)	61.7
Crop+weeds g m^{-2}	911	1354	0.001(2)	15.4
Stem density m^{-2}	28.7	26.7	0.635(2)	15.9
Mid-season crop g m^{-2}	102	101	0.474(1)	28.9
Roots g m^{-2}	105	96.9	0.328(1)	30.6
FARM 8				
Grain g m^{-2}	423	262	0.086(1)	55.3
Grain+pods g m^{-2}	529	350	0.069(1)	55.2
Stem+leaves g m^{-2}	341	329	0.444(1)	55.1
Crop g m^{-2}	870	679	0.159(1)	53.7
Weeds g m^{-2}	11.9	38.1	0.016(1)	72.3
Crop+weeds g m^{-2}	882	717	0.394(2)	53.5
Stem density m^{-2}	28.3	33.0	0.538(2)	25.3
Mid-season crop g m^{-2}	70.9	62.5	0.138(1)	29.7
Roots g m^{-2}	72.3	68.8	0.402(1)	26.1

[a] Crop = grain + pods +stems + leaves.
[b] Probability of Type I error; numbers in parentheses indicate one or two tail t tests.

Appendix Table 5. Values of fababean leaf nutrients and ratios of leaf K to leaf N for the 8 farms in PEI.

LEAF NUTRIENT	F1	F2	F3	F4	F5	F6	F7	F8
MINUS WEEDS								
N g kg^{-1}	.520	.540	.490	.610	.600	.590	.630	.550
P g kg^{-1}	.052	.054	.056	.040	.056	.034	.048	.048
K g kg^{-1}	.110	.150	.180	.340	.220	.420	.360	.270
Ca g kg^{-1}	.207	.114	.191	.040	.106	.040	.123	.135
Mg g kg^{-1}	.066	.041	.070	.021	.043	.019	.037	.040
S g kg^{-1}	.010	.012	.022	.012	.016	.011	.023	.019
Zn mg kg^{-1}	44.0	64.0	42.0	21.0	44.0	21.0	79.0	31.0
Mn mg kg^{-1}	164	146	95.0	47.0	60.0	37.0	90.0	98.0
Fe mg kg^{-1}	98.0	97.0	105	43.0	98.0	58.0	106	104
Cu mg kg^{-1}	20.0	10.0	6.00	4.00	11.0	5.00	5.00	3.00
B mg kg^{-1}	32.0	52.0	30.0	23.0	64.0	28.0	48.0	32.0
K/N	0.212	0.278	0.367	0.557	0.367	0.700	0.571	0.491
PLUS WEEDS								
N g kg^{-1}	.550	.550	.600	.650	.510	.610	.540	.540
P g kg^{-1}	.055	.046	.054	.068	.061	.044	.034	.056
K g kg^{-1}	.110	.140	.180	.220	.230	.280	.340	.240
Ca g kg^{-1}	.149	.098	.128	.096	.108	.036	.167	.092
Mg g kg^{-1}	.051	.038	.051	.035	.043	.017	.045	.033
S g kg^{-1}	.013	.009	.018	.022	.016	.011	.021	.011
Zn mg kg^{-1}	50.0	54.0	41.0	56.0	45.0	27.0	88.0	36.0
Mn mg kg^{-1}	156	139	80.0	79.0	64.0	100	115	79.0
Fe mg kg^{-1}	102	89.0	98.0	105	119	72.0	104	90.0
Cu mg kg^{-1}	20.0	10.0	7.00	18.0	11.0	4.00	5.00	3.00
B mg kg^{-1}	53.0	25.0	29.0	40.0	73.0	23.0	36.0	36.0
K/N	0.200	0.255	0.300	0.338	0.451	0.459	0.629	0.444

Appendix Table 6. Correlations of yield variables with leaf nutrients. r values of 0.75 or greater are underlined.

VARIABLE	Grain	Crop	Weeds	Mid-season crop
MINUS WEEDS				
Leaf N	.459	.608	.164	.564
leaf P	-.410	-.565	-.308	-.507
leaf K	.685	.672	.107	.783 (.801)a
Leaf Ca	-.377	-.345	-.338	-.316
Leaf Mg	-.485	-.480	-.402	-.436
Leaf S	.466	.217	-.468	.537
Leaf Zn	-.269	-.261	.317	.189
Leaf Mn	-.601	-.467	.268	-.433
Leaf Fe	-.064	-.330	-.247	-.135
Leaf Cu	-.749 (.905)	-.468	.064	-.675
Leaf B	-.126	-.388	.053	-.410

Appendix Table 6. (concluded).

VARIABLE	Grain	Crop	Weeds	Mid-season crop
PLUS WEEDS				
Leaf N	.001	.090	-.374	-.250
leaf P	.172	.277	-.838 (.879)	-.585
leaf K	.777 (.884)	.645	.549	.803 (.834)
Leaf Ca	-.039	.107	.424	.210
Leaf Mg	-.186	-.090	.068	-.033
Leaf S	.580	.664	.176	.377
Leaf Zn	.112	.245	.760	.553
Leaf Mn	-.753 (.959)	-.564	.406	-.312
Leaf Fe	.374	-.440	.033	.113
Leaf Cu	-.256	.021	-.277	-.670
Leaf B	.398	.435	-.097	-.157

[a] Number in brackets is r value between residuals from regressions of each of the two variables on stem density.

Appendix Table 7. Correlations of fababean yields with roots, mycorrhizae, and nodules. r values of 0.75 or greater are underlined.

VARIABLE	Roots	Myc.	Nodules
	MINUS WEEDS		
Grain	.529	.515	.105
Crop	.274	.608	-.061
Weeds	.113	-.409	.266
Mid-season crop	.645	.644	.208
	PLUS WEEDS		
Grain	.804 (.870) [a]	.361	.466
Crop	.588	.244	.342
Weeds	.457	.701	.298
Mid-season crop	.839 (.946)	.840 (.792)	.403

[a] Number in brackets is r value between residuals from regressions of each of the two variables on stem density.

Appendix Table 8. Correlations of yields, weeds, and mid-season crop with soil variables. r values of 0.75 or greater are underlined.

VARIABLE	Grain	Crop	Weeds	Mid-season crop
MINUS WEEDS				
CO_2-C	.605	.377	.158	.535
SNO_3^--N	.737	.759	- .157	.763
SOM	.469	.302	- .926	.077
Clay	.087	- .338	.399	.147
Sand	.405	.475	- .469	- .077
Silt	- .476	- .335	.297	- .007
CEC	.144	.108	.380	.517
pH	.118	.198	- .477	- .079
BS	.030	.199	- .796	- .332
Total K+Ca+Mg	.171	.246	- .002	.457
P	.628	.864	- .202	.445
K	.516	.704	.020	.845
Ca	.173	.256	.180	.459
Mg	- .183	- .260	- .630	- .217
S	.553	.283	.057	.439
Zn	- .532	- .063	.078	- .359
Mn	- .683	- .428	.636	- .456
Fe	- .357	- .166	.249	- .253
Cu	- .526	- .093	.035	- .559
B	- .027	.024	- .288	- .629

Appendix Table 8. (concluded).

VARIABLE	Grain	Crop	Weeds	Mid-season crop
PLUS WEEDS				
CO_2-C	.334	.240	.662	.559
SNO_3^--N	.886	.825	.395	.638
SOM	.770	.632	- .186	.263
Clay	- .066	- .314	.676	.619
Sand	.251	.379	- .319	- .446
Silt	- .234	- .244	.005	.160
CEC	.309	.155	.438	.481
pH	.345	.326	- .257	- .378
BS	.243	.371	- .609	- .381
Total K+Ca+Mg	.564	.444	.194	.427
P	.619	.794	- .016	.191
K	.640	.685	.678	.774
Ca	.466	.367	.208	.329
Mg	.264	.130	- .253	.158
S	.622	.433	.455	.806
Zn	- .406	- .145	- .008	- .687
Mn	- .849	- .633	.031	- .471
Fe	- .436	- .257	- .186	- .152
Cu	- .061	.116	- .263	- .591
B	- .022	.110	- .392	- .510

Appendix Table 9. Correlations of leaf nutrients with roots, mycorrhizae, and nodules. r values of 0.75 or greater are underlined.

VARIABLE	Roots	Myc.	Nodules
		MINUS WEEDS	
Leaf N	.729	.162	-.18
Leaf P	-.19	.156	-.298
Leaf K	.658	.179	.179
Leaf Ca	-.545	.254	.164
Leaf Mg	-.565	.138	.044
Leaf S	.508	.820(.898) a	-.052
Leaf Zn	.355	.305	.056
Leaf Mn	-.581	-.037	.177
Leaf Fe	-.023	.358	.187
Leaf Cu	-.666	-.449	.100
Leaf B	.443	-.095	-.189
		PLUS WEEDS	
Leaf N	-.242	.092	.147
Leaf P	-.256	-.721	-.469
Leaf K	.876(.867)	.786(.782)	.781(.765)
Leaf Ca	-.073	.19	-.482
Leaf Mg	-.261	-.142	-.733
Leaf S	.366	.381	-.105
Leaf Zn	.273	.553	-.192
Leaf Mn	-.602	-.059	-.237
Leaf Fe	.226	-.223	-.603
Leaf Cu	-.562	-.633	-.708
Leaf B	.188	-.527	-.400

[a] Number in brackets is r value between residuals from regressions of each of the two variables on stem density.

Appendix Table 10. Correlations between soil and leaf macronutrients. r values of 0.75 or greater are underlined.

VARIABLE	Leaf N	Leaf P	Leaf K	Leaf Ca	Leaf Mg	Leaf S
			MINUS WEEDS			
SNO_3^--N	.874	-.570	.895	-.638	-.690	.320
P	.584	-.335	.446	-.385	-.494	.149
K	.777	-.239	.615	-.309	-.427	.527
Ca	.661	-.674	.779	-.795	-.695	-.125
Mg	-.151	.599	-.316	.266	.452	.442
S	.788	-.137	.572	-.608	-.627	.353
			PLUS WEEDS			
SNO_3^--N	.131	-.155	.940	-.141	-.425	.525
P	.118	.354	.430	.053	-.158	.458
K	-.056	-.348	.807	.372	.004	.660
Ca	.568	-.097	.580	-.417	-.527	.433
Mg	-.041	.398	-.114	.362	.609	.551
S	-.252	-.227	.753	-.150	-.333	.240

Appendix Table 11. Correlations for soil variables with roots and symbiont variables. r values of 0.75 or greater are underlined.

VARIABLE	Roots	Myc.	Nodules
		MINUS WEEDS	
CO_2-C	.518	.214	.623
SNO_3^--N	.758	.393	-.048
SOM	.223	.415	-.282
Clay	.594	-.160	.443
Sand	-.473	.095	.338
Silt	.201	-.020	-.585
CEC	.659	-.226	.175
pH	-.315	-.279	.372
BS	-.460	.368	-.565
Total K+Mg+Ca	.613	-.035	-.239
P	.270	.590	-.452
K	.739	.704	-.159
Ca	.557	-.189	-.067
Mg	.103	.219	-.635
S	.938	.225	-.245
		PLUS WEEDS	
CO_2-C	.561	.557	.742
SNO_3^--N	.847	.597	.674
SOM	.536	-.030	.077
Clay	.495	.412	.332
Sand	-.178	-.324	.289
Silt	-.062	.136	-.476
CEC	.540	.532	.565
pH	-.020	-.290	.357
BS	-.219	-.504	-.515
Total K+Mg+Ca	.592	.382	.333
P	.349	.196	.166
K	.699	.773	.357
Ca	.509	.368	.464
Mg	.204	-.154	-.515
S	.927	.485	.367

Appendix Table 12. Correlations between soil and leaf micronutrients. r values of 0.75 or greater are underlined.

VARIABLE	Leaf B	Leaf Cu	Leaf Zn	Leaf Mn	Leaf Fe
			MINUS WEEDS		
Zn	-.215	.845	-.009	.598	.070
Mn	.043	.569	.316	.824	.128
Fe	.045	.065	.246	.483	.088
Cu	.098	.612	-.246	.044	-.425
B	.238	.495	-.176	.342	.198
			PLUS WEEDS		
Zn	.291	.650	.014	.706	.072
Mn	-.141	.509	.193	.814	- .092
Fe	-.064	.427	.348	.199	.290
Cu	.626	.898	-.007	.155	.477
B	.689	.436	-.212	.019	.410

Appendix Table 13. Estimation of percent of crop N derived from soil.

Farm	Crop N[a] (kg N ha^{-1})	Weed N[b] (kg N ha^{-1})	Incub. N[c] (µg NO_3-N $g\ soil^{-1}$ $7\ days^{-1}$)	Field N[d] (µg NO_3-N $g\ soil^{-1}$)	Available soil N[e] (kg ha^{-1})	Percent of crop N from soil[f]
Farm 1	132	6.4	9.5	6.7	80.5	56.3
Farm 2	115	16.1	9.1	6.7	77.6	53.4
Farm 3	159	0.6	7.6	11.3	75.0	46.8
Farm 4	213	6.9	15.6	11.3	133	59.0
Farm 5	182	0.5	14.3	11.3	123	67.6
Farm 6	204	10.0	15.9	11.3	135	61.0
Farm 7	239	8.7	19.1	11.3	158	62.5
Farm 8	261	2.6	12.6	11.3	111	41.6

[a] kg N ha^{-1} in crop = kg ha^{-1} (grain+pod) x 3.92%N + kg ha^{-1} (stem+leaf) x 1.25%N+ kg ha^{-1} roots x 1.55%N (%N values from Patriquin et al. 1981,1986)

[b] kg N ha^{-1} in weeds = kg ha^{-1} weeds x 1.79%N x 1.2. (%N values and factor of 1.2 to account for root N in weeds from Patriquin et al. 1981,1986)

[c] NO_3-N released during 7 day incubation

[d] NO_3-N in field June 13-15

[e] Assuming bulk density of 1.2; soil depth of 15 cm and total mineralized N is field N + 4 x N released in 7 day incubation

[f] (Available Soil N - weed N)/crop N x 100

Appendix Table 14. Fababean nodule biomass and acetylene reduction at various locales.

Locales	Nodule dry wt mg, pl^{-1}	ARA [a] $\mu mol\ C_2H_4\ pl^{-1}\ h^{-1}$	Reference
Nova Scotia;			Patriquin, unpublished data
farm 1	453	35.7	
farm 2	434	34.3	
farm 3	210	29.0	
farm 4	200	19.4	
farm 5 [b]	110	8.4	
Winnipeg, Canada	-	18.2-22.1	Candlish and Clark, 1975
Winnipeg, Canada	-	15.0-18.0	Dean and Clark, 1980
UK	270-370	-	Sorwli and Mytton, 1986
UK		24-35	Sprent, 1977
Scotland	390	30.0	Sprent and Bradford, 1977
Australia	260-300	12.8-24.7	Herdina and Silsbury, 1990
Australia	-	50.0	Herdina and Silsbury,1990
Spain	80-240		Caba et al., 1990
PEI, 8 farms	183-875	-	Present study
PEI, Farm 7	284	39.3	Present study
PEI, Fram 8	226	22.4	Present study

[a] ARA = acetylene reduction activity.
[b] Averages for 3 assays of 2 plants in jars, sampled from July 12 to 26 1977.

Appendix Table 15. Effects of fertilizers (N, P, K) on fababean and weed biomass at PEI Farm 7 (Means are average values for 6 plots, harvested on August 30, 1989).

Treats	Grain+ pods	Stem+ leaves	Crop	Weeds	Crop+ weeds	Stem density
	----------g m^{-2}----------					m^{-2}
C	375.7	303.9	679.6	422.3	1101.9	33
N	359.9	342.8	702.7	474.3	1177.0	32
P	321.7	310.9	632.6	181.3 *a	813.9 **	31
K	404.7	354.6	759.3	303.7	1062.9	33
F(3, 15)=	0.309	0.363	0.355	3.394	5.490	0.235
Prob. =	.819	.780	.786	.046	.009	.870
CV%	41.7	30.3	31.2	50.3	15.8	15.8

a *, **, significantly different from control values at $\alpha = 0.05, 0.01$ respectively.

Appendix Table 16. Effects of fertilizers (N, P, K) on fababean mid-season crop, roots, nodules, mycorrhizal infection, and chocolate spot at PEI Farm 7 (Means are average values for 6 plots).

Treats	Mid-season crop	Roots	Nodule (FW)	AR[a] per plan (AR per g nodule)	Myc.	Chocolate spot
	---------g m^{-2}-------		g $plant^{-1}$		%	Average rating
C	457.8	393.9	1.18	39.3 (34.7)	44.7	2.17
N	355.5+[b]	337.2	0.57**	14.4 (32.7)	35.9	2.58
P	440.6	410.4	1.03	32.9 (33.9)	27.8*	3.00
K	393.6	374.5	0.99	23.9 (26.2)	34.9	2.25
F(3, 15)=	1.366	0.305	4.598	3.351 (0.271)	1.579	0.653
Prob. =	.291	.821	.018	.047 (.845)	.236	.593
CV%	23.6	36.8	31.6	52.5 (57.4)	37.8	59.5

[a] Acetylene reduction.

[b] +, **, significantly different from control values at α = 0.1, 0.01 respectively.

Appendix Table 17. Effects of fertilizers (N, P, K) on fababean leaf macronutrients at PEI Farm 7 (Means are average values for 6 plots).

Treats	N	P	K	Ca	Mg	S
	----------g kg^{-1}----------					
C	.560	.042	.343	.138	.041	.027
N	.568	.044	.333	.139	.041	.024+[a]
P	.563	.041	.340	.136	.040	.026
K	.587+	.044	.338	.140	.042	.028
F(3, 15)=	1.379	1.000	0.472	0.215	0.853	2.514
Prob. =	.287	.419	.707	.884	.487	.098
CV%	4.3	9.3	4.2	7.2	4.4	10.6

[a] +, significantly different from control value at $\alpha = 0.1$.

Appendix Table 18. Effects of fertilizers (N, P, K) on fababean leaf micronutrients at PEI Farm 7 (Means are average values for 6 plots).

Treats	B	Cu	Zn	Mn	Fe
	----------	----------	mg kg^{-1}	----------	----------
C	46.7	9.50	98.5	133	103
N	48.0	9.17	95.5	131	106
P	48.3	9.17	93.8	131	100
K	49.5	9.50	91.5+[a]	132	108
F(3, 15)=	0.064	0.571	1.459	0.078	2.825
Prob. =	.978	.642	.266	.971	.074
CV%	23.5	6.68	6.29	6.92	4.97

[a] +, significantly different from control value at $\alpha = 0.1$.

Appendix Table 19. Effects of fertilizers (N, P, K) on fababean and weed biomass at PEI Farm 8 (Means are average values for 6 plots, harvested on August 29, 1989).

Treats	Grain+ pods	Stem+ leaves	Crop	Weeds	Crop+ weeds.	Stem density
	----------g m^{-2}----------					m^{-2}
C	244.9	243.6	488.5	66.4	554.9	31.0
N	192.6	217.5	410.1	80.5	490.6	28.3
P	208.4	283.9	492.3	51.1	543.4	32.8
K	280.9	365.4+[a]	646.3	56.0	702.3	29.0
F(3, 15)=	0.680	2.444	1.580	0.637	1.354	0.385
Prob. =	.578	.104	.236	.603	.295	.765
CV%	50.6	36.4	37.8	62.8	33.3	26.5

[a] +, significantly different from control value at $\alpha = 0.1$.

Appendix Table 20. Effects of fertilizers (N, P, K) on fababean mid-season crop, roots, nodule biomass, mycorrhizal infection, and chocolate spot at PEI Farm 8 (Means are average values for 6 plots).

Treats	Mid-season crop	Roots	Nodule (F.W)	AR[a] per plan (AR per g nodule)	Myc.	Chocolate spot
	----------g m^{-2}-------		g $plant^{-1}$		%	Average rating
C	278.2	162.9	1.03	22.5 (22.1)	34.9	2.08
N	221.5	126.3	0.56**[b]	17.1 (31.7)	16.5**	3.17
P	319.4	184.9	1.19	24.4 (23.6)	15.6**	1.75
K	316.5	155.3	1.12	22.6 (19.6)	28.2	3.00
F(3, 15)=	1.620	1.083	6.723	0.629 (1.35)	10.00	2.010
Prob. =	.227	.386	.004	.607 (.297)	.001	.160
CV%	30.9	36.2	27.4	44.9 (45.5)	30.4	59.6

[a] Acetylene reduction.

[b] **, significantly different from control value at $\alpha = 0.01$.

Appendix Table 21. Effects of fertilizers (N, P, K) on fababean leaf macronutrients at PEI farm 8 (Data are from 6 plot combined).

Treats	N	P	K	Ca	Mg	S
	----------g kg^{-1}----------					
C	.53	.059	.26	.14	.046	.025
N	.52	.053	.25	.16	.045	.018
P	.57	.056	.23	.13	.043	.022
K	.56	.051	.24	.14	.0.3	.023

Appendix Table 22. Effects of fertilizers (N, P, K) on fababean leaf micronutrients at PEI F8 (Data are from 6 plots combined).

Treats	B	Cu	Zn	Mn	Fe
	----------mg kg^{-1}----------				
C	38	5.0	49	116	87
N	36	5.0	47	143	93
P	38	4.0	48	110	94
K	37	4.0	42	115	94

Appendix Table 23. Effects of weeds on fababean yields at different fertilizer (N, P, K, Ca) treatments at final season (means average of 6 replicates) at the NS 1 site.

Treats [a]	Grain+ pods	Stem+ leaves	Crop	Weeds	Crop+ weeds	Stem density
			g m^{-2}			m^{-2}
C -w	212.2	71.2	283.5	224.4	507.9	26.2
+w	131.2	113.6	244.8	372.6	617.4	22.2
F(1 ,5)=	9.949	2.849	0.767	4.971	1.208	1.224
Prob.=	.025	.152	.421	.076	.321	.319
CV%	25.9	47.0	28.9	38.6	30.7	14.8
N -w	237.9	129.8	367.7	255.7	623.4	28.3
+w	59.2	71.8	131.0	335.9	466.9	14.7
F(1 ,5)=	32.7	4.863	17.75	2.92	4.45	23.2
Prob.=	.002	.079	.008	.049	.088	.005
CV%	36.4	45.2	39.1	27.5	23.6	22.8
P -w	316.4	173.6	490.0	184.9	674.9	33.0
+w	213.1	168.9	382.0	227.1	609.1	31.8
F(1 ,5)=	3.12	0.011	1.136	0.617	0.317	0.177
Prob.=	.137	.922	.335	.468	.598	.692
CV%	38.3	45.1	40.2	45.2	31.5	14.8
K -w	389.9	182.0	571.9	220.3	792.2	30.5
+w	199.8	129.5	329.3	229.8	559.1	22.2
F(1 ,5)=	14.5	1.23	6.85	0.03	4.54	2.56
Prob.=	.013	.318	.047	.863	.086	.123
CV%	29.4	52.7	35.6	40.2	28.0	16.8
Ca -w	245.1	129.6	374.7	277.4	652.2	33.2
+w	130.2	98.5	228.7	344.1	572.8	28.0
F(1 ,5)=	2.78	2.16	3.14	0.745	0.41	3.56
Prob.=	.157	.202	.136	.428	.552	.118
CV%	63.6	32.2	47.2	43.0	35.2	15.5

Appendix Table 24. Effects of fertilizers on fababean yields, weed, and stem density at final season in the minus weed plots. (average of 6 replicates). NS 1 3-way ANOVA.

Treats	Grain+ pods	Stem+ leaves	Crop	Weeds	Crop+ weeds	Stem density
	----------g m^{-2}----------					m^{-2}
C	212.2	71.2	283.4	224.4	507.8	26.2
N	237.9	129.8	367.7	255.7	623.3	28.3
P	316.4	173.6*	490.0+	184.9	674.9	33.0+
K	389.9*	182.0*	571.9*	220.3	792.2	30.5
Ca	245.1	129.6	374.7	277.4	652.2	33.2
F(4, 20)=	2.085	1.932	2.364	0.419	1.35	1.534
Prob.=	.121	.144	.088	.793	.286	.231
CV%	43.8	56.7	43.2	57.7	33.1	19.8
F * W						
F(4, 25)=	0.938	1.404	1.227	0.733	1.443	2.658
Prob.=	.4580	.2616	.3245	.578	.2493	.056
CV% of Mp	52.0	49.2	43.1	54.3	29.8	24.6
CV% of Sp, Sp*Mp	40.3	47.4	39.9	39.1	30.3	18.8

[a] +, *, **, significantly different from control values at α = 0.1, 0.05, 0.01 respectively.

Appendix Table 25. Effects of weeds on fababean mid-season crop and roots, nodule, myc. infection, and chocolate spot at different fertilizer treatments at mid-season. (average of 6 replicates). NS1

Treats	Mid-season crop	Roots	Nodules (F.W)	Myc.	Chocolate spot
	----------g m^{-2}--------		g $plant^{-1}$	%	Average rating
C -w	204.6	119.9	1.92	17.8	2.50
+w	110.4	69.4	1.05	20.4	2.67
F(1, 5)=	8.09	5.62	3.42	0.114	0.123
Prob.=	.036	.064	.182	.749	.865
CV%	36.5	38.9	17.2	69.3	16.5
N -w	205.6	109.1	1.25	7.60	2.58
+w	76.5	40.6	0.69	10.3	2.08
F(1, 5)=	18.3	32.0	2.17	0.585	0.974
Prob.=	.008	.002	.201	.479	.765
CV%	37.1	28.0	67.5	64.1	17.2
P -w	218.2	188.4	2.77	11.5	3.83
+w	193.5	139.9	2.19	10.5	3.42
F(1, 5)=	2.85	4.64	3.714	0.142	1.012
Prob.=	.152	.083	.162	.721	.678
CV%	12.3	23.7	17.2	43.9	18.3
K -w	219.4	204.7	4.04	16.1	2.83
+w	136.7	105.8	2.92	18.0	3.42
F(1, 5)=	13.86	55.4	1.846	0.298	1.21
Prob.=	.014	.0007	.232	.608	.543
CV%	21.6	14.8	41.0	37.4	15.2
Ca -w	200.3	151.9	2.89	11.7	3.25
+w	163.3	127.3	2.10	9.20	3.42
CV%	17.2	21.5	20.3	23.8	14.9

Appendix Table 26. Effects of fertilizers on fababean mid-season crop and roots, nodule, mycorrhizal infection, and chocolate spot at mid-season in the minus weed plots. (average of 6 replicates). NS1

Treats	Mid-season crop	Roots	Nodules	Myc.	Chocolate spot
	----------g m^{-2}------		g $plant^{-1}$	%	Average rating
C	204.7	119.9	1.92	17.8	1.30
N	205.6	109.1	1.25	7.75*	1.55
P	218.2	188.4**	2.77	11.5+	1.71+
K	218.2	204.7**	4.04**	16.0	1.37
Ca	200.2	151.9	2.89+	11.7	1.50
F(4, 20)=	0.168	7.99	4.09	2.52	1.56
Prob.=	.952	.0005	.014	.073	.305
CV%	51.2	28.3	49.7	47.8	19.6
F * W					
F(4, 20)	3.035	2.403	0.265	0.29	1.172
Prob.	.0361	.0767	.897	.879	.347
CV%, of Mp	28.1	83.4	62.3	49.3	23.2
CV% of Sp, Sp*Mp	24.7	70.1	35.4	56.2	18.4

[a] +, *, **, significantly different from control values at $\alpha =$ 0.1, 0.05, 0.01 respectively.

Appendix Table 27. Effects of weeds on fababean leaf nutrients at different fertilizer treatments at mid-season. (average of 6 replicates).

Treats	N	P	K	Ca	Mg
	g kg^{-1}				
C -w	.478	.045	.222	.085	.041
+w	.476	.044	.220	.095	.047
F(1, 5)=	0.009	0.561	0.048	8.423	54.56
Prob.=	.925	.487	.835	.0337	.0007
CV%	8.4	7.4	7.8	3.5	3.3
N -w	.481	.047	.219	.096	.045
+w	.476	.046	.215	.089	.047
F(1, 5)=	0.198	0.435	0.375	3.086	4.878
Prob.=	.675	.539	.567	.139	.078
CV%	4.2	8.1	6.5	7.0	3.8
P -w	.472	.042	.220	.084	.040
+w	.504	.040	.190	.079	.040
F(1, 5)=	1.423	5.033	10.26	6.13	0.002
Prob.=	.287	.075	.0239	.056	.971
CV%	9.8	5.2	8.4	4.2	3.7
K -w	.475	.040	.219	.082	.040
+w	.461	.0395	.202	.083	.040
F(1, 5)=	0.587	0.171	2.768	0.862	17.69
Prob.=	.478	.696	.157	.862	.008
CV%	7.1	8.4	8.2	6.6	4.1
Ca -w	.484	.044	.191	.084	.041
+w	.486	.040	.171	.088	.046
F(1, 5)=	0.021	1.16	3.578	0	3.729
Prob.=	.891	.331	.117	1.0	.111
CV%	5.8	23.8	9.6	6.9	88.0

Appendix Table 28. Effects of fertilizers on fababean leaf nutrients at mid-season. (average of 6 replicates).

Treats	N	P	K	Ca	Mg
	----------		g kg^{-1}		----------
C	.478	.045	.222	.085	.041
N	.481	.047	.219	.096**[a]	.045
P	.472	.042	.220	.084	.040
K	.475	.040	.219	.082	.039
Ca	.484	.044	.191*	.088	.041
F(4, 20)	0.147	1.399	1.948	3.874	1.455
Prob.	.962	.270	.142	.017	.253
CV%	6.48	12.5	10.8	7.29	10.8
F * W					
F(4, 25)	0.78	0.35	1.41	4.16	3.42
Prob.	.548	.838	.259	.0102	.023
CV% of Mp	7.58	10.4	18.1	11.5	14.7
CV% of Sp, Sp*Mp	7.32	10.4	8.1	7.02	5.17

[a] +, *, significantly different from control values at $\alpha =$ 0.1, 0.05 respectively.

Appendix Table 29. Effects of fertilizers (N, P, K, Ca) on fababean and weed biomass at NS2 (Means are average values for 4 plots, harvested on August 24, 1990).

Treats	Grain+ pods	Stem+ leaves	Crop	Weeds	Crop+ weeds	Stem density
	----------g m^{-2}----------					m^{-2}
C	65.6	342.5	408.1	95.9	504.0	34.3
N	77.0	286.4	363.4	116.3	479.7	32.3
P	54.6	312.7	367.3	189.6	556.9	28.5
K	81.6	281.2+[a]	362.8	202.6	565.4	25.8
Ca	112.8*	311.6	424.4	122.4+	546.8	33.0
F(4, 12)=	3.607	1.035	0.881	1.286	0.807	0.906
Prob.=	.038	.429	.504	.329	.544	.491
CV%	29.5	15.7	16.0	57.7	15.5	24.0

[a] +, *, significantly different from control values at $\alpha = 0.1, 0.05$ respectively.

Appendix Table 30. Effects of fertilizers (N, P, K, Ca) on fababean mid-season crop, roots, nodule biomass, mycorrhizal infection, and chocolate spot at NS2 site (Means are average values for 5 plots, sampled at mid-season 1990).

Treats	Mid-season crop	Roots	Nodules (F.W)	Myc.	Chocolate spot
	----------g m^{-2}--------		g $plant^{-1}$	%	Average rating
C	233.7	57.0	1.04	17.9	3.60
N	237.5	58.3	0.67	6.09**a	2.90
P	221.2	50.7	1.44	10.3+	2.60
K	195.8	51.3	1.83*	9.28*	2.90
Ca	228.1	61.4	1.52	16.0	3.00
F(4, 16)=	0.313	0.415	2.824	3.140	0.798
Prob.=	.865	.796	.073	.052	.234
CV%	28.1	28.7	37.6	53.5	18.6

[a] +, *, **, significantly different from control values at α = 0.1, 0.05, 0.01 respectively.

Appendix Table 31. Effects of fertilizers (N, P, K, Ca) on fababean leaf macronutrients at NS2 site (Means are average values for 5 plots, sampled at mid-season 1990).

Treats	N	P	K	Ca	Mg
	---------- g kg^{-1} ----------				
C	.482	.030	.234	.062	.033
N	.482	.029	.231	.066	.036+b
P	.466	.028	.220	.068	.034
K	.521	.025*a	.263*	.059	.032
Ca	.480	.031	.252	.060	.033
F(4, 16)=	0.817	2.402	5.170	2.390	1.932
Prob.=	.533	.093	.007	.094	.154
CV%	10.5	12.4	7.22	8.97	7.73

[a] +, *, significantly different from control values at α = 0.1, 0.05 respectively.

Appendix Table 32. Effects of fertilizers on fababean yields in the HF, LF systems at final season and mid-season crop.(average of 6 replicates).

Treats	Grain+ pods	Crop	Mid-season crop	Weeds	Crop+ weeds	Plant bug No. pl^{-1}
	---------- $g\ m^{-2}$ ----------					
HF.						
C	144.2	264.6	138.0	87.2	351.8	0.77
N	130.9	270.1	142.2	92.7	362.8	1.61**a
P	109.3	215.2	116.4	86.1	301.3	0.78
K	133.1	299.5	185.2+	58.5	358.0	0.56
Ca	119.8	237.4	124.3	120.3	357.7	1.00+
F(4, 20)	0.408	1.708	2.462	1.682	0.821	5.06
Prob.	.800	.187	.114	.194	.527	.006
CV%	40.2	23.5	35.2	46.7	19.9	3.1
LF						
C	48.8	111.5	70.5	24.3	135.8	0.056
N	81.5	152.5	76.4	35.3	187.8	0.062
P	103.2*	197.5**	111.1**	29.8	227.3*	0.094
K	85.9	165.8+	86.7+	23.2	189.0	0.093
Ca	57.7	124.8	74.2	44.2	169.0	0.062
F(4, 20)	2.00	2.496	4.023	0.256	1.301	0.210
Prob.	.133	.076	.021	.903	.303	.930
CV%	50.6	35.1	20.1	63.3	39.4	2.04

[a] +, *, ** significantly different from control values at α = 0.1, 0.05, 0.01 respectively.

Appendix Table 33. Effects of fertilizers on fababean yields in HF, LF systems at final season. (average of 6 replicates).

Treats	Grain+ pods	Crop	Mid-season crop	Weeds	Crop+ weeds	Plant bug No. pl^{-1}
	----------	----------	$g\ m^{-2}$	----------	----------	
HF	127.5	257.4	141.2	89.6	346.3	0.889
LF	74.5	150.4	83.8	31.3	181.8	0.111
HFvsLF						
F(1, 5)=	23.26	25.79	12.5	130.2	62.94	25.79
Prob.=	.0048	.0038	.0010	.0001	.0005	.004
CV%	44.6	47.6	36.7	37.3	36.9	12.5
Mp*Sp						
F(4, 40)=	1.27	2.08	1.970	0.36	1.45	3.363
Prob.=	.292	.0833	.091	.875	.222	.011
CV%	44.7	27.8	42.1	68.9	26.6	81.2

Appendix Table 34. Effects of fertilizers on leaf nutrients in LF and HF systems at mid-season. (average of 6 replicates).

Treats	N	P	K	Ca	Mg
	----------	----------	g kg^{-1}	----------	----------
HF					
C	.438	.042	.071	.161	.069
N	.437	.039	.082	.147	.069
P	.438	.042	.069	.134*[a]	.068
K	.431	.040	.117**	.135*	.052*
Ca	.463	.041	0.85	.151	.068
F(4, 20)=	0.639	1.225	5.214	1.678	1.93
Prob.=	.641	.332	.005	.195	.144
CV%	8.72	7.69	24.7	3.23	20.5
LF					
C	.366	.032	.069	.099	.045
N	.437**	.031	.095+	.126*	.043
P	.427*	.035**	.063	.119+	.057*
K	.350	.032	.139**	.125*	.039
Ca	.360	.031	.064	.102	.040
F(4, 20)=	5.198	7.7	11.7	3.59	4.112
Prob.=	.005	.0006	.0001	.023	.0136
CV%	9.45	3.90	27.3	87.7	18.7

[a] +, *, **, significantly different from control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Appendix Table 35. Effects of fertilizers on leaf nutrients in LF and HF systems at mid-season. (average of 6 replicates).

Treats	N	P	K	Ca	Mg
	----------g kg^{-1}----------				
HF	.438	.041	.084	.144	.064
LF	.385	.032	.085	.112	.044
HFvsLF					
F(1, 5)=	9.91	30.3	1.207	12.6	52.1
Prob.=	.025	.001	.992	.016	.001
CV%	15.9	7.2	48.5	29.2	18.5
Mp*Sp					
F(4, 40)=	3.68	0.593	1.58	3.56	1.52
Prob.=	.012	.705	.182	.008	.202
CV%	10.0	2.2	26.3	15.6	18.5

Appendix Table 36. Effects of fertilizers on nodule, mycorrhizal infection, soil pH, conductivity, NO_3^- in LF and HF systems at mid-season.(average of 6 replicates)

Treats	Soil pH	Electrical Conduct. $\mu S\ cm^{-1}$	Soil NO_3^- $mg\ kg^{-1}$	Roots M^{-2}	Nodules (F.W) $g\ plant^{-1}$	Myc. %
HF						
C	6.28	69.5	5.0	72.7	0.95	52.5
N.	6.23	150**a	37.5**	83.9	0.70	26.0**
P	6.22	161**	5.0	80.5	1.32+	42.6
K	6.33	97.3	5.0	73.9	1.29	44.4
Ca	6.27	164**	5.0	76.5	1.22	25.7**
F(4, 20)=	0.786	8.93	53.9	0.422	2.84	7.32
Prob.=	.546	.0003	.0001	.791	.0516	.0008
CV%	2.0	27.2	42.2	22.9	35.2	28.3
LF						
C	6.08	57.5	5.0	53.6	.252	40.4
N	5.82**	142**	49.2**	68.1	.100	49.3
P	6.07	124**	5.0	70.8+	0.495*	40.7
K	6.08	90.8	5.0	75.6*	0.238	45.6
Ca	5.97+	159.8**	5.0	60.7	0.263	19.9+
F(4, 20)=	8.368	5.239	280.9	1.410	3.39	2.56
Prob.=	.0004	.0047	.0001	.267	.028	.071
CV%	1.58	38.2	6.6	27.2	70.5	44.6

[a] +, *, **, significantly different from control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Appendix Table 37. Effects of fertilizers on nodule, mycorrhizal infection, soil pH, conductivity, NO_3^- in LF, and HF systems at mid-season. (average of 6 replicates)

Treats	Soil pH	Electrical Conduct. $\mu S\ cm^{-1}$	Soil NO_3^- $mg\ kg^{-1}$	Roots m^{-2}	Nodules (F.W) $g\ plant^{-1}$	Myc. %
HF	6.29	119	8.33	75.9	1.097	38.3
LF	6.03	105	10.3	64.8	0.265	39.2
HFvsLF						
F(1, 5)=	4.71	1.49	5.57	4.79	66.6	0.055
Prob.=	.082	.276	.065	.080	.0004	.823
CV%	7.2	43.8	41.1	26.4	57.6	40.4
Mp*Sp						
F(4, 40)=	2.23	0.345	6.71	0.636	1.09	2.57
Prob.=	.066	0.883	.0001	.639	.371	.053
CV%	1.83	35.4	37.4	25.3	44.5	37.4

Appendix Table 38. Effects of fertilizers (P, Rp) on fababean yields in the HF, LF systems at final season and mid-season crop.(average of 6 replicates).

Treats	Grain+ pods	Crop	Mid-season crop	Weeds	Crop+ weeds	Plant bug No. pl^{-1}
	---------- $g\ m^{-2}$ ----------					
HF.						
C	144.2	264.6	138.0	87.2	351.8	0.77
P	109.3	215.2	116.4	86.1	301.3	0.78
Rp	104.3	216.3	103.5	92.7	309.0	0.62
F(2, 10)=	1.396	1.725	1.198	0.04	0.772	2.672
Prob.=	.292	.227	.343	.961	.488	.121
CV%	37.8	22.7	25.1	50.0	23.6	9.8
LF						
C	48.8	111.5	70.5	24.3	135.8	0.056
P	103.2*[a]	197.5**	111.1**	29.8	227.3*	0.094
Rp	69.9+	125.9	91.0	25.4	151.3	0.083
F(2, 10)=	11.1	16.9	17.8	0.071	12.8	0.301
Prob.=	.003	.0006	.007	.932	.002	.942
CV%	27.3	18.9	30.9	102	19.5	16.2

[a] +, *, **, significantly different from control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Appendix Table 39. Effects of fertilizers (P, Rp) on fababean yields in HF, LF systems at final season. (average of 6 replicates).

Treats	Grain+ pods	Crop	Mid-season crop	Weeds	Crop+ weeds	Plant bug No. pl^{-1}
	----------	----------	$g\ m^{-2}$	----------	----------	
HF	119.2	232.0	111.8	88.7	320.7	0.081
LF	73.9	144.9	70.9	26.5	171.4	0.063
HFvsLF F(1, 5)=	8.54	13.4	9.20	222.8	41.1	27.8
Prob.=	.033	.015	.029	.0001	.001	.005
CV%	48.1	37.8	42.1	12.9	28.4	16.2
Mp*Sp F(2, 20)=	5.12	7.825	11.96	0.071	4.45	4.23
Prob.=	.016	.003	.0004	.932	.025	.021
CV%	36.2	22.2	27.5	37.4	23.8	19.3

Appendix Table 40. Effects of fertilizers (P. Rp) on leaf nutrients in LF and HF systems at mid-season. (average of 6 replicates).

Treats	N	P	K	Ca	Mg
	----------g kg^{-1}----------				
HF					
C	.438	.042	.071	.161	.069
P	.4.8	.042	.069	.134*	.068
Rp	.426	.038	.082	.138*	.056*
F(2, 10)=	0.579	1.154	1.575	4.976	5.769
Prob.=	.578	.354	.254	.032	.022
CV%	5.21	13.7	19.2	11.1	11.3
LF					
C	.366	.032	.069	.099	.045
P	.427*[a]	.035**	.063	.119+	.057*
Rp	.368	.030	.077	.0.8	.040
F(2, 10)=	2.85	12.9	2.99	2.87	5.09
Prob.=	.105	.002	.096	.103	.030
CV%	12.9	4.41	14.9	1.6	20.8

[a] +, *, **, significantly different from control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Appendix Table 41. Effects of fertilizers (P, Rp) on leaf nutrients in LF and HF systems at mid-season. (average of 6 replicates).

Treats	N	P	K	Ca	Mg
	----------g kg^{-1}----------				
HF	.434	.041	.074	.144	.065
LF	.387	.032	.069	.105	.047
HFvsLF F(1, 5)=	4.29	129.9	0.391	19.3	125.5
Prob.=	.093	.0001	.559	.007	.0001
CV%	16.3	6.1	31.3	21.2	8.4
Mp*Sp F(2, 20)=	2.03	0.602	0.064	6.04	2.213
Prob.=	.158	.557	.939	.009	.136
CV%	9.4	11.2	19.8	13.9	17.9

Appendix Table 42. Effects of fertilizers (P. Rp) on nodule, mycorrhizal infection, soil pH, conductivity, NO_3^- in LF and HF systems at mid-season.(average of 6 replicates)

Treats	Soil pH	Electrical Conduct. $\mu S\ cm^{-1}$	Soil NO_3^- $mg\ kg^{-1}$	Roots M^{-2}	Nodule $g\ plant^{-1}$	Myc. %
HF						
C	6.28	69.5	5.0	72.7	0.95	52.5
P	6.22	161**a	5.0	80.5	1.32+	42.6
Rp	6.40	70.0	5.0	67.6	1.16	42.0
F(2, 10)=	2.82	177.5	.0000	2.67	1.84	1.80
Prob.=	.107	.0001	1.0	.118	.209	.215
CV%	2.15	9.68		13.3	29.4	23.6
LF						
C	6.08	57.5	5.0	53.6	.252	40.4
P	6.07	124**	5.0	70.8**	0.495*	40.7
Rp	6.22+	55.5	5.0	59.8	0.19	43.3
F(2, 10)=	2.55	25.8	.0000	7.24	6.72	0.04
Prob.=	.127	.0001	1.0	.011	.014	.963
CV%	2.1	23.7		12.9	49.3	46.9

[a] +, *, **, significantly different from control values at $\alpha = 0.1, 0.05, 0.01$ respectively.

Appendix Table 43. Effects of fertilizers (P, Rp) on nodule, mycorrhizal infection, soil pH, conductivity, NO_3^- in LF, and HF systems at mid-season. (average of 6 replicates)

Treats	Soil pH	Electrical Conduct. $\mu S\ cm^{-1}$	Soil NO_3^- $mg\ kg^{-1}$	Roots m^{-2}	Nodule $g\ plant^{-1}$	Myc. %
HF	6.3	100.2	5.0	73.4	1.14	45.7
LF	6.12	78.8	5.0	61.4	0.31	41.5
HFvsLF F(1, 5)=	2.33	12.4	1.00	6.49	45.2	0.853
Prob.=	.187	.017	.363	.05	0.001	.398
CV%	5.6	20.4		21.2	51.2	31.4
Mp*Sp F(2, 20)=	0.114	2.71		1.37	0.804	0.585
Prob.=	.893	.091		.276	.461	.567
CV%	2.1	16.6		13.2	35.9	36.1

Appendix Table 44. Occurrence of black bean aphids in fertilizer experiments.

Site	Observations
PEI F7	Aphids first observed on July 15, 1989, only in one plot (Block I, P treatment); on August 2, most plants heavily infested. On August 2, aphids were also observed in one additional plot (Block 2, N treatment) in which approximately 50% of plants were heavily infested.
PEI F8	No aphids observed
NS1	Aphids first observed on July 7, 1990. Counts of heavily infested plants in each weeded or nonweeded plot (6 x 2 m) on July 17:

Block	Fertilizer	Weeds	No. plants
2	none	-	21
	P	-	3
	P	+	1
	Ca	+	2
3	K	+	1
5	P	-	1
	Ca	-	3
6	none	+	1

NS2	No aphids observed
LFcyl.	No aphids observed
HFcyl.	No aphids observed

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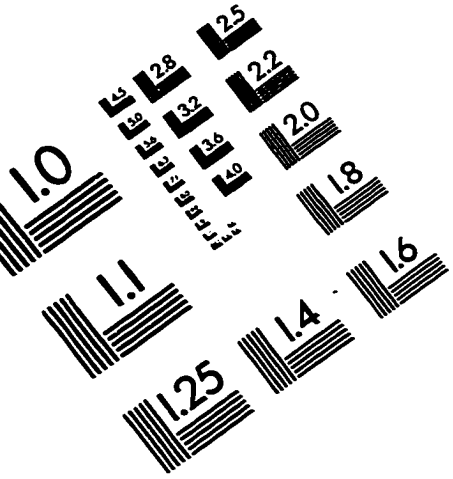
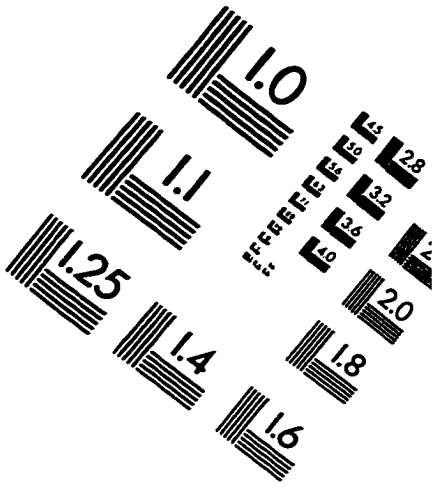
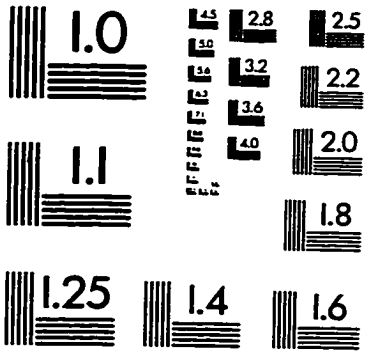
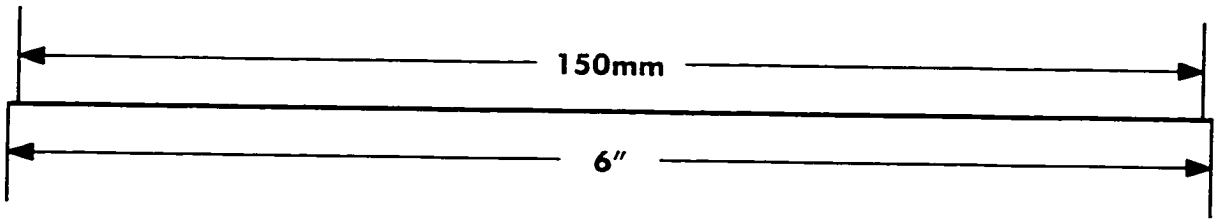
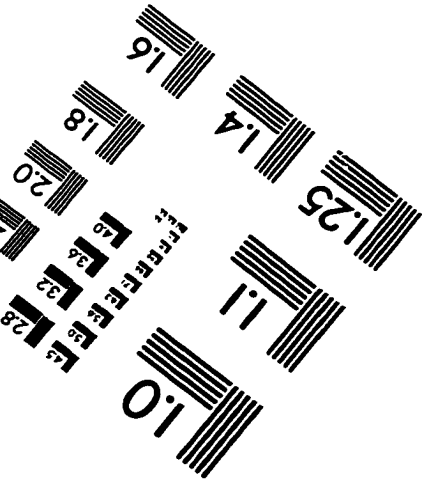
IMAGE EVALUATION TEST TARGET (QA-3)

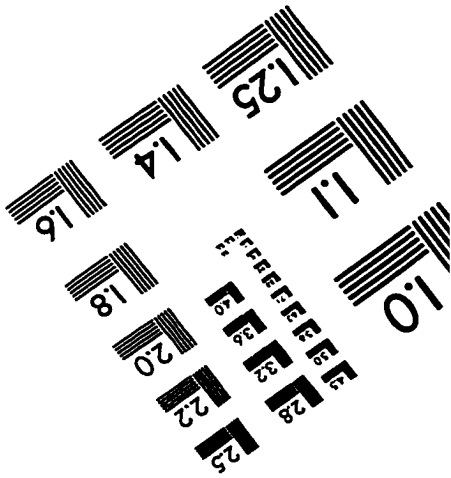












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