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STRATEGIES FOR ACHIEVING SELF SUFFICIENCY IN NITROGEN ON A MIXED FARM IN EASTERN CANADA BASED ON USE OF THE FABA BEAN

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INTRODUCTION

There have been substantial advances in the past decade in our understanding of the biology of N_2 fixation in legumes, but these have not yet led to appreciably lowered reliance on industrial N_2 fixation.

This study is an investigation into the potential for enhancing N_2 fixation in locally grown faba beans (*Vicia faba* L. *minor*) through selection of efficient rhizobia-legume associations. In western Canada where this crop was introduced in 1971, inoculation was reported to be essential for nodulation and N_2 fixation (Candlish and Clark, 1975). Evaluation of growers practices suggested that increasing the use of biologically fixed N_2 locally depended more on making better use of existing N_2 fixation than on increasing the specific rates of N_2 fixation. Plants growing for the first time on dykeland soils that had received no inoculant were well nodulated and exhibited high C_2H_2-reducing activity. A number of practical problems required consideration including: is "starter" N required, how much N_2 is fixed, and how should inorganic fertilizers be managed for crops grown in rotation with the beans?

Faba beans do stimulate growth of grain crops following it in rotation (unpublished observations). Thus we suspected that there would be a positive N balance for the faba bean. However, our observations indicated that a net gain in soil-N could be achieved only by recycling some of the N removed in harvested seeds. This aspect of the utilization of recently fixed N has not received much attention because pulses are commonly grown for export. An opportunity to study the problems and potential of a system in which inputs of N were provided largely by faba bean N_2 fixation and in which the bean-N was recycled via manures was provided by an upland farmer who grew faba beans on one-third of his cultivated land. He had not applied any commercial fertilizer-N for four years.

STUDY SITES

Both of the farms included in this study are located in the western part of the Annapolis Valley, Nova Scotia, in a cool, humid temperate climatic zone. There are approximately 120 frost free days, 2800 degree days above 42 F, and the average annual rainfall is about 114 cm of which 45 cm occur between May 1 and September 30 (MacDougall et al., 1969).

At the dykeland farm (Farm A), cereals, corn and faba beans are grown in rotation on 135 ha of reclaimed saltmarsh. The soil is a deep silty loam, drained by a system of mole and tile drains. The combination of a shallow water table and effective surface drainage provides almost ideal soil water conditions. In 1978, faba beans were sampled in a field where they were grown for the first time. Barley was the previous year's crop. No inoculant was used. "Treflan" herbicide was incorporated in the soil before planting.

Thirty hectares of cultivated land on the upland farm (Farm B) encompass three soil series of capability classes 3 and 4 (moderately severe to severe limitations). Individual fields are level to rolling in slope, sand to silty clay loam in texture, and contain 2.9 to 5.8% organic matter. The principal limitations are described as "texture and imperfect drainage" on the silty loam soils, and droughtiness on sandy soils (MacDougall et al., 1969). 2100 laying hens are maintained (Rhode Island Red x Light Sussex) in a floor operation with deep litter. From 1954 to 1975 cereals were grown for poultry feed according to conventional recommendations. Faba beans were introduced in 1968. In 1975 oat yields (98 imperial bushels per acre) were the highest recorded in the Provincial Soils and Crops Department competition. However, with the rising costs of petroleum products, it was suggested that a chemically intensive system might not be economically viable in the future. In an attempt to determine the biological limitations to production in a recycling system, no commercial fertilizer or pesticides have been used since 1975.

Because of excessively wet field conditions in the spring, only one-third of the acreage on the upland farm was seeded in 1979, the year most of our data were obtained. Crop yields in 1979 were much below, slightly below and slightly above yields of the previous few years for faba beans, oats and wheat, respectively.

METHODS

Faba beans were taken throughout prescribed areas of about 0.5 ha chosen for their accessibility. An outbreak of Chocolate Spot disease occurred at the dykeland site (Farm A) in mid-August; sampling was then restricted to regions not severely affected. For C_2H_2 reduction assays of nitrogenase activity (Hardy et al., 1968) roots and nodules from 6 plants were placed individually, or in pairs, in 1000 ml jars with 8 kPa C_2H_2. The jars were incubated in the soil for 0.5 hr and gas samples taken for analysis of C_2H_2 using a Carle model 9500 gas chromatograph equipped with flame ionization detector and a 0.32 x 50 cm column containing 80-100 mesh Porapak T. Hourly rates of C_2H_2 reduction were converted to daily rates by multiplying by 18.6; this was the ratio of total C_2H_2 reduction in one day estimated by integration of rates measured at 4 to 5 hr intervals to the rate measured at 1100 hr, the time of routine sampling. The integrated seasonal values of C_2H_2 reduction were converted to values of N_2 fixation by use of a molar ratio of nodule C_2H_2-reducing activity to whole plant N_2 fixation of 1.8 (Hudd et al., 1980). The general magnitude of N_2 fixation was also estimated for the upland crop in 1979 by comparing the total N accumulated in faba beans and associated weeds on September 21 with the total N accumulated in weeds and in grasses planted in 6 microplots (25 cm diameter) in a separate study. Estimates of N_2 fixation based on this apparent molar ratio (2.4) are referred to as "conservative estimates of N_2 fixation."

Nitrate reductase activity of faba bean leaves was assayed by an _in vivo_ technique. Twenty or more 0.7 cm leaf discs, taken from all leaves, were treated as described by Patriquin et al. (1978). Fresh weights of discs and punched leaves were determined in order to calculate whole plant nitrate reductase activity.

For assay of denitrification by the C_2H_2 blockage technique (Yoshinari et al., 1977), duplicate samples, each consisting of 7 or more 15 cm depth x 1.8 cm diameter soil cores were placed vertically and compactly in 1000 ml jars. Acetylene (8 kPa) was added, jars were incubated in the soil and gas samples were taken at 3 and 24 hr for analysis of N_2O (Patriquin et al., 1978).

Fifteen faba bean plants, not including roots, were taken for biomass measurements. Plant densities were counted in 20-one m^2 quadrats. To sample other crops and weeds in 1979, six to ten 35 x 35 cm quadrats were placed randomly in each of 1) a 0.9 ha field of winter wheat, 2) a 3.5 ha field of oats, 3) a 6 ha field which was fallowed early in the summer and later seeded with winter wheat, and 4) one-half of a 3 ha field in which clover was undersown in winter wheat in 1978. Aboveground plant material was removed, sorted (crop, leguminous weeds and non-leguminous weeds), dried, weighed and subsampled to provide duplicate 100 mg samples for analysis of N by the standard Kjeldahl technique. For oats and wheat, the ratio of grain to straw was measured on two composite samples taken separately. The biomass values reported for clover and fallow fields are the highest values observed during the summer, which were on June 13. A weed survey in a bean field (7 ha) was conducted on August 21, but the final preharvest samples were taken on September 21. Belowground biomass was measured for a 30 x 30 cm sod of wheat taken on August 1; the ratio of root-N to aboveground-N was 0.21. For oats, clover and weeds, we have assumed that the belowground-N to aboveground-N ratio is 0.15. Combine yields were calculated from the area of the field measured by a counter on the grain drill, and from the number of boxes of seeds transported from the field. One level box (4 ft high) contained 100 imperial bushels.

Total (Kjeldahl) N was determined on seven 10 g (fresh weight) samples of manure taken from a manure pile or the barn, and either not exposed, or spread out on a sheet out of doors and exposed for 3 or 24 hr to simulate different periods of exposure before manure is turned into the soil. Volatilization of ammonium after incorporation of manure (5.6 metric tons/ha) in the soil was measured in 8 microplots created by enclosing soil for 3 days in 25 cm diameter bottomless buckets. The ammonia was absorbed in 100 ml of 0.1 N H_2SO_4 contained in 15 cm diameter petri dishes placed on stands at 5 cm above the soil, and was measured by a colorimetric technique (Strickland and Parsons, 1972).

For routine sampling of soils, 15 or more cores (15 cm depth x 1.8 cm diameter) were taken within the crop sampling areas. Nitrate in air dried soils from Farm A was extracted in 0.025 molar aluminum sulfate solution and measured using an ORION specific ion electrode. Nitrate in frozen soils from Farm B was measured on a 2:1 water extract by a colorimetric technique (Cataldo et al., 1975). An average value of soil-N for the upland farm was estimated by multiplying the Kjeldahl N content of soil samples from each of 10 fields by their bulk densities (determined by the excavation technique) (Blake, 1965) weighting the values according to the area of each field.

Compositions of weed populations in oat, bean and wheat fields were examined on 3 occasions between June 20 and August 15 on Farm B, and in a wheat field on a neighboring farm on July 11, 1979. At each of 15 sites in each field cover by each species in a 4 m^2 area was estimated using the Braun-Blanquet scale transformed according to Dagnelie (1960). Values for different dates were added to give overall values and the ranks of these values are reported in the results. For seed bank studies, soil samples were taken between May 30 and July 11, 1979. Nine samples were taken from the bean field, and three from each of the other fields. Each sample consisted of twenty 15 cm depth x 1.8 cm diameter cores split into top and bottom fractions. The soil was mixed with an equal volume of coarse silica sand and spread over a base on silica sand in 1290 cm^2 trays with separations between shallow and deep fractions. These were placed in a greenhouse and seedling emergence monitored until December 5.

RESULTS

Nitrogen Balance in Faba Beans

At site on Farm A in 1978 (Fig. 1) and at site on Farm A in 1979 (weekly or biweekly assays, data not shown), nitrogenase activity was initiated at about 2½ weeks after planting and reached a maximum during vegetative growth, while nitrate reductase activity was highest during reproductive growth. More than half of the total N in the crop on Farm A accumulated after vegetative growth (Fig. 1). Cumulative N_2 fixation, calculated from C_2H_2 reduction rates, kept pace with N accumulation during vegetative growth, but not thereafter. These data suggest that atmospheric N_2 and soil-N were major sources of N during vegetative and reproductive growth successively. A sequence of high nitrogenase activity followed by high nitrate reductase activity has also been reported for *Phaseolus vulgaris* (Franco et al., 1979).

Increase in total seed-N (Fig. 1) occurred partially at the expense of pod-N, which declined during August, but most of the decline in total leaf-N was associated with leaf fall rather than with transport of N out of the leaves. The N content of green leaves declined from 5.50 to 4.05% during August while the number of green leaves per plant declined from 127 to 31 (counts for 3 plants August 1 and 31). Old leaves about to fall contained 4.4 to 5.3% N. Loss of N by leaf fall is estimated as (4.05/5.50) x (total leaf-N on August 1 minus total leaf-N on August 31) = 159 mg N per plant or 56 kg N per hectare.

Comparison of estimated inputs of N_2 with outputs of N in harvested seeds (Table 1) suggests that N_2 fixation was not sufficient to provide a positive N balance at the sites on both Farm A and B in 1978. There would be very large negative balances if straw was harvested, as it is when the plants are used for sileage.

Rapid decline of soil N under continuous growth of pulses is referred to in older literature (Harmsen and van Schreven, 1955) and more recently has been documented for soybeans (Johnson et al., 1975). The short term stimulation of crops following pulses was believed to be due to the accumulation of crops following pulses was believed to be due to the accumulation of N in legume residues in a readily decomposable form. The large amounts of N returned to the soil in high N (Fig. 1) residues after harvest of faba beans

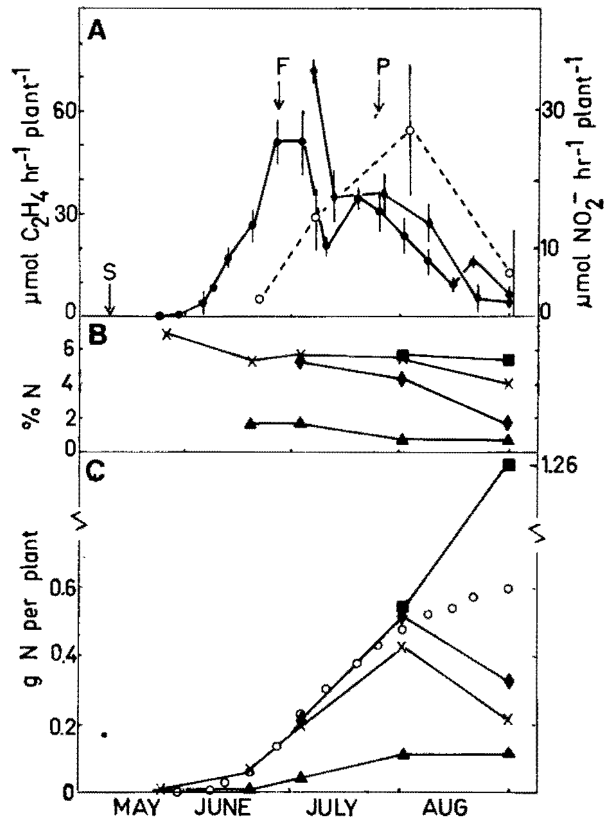


Fig. 1. Seasonal distribution in field grown faba beans of (a) whole plant nitrogenase and nitrate reductase activities and of (b) percent N and (c) total N in different plant parts. Calculated cumulative N_2 fixation is indicated in (c). (a): nitrogenase activity of Farm A plants (●) and Farm B (1978) plants (♦); nitrate reductase activity of Farm A plants (o); bars indicate standard errors; S = seeding, F = first flowers, P = first pods. (b & c): Farm A plants, stems (▲), leaves (x), pods (♦), seeds (■), cumulative N_2 fixation (o); roots (+ nodules) on August 1 contained 1.55% N, 0.061 g N/plant.

(Table 1) could likewise be expected to mineralize rapidly, and be lost by leaching and/or taken up by weeds and the succeeding crop.

Table 1. Crop and weed biomass and N data. Numbers in brackets are standard errors.

Crop	Biomass at harvest				Inputs of N			Output	Field residues		
	Total crop	Seeds	Weeds	Combine	Seed	Man.	N_2 fix	Seed-N	Straw (+ roots)	Weeds	Oct. 28 weeds (- roots)
	(metric ton/ha)			(bu/ac)	(kg N/ha)			(kg/ha)	(kg N/ha)		
Farm A											
Beans 1978 (cv Minden)	16.2 (1.29)	7.16 (1.50)			9		217	303[a]	204[b]		
Farm B											
Beans (cv Akerp.)											
1978	9.57 (0.47)	4.83			9		207[c]	222	110		
1979	4.56 (1.27)	2.34 (0.44)	1.23 (0.18)	33	9		123	101	57.2	38.6	29.3[d]
Oats 1979 (cv Garry)	3.11 (0.52)	1.74	0.23 (0.04)	49	2.2	105[e]		39.9	22.9	4.4	3.3
Wheat 1979 (cv Lennox)	8.66 (1.81)	2.86	1.88 (0.64)	40	1.8	105	3.5[f]	41.3	28.6	18.2	23.0
Clover 1979 (cv Alsike)	3.73 (1.12)		1.65 (0.50)		0.3		51		117	41.0	
Fallow 1979			3.49 (0.06)				7.5			70.6	

Total inputs (+) and output (-) of N for Farm B (kg N/farm)[g]: 119+ 1470+ 1859+ 2188-

Denitrification, assayed biweekly at Farm A, was undetectable in most samples (sensitivity about 1 g N/ha per day); the maximum value for an individual sample was 3.4 g N/ha per day. Soil nitrate concentrations were low (3 to 7 ppm).

Nitrogen Budget for Farm B

Grain yields on Farm B declined by about 50% after commercial fertilizer use was terminated in 1976. Yields of beans were unaffected. General field crop ratings of soil samples taken from 6 of 10 fields in the fall of 1978 were in the range medium to high plus for Ca, Mg, K and P, and pH values were in the range 6.0 to 6.5. Thus we consider it likely that the declines in grain yields were due to low levels of available N. To gain some idea of whether the apparent N limitation was attributed to inadequate inputs of N to the farm through N_2 fixation, or to the nature of N cycling within the farm, a nitrogen budget (Fig. 2) was constructed from data obtained in 1978 and 1979 (Table 1 and footnotes to Fig. 2).

Notes to Table 1. (a) Output-N is corrected for harvest losses estimated as 8% for beans (seeds left in field after harvest of Farm B crop in 1978, counted in twenty 25 x 25 cm quadrats), and as 3% for grains (Kepner et al., 1978). (b) Straw-N for the beans includes the leaf loss before harvest (estimated as 11.8 mg N/g stem tissue from data for Farm A crop) x 0.75 assuming 25% of this N is recycled in season. Root-N for upland crop was estimated as 3.7 mg N/g stem tissue based on data from Farm A crop. (c) C_2H_2-reducing activity of Farm B crop in 1978 was measured only from July 7 onwards; to calculate seasonal activity we have assumed that the ratio of total activity before July 7 to that from July 7 onwards was the same as that of the Farm A crop (Fig. 1). (d) Biomass values in metric tons (m.t.) per ha for October 28 weeds were: bean field 1.34 (0.23), oat field 0.12 (0.016), wheat field after harvest 0.78 (0.20). Wheat planted in the fall of 1979 had a biomass on October 28 of 0.63 (0.086) m.t./ha and the weed biomass was 0.13 (0.08); total aboveground N was 20.6 and 4.6 kg N/ha for wheat and weeds, respectively. (e) Avg. manure-N was 1.88% on fresh weight basis (range 1.24 to 2.42) or 2.89% on dry weight basis. Field application rate was 5.6 m.t./ha. Losses of NH_3 from microplots after incorporation of manure were small (range 0.12 to 0.72 g N/ha). (f) N_2 fixation by leguminous weeds and clover was conservatively (Edmeades and Goh, 1978) estimated as 50% of the aboveground N. (g) Based on acreage of 10 ha in beans, 7 ha in oats, 7 ha in wheat, 3 ha in clover, and 3 ha under fallow, the approximate pre-1979 values. Data for faba beans were averaged.

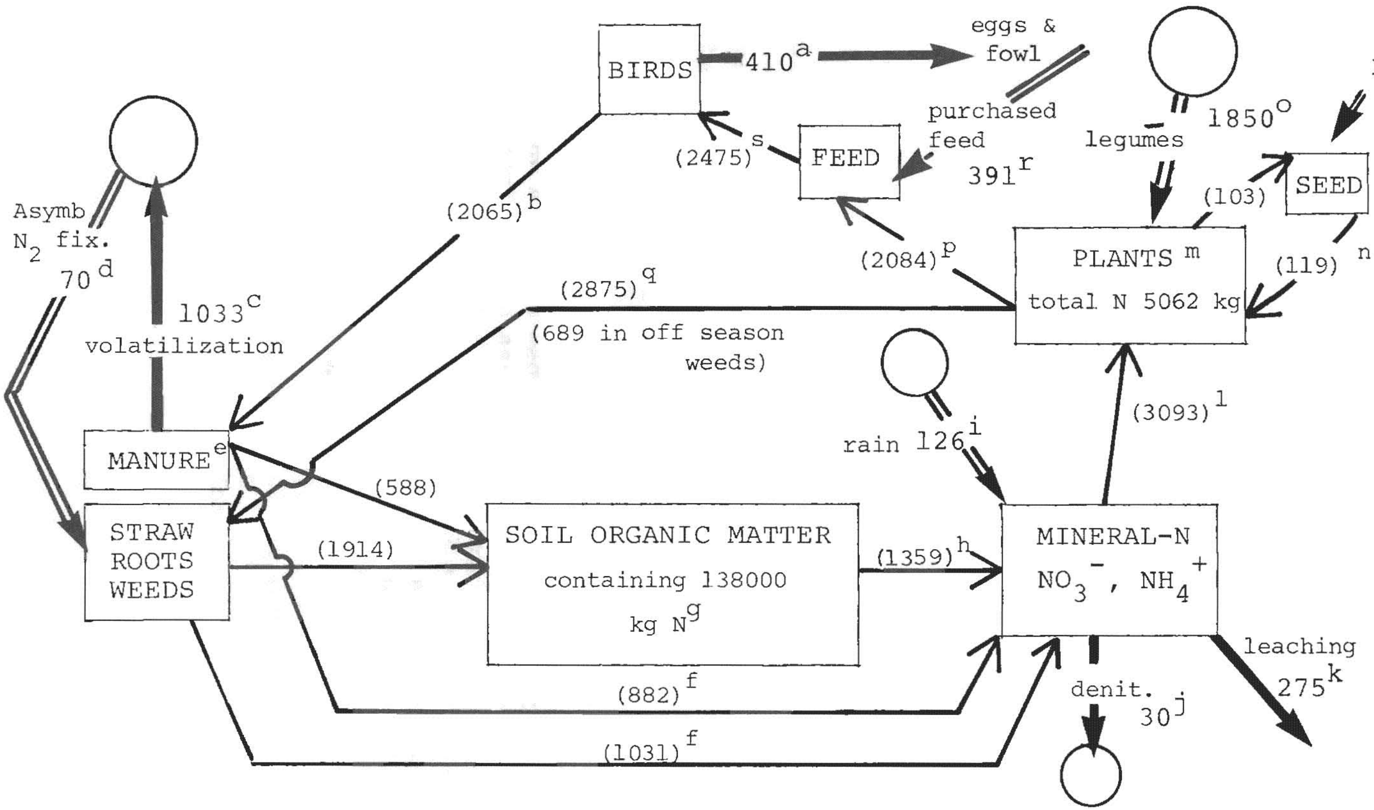


Fig. 2. Nitrogen budget for Farm B. Numbers in brackets are flows of N between compartments within the farm. Big arrows and accompanying numbers not in brackets are flows of N into and out of the farm. Circles represent the atmosphere. Units are kg N per farm per year. Calculations refer to 10 ha in beans, 7 in wheat, 7 in oats, 3 in clover and 3 fallow.

The results suggest: 1) For Farm B as a whole (Fig. 2), inputs of N through N_2 fixation are more than sufficient to balance losses associated with export of products, volatilization, leaching and denitrification, and the farm is therefore potentially self sufficient in N. 2) Losses due to leaching and denitrification appear to be low (footnotes (j) and (k) to Fig. 2) and therefore we conclude that most of the difference between inputs of legume N_2 fixation and manure-N to the fields (Table 1) and the outputs of harvested seed-N from the fields is accumulating in the fields, i.e., in the soil. This difference amounts to 37.7 kg N/ha, or to 24.0

Notes to Fig. 2. (a) Export of 384000 eggs x 1 g N/egg plus approx. 500 fowl at 1.8 kg, 18% protein. (b) Feed-N minus exported N. (c) Assumed 50% of manure-N was volatilized (National Academy of Sciences, 1978). (d) For 5200 kg/ha low N (0.26%) straw on wheat fields this is a conservative estimate of asymbiotic N_2 fixation (Brouzes et al., 1969). (e) The manure output is the field application rate. This is lower than inputs after volatilization losses. The latter could be reduced if the output is not sustainable, for example by application of gypsum (Roberts, 1897), available locally, to the roots. (f) It is assumed that 60% of manure-N and 35% of residue-N is mineralized in one year (Reddy et al., 1979; Mathers and Goss, 1979). (g) Soil-N in top 15 cm x 1.25 (Magdoff, 1978). (h) Calculated as (plant-N + groundwater-N + denitrification) minus (legume N_2 fixation + seed-N + manure & residue mineralization + rain-N). (i) Data from J. Underwood, Nova Scotia Dept. Environment. (j) Denitrification is assumed to be low because soil nitrate values (< 6 ppm dry soil except after manure application in fall when they rose to 14 ppm) were similar to those at Farm A where denitrification was very low. (k) Twenty samples of tile drain water were collected over one year from May 1979 in a field which was cultivated intermittently and later fertilized with manure and sown with winter wheat. Average nitrate-N in tile drain water from May to November was 2.0 ppm (range 0.6 to 3.1) and from December to April 1980, 5.5 ppm (3.6 to 7.9). The average values were multiplied by total rainfall for the 2 periods (84.1 and 36.1 cm, respectively) and by a percolation factor of 0.25 (provided by J. Kerekes, Canadian Wildlife Service as a maximum possible value) giving a value for leaching loss of 9.16 kg N/ha. (l) Calculated as plant-N minus (legume N_2 fixation + seed-N). (m) Table 1, total plant-N including weeds. (n) Oat and clover seed are purchased, other seed is produced internally. (o) Table 1. (p) Harvest-N (Table 1) minus seed-N. (q) Calculated as plant-N minus harvest-N. (r) Calculated as the difference between the supply and the requirement (see (s)). This value is 16%. About 25% of the bulk feed requirement is bought as grain. (s) Feed requirement is 91000 kg of 17% protein.

kg N/ha if a conservative estimate of N_2 fixation in faba bean is used. The current output in harvested seed-N is 73 kg N/ha implying that significant gains could be made if the excess N accumulating in the soil at present could be diverted to the grains. 3) Substantial amounts of N cycle through weeds.

Post-harvest weeds and weeds on uncultivated fields may play an important role by retaining N (Table 1) that would otherwise be lost by leaching in this high rainfall region. Lysimeter studies in New York state (Bizell and Lyon, 1927) indicated losses of 77.5, 8.8 and 2.8 kg N/ha under bare soil, rotation and grass, respectively. Present losses on Farm B, of the order of 10 kg N/ha, appear to be tolerable but losses of the order of 30 to 40 kg N/ha would negate most of the potential gains in yields.

Composition, Seed Banks and Biomass of Weeds

Factors affecting the distribution and abundance of weeds were studied initially in the context of their being considerations in crop rotation strategy, that in turn being a factor determining the nature of N cycling between crops.

The composition of weed populations (Table 2) was consistent with the basic tenet of agriculture that weeds whose life cycles are most closely synchronized to the crop make the best competitors (Bunting, 1959). Winter annuals and perennials were the dominant weeds amongst winter wheat, which has the longest growing season of any of the crops. Summer annuals were dominant amongst oats which have the shortest growing season, and summer annuals and perennials were dominant amongst faba beans, which have a long summer growing season.

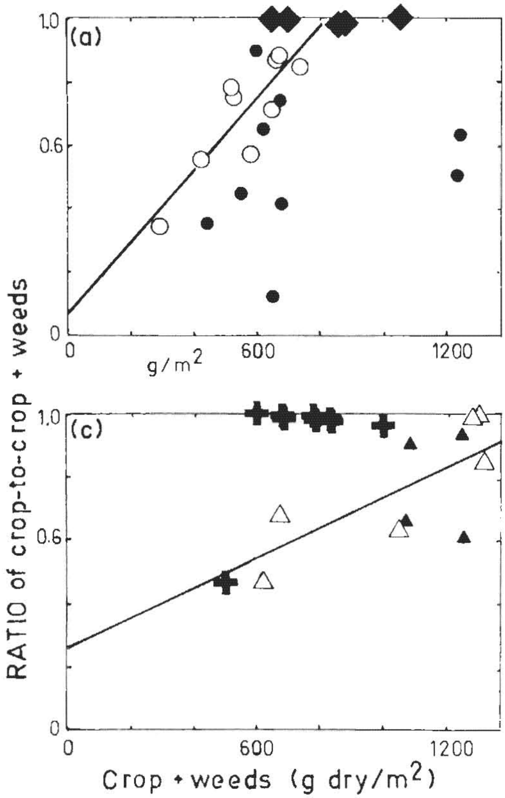
Seed banks of *Raphanus raphanistrum* (wild radish), the most abundant summer annual amongst oats and beans, were much lower under winter wheat than under the summer annual crops (compare numbers for shallow horizons, Table 2). This is due to germination of the weed with wheat following tillage operations in late summer, and subsequent frost kill during the winter. Few seeds of *Vicia tetrasperma*, the most abundant weed amongst winter wheat were evident in the seed banks, but pods of *V. tetrasperma* of similar geometric form to that of wheat grains were found in the wheat seed, suggesting that this weed is distributed with the seed.

Within fields, the ratio of crop biomass to total (crop + weed) biomass increased with increasing total biomass, reaching values close to 1.0 at sites of highest total biomass (Fig. 3). When fertilizer-N was applied shortly after planting in the bean field, this relationship was upset in favor of the weeds (Fig. 3a).

Table 2. Dominant weeds and their seed banks in fields of oats, faba beans and winter wheat on Farm B, and in a field of winter wheat on Farm R about 5 km distant. The three most common species in each field are listed with those of the oat field first, followed by additional species, if they differ from the oat field species, from the faba bean and winter wheat fields, respectively. Nomenclature is after Roland and Smith (1969). The habit of each species is indicated by letters in brackets; (S) = summer annual, (W) = winter annual, (P) = perennial. cov = ranked cover values for each field. top = top, and bot = bottom halves of 15 cm deep soil cores. Seed bank numbers are tens per square meter of field surface sampled. Under cov, np = not present.

Species	Oats[a]			Faba beans[b]			Winter wheat[c]			Winter wheat[d] (R)		
	cov	top	bot	cov	top	bot	cov	top	bot	cov	top	bot
Raphanus raphanistrum (S)	1	20	33	2	81	15	21	13	85	17	0	13
Ambrosia artemisiifolia (S)	2	0[e]	0	20	0[f]	0	7	0	0	np	0	0
Plantago major (P)	3	79	380	4	308	59	22	92	79	9	7	20
Agropyron repens (P)	18	0	0	1	2	5	9	26	26	7	20	7
Solidago graminifolia (P)	14	20	0	3	111	22	np	0	0	np	0	0
Vicia tetrasperma (W)	np	0	0	np	0	2	1	3	13	1	0	7
Phleum pratense (P)	18	0	7	11	94	50	2	98	52	2	7	7
Galeopsis tetrahit (S)	7	0	0	6	33	51	3	46	52	13	0	0
Poa pratensis (P)	np	7	13	11	15	13	4	20	33	3	327	72
Total seed bank		242	603		1055	465		1447	1624		766	439
Standard error		17	46		112	42		114	162		234	93

[a] Faba beans were planted in this field in 1977 and oats in 1978; intense cultivation 1978-1979. [b] Faba beans on this field in 1978. [c] Hay field prior to 1979. [d] Continuous winter wheat for 5 years, no herbicide. [e] After a vernalization period 70 and [f] 20 plants/m^2 germinated in the trays.



Crop	Symb.	Farm	Fert.	Herb.
Beans	○	B	-	-
	●	B	e	-
	◆	A	-	+
Oats	◇	H	e	-
	□	B	-	-
	■	B	l	-
	X	A	e	+
	+	A	e	-
Wheat	△	B	-	-
	▲	B	l	-
	✚	L	le	-

Fig. 3. Ratio of crop biomass to crop + weed biomass in relation to total (crop + weed biomass in 35 x 35 cm quadrants randomly placed in (a) fields of faba beans, (b) oat fields, and (c) fields of winter wheat. Sampling was on August 1 for winter wheat, August 21-24 for faba beans and oats, except for oats from Farm B which were sampled on September 9. Open symbols are used and regression lines are indicated for fields or treatments in which there were significant (α = 0.05) linear regressions between the two statistics. Farm B refers to the Aldhouse (upland) farm, Farm A to the Warren (dykeland) farm, and Farms H and L are other farms in Annapolis Co. Under FERT, e refers to application of fertilizer-N at about the time of seeding, and l to later application. On Farm B, 100 kg N as ammonium nitrate were broadcast on 2 x 2 m plots in wheat and bean fields on May 30, and in the oat field on August 7. HERB refers to the use of herbicide.

For beans and wheat on Farm B, and for oats on Farm H (see Fig. 3) (not treated with herbicide because of rain), regressions through the origin do not significantly ($\alpha = 0.05$) reduce the fits from those of regressions indicated in Figure 3. This was not true for oats on Farm A for which the ratio of crop to total biomass was high at low total biomass values. This field was also characterized by a significantly lower seed bank than other fields (Table 2) and by low post-harvest weed biomass (Table 2). Because of abundant Canada thistle on this field in 1978 (under oats), the field was deep ploughed in the fall of 1978 to break up perennial rhizomes, and harrowed following two rotovatings before planting oats in 1979.

Our interpretation of the regressions in Figure 3 is that increasing total biomass is related to increasing soil fertility, and provided that the crop has an initial advantage (given by seed bed preparation, optimal planting time, etc.), higher soil fertility enables the crop to compete more effectively with weeds for available nutrients. At low soil fertility when crop plants do not grow fast enough, or are not sufficiently dense to take up all available nutrients (or available N), weed growth acts as a negative feedback mechanism recycling nutrients that might otherwise be lost, and increasing soil fertility in the long run. When weed seed banks are low, as in the intensively cultivated oat field, post-harvest weed growth may be insufficient to take up a large fraction of the available N, which may then be lost through leaching.

Predicted Changes in Crop, Weed and Soil Nitrogen

As a first approximation, changes in soil-N can be described by the relation $dS/dt = I - kS$ where S = soil organic N, I = rate of addition of organic N to the soil and k = mineralization constant (Magdoff, 1978). Our data suggest that inputs of N to the fields exceed outputs, and thus we conclude that soil organic N, and accordingly the amount of N mineralized from this each year (kS) are increasing annually and will continue to increase until output of N is equal to input of N. The weed and crop biomass data (Fig. 3) suggest that crops will obtain a greater proportion of the available N as total available N increases, and hence that crop yields will increase faster than the increase in total available N. We have estimated changes in soil-N and yields with time as follows.

The field system is regarded as a black box into which net inputs of N are provided by manure-N (M) and faba bean N_2 fixation (F), and net outputs occur in the products removed from the field, i.e., cereal grain-N (G), and in faba bean seed-N (B). Transformations involving straw, roots and weeds are considered as recycling within the box, and denitrification, asymbiotic N_2 fixation, rain-N and (sowing) seed-N are ignored as they are individually small, and collectively add up to about zero (Fig. 2). Since the mineral-N pool is small, we assume that the difference between inputs and outputs is accumulating in soil organic N, and

$$dS/dt = F + M - (G + B)$$

F and M are regarded as constants. Nitrogen in cereal grains comes from manure-N and from soil-N. For 1979 (Table 1), this is described as

$$G_{79} = M_G + k_G \times S_{79}$$

M_G is the grain-N derived from manure, and is given by

$$M_G = M \times A \times G/P \times P/PW$$

where A is the fraction of manure-N that is mineralized during the crop season, G/P is the ratio of seed-N removed at harvest to total plant-N (Table 1), and P/PW is the ratio of total crop-N to (weed + total crop)-N (as in Table 1 except that we use a P/PW value of 0.73 for oats, on the assumption that the oat fields are not normally intensively cultivated). N_2 fixation in the clover and fallow fields (Table 1) is included in M as we consider the forage legumes as green manure. Based upon the percentage of N in the manure, A is estimated as 0.50 for corn and sorghum in the southwest U.S. (Mathers and Goss, 1979). Allowing for the colder climate in Nova Scotia, and for differences in growing season between winter wheat and oats, we assume that the values of A are 0.45 and 0.4 for winter wheat and oats, respectively. k_G is the ratio of (grain-N minus M_G) to soil-N, where soil-N is the N in the top 15 cm multiplied by 1.25 to allow for use of N from deeper horizons (Magdoff, 1978). The terms M_G and k_G include explicitly or implicitly the ratio P/PW and we assume that this ratio will increase (to a maximum of 1) in direct proportion to increases in available N, given by

$$(M_s + k_{PW} S_t) / (M_s + k_{PW} S_{79})$$

where M_s is the manure-N mineralized during the crop season (M x 0.45 or 0.4) and k_{PW} is the ratio of (crop + weed)-N to total soil-N in 1979. Thus

$$G_t = (M_G + k_G S_t) \times (M_s + k_{PW} S_t) / (M_s + k_{PW} S_{79})$$

where the latter expression cannot exceed a value of 1/(P/PW).

Nitrogen in faba beans is derived partly from N_2 fixation, which is not available to weeds, and in part from soil-N which could also be used by weeds. Thus the harvested bean-N is described by

$$B = B_F + k_B S_t \times (F + k_{PW} S_t) / (F + k_{PW} S_{79})$$

B_F is the proportion of N in seeds derived from N_2 fixation and is given by F x ratio (harvested seed-N/total plant-N) obtained from Table 1. The second part of the expression is analagous to the previous expression describing soil N in cereal grains. Data from both 1978 (upland farm only) and 1979 were used in calculation of the various parameters for beans; it was assumed that P/PW in 1978 was 1.0 (cf. Table 1 and Fig. 3).

Grain-N, weed-N at harvest and soil-N were calculated according to these assumptions by an iterative procedure beginning with S = 1900 kg/ha, and up to a value of 6900 kg/ha (Fig. 4) which cover the range of soil-N values on Farm B. Data for oats and wheat were combined in Figure 4. This model is a considerable simplification of the real situation, and is used only to give an impression of the general magnitude of changes in yields and weeds that could be expected with time and with differences in soil-N. Calculations based on crop data obtained over a period of years and from more soil types might change the absolute values, but would not alter the relative changes greatly. If differences in the mineralization constant for different soils, and the carry-over of residue-N and manure-N for more than one year were considered, the slopes of the curves would probably be lower than in Figure 4. In any case, it is reasonable to conclude that (1) changes in yield are likely to take place very slowly; from an initial value of S of 4600 kg/ha, the average value of soil-N on Farm B in 1979, grain yields increase by 11% and bean yields by 2% after 20 years in Figure 4; and (2) considerable variation can be expected in the amount of weeds at harvest, with practically none in fields of highest fertility, and possibly severe weed problems in fields of lowest fertility. Both these conclusions are consistent with the experience of the grower on Farm B since 1976.

Introduction of a Regular Rotation

These various considerations suggest that management practices on Farm B are a step in the right direction toward achieving high yields and self sufficiency in N, but that the changes are likely to occur at a frustratingly slow pace. Nevertheless, we have attempted to be conservative in our evaluation of the potential for self sufficiency, and it seems fairly clear that the potential is there. Thus alternative strategies may be sought to increase the yields more quickly.

This is a matter of changing the internal structure of the system so that at the current level of accumulated soil fertility more of the manure-N and recently fixed N_2 is removed as product, and less accumulates in the soil or cycles through weeds.

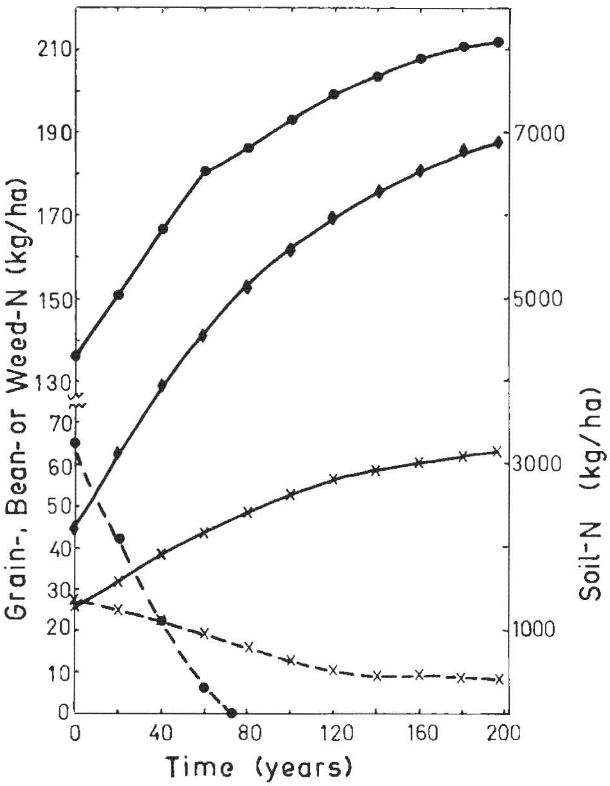


Fig. 4. Predicted changes in crop, weed and soil nitrogen with time. Present range of soil-N on Farm A is 2630 to 6230 kg/ha (N to 15 cm depth, x 1.25), and the mean value is 4600 kg. (—●—) faba bean seed-N (corrected for 8% harvest loss), (—x—) grain-N (3% harvest loss), (--●--) weed-N in bean fields at harvest, (--x--) weed-N in grain fields at harvest, (—♦—) soil-N.

Figuratively described, we need to change the interest rate rather than increase the bank account. The division of the land to various crops as it existed under a ferterilizer- and herbicide-intensive system is probably not the most appropriate division now.

Based in part on these considerations, in 1980, the grower on Farm B adopted a new management scheme involving a regular rotation of beans - oats - clover - winter wheat. The clover is seeded with oats in year 2, and is turned under in year 3 prior to planting winter wheat. Manure is applied to the oats and to the wheat.

Some of the considerations involved in formulating this scheme are as follows. 1) A regular rotation is required for weed control, facilitates planning, and the legume-cereal sequences provide for mopping up of N released from high N legume residues. 2) Faba beans are a long season crop; manure-N applied in the fall (after beans) may be immobilized long enough, or temperatures may be low enough to avoid substantial losses of N. Fall application of manure would facilitate field operations generally because of late wet springs in this area. 3) Underseeding of oats with clover provides an overwintering green manure crop prior to winter wheat and will help keep weeds under control after oats are harvested. 4) Wheat leaves behind a lot of low N straw (Table 1). This could be expected to immobilize mineral-N during vegetative growth of beans in the following year thereby stimulating N_2 fixation, and to release N during reproductive growth when NRA is high (Fig. 1). Production of CO_2 by decomposing straw may also stimulate N_2 fixation in the beans (Shrivashankar and Vlassak, 1978).

Maintenance of nearly continuous plant cover is a key consideration. Thus it is desired to control annual weeds during the crop season, but not to eliminate them so that they provide a self-seeding cover when crops are not present. The crop rotation keeps individual species off balance. Inclusion of a short season crop (oats) provides time for recurrent cultivation if necessary, but this is seen as a last resort because of the potential for increased losses of N by leaching. Introduction of biological controls for Canada thistle (e.g., Peschken and Harris, 1975) could reduce the need for intensive cultivation. Our observations suggest that weed problems are likely to be most severe on soils of low fertility. Denser seeding of crops and/or heavier application of low manure may be effective in controlling weeds on such soils. The latter would have to be accompanied by lower applications of manure on soils of highest fertility, where the response to manure is likely to be less, and overall would result in more N being cycled through crops than if manure was applied at a uniform rate throughout.

The total yields of N predicted from per hectare crop yields in Table 1 would be less than in the past (1824 versus 2188 kg) simply because 7½ rather than 10 ha are planted with faba beans. However, production of beans has generally exceeded requirements in the past, and with the addition input of clover-N before winter wheat, the balance may be redressed in favor of the grains. The difference between inputs of N from manure and N_2 fixation and outputs in harvested seed in this scheme is estimated as 34 (conservative estimate of N_2 fixation in faba beans) to 46 kg N/ha, so the potential increases in yields are high (present output 73 kg N/ha), and if realized would result in yields similar to those achieved with inputs of commercial fertilizer-N.

CONCLUSION

These studies suggest that for Farm B, there is a potential to be self sufficient in feed production and in N on a sustainable basis without having to increase the land base. A large input of N from N_2 fixation, and efficient recycling of N in manure and plant residues are required. The resources required for N_2 fixation are available now and are being utilized. The major part of the N_2 fixation is provided by the faba bean which also provides the high protein component of the poultry feed. The limiting factors to achieving self sufficiency are ones concerned with management of the N once it is fixed, rather than with the amounts of N_2 fixed. A regular rotation of crops appears to be essential.

Traditional crop rotation systems are up to 45% more energy efficient than modern monoculture systems, although the yields are frequently lower (Heichel, 1978). If advances in our understanding of plant and microbial processes are applied to the design and management of rotations, then their outputs might become competitive with those of monoculture systems, and they could provide an important low energy option for the future.

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Thank you.
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