Biological Agriculture and Horticulture, 1986, Vol 3, pp. 167–189
0144-8765/86 $5

Printed in Great Britain

Biological Husbandry and the "Nitrogen Problem"

David G. Patriquin

Biology Department, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 4J1

INTRODUCTION

There are few agricultural systems today that operate without substantial inputs of nitrogen fertilizer. Because of the high cost of these inputs, and increasing concern over aquatic, groundwater and atmospheric pollution by N fertilizer (Stewart & Rosswall, 1982) considerable research is being conducted with the goal of making plants "self-sufficient" in nitrogen (Earl & Ausubel, 1983). However, a decade of intensive research into biological N_2 fixation has failed to bring about a substantial reduction in the use of nitrogen fertilizer, and there is little prospect that it will do so in the near future. We need to seriously consider, therefore, whether it is possible to practice agriculture with greatly reduced inputs of N fertilizer by using existing N_2-fixing resources in conjunction with recycling; in other words, to consider to what extent biological husbandry could reduce the requirements for nitrogen fertilizer.

Over the past five years I have had an opportunity to study the practical and theoretical aspects of this question. This opportunity resulted from meeting a farmer who had stopped using fertilizer and pesticides and was attempting to meet the N needs of his cereals by use of legumes and manure produced on the farm. In this paper I will describe what we have learned, factually and conceptually, about the "N problem" from our studies. By "we" I refer to Mr. Basil Aldhouse (the farmer), myself, and to a succession of Honors Biology students (David Burton, Nick Hill, Gillian Allan, Mary Bishop and Danica Baines) each of whom contributed in his or her own unique way to an enlarged vision of "the farm".

REGIONAL SETTING

The farm is located in the Annapolis Valley of Nova Scotia (Canada), a cool (120 frost free days), humid (114cm rain annually), temperate region. It consists of approximately 35 ha of field crops, 2 ha of pasture and garden, and 35 ha in woodland and water. The fields are level to rolling, contain 2.8 to 7.1% organic matter, vary in texture from loamy sand to sandy clay loam and are classified as being in categories 3 and 4 with moderately severe to severe limitations. Approximately 2000 laying hens are maintained in a traditional floor operation with deep litter. Mr. Aldhouse attempts to be self sufficient in feed; this number of birds is roughly that which he found could be supported by grain production on 30 ha of land managed conventionally. In 1975, he achieved the highest oat yield (98 bushels/acre) in a provincial competition. Out of concern over rising requirements for inputs and the large amounts of toxic materials he was using, he decided in 1976 to stop using fertilizer and pesticides and to see how the farm could manage on its own resources. His cereal yields promptly fell by about 50%. Rather than reduce the size of his flock, he purchased grains to make up the difference, and explored ways to increase his yields. From 1980 to 1983, yields of faba beans, winter wheat and oats averaged about 25% below those cited as normal for this region with full fertilization (2.7 to 3.1 tonnes/ha). In spite of those reductions, the farm has remained profitable; the cost opf purchasing grain to make up for the shortfalls in production is equal to or less than the cost he would otherwise have spent on fertilizer and pesticides. Oat yields improved substantially in 1984.

USING A GRAIN LEGUME TO SUPPLY N TO OTHER CROPS

We didn't set out to study Mr. Aldhouse's farm. We were interested in the faba bean (*Vicia faba* minor), and Mr. Aldhouse was one of the few farmers growing this plant locally.

The faba bean is a grain legume, grown traditionally in China, Europe, the Middle East, North Africa and Peru. Its use in Europe declined dramatically in the mid 20th century but there is now renewed interest in the crop (Thompson & Taylor, 1982). It was first grown commercially in Canada in 1967, by Robyn Warren, an Englishman farming the dykelands of Nova Scotia. Several other farmers, including Mr. Aldhouse, took it up in the next few years, and subsequently it was introduced to western Canada (Evans *et al.*, 1972).

As faba beans in western Canada had been reported to respond to inoculation (Candlish & Clark, 1975), we thought we might be able to increase N fixation on local farms by inoculating crops with "superior" *Rhizobium* strains. A preliminary survey revealed, however, that there was no need for inoculants. Plants were well nodulated and exhibited high nitrogenase activity (Patriquin & Burton, 1982). Further, the farmers were less interested in increased N_2 fixation, than they were in learning how to use existing N fixation. Mr. Warren showed me several examples of how maize and cereals exhibited better growth where they followed faba beans in a crop rotation. He assumed this was due to N_2 fixation and wanted to know how much he could allow for it in fertilizer applications. We supposed that you could reduce the N applications to subsequent crops by roughly the difference between the nitrogen fixed and the nitrogen removed at harvest.

However, a N budget for Mr. Warren's beans suggested that the bean crop was withdrawing substantially more N from the soil than it was putting in through N_2 fixation (Fig. 1). That particular site had an unusually high yield, but studies at sites of lower yields also indicated near zero or negative N balances (Patriquin *et al.*, 1981). Similarly, negative N balances have been found for soybean (Johnson *et al.*, 1975) and even some forage legumes when the latter are not consumed in the field (Rice, 1980).

Interestingly, it was apparently well known in the pre-chemical era that continuous culture of grain legumes leads to rapid decline in soil N (Harmsen & van Schreven, 1955).

How, then, does the faba bean benefit subsequent crops? Possibly by bringing up nutrients from deep horizons via their well developed tap roots, or by putting N in a highly available form, i.e. in high N residues (Fig. 1).

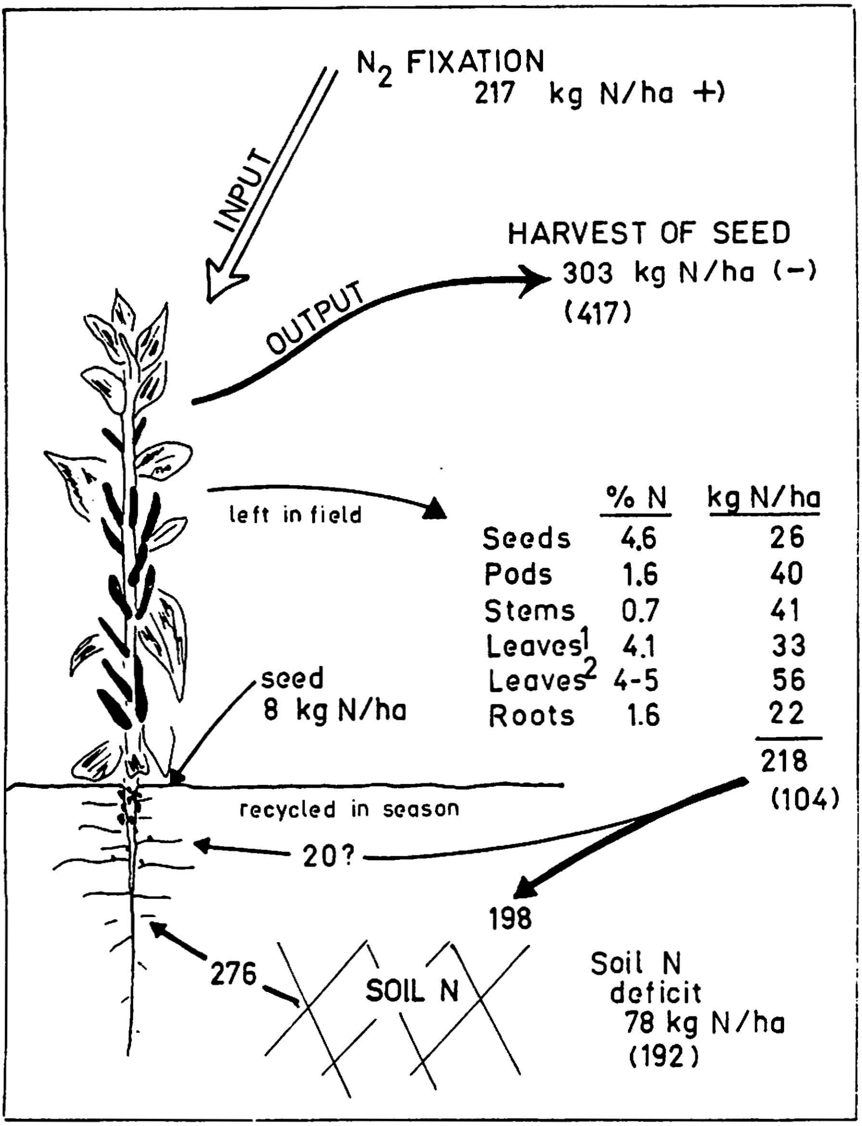
In any case, the negative or near zero N balances mean that N_2 fixed by this grain legume cannot reduce the net N requirement of other crops grown in rotation with it unless some of the legume-N removed at harvest is recycled, i.e. as manure.

RECYCLING GRAIN LEGUME N

That was in effect how Mr. Aldhouse was attempting to use N_2 fixed by the faba beans. He had beans on 1/3 of his land, fed the grains to his hens, and applied the hen manure to the cereal fields. Yet the cereals still suffered from a severe shortage of N. Why?

Figure 2 illustrates the major flows and reservoirs of N on the Aldhouse farm in 1979 (Patriquin *et al.*, 1981). For the moment, there are three points to be noted:

(1) There were roughly 5000 Kg N cycling around the farm and only 400 Kg being exported as eggs. It can immediately be appreciated that the greatest inefficiencies in conventional egg-producing systems result from separating the sites of N_2 fixation (e.g. in soybean) and of manure production from the sites of cereal production.



	% N	kg N/ha
Seeds	4.6	26
Pods	1.6	40
Stems	0.7	41
Leaves[1]	4.1	33
Leaves[2]	4-5	56
Roots	1.6	22
		218
		(104)

FIGURE 1 N budget for faba beans on Warren farm in 1978 (Patriquin *et al.*, 1981; Patriquin & Burton, 1982). The faba bean fixed 217 kg N from the atmosphere but 303 kg were removed in grains at harvest, indicating a net withdrawal from the soil of 78 kg (192 kg if straw were also harvested). The large amount of N taken up from the soil (276 kg) may have come in large part from recovery of N leached to deeper horizons prior to 1978 when normally fertilized cereal and maize crops were grown at this site.

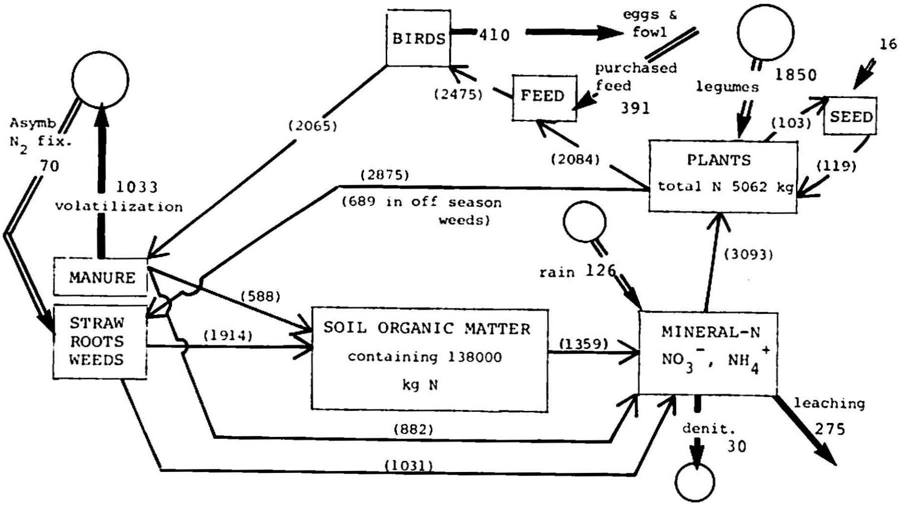


FIGURE 2 Nitrogen budget for the Aldhouse farm in 1979 (from Patriquin *et al.*, 1981). Numbers in brackets are flows of N between compartments within the farm. Big arrows and accompanying numbers not in brackets are flows of N into and out of the farm. Circles represent the atmosphere. Units are kgN per farm per year.

(2) For the farm as a whole, the inputs of N exceeded the outputs, even when the inputs in purchased grain are discounted. This illustrates that the deficiency of N for cereals was related to the manner in which N cycled around the farm, rather than to inadequate inputs.

(3) On the average, there was more N going into the fields than was being removed. Inputs to or outputs from the fields due to rain, asymbiotic N_2 fixation, leaching, denitrification and seeding were relatively small and roughly added up to zero; thus the major determinants of field N balances were the amounts of manure-N applied to fields, of N_2 fixation, and of crop-N removed at harvest. For bean fields, N_2 fixation (165 Kg) was approximately equal to the N removed at harvest (162 Kg). For the cereal fields, the inputs in manure (105 Kg) greatly exceeded the average outputs in grain (40 Kg). In other words the "N problem" appeared to be one of unavailability of most of the manure-N.

This excess input of N does not just disappear. If inputs exceed outputs, then the store of soil (humic) N, and the amount of N mineralized from this store each year, should increase each year until the outputs equal the inputs (Magdoff, 1978). The pertinent question is: how long would it take for this store of N to build up to a level at which good yields of cereals could be obtained? Some rough calculations indicated that we could expect cereal yields to increase by 11%, and bean yields by 2% in twenty years. Even allowing for conservatism in making these estimates, a "wait and let soil fertility accumulate" strategy was not a practical proposition (Patriquin *et al.*, 1981).

RESTRUCTURING THE SYSTEM

At this point, we considered that we needed to restructure the system in such a way that more of the N would cycle through crops, and less through weeds and humus; to make the system do more work for us at its present level of accumulated fertility; to take care of it in such a way that the release of N from humus, residues and manure coincides more closely with crop growth; overall, to increase the ecological efficiency of the system. Five areas that we have looked or are looking at in this regard are discussed below.

Crop rotation

In 1980, Mr. Aldhouse instituted a regular rotation of crops: Faba beans—oats underseeded with clover–clover–winter wheat. The clover is rotovated in the third year prior to planting winter wheat. Clover and winter wheat provide winter cover on the fields after the oat and clover crops respectively. Straw and weeds provide cover in the other two years. It is a cereal-legume rotation; legumes follow cereals so that the immobilizing properties of straw, and possibly carbon dioxide release (Shivashankar & Vlassak, 1978) stimulate N_2 fixation, and cereals in turn mop up N from decomposing legume residues. In a monoculture of cereals straw is frequently burned because of its immobilizing properties (Lynch, 1984). In this system those properties are a benefit. The faba bean is especially suited to this sequence because it begins to fix N shortly after germination when the wheat straw is likely to be immobilizing N, and it can use soil N during pod-fill when immobilization has likely ceased (Patriquin *et al.*, 1981; Patriquin & Burton, 1982).

In order to have as close as possible to one quarter of his farm in each stage of the rotation, Mr. Aldhouse brought two more fields into production, increasing the field crop area from 30 to 34.5 ha. For this system the calculated inputs to the fields from manure (1034 Kg) and N fixation (1858 Kg) exceed the outputs in grains (2087 Kg) by 805 Kg. Cycled into cereal grains at 2% N, this excess represents a potential increase in cereal yields of approximately 2 tonnes/ha, which is well above what is required for the yields to be similar to those achieved under conventional management.

Mineral nutrients and pH

Except for a few tonnes of lime applied in 1976, no fertilizer or lime has been used on the farm since 1976, and heavy liming has not been practiced since the sixties. Analyses of all fields in 1980 and most in 1983 indicated generally satisfactory base saturation (average 73%), no deficiencies in P, Ca or Mg, and slightly low K on 4 of 14 fields. Ratios of Ca:Mg are low (average 2.6) compared to those frequently cited as desirable (Albrecht, 1975).

Comparison of these and other data obtained since 1971 suggests that pH increased and stabilized at desirable values after Mr. Aldhouse stopped using fertilizer and lime, and that Ca and Mg increased in surface horizons by factors of about 20 and 50% respectively (Fig. 3). These changes are remarkable given that this is a high rainfall region of naturally acid soils. We believe that the changes are associated with, firstly, more complete cycling of N within the farm, and with the major inputs and outputs now being in non-ionic form (Helyar, 1976); and, secondly, enhanced vertical cycling associated with greater abundance of deep rooted herbs, particularly *Taraxacum officinale*, and possibly with more faunal activity. The herb and faunal effects could be related. Pfeiffer (1974) noted a close association of earthworms with *Taraxacum*, and we have noted the same phenomenon.

Cultivar selection

Comparisons of 6 oat cultivars illustrated that cultivars used in systems of biological husbandry, need to be selected in the same systems (see Fig. 5 and accompanying discussion below). On the basis of those comparisons, Mr. Aldhouse began to use the Fundy oat cultivar in 1984. We have yet to make comparisons of different wheat and bean cultivars.

Manure

There is a finite amount of manure coming out of the barn, and certainly less than we would need to relieve all N shortages immediately. Thus we would like to apply more manure where it imparts greatest benefits, and less elsewhere. To do so, we require estimates of the sustainable output of manure, and information on the variation in response to manure according to the crop (wheat or oats) and the particular field.

Information from the N balance (Patriquin *et al.*, 1981), a P balance, and from the literature (Patriquin *et al.*, in preparation) indicates that the sustainable output of manure is approximately 55 tonnes/year containing 1034 Kg N after volatilization losses. We are planning some trials on the use of

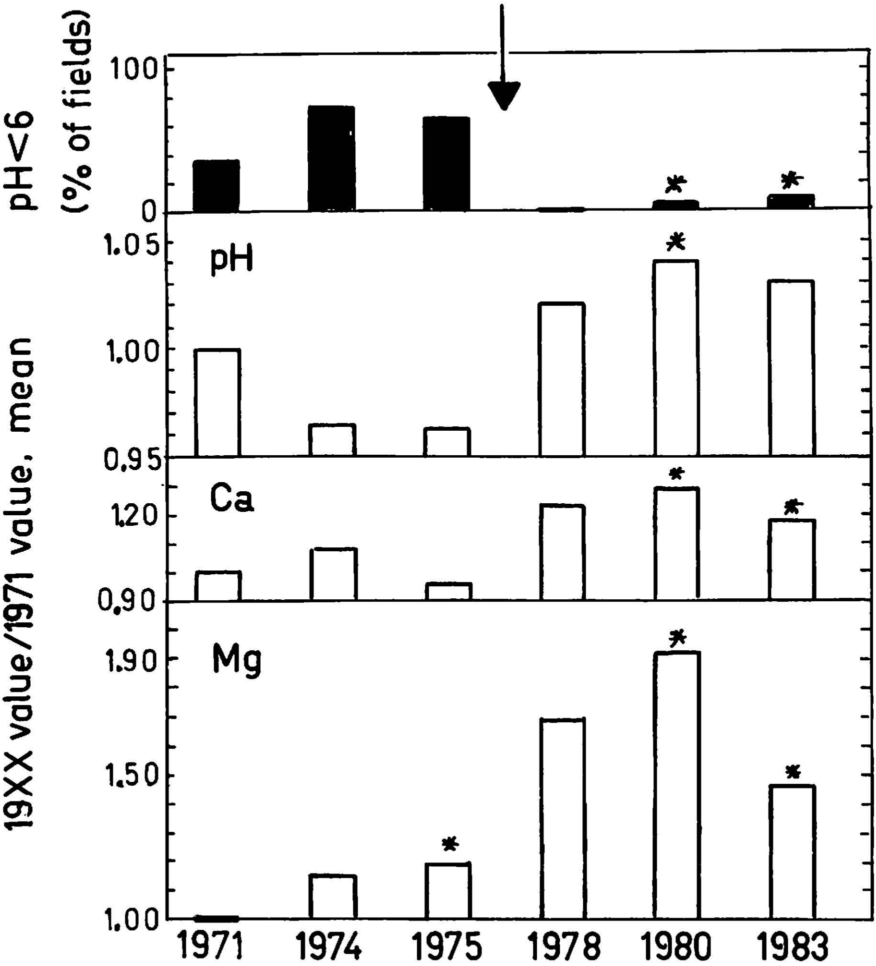


FIGURE 3 Summary of comparable data from analyses of soils taken from the Aldhouse farm, 1971-1983 (Patriquin *et al.*, in preparation). Arrow indicates cessation of fertilizer, lime and herbicide applications. Asterisks indicate significant differences ($\alpha = .05$) from 1971 values as assessed by binomial theorem for proportions, or rank- sum test for ratios. All (14) fields were sampled in 1971 and 1980. Seven fields were sampled in 1974, 11 (pH) or 12 (Ca and Mg) in 1975, 5 in 1977 and 10 in 1983. Samples taken from 1971 to 1978 were analyzed by the Nova Scotia Department of Agriculture, 1980 samples by the Woods End Laboratory, Temple, Maine, and the 1983 samples in our laboratory. Average values in 1971 were 6.06 for pH, and 6.41 and 2.08 meq/100g for Ca and Mg respectively.

gypsum to reduce volatilization losses in the roost (Roberts, 1897). Reduction of these losses by 50% would save about 500 Kg N (Fig. 2). Gypsum will be used because we also wish to increase the Ca/Mg ratio without increasing pH.

When Mr. Aldhouse stopped using fertilizers, he had an excess of manure available and applied it to all cereal fields at a rate of 5.6 tonnes/ha. As our calculation suggested this rate could not be sustained, after 1979 he stopped applying manure to oats which is considered the less demanding of the two cereals. From 1980 to 1983, wheat yields were about 30% below those achieved under conventional management. This degree of reduction in wheat yield appears to be typical of organic systems (Berardi, 1978; Lockeretz *et al.*, 1981).

Lockeretz *et al.* (1981) found yields of oats under organic management to be similar to those under conventional management. On the Aldhouse farm, however, oats yielded about 50% of normal from 1980 to 1983 with the exception of a good yield on one of the more fertile fields in 1981. In 1982 we applied 17 different combinations of fertilizer elements to plots on the oat fields. There was a consistent and large response to manure, and erratic responses to treatments which included N fertilizer. From these and other observations (discussed below) we concluded that the poor yields of oats are related in large part to phytotoxic effects of the bean residues. Manure may relieve this problem by feeding microbes as well as the plant, the microbes in turn breaking down the phytotoxins. Thus application of manure to oats appears to be one means of solving the problem. We do not know precisely how much is required, and how this requirement varies field by field.

In an attempt to begin to sort out the factors involved in field to field variation in response of crops to manure, we examined the mineralization of N and C in experimental soil-sand systems with or without manure or straw (Baines, 1984). There was substantial variation between soils from different fields in the amount of additional carbon dioxide or nitrate released or immobilized when residues were added (Table 1). The three soils with highest respiration (A4, A5, B2) in the presence of manure mineralized more additional N in the presence of manure than did three soils (A1, A2, C) with lower respiration values. The same three soils also exhibited the highest respiration when straw was added, and with the exception of soil A4, those three soils exhibited less immobilization of N than did the soils with lower respiration values. Assuming that the N required for microbial growth is proportional to the carbon dioxide output (Paul & Juma, 1981), one would expect the reverse, i.e. soils with lower respiration values to immobilize less in the presence of straw, and (possibly) to mineralize more in the presence of manure. A possible explanation is suggested by the straw carbon dioxide values, which for the three soils of highest activity, exceed the amount of carbon added as straw by substantial amounts. This suggests that there was substantial priming of the soil humus in soils with higher respiratory activity,

TABLE 1

Mineralization of C and N by soil from different fields without and with added residues (from Baines, 1984). Asterisks indicate soils for which the amount additional CO_2-C evolved in the presence of straw exceeded the amount of carbon added as straw (2250 μg C/g soil). Data are from Baines (1984).

	CARBON DIOXIDE-C			NITRATE-N		
	Soil alone	Additional CO_2 in presence of		Soil alone	Additional NO_3-N in presence of	
FIELD		straw	manure		straw	manure
		(μg CO_2-C or NO_3-N/g soil in 98 days)				
B2	1422	3114 **	2624	59	-26	112
A5	1985	3053 **	2650	67	-24	116
A4	2806	2812 **	2880	143	-53	95
C	1408	2122	1884	101	-32	54
A2	1337	1946	1566	91	-35	68
A1	1324	1867	2282	109	-58	84

Each sample consisted of 150 g air dried, sieved (1 mm mesh) soil mixed with 450 g quartz sand and 56 ml water in a 1.5 liter jar. Jars were closed with polyethylene and incubated at 30°C. Water was added as necessary to maintain the initial level. After 2 weeks (time zero), residues (0.75 g oat or 1.0 g manure) were added. Each treatment was replicated 3 times. For measurement of CO_2 production, jars were aerated for 30 minutes, closed, and and CO_2 measured after 19 hours. Cumulative values of CO_2 production were calculated from rates measured at 1, 2, 6, 7, 14, 28, 42, 70 and 98 days. For measurement of nitrate, 10 g soil + sand were removed and analyzed at 0, 2, 6, 14, 28, 59, 98 days.

N added in straw was 36 μg/g soil; N added as manure, 252 μg/g soil.

resulting in release of N and consequently in lower apparent immobilization and higher apparent mineralization of manure-N than in soils with lower respiratory activity. Regardless of the precise mechanisms involved, these observations suggest that the more biologically active the soil, the lower will be the amount of manure required to augment the N supply by a given amount, and the less immobilization there will be when low N residues are incorporated in the soil.

In the absence of a fully formulated analytical understanding of the variation in response to manure by crop and field, Mr. Aldhouse is continuing to apply manure to wheat at standard rates, and to oats as the excess allows. In time, this will give us an empirical assessment of the benefits of manure on each field.

Tillage

In terms of the biology involved, tillage is probably the most complex, most important and yet least understood of farming operations. On the Aldhouse farm, tillage operations are conducted with at least the following objectives in mind:

1. to facilitate good surface drainage and accordingly, rapid warming of the soil in spring;
2. to eliminate standing weeds, and to reduce seed banks but not to the point that weeds cannot function as a self-seeding cover crop;
3. to break up and incorporate the large amounts of residues from the wheat and bean crops in order to dissipate them and to encourage biological activity so as to minimize possible phytotoxic and immobilizing properties of these residues;
4. to incorporate the green manure (clover) crop prior to planting winter wheat;
5. to break up hard-pan smears left by shallow tillage;
6. to distribute straw in such a way that uniformly good drainage characteristics develop;
7. to break up surface soil and leave some residues near the surface so as to encourage capillary rise of water;
8. to encourage biological activity and release of mineral-N at the most appropriate time. In effect we are trying to sheet compost the residues, and want to provide as near as possible optimal conditions of air, water and temperature for the decomposers.

At the same time, we wish to minimize the well known negative effects of tillage including:

(i) leaving the surface bare and subject to erosion;
(ii) compaction;
(iii) use of fuel, time and labor.

It can be appreciated, I think, that even given all of the analytical information we asked for, it would be exceedingly difficult, if not impossible, to conceptualize precisely how the multitude of factors involved in tillage interact. The problem is additionally complicated by the presence of at least four distinct soil series. Yet decisions about the timing, frequency and type of tillage had to be made. In such circumstances, the farmer has to make as reasoned a guess as possible, try it out for a number of years, observe the effects and then adjust or try new techniques. In this regard it is the farmer who is the experimenter, and the scientist's role is primarily that of an observer and interpreter (L.H. Bailey in Roberts, 1897). Following is a brief account of how tillage operations have developed over the past five years.

Prior to 1976, Mr. Aldhouse mouldboard ploughed his fields regularly in the fall. He stopped doing so after taking up biological husbandry because of (i) the difficulty of ploughing after high residue crops (such as wheat and clover), (ii) the difficulty of contour ploughing on irregularly shaped fields; and (iii) the probable ill-effects of burying residues in a layer at depth (Faulkner, 1945). Since 1976, tillage has consisted primarily of rotovating residues into the ground in the fall or spring after beans, in September after wheat, and in June or July after clover. The seedbed is then prepared by harrowing with a spring tooth harrow, and according to the weediness of the field, it may be gone over once or twice with a spike-tooth harrow after the crop is planted.

In 1979, Mr. Aldhouse decided not to conduct tillage operations in the fall because of the possibility that to do so would encourage leaching and erosion. In the spring of 1980, there was a very heavy growth of weeds following the previous year's bean crop. The field was rotovated about two weeks prior to planting oats. The oat yield that year was exceptionally poor, which we attributed to phytotoxic effects of the decomposing weed residues. In order to avoid this problem, Mr. Aldhouse then decided to rotovate the bean residues in the fall which is more desirable with regard to the seasonal distribution of labor and to the workability of the land. We think that this practice does not cause excessive leaching or erosion because (i) the bean crop is harvested in October by which time soil temperatures have begun to drop (i.e. there should not be a lot of decomposition before winter sets in); (ii) laboratory studies suggested that the bean residues would immobilize N initially (Patriquin *et al.*, in preparation), (iii) the surface is left rough, and there is still a fair amount of weed growth.

In spite of these adjustments, oat yields remained poor over the next three years, with one exception, that being on one of the most fertile fields in 1981. Data from an oat cultivar experiment (Fig. 4) suggested that even with fall tillage, we had problems with phytotoxicity—presumably from the bean residues, since there was not now a heavy growth of weeds. A solution to this problem could lie in applying manure to the oats, as discussed above, but alternative tillage operations may provide the most appropriate solution.

Mr. Aldhouse considered that rotovation of residues is not completely satisfactory because while it mixes residues into the soil, it leaves a fair amount on the surface, and leaves the surface flat which tends to keep it cold. In the fall of 1983, he tilled one field after beans with a tool bar equipped with six right hand throw shanks and 3-inch shovels. This left the soil surface in nicely ridged condition (spaced at 14 inches) and effected good mixing of residues within the soil without actually turning the soil over—or with residues occasionally lumping together as they are liable to do with chisel ploughs. The oat crop that developed on this field in 1984 was a good one (oat biomass, 5144 kg/ha; compare with Fig. 4) and the yield on a manure-fertilized section was similar to those on the non-fertilized section (Patriquin *et al.*, in preparation).

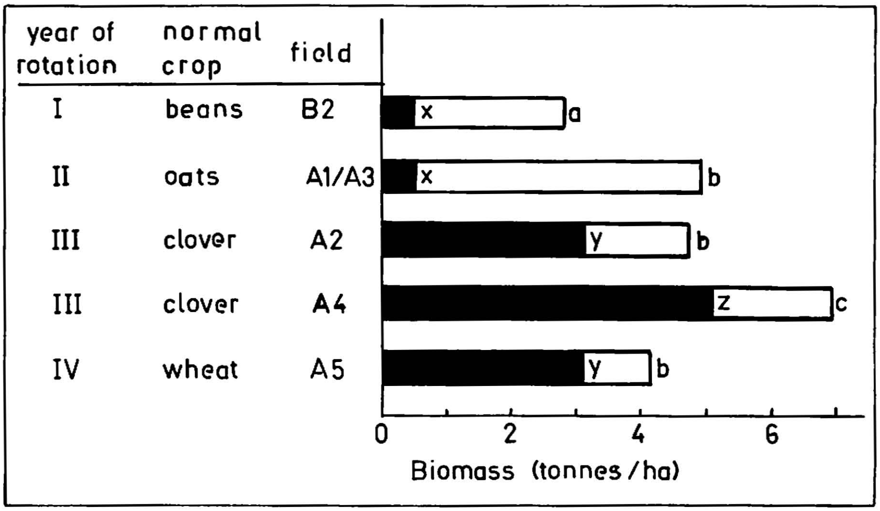


FIGURE 4 Total biomass (crop + weeds) and crop (shaded) biomass on oat cultivar test plots in 5 fields in 1982. Bars followed by different letters represent yields which differed significantly from each other as assessed by the rank sum test ($\alpha = 0.05$). On each field, six cultivars were planted, each cultivar in three 2 × 2m plots. The central 35 × 35cm were harvested at maturity. The low oat yields on field B2 and A1/A3 are indicative of phytotoxic effects of residues from the previous years' crops (wheat and beans respectively). The low total yield on field B2 is attributed to immobilization of N by wheat residues. Data from Patriquin *et al.* (in preparation).

Likewise, a good oat crop (oat biomass 4718 kg/ha) grew on another field which Mr. Aldhouse mouldboard ploughed in the fall of 1983. In both cases, we think that the apparent improvement over the previous situations is related to improved surface drainage and more rapid warming of the soil in the spring, that resulting in turn in accelerated biological activity and breakdown of phytotoxins.

At this point, tillage operations on the farm are planned as follows: (i) to rotovate in the fall after beans, followed by ridging with twisted shovels; (ii) to rotovate after wheat, in the fall (there is too much residue for the ridging operation); (iii) to "partial summer fallow" in year III after clover by deep rotovating (with rear doors left up so that weeds thrown on the surface remain there), and use of twisted shovels and harrows. These operations will be followed by harrowing for seedbed preparation and weeding. We consider that a partial summer fallow is necessary to control perennial weeds, particularly Canada thistle (*Cirsium arvense*), which have increased in abundance over the past four years (unpublished data). Cultivations will begin in early June and will be spaced at approximately 21 day intervals, which has been found effective for control of Canada thistle (Hodgson, 1958), until wheat is planted in late August. Clover reaches near maximum biomass by early June. As we are following it with a long season crop (winter wheat), we are hopeful that most of the N mineralized during the fallow will be recovered.

ANNUAL WEEDS AND THE CONSERVATION OF N

In a recycling system, the conservation of even small amounts of N is of great importance. Present losses due to denitrification and leaching are of the order of 10 kg N/ha and are approximately balanced by inputs in rain, asymbiotic N fixation and seed. If the losses increased, then the sustainable output of grain N would decline accordingly. In terms of the soil N balance, 20 Kg N lost by leaching is equal to a grain output of about 1 tonne/ha. Off-season growth of weeds on the farm conserve of this order of magnitude of N, and thus are of critical importance.

Note by contrast that such amounts of N have much less significance in conventional, more open systems. For example, given a grain crop with 60 Kg N in the grain, 30 Kg N in the straw which is harvested or burned, and 50% loss of fertilizer-N, the N requirement is 180 Kg N, and a saving of 20 Kg N represents a saving of only 0.3 tonnes grain—roughly we can say that N is three times more valuable in the recycling system.

In addition to their role in conserving N, weeds protect the surface of the soil, and fix carbon and some, N_2, where or when crops are not present, and bring up nutrients from deep horizons. They may play a critical role in insect pest control (Altieri & Whitcomb, 1978/79). Thus the strategy sought with regard to weeds is to control them so that they do not interfere with crops, but not to eliminate them so that they are always available as "self-seeding cover crops". This strategy, and the discussions following, apply to annual (and biennial) rather than to perennial weeds, because the annuals are easier to control, compete less with the crop, and by their presence, help to control the more problematical perennials (i.e. perennials would be much more of a problem in the total absence of annuals).

The key to this strategy lies in the epigenetic relationship (Thomas, 1983) between weeds and crops: crops have a negative effect on weeds and weeds a negative effect on crops. In such a relationship, whoever gets a head start will hold the upper hand. Thus we can control weeds both by giving a helping hand to the crop or by hindering the weeds.

Of the many factors influencing the crop-weed relationship, the most important are crop rotation and cultivation, which hinder the weeds, and fertility, which has a positive effect on the crop.

Each crop has a characteristic assemblage of associated weeds, and changing the crop each year helps to keep prevent any one species from building up to the point that it cannot be controlled. For example, cultivation of soil for winter wheat in the fall stimulates wild radish (*Raphanus raphanistrum*) the most abundant summer annual weed, to germinate. The radish grows between rows of wheat in the fall, protecting the soil and conserving nutrients, but is killed over winter, resulting in a substantial reduction in the seed bank (Patriquin *et al.*, 1981).

The critical question with regard to cultivation of annual weeds is: how much is enough, and how much is too much? A completely clean soil is undesirable as is a crop overgrown by weeds. Our studies on fertility-weed interactions have provided us with a tool for looking at this question.

We argued that given an epigenetic relationship and provided the crop gains the initial advantage, the higher the fertility, the better the crop will do and the fewer weeds there will be at harvest. An analysis of quadrat data from three crops and several farms supported this concept (Patriquin *et al.*, 1981). We assumed that the total biomass is a relative measure of fertility (i.e. something will grow whether it is weeds or crop). Thus we would expect that the higher the total biomass, the fewer weeds there should be in the sample. Four types of relationships were observed (Fig. 5). The type 4 relationship appears to represent the limit of permissable weediness for beans, i.e. it represents a situation in which the crop holds the upper hand and the weeds fill in all available spaces between the crop but do not overwhelm the crop. Comparison of bean yields on weeded and unweeded plots support this concept; yields on weeded plots averaged only 9.7% higher than those on unweeded plots (and the differences were not statistically significant). There was no trend of increasing advantage for the weeds at low total biomass when the crop to weed ratio is low. Oat yields on untreated plots in a field where the relationship between percent crop and total biomass was of type 3 were 17% below those of herbicide treated plots (Patriquin *et al.*, in preparation). Relationships of type 5 clearly represent situations in which the weeds have gained the upper hand. The relationships are obvious visually: where the crop has the advantage, annual weeds predominate only in regions of poor (short or sparse) crop growth.

The relationships have fundamental practical significance for biological husbandry: (i) they illustrate that a high proportion of annual weeds is "normal" at low fertility, and even desirable; (ii) they indicate that problems with annual weeds should decline as fertility increases, and finally (iii), relationships of type 5 illustrate situations in which more cultivation is required. For example, for wheat fields over the last four years, we have noted a tendency for a shift from a type 3 to a type 5 relationship, suggesting that more control of weeds is required.

We have used the same approach to analyze the performance of different cultivars of oats. Such analyses illustrated that certain modern varieties, selected under conditions of few or no weeds, are not competitive with weeds

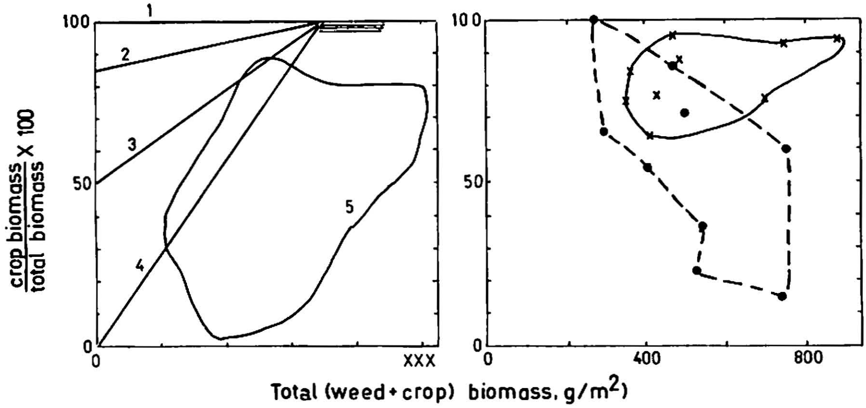


FIGURE 5 Relationships between the proportion of crop in a sample taken at harvest (expressed as percentage) and the total (weed + crop) biomass (Patriquin *et al.*, 1981 and in preparation). Relationship (1) is characteristic of fields in which there is nearly total elimination of weeds by herbicides. Relationships 2, 3, and 4 represent fields in which there was a significant positive linear correlation between percent crop in a sample and total biomass. Relationship (2) was observed for oats in 1979 following a cultivated fallow and for wheat in 1980, relationship (3) for wheat (most years) and for oats in 1981 and 1984, and relationship (4) for faba beans (most years). Relationship (5) represents faba beans on N fertilized plots, oats in 1980, 1982 and 1983, and one wheat field in 1984.

FIGURE 5 Right illustrates these relationships for the best performing oat cultivar (a traditional type) and the most poorly performing oat cultivar (a modern selection) in oat cultivar comparisons, excluding fields following faba beans or wheat (see Fig. 4 above).

(Fig. 5). Unfortunately, some of the older varieties are now difficult to obtain. In any case, if biological husbandry is to progress, cultivars with the benefits of other modern cultivars such as high harvest index need to be selected *de novo.*

IS NITROGEN LIMITING?

It is generally assumed that if a crop responds to fertilization with a certain mineral, then the mineral concerned is "limiting" for plant growth. This may be true for the plant considered alone, but it does not necessarily follow that adding more of the element is the most appropriate way to solve the limitation; or, for example, that the quantity of N in the system is insufficient to support higher yields. The limiting factor concept becomes especially clouded when we are dealing with cyclical processes, because we must then ask what is "limiting" production of the mineral by the previous step in the cycle, and then the previous step to that . . . and so on.

Even in a narrower context, the limiting factor concept can be misleading. In 1980, we observed a pronounced response of wheat on field A1 to N fertilizer applied in 2 × 2 m plots. Since the standing amount of inorganic N in the field at large was small compared with that taken up by wheat, we supposed that variations in growth and N accumulation by wheat in that field would be related to the N mineralization capacity of the soil. A comparison of plant N accumulation with the soil N mineralization potential suggested that the former was indeed related to the latter, but that other factors were also limiting (Fig. 6). What are those other factors? At least one of them involves drainage.

In 1983, we measured plant height and soil matric potential during a saturating rainfall at 25 randomly chosen sites, and at 12 sites of adjacent tall and short wheat in each of 3 fields. For the randomly chosen sites there was no correlation between height and soil matric potential. However, at 12/12, 11/12 and 9/12 of the paired sites, soil matric potential was lower in the stand of taller growth (Patriquin *et al.*, in preparation), i.e. the stands of taller growth drained more rapidly. This suggests that over the field(s) at large, variation in growth is related to variation in potentially mineralizable-N, but within regions of the field, to drainage and possibly other factors.

What is "limiting" drainage? The stands of tall and short wheat tended to be oriented parallel to each other and in the direction of operation of the combine and to be separated by approximately the width of the combine. This suggested that variations in drainage are related to the pattern of straw distribution and/or compaction caused by passage of the combine. Examination of several sites revealed obvious straw residues in soil blocks from stands of good growth but not in those of poor growth, confirming that the regions of poor growth at least include some of those where little straw is laid down and where compaction may be greatest.

In 1980, yields on all six N-fertilized plots exceeded those of controls, and averaged 2.6-fold higher. How then could drainage also have been a limiting factor? Would simultaneous improvement of drainage have increased yields in the presence of N fertilizer even further? The answer is probably no. The effects of drainage are not independent of those of N. Drainage affects the efficiency of N use by the wheat (Armstrong, 1980), the efficiency being higher in better drained soil. It might also affect the actual mineralization (i.e. the degree to which the potential mineralization is actually realized); the literature is not very clear on this point. When wheat is fertilized at levels found to be necessary for uniformly high yields (the usual criterion), the effects of variation in drainage are essentially compensated for—and unless one is actually measuring the efficiency of fertilizer use, or fertilizing at submaximal levels, go unnoticed. More poorly drained wheat uses N less efficiently, but since excess N at sites in which it is being used efficiently by the plant is probably lost by leaching or denitrification anyway, these differences in

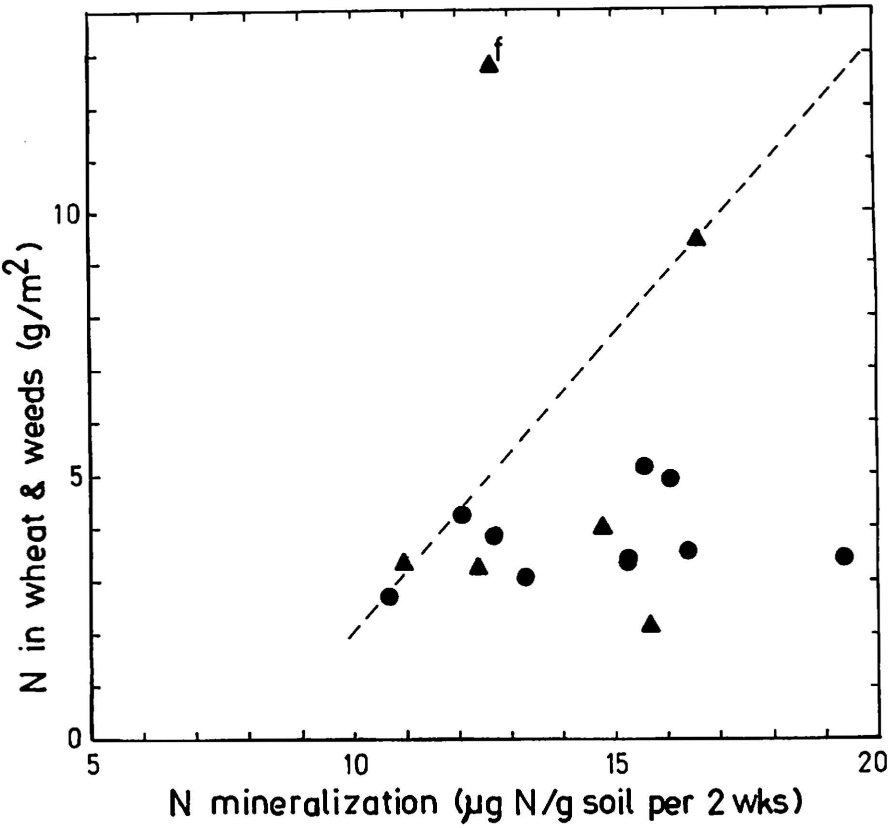


FIGURE 6 Relationship of total N in winter wheat and weeds on June 4, 1980, and mineralizable-N (from Patriquin *et al.*, in preparation). Circles represent samples from randomly chosen sites; triangles represent samples taken from sites chosen to include a wide range of productivity. Triangle "f" represents a plot fertilizer with 115 kg N/ha as urea on May 18. The broken line links sites at which N was limiting; points below this line represent sites at which the maximum potential for N accumulation was not realized because of the operation of other limiting factors (for discussions of this sort of interpretation, see Balandreau & Ducerf, 1980; Parnas, 1975). Mineralizable N was measured by a laboratory incubation technique on 150 g soil from each site.

efficiency are not normally evident. One of the most striking differences between fields managed by biological husbandry and those managed chemically is the much greater variation in growth in the former, at least during the transition to biological husbandry, i.e. when the masking effects of fertilizers are initially removed.

The interaction between drainage and N illustrates an important point: if we diagnose our systems purely in terms of chemistry, we will come up with only chemical "solutions". The problem with such solutions is that by masking or compensating for other limitations or inefficiencies in the system,

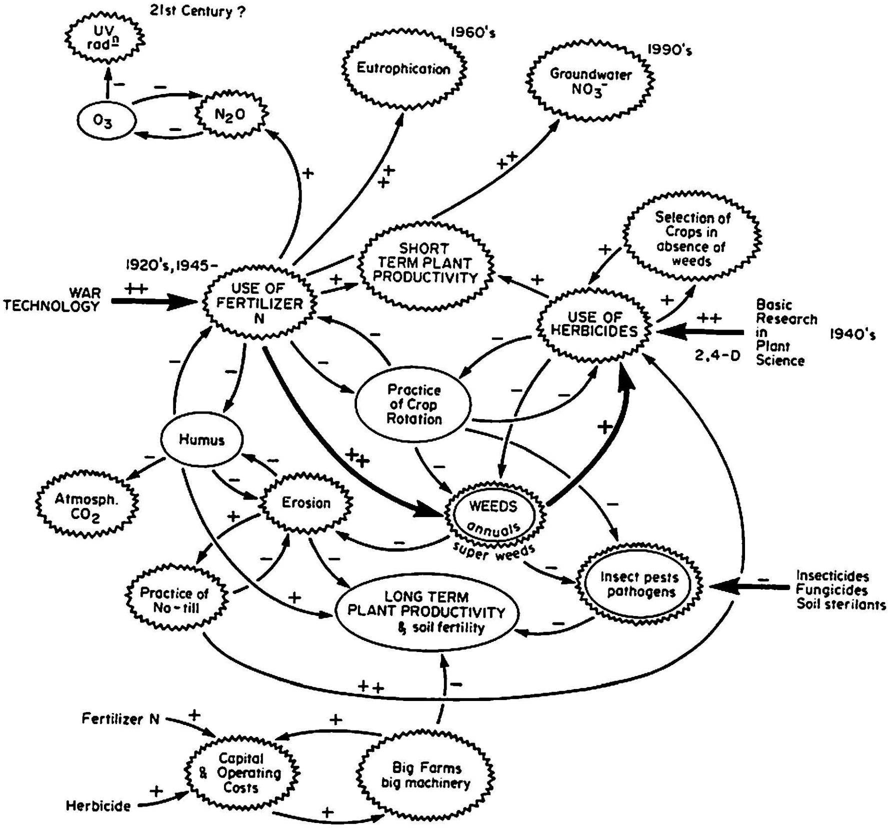


FIGURE 7 Some positive feedback loops generating dependence on N fertilizer and herbicide, and resulting in deterioration of the environment and increased cost of production. The net effect (positive and negative) of increase or intensification of one variable or process on another or on itself via a given pathway is given by the parity of the number of negative interactions on that pathway; if the number is odd, the net effect is negative, if it is even, the net effect is positive (Meadows *et al.*, 1972; Thomas, 1983). Hatched enclosures represent processes or variables which have intensified or increased, and smooth enclosures, those which have slackened or decreased since the 1940's. The author suggests that initiation of widespread use of fertilizer-N and herbicide in the forties was related to these materials suddenly becoming readily available rather than to real requirements for them. Their use in turn, generated real requirements via the illustrated pathways. For example, use of N fertilizer stimulates weeds; herbicides are used to control weeds eliminating the relatively innocuous annuals which normally protect the soil after harvest; erosion increases, there is loss of humus and the requirement for N fertilizer increases.

they lead to deterioration of these other factors, and to greater dependence on chemicals. The high degree of correlation between cereal yields and fertilizer use is repeatedly cited as evidence that nutrients are limiting, and that more inputs of fertilizer, particularly of N are necessary for enhanced food production (e.g. Greenwood, 1982). By neglecting the factors leading to "N limitation", i.e. by dealing with the proximate rather than ultimate causes of N limitation, such diagnoses generate greater dependence on fertilizer (Fig. 7).

We are frequently asked if we would consider composting manure in the system. The answer is that we think there is no question that to do so would benefit the soil and improve cycling and productivity, both through its effects on soil structure, and on its biological activity. However, there is not excess carbon available for composting. Is the system then carbon limited? Should we grow some high carbon crops purely for composting? If the concept of limiting factors is valid at all in biological husbandry, it must be applied to the decomposers as well as to the producers, and be extended to non-chemical parameters of the system.

CONCLUSION

If there is a "N problem" in biological husbandry it is this: given a bag containing 100 kg fertilizer-N, we know exactly what to do with it. It may be wasteful, but we can pretty well guarantee that there will be no N shortage for the crop. However, given 100 kg N in soil humus, or in manure or in plant residues, we have very little idea of how to use it. If it is manure -N, we generally consider that only the N mineralized in the first year is available. If it is N in straw, we may burn it. Associated with graminoid crops, legumes are more often considered weeds than they are donors of N to the crop.

Many attempts have been made to relate the N-fertilizing values of organic materials to some chemical fraction of those materials, e.g. %N, N released after autoclaving etc. (e.g. Whitehead, 1981). In relation to the efficiency of use of fertilizer-N, these chemical indices may give acceptable results. For biological husbandry, however, such approximations are simply too crude, because the amount of N transformed is as much a function of living catalytic activity as it is of initial chemical composition of the materials themselves.

When Mr. Aldhouse stopped using N fertilizer on his farm, his cereals suffered from a severe shortage of N. By analogy with the use of industrially fixed N to overcome N shortages in conventional agriculture, we supposed that this shortage could be overcome by increasing biological N fixation. We promptly found that the problem lay not in the quantities of N entering the system, but in the way it cycled around the system. That in turn was not really a N problem as much as it was a complex of problems related to weed, residue and manure management; in effect of basic ecology. We finally began to recognize what is probably the most important principle in biological husbandry: productivity is intensified not by augmenting inputs but by intensifying cycling (Koepf *et al.*, 1977). This is achieved by maximizing the biological activity of all components of the systems. In the parlance of self-organization theory (Jantsch, 1980) the farm is a "hypercycle"—a cyclical process in which some of the stages are autocatalytic. The intensity of cycling in such systems is dependent primarily on the input of solar energy and on the catalytic activity. The catalysts are made up of the totality of the biological materials on the farm—the humus, the microbes, the soil fauna ... the livestock and man himself; each is at once a product, a precursor and a catalyst, and the well being of each depends on and contributes to the well being of the other.

This is not to say that all N deficiencies can be overcome by intensifying cycling. There is a certain minimum amount of N that must be present in a system to "create" a N cycle (Bradshaw *et al.*, 1982)—in effect to build up the catalytic material—and to a point, the more N that there is in the system, the greater will be the catalytic activity. The sustainable inputs of N to the system in turn determine its sustainable output as product after discounting losses such as leaching. But the important point is that the problem begins rather than ends with the input-output balance, as opposed to conventional systems in which the main concern is; how much N is enough? And from that point on, diagnosis of the system's "limitations" is essentially an ecological problem that must be approached with "all sensory and intellectual channels open" (Hill, 1982).

SUMMARY

Since 1978, the author has been conducting research into the theory and practice of biological husbandry in collaboration with a farmer who stopped using pesticides and mineral fertilizers in 1976. Eggs are exported from the farm. About 60% of feed is grown on the farm in a legume-cereal rotation (faba beans-oats-clover-winter wheat), and plant and animal residues are recycled. Annual weeds function as a self-seeding cover crop, protecting the soil, conserving nutrients and fixing carbon where and when cultivated crops are not present.

Yields average about 25% lower than those on conventional farms, but the farm is more profitable because of lower input costs. A nitrogen budget suggests that inputs of nitrogen are sufficient to sustain cereal yields equivalent to those of conventional systems. However, much of the annual input of N to cereal fields, in manure, is not available in the short term. Various laboratory and field studies suggest that as fertility or the biological activity of soils increases, problems related to immobilization of N by straw, phytoxicity and annual weeds decline, and that less manure is required to

augment the N supply by a given amount. While N might be identified as the "limiting factor" for cereal production, alleviation of N shortages is dependent on intensifying cycling, rather than on increasing N inputs. This intensification is achieved by augmenting natural rhythms on the farm through appropriate tillage techniques, and by ensuring an abundance and high activity of the catalysts of the N cycle, i.e. of all of the farm biota.

ACKNOWLEDGEMENTS

The scientific work referred to in this paper was supported in part by the Natural Sciences and Engineering Research Council of Canada. I trust it is apparent that this work owes most to the insight, labor and hospitality of Basil and Lillian Aldhouse.

References

Albrecht, W.A. (1975). *The Albrecht Papers* (C. Walters Jr., ed.). Acres U.S.A.; Raytown, Missouri.

Altieri, M.A. & Whitcomb, W.H. (1978/1979). Manipulation of insect populations through seasonal disturbance of weed communities. *Protection Ecology*, **1**, 185–202.

Armstrong, A.C. (1980). The interaction of drainage and the response of winter wheat to nitrogen fertilizers: some preliminary results. *Journal of Agricultural Science (Cambridge)*, 95, 229–231.

Baines, D. (1984). Effect of different soil types on mineralization of nitrogen from agricultural residues. Honors Biology thesis, Dalhousie University; Halifax, Canada.

Balandreau, J. & Ducerf, P. (1980). Analysis of factors limiting nitrogenase (C_2H_2) activity in the field. In *Nitrogen Fixation*, Volume II (W.E. Newton & W.H. Orme-Johnson, eds), pp. 229–242. University Park Press; Baltimore.

Berardi, G.M. (1978). Organic and conventional wheat production; examination of energy and economics. *Agro-Ecosystems* **4**, 367–376.

Bradshaw, A.D., Marrs, R.H., Roberts, R.D. & Skeffington, R.A. (1982). The creation of nitrogen cycles in derelict land. *Philosophical Transactions of the Royal Society of London*, B296, 557–561.

Candlish, E. & Clark, K.W. (1975). Preliminary assessment of small faba beans grown in Manitoba. *Canadian Journal of Plant Sciences*, **55**, 89–93.

Earl, C.D. & Ausubel, F.M. (1983). The genetic engineering of nitrogen fixation. *Nutrition Reviews*, **41**, 1–6.

Evans, L.E., Seitzer, J.F. & Bushuk, W. (1972). Horsebeans—a protein crop for Western Canada? *Canadian Journal of Plant Sciences*, **52**, 657–659.

Faulkner, E. (1945). *Ploughman's Folly*. Michael Joseph Ltd., London.

Greenwood, D.J. 1982. Nitrogen supply and crop yield: the global scene. *Plant & Soil*, **67**, 45–59.

Harmsen, G.W. & van Schreven, D.A. 1955. Mineralization of organic nitrogen in soil. *Advances in Agronomy*, 7, 299–337.

Helyar, K.R. (1976). Nitrogen cycling and soil acidification. *Journal of the Australian Institute of Agricultural Science*, **42**, 217–222.

Hill, S.B. (1982). Steps to a holistic ecological food system. In *Basic Technics in Ecological Farming*, (S.B. Hill and Pierre Ott, eds.), pp. 15–21. Birkhauser Verlag; Basel, Boston, Stuttgart.

Hodgson, J.M. (1958). Canada thistle (*Cirsium arvense* Scop.) control with cultivation, cropping, and chemical sprays. *Weeds*, **6**, 1–11.

Jantsch, E. (1980). *The self-organizing universe*. Pergamon; Oxford, New York.

Johnson, J.W., Welch, L.F. & Kurtz, L.T. (1975). Environmental implications of N fixation by soybeans. *Journal of Environmental Quality*, **4**, 303–306.

Koepf, H., Pettersson, B.D. & Schaumann, W. (1976). *Biodynamic Agriculture. An Introduction* The Anthroposophic Press; New York.

Lockeretz, W., Shearer, G. & Kohl, D.H. (1981). Organic farming in the corn belt. *Science*, **211**, 540–547.

Lynch, J.M. (1984). Interactions between biological processes, cultivation and soil structure. *Plant & Soil*, **76**, 307–318.

Magdoff, F.R. (1978). Influence of manure application rates and continuous corn on soil-N. *Agronomy Journal*, **70**, 629–632.

Meadows, D.H., Randers, D.L. & Behrens, W.W. (1972). *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind.* Universe; New York.

Parnas, H. (1975). Model for decomposition of organic material by microorganisms. *Soil Biology & Biochemistry*, **7**, 161–169.

Paul, E.A. & Juma, N.G. (1981). Mineralization and immobilization of soil nitrogen by microorganisms. *Ecological Bulletins (Stockholm)*, **33**, 179–195.

Patriquin, D.G. & Burton, D. (1982). Faba bean: an alternative to soybean in Nova Scotia, Canada. In *Basic Technics in Ecological Farming* (S.B. Hill and P. Ott, eds), pp. 98–107. Birkauser Verlag; Basel, Boston, Stuttgart.

Patriquin, D.G., Burton, D. & Hill, N. (1981). Strategies for achieving self sufficiency in nitrogen on a mixed farm in eastern Canada. In *Genetic Engineering for Nitrogen Fixation and Conservation of Fixed Nitrogen* (J.M. Lyon, R.C. Valentyne, D.A. Phillips, D.W. Rains & R.C. Huffaker, eds.), pp. 651–671. Plenum; New York.

Patriquin, D.G., Hill, N., Baines, D., Bishop, M. & Allan, G. (In prepn.) Observations on a mixed farm in the transition to biological husbandry.

Pfeiffer, E.E. (1974). *Weeds and What They Tell.* Biodynamic Farming and Gardening Association; Springfield, Illinois.

Rice, W.A. (1980). Seasonal patterns of nitrogen fixation and dry matter production by clovers grown in the Peace River region. *Canadian Journal of Plant Scences*, **60**, 847–858.

Roberts, I.P. (1897). *The Fertility of the Land.* MacMillan; New York.

Shivashankar, K. & Vlassak, K. (1978). Influence of straw and CO on N-fixation and yield of field-grown soybeans. *Plant & Soil*, **49**, 259–267.

Stewart, W.D.P. & Rosswall, T., eds. (1982). The nitrogen cycle. *Philosophical Transactions of the Royal Society of London*, **B296**, 299–576.

Thomas, R. (1983). Logical description, analysis, and synthesis of biological and other networks comprising feedback loops. In *Aspects of Chemical Evolution* (G. Nicolis, ed.) p.247, Wiley; New York.

Thompson, R. & Taylor, H. (1982). Prospects for *Vicia faba* L. in Northern Europe. *Outlook on Agriculture*, **2**, 127–133.

Whitehead, D.C. (1981). An improved chemical extraction method for predicting the supply of available soil nitrogen. *Journal of Science of Food and Agriculture*, **32**, 359–365.