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Observations on a Mixed Farm during the Transition to Biological Husbandry

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INTRODUCTION

"Biological Agriculture" is an holistic or "systemic" (de Rosnay, 1979) approach to agriculture (Hodges, 1982; Merrill, 1983). If this approach is to be formally understood and developed, then observations and experiments need to be conducted on whole, functioning systems.

In this regard, the relative sparsity of biological farming systems (which include those described as "traditional", "ecological", "organic", "alternative" or "bio-dynamic"), at least in industrialized countries, is a serious impediment to their further development. Probably the majority of organic farmers in North America are one time conventional farmers who took up biological husbandry in the sixties and seventies following recognition of the dangers of chemical pesticides (Lockeretz *et al.* 1981), or more lately, for economic reasons (Brusco *et al.*, 1985). Such farmers have to adapt varieties and machinery developed under conventional conditions, to use in biological systems. Any science involved generally begins with educated guesses about what might work rather than with study of and subsequent improvement of traditional systems, as may be possible in some of the lesser developed countries (Altieri, 1983).

It was in the former context that the studies which are the subject of this paper, were initiated. In 1977 the first author met a farmer, Basil Aldhouse, who had ceased all use of fertilizers and pesticides on his laying hen/grain farm in 1976, and was attempting to use legumes and manure as the major sources of nitrogen for his cereals.

Using conventional methods of crop management, Mr. Aldhouse had achieved the highest yield of oats in a provincial competition in 1975. When he stopped using fertilizers, the yields of cereals immediately fell by about 50%, apparently because of a severe deficiency in nitrogen (N). The question Mr.

Aldhouse posed was "with legumes on a third of my land, why are my cereals N deficient?"

In 1979 we conducted studies which allowed preparation of a detailed N budget. This revealed that in spite of large losses of N from the farm as ammonia (from the hen house), inputs from N_2 fixation were sufficient to result in a positive N balance for the farm as whole (Patriquin *et al.*, 1981).

Field budgets indicated that the excess of N inputs over outputs was accumulating in the soil. In essence, soil organic matter (containing about 5% N by weight) was increasing at the expense of increased crop production. Since the amount of N made available to plants by mineralization of soil organic matter increases as soil organic matter increases (Jenkinson, 1981), we could expect that in time the amount of N available to crops would increase. Rough calculations indicated that once a steady state was reached, the N mineralized would be sufficient to support yields equivalent to or better than those attained with use of fertilizer-N. However, these calculations also suggested that it would take of the order of one hundred years for yields to approach desired levels.

We therefore considered that a strategy for increasing yields of "wait and let the organic matter accumulate" was not a practical one. We then sought to effect a faster increase in yields by "restructuring" the system so that more of the N circulated through the crops and less through weeds and soil organic matter. This was considered to be a matter of (1) better synchronization of soil and plant processes, (2) correcting any mineral deficiencies or imbalances, (3) varying application of manure between fields and crops according to response (i.e. to put more where the response is greater), and (4) developing strategies for weed control which would allow them to function in conservation of N without interfering with crops.

Taking these considerations into account, in the fall of 1979 Mr. Aldhouse initiated a four course, cereal-legume rotation. Most of the research reported in this paper was conducted from 1980 to 1984. It consisted each year of one to a few discrete experiments or sets of observations intended to test hypotheses related to items (2) (3) and (4) above. By 1982, it was becoming apparent that crop yields were being suppressed or limited by a factor or factors other than those we had anticipated might do so (weeds, inadequate N, mineral deficiencies). The suppression was overt in oats. It was not until 1984/85 that it was clear that fababeans and wheat were being similarly suppressed. In 1982 we began to conduct experiments to test hypotheses concerning the nature of this suppression. In 1983, the farmer began to experiment with alternative tillage, rotation and manuring schemes. By 1985, the problem was resolved for oats, fababean yields were improving, and we felt we had identified the limitations in winter wheat.

The purpose of this paper is to communicate what we have been able to document and conclude or infer from the entirety of our observations—

including those obtained from 1980 to 1984, from an earlier study (Patriquin *et al.*, 1981) and from records of crop yields and soil analyses extending from the mid-1960's to 1985—about the overall direction and functioning of this system during its transition to biological husbandry.

REGIONAL SETTING AND GENERAL FARM PRACTICES

The farm (Figs. 1, 2) is named "Tunwath", an Anglo-Saxon word meaning "clearing in the woods". It is located in the western part of the Annapolis Valley, Nova Scotia (Canada), in a cool, humid temperate climatic zone. There are approximately 125 frost free days, 2800 degree days above 42°F (1800 degree days above 5°C), and the average annual rainfall is about 114 cm of which 45 cm occur between May 1 and September 30 (MacDougall *et al.*, 1969; Edey, 1977).

Eggs, the only commercial product of the farm, are produced under quota and marketed locally. Approximately 2100 laying hens (Rhode Island Red × Light Sussex) producing 384,000 eggs per year are maintained in a floor operation with deep litter. The current feed formulation is given in Table I. The total feed amounts to approximately 91 tonnes per year containing 17% protein. One of Mr. Aldhouse's objectives in choosing this number of birds was to be self sufficient in feed, exclusive of soybean meal and methionine. He

FIGURE 1 View of Tunwath farm from field A4 (with wheat stubble) looking south in August, 1979.

calculated that he should be capable of that with 30 hectares of land under cultivation and grain yields of about 3 tonnes/ha (a figure cited as typical under conventional management in this region).

The cultivated land encompasses four soil series of capability classes 3 and 4 (moderately severe to severe limitations). Individual fields are level to rolling

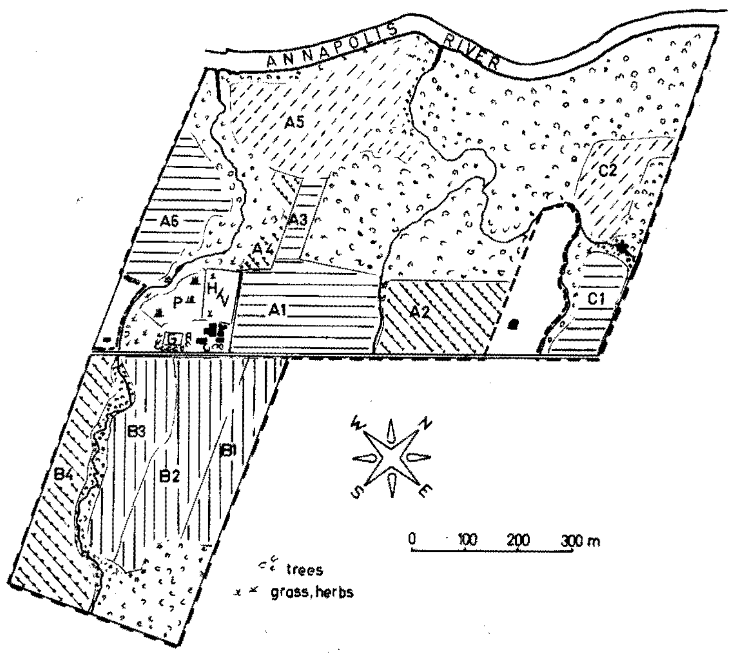

FIGURE 2 Map of Tunwath farm. Cultivated fields are designated by A, B or C and a number; four types of cross hatching designate different phases of the crop rotation (see Table II for the crops). G=garden, P=pasture, H/V=alfalfa hay and vegetables.
Recent History of Cultivated Fields: The farm has been in operation since the late 1700's or earlier. Some fields have been repeatedly cleared, cultivated, allowed to revert to forest and then cleared again. Fields A1, A2, A3 and A6 were cultivated when the farm was purchased in 1959. The northern half of field A4 was cultivated in 1959. There was an apple orchard on the southern half; it was cleared in the late 1960's and maintained as a hay field until 1978 when it was cultivated for winter wheat. Field A5: approximately one-third of this field (intervale land next to the river) was cultivated in 1959; the western one third was pasture until 1965, then was cultivated; the eastern third had at one time been cultivated but in 1959 had reverted to bush which was cleared in the late 1960's and early 1970's. Field B1/B2: most of this was cultivated in 1959; there was an apple orchard in part of the field until 1974 when it was cleared and the land cultivated. Field B3 was under hay until 1980 when it was cultivated. Field B4: part of this field was forest, part pasture and part cultivated in 1959; trees were cleared and by 1973 the whole field was under regular cultivation. Field C2 had once been cultivated but in 1959 had reverted to trees; it was cleared for cultivation in the mid-1960's. Field C1 was in hay until 1981 when it was cultivated. Tile drains were installed in the wetter parts of all fields in the 1960's or early 1970's, except for fields A6, C1 and C2.

TABLE 1

Composition of the regular ration

Component	Relative proportion in feed, by weight
Barley	650
Wheat	450
Oats	375
Fababeans	375
Soybean meal	88
Alfalfa hay	20
Methionine (according to age)	1–4
Premixed vitamins & minerals	10
Dicalcium phosphate	30
Sodium chloride	8

in slope, sand to silty clay loam in texture, and contain 2.8 to 7.1% organic matter. The principal limitations are described as "texture and imperfect drainage" on the heavier soils, and droughtiness on the lighter soils (MacDougall *et al.*, 1969). Prior to 1976, Mr. Aldhouse grew winter wheat, barley, oats and fababeans, meeting about 90% of his requirements for these grains. In 1975, his oat yield (98 imperial bushels per acre) was the highest recorded in a provincial competition.

He became concerned, however, about his increasing requirement for fertilizers and pesticides, the rising cost of fuel, local incidents of herbicide poisoning, and about what he perceived as a decline in soil structural quality and in the numbers of earthworms. In 1976, Mr. Aldhouse stopped using commercial fertilizers, pesticides and lime in an attempt to determine the biological limitations to production in a recycling system. The other major change in practice made at that time was to work fields with a rotovator after harvest, rather than with a mouldboard plough. Because he anticipated a decline in yields, he stopped growing barley, the cheapest of his grains to purchase. He applied manure at a rate of about 5.6 tonnes/ha to both wheat and oats. Initially, crops were rotated on a somewhat *ad hoc* basis, according to the weed problems and need for a particular grain.

Taking into account our observations in 1979 (Patriquin *et al.*, 1981), in the fall of 1979 Mr. Aldhouse instituted a regular rotation of crops (fababeans—oats underseeded with clover—clover used as green manure—winter wheat), and applied manure only to winter wheat. In order to have as close as possible to one-quarter of his cultivated land in each stage of the rotation (Fig. 2), he brought two more fields into production bringing the total to 34.5 ha. Except to change from spring to fall cultivation after fababeans in 1980 (he had experimented with spring cultivation in the previous year) no major changes were then made until the fall of 1983.

In the fall of 1983, Mr. Aldhouse began to ridge soil after rotovation of fababean and wheat residues. The ridging process is one step in a minimum tillage system being advocated by Schrieffer (1979, 1984) as a replacement for mouldboard ploughing. There is now equipment available that cuts and incorporates residue and ridges the soil in one operation. Following preparation of the fields in the fall using this equipment, it is usually possible to prepare the seedbed in a one trip operation. Mr. Aldhouse accomplished ridging by use of a tool bar equipped with six right hand throw shanks and 3 inch (7.6 cm) shovels; the shanks are spaced at 28 inch (71 cm) intervals.

The seasonal schedule of field operations followed from 1979 to 1983 is outlined below:

Winter: manure piled in next year's winter wheat fields

End of April to early or mid-May: seedbed preparation & planting of fababeans

Mid- to late May to early June: seedbed preparation & planting of oats

Early to late July: rotovation of clover, and subsequent harrowing at about 10 day intervals

Early August: harvest of winter wheat

Late August: spreading and immediate incorporation of manure in fields to be planted with winter wheat

Early September: winter wheat planted & oats harvested

September: rotovation after winter wheat

End of September, October: harvest of fababeans & rotovation of fields.

Cultivars used are: (i) for fababeans, Akerperle; (ii) for oats, Garry from 1979 to 1983, Fundy in 1984, and Garry and Rodney in 1985 (Fundy, a short season oat, is retained for late planting); (iii) for winter wheat, Lennox from 1979 to 1983; Yorkstar was planted in one field in 1983, and in 1984 and 1985 a mixture of the two cultivars was grown; (iv) for clover, an unspecified Alsike variety. Manure is incorporated by rotovation. A spring tooth harrow is used to prepare the seedbed for fababeans and oats. Oats and wheat are drilled in 7 inch (18 cm) rows at 1.5 inches (3.8 cm) depth and fababeans at 3 inches (7.6 cm); seeding rates are 95 kg/ha for cereals, 225 kg/ha for fababeans, and 3.5 kg/ha for clover. Clover is dropped onto the surface (7 inch rows) at the same time that oats are drilled. According to the weediness of fababean fields, they are harrowed using a spike tooth harrow set at 1 inch (2.5 cm) depth before germination, and once or twice again when plants are about 8 cm height. Oat fields usually receive one or two harrowings before planting, and at least one post-emergence harrowing. Weed seed and chaff collected during combining (typically 1 bag per 15 bags of grain) is composted.

No fertilizer except for that produced on the farm, or pesticide, has been used since 1975, except for some spot application of herbicide to Canada thistle in 1982. No lime was applied after 1976 until 1983, when 800 lbs of ground shells were applied to 2 hectares of field A2.

In addition to the field crops, the farm includes about 2 hectares of pasture, alfalfa hay, and gardens, and 35 hectares of woodland and water. These provide food and heating fuel for three or four residents. Organic refuse including household items, weed seed from combine screenings, and wood ash, goes into a compost pile which is mixed with manure for the cultivated fields and the garden.

METHODS

Field experiments and biomass at harvest

As much as possible, our observations and experiments were conducted in conjunction with normal farm operations. Generally experimental plots were set out in a randomized complete block design (Little & Hills, 1978). There was one replicate (one plot) per treatment in each block, plots were 2×2 m, and were set at least 2 m from the edge of fields. There was a minimum distance of 1 m between adjacent plots and the plots were seeded and harrowed by the farmer.

For estimation of yield at harvest, vegetation was sheared at soil level in 35×35 cm quadrats located at the centre of the 2×2 m plots; if samples were taken earlier in the season, they were taken to one side of the central 35×35 cm area. For monitoring crop growth or yields, not in the context of a specific experiment, samples were likewise taken from 35×35 cm plots; to minimize trampling of the crop, these were usually taken from a subregion of the field, or along the perimeter, but set at least 2 meters from the edge. Biomass was sorted into weed and crop components, placed in paper bags and subsequently dried at 105°C in a forced draft oven. Samples were weighed immediately on removing them from the oven. In some experiments involving a lot of crop material, fresh weights of all crop samples were determined in the field and subsamples were dried to obtain dry-to-fresh weight ratios. Because of variability in species composition, all weed samples were dried. To estimate biomass of fababeans at individual sites, the average weight of individual plants collected in 35×35 cm quadrats was multiplied by the number of plants counted in a 1×1 m quadrat at the same location; additional fababean plants were collected as necessary to base the per plant weight on a minimum of 8 plants.

Details of the experiments and observations conducted from 1980 to 1984 inclusive are identified below by year, field and crop which is how they are identified in the text. For simplicity in describing the location of the plots, the fields are considered to have a NS/EW orientation. Details of procedures followed in 1979 are given in Patriquin *et al.* (1981).

1980 A5 oats: Six experimental blocks, each including 5 treatments and 1 plot per treatment were set out on 18th May in field A5 prior to rotovation, harrowing and seeding. For each block, the treatments were randomly distributed in a linear series oriented perpendicular to the perimeter of the field. Fertilizer and manure were broadcast over the plots (2×2 m) and turned into the soil with a spade; application rates in kg/ha were: hen manure 9200: wheat straw 5660 and urea 162, urea alone 558, 0–20–0 fertilizer 2000. Final biomass samples were taken on 12th September.

1980 A1 & A6 wheat: six experimental blocks to a field, each including a control and +N (A1) or +N and +P (A6) treatments were set out on the SE corner of the field A6 and at the NW corner of field A1, at about 10 m from the perimeters of these fields on May 18th (wheat was planted in the fall of 1979). Fertilizer (250 kg/ha urea or 2000 kg/ha 0–20–0) was broadcast onto the soil surface; plots were harvested on 12th September.

1980 A2 & A4 fababeans: these plots were set up to obtain estimates of N_2 fixation by fababeans by comparing N accumulation in fababeans and associated weeds with that in weed-only plots and plots seeded with a broadleaved crop. On 8th May, after fababeans had been planted, seven blocks were set up in each of fields A4 and A2; those on A4 were distributed randomly through the southern 1/3 of the field; those on A2 were distributed parallel to the southern border of field A2, at about 3 m from the border. Each block included a no-treatment plot, a no-crop plot (with weeds) and a New Zealand spinach (A4) or sunflower (A2) plot (with weeds); for the latter crops, 150 ml of seed were broadcast and worked into the soil with a rake or hoe. The New Zealand spinach did not germinate. Fababeans were removed from the no-crop treatments as they emerged. Plots were harvested on August 27th.

1981 A2 & A4 oats: six experimental blocks were set out parallel to the southern borders on each of fields A2 and A4 on May 14th and 15th prior to seeding. Treatments included control, +manure and +NPK all without herbicide, and control, + manure and +NPK all with herbicide, set out in a split plot design (Little & Hills, 1978). Manure was applied at a rate of 8312 kg/ha; the NPK treatment included 130 kg urea, 300 kg of 0–20–0 fertilizer and 100 kg 0–0–60 fertilizer per hectare. Herbicide (MCPA: 4-chloro-2-methylphenoxy acetic acid) was applied using a sprinkler at 36 days after seeding (May 15th, when oats were 20 to 30 cm in height and clover was in the 2–3 trifoliate stage; locally recommended rate and timing for oats underseeded with clover). Quadrat samples were taken from these plots on July 8th–9th, and August 18th–19th.

1981 B2 wheat: in the fall of 1980, Mr. Aldhouse deleted the normal application of manure from a strip on the northern border of field B2. On August 17th, 1980, prior to seeding winter wheat, ten blocks, each including a no treatment plot and a plus manure plot were set up in this strip; manure (5600 kg/ha) was broadcast and worked into the soil with a spade. Plots were harvested on August 2nd, 1981.

1981 A1, A6 & C1 fababeans: five blocks were set up on each field along the western, southern and eastern borders respectively, and were distributed along the whole length of those borders. Each block included a no-treatment plot, and a weeded plot; for the latter, weeds were removed by hand hoeing at one week intervals until canopy closure. Plots were harvested on 18th September.

1982 Fields A1, A2, A4, A5, B2 oats: to compare performance of different cultivars of oats, 6 cultivars provided to us by Dr. John Bubar of the Nova Scotia Agricultural College, were planted within areas of about 30 × 30 meters (chosen to cause minimal disturbance to farmer's operations) of each field during the first week of June. On each field, 3 replicate plots of each cultivar were set out in a completely randomized block design. Soil was rotovated, seed broadcast at a rate of 100 kg/ha and the soil raked to bury the seed. Plots were harvested on August 27th.

1982 A1 & C1 oats: plots receiving different fertilizer treatments were set out randomly in approximately 30 × 30 m areas within fields A1 and C1 prior to seeding in mid-May, 1982. There were 1 or 2 plots per treatment for each of 17 different fertilizer treatments on each field, and 4 or 6 no-treatment plots, as indicated in the text. Fertilizer materials were broadcast on the soil and spaded in just prior to seeding; fertilizers were applied at the following rates in kg/ha: urea-N 60, dolomitic limestone (> 100 mesh) 1000, gypsum (as solution) 500, elemental sulfur 10, potassium fertilizer (0–0–60) 100, phosphate fertilizer (0–20–0) 300, manure 8312 kg/ha. Trace elements were applied in liquid foliar form during the last week of June, including 1 kg/ha for each of Zn, Cu, Mn, Fe, Bo and 250 g/ha of Mo. Plots were harvested on August 27th.

1982 A5 & C2 wheat. Six quadrat samples were taken from each field, (along the southern border of A5, and southern and eastern borders of C2) on July 27th, 1982.

1983 A2, A4 & B4 wheat: wheat was planted on this field in the fall of 1982; on May 9th, 1983, plots were set out parallel to the southern borders of fields A2 and A4 and to the northern and eastern borders of B4; there were 6 or 7 blocks per field and each block included a control, +N (150 kg urea/ha) and +K (170 kg 0–0–60/ha) treatments. Fertilizer was broadcast on the soil surface. Biomass samples were taken on July 25th.

1983 A5 fababeans: on May 9th, fababeans planted on this field were overseeded with oats. The oats were seeded in a strip oriented at approximately 75° to the orientation of fababeans (E–W); the strip was 3 seed drills in width and traversed the entire field. On July 5th, 18 transects and on Sept. 24th, 20 transects, were made across the strip moving west to east; on each transect, quadrats were placed at 4 points: approximately 10 m to the west and 10 m to the east of the strip, and at approximately 3 m inside of the strip on each side of it.

1983 A1 & A6 clover: quadrats were distributed randomly throughout the field A1 (10 positions) and field A6 (9 positions) on June 14th.

1984 A5, C2 & garden oats: manure was applied to the eastern half of field A5 in the spring. On August 30th, quadrats were taken from 8 positions in each of the manured and non-manured parts of the field, these positions being distributed in a strip parallel to and covering the entire length of the southern border of the field. On the same date, 7 quadrats were taken from field C2 along the southern and eastern borders, and from a small strip of oats (2 seeder widths × 75 m) in the garden.

1984 A1 and A6 wheat: seven quadrats were taken from each of fields A1 and A6, in the same regions sampled in 1981 (above), on July 24th and 30th respectively.

1984 A4, A2 & B4 fababeans: on September 23rd, fababean plants were counted in ten 1 × 1 m quadrats placed randomly within the entire areas of these fields, and pods were taken from 15–21 plants.

Periodic sampling of biomass, soil and light penetration

In 1979, 1980 and 1981, subsections (approximately 0.1 ha) of selected fields were sampled through the growing season for plant biomass and/or soil nitrate and/or acetylene-reducing activity. These subsections were located adjacent to the southern borders of fields A2, A4, A5 and C2, and at the junction of fields A1 and A3 (treated then as one field). Vegetation was taken from nine 35 × 35 cm quadrats distributed throughout the designated areas. Quadrat samples were bagged and subsequently weighed in groups of 3 (i.e. first 3 quadrats in one bag, etc.). For soil samples, a minimum of 20 soil cores (15 cm depth × 2.0 cm diameter) were taken. Measurements of light extinction under the crop canopy were made between 1000 and 1400 h using a Licor model 185 light meter equipped with a radiometer sensor (units were watts/m^2). At each of five or more positions within the sampling area, light was measured at the top of the crop canopy, and at the bottom of the canopy with the light sensor oriented perpendicular to the ground. For measurements at the bottom of the canopy, the sensor was placed on top of a flat surface which was pressed down to remove interference from the weedy understory, and 3 or more measurements were made at ground level at each position.

Soil surveys and bulk densities

In 1980 and 1983 soil samples were taken from most or all of the fields. Fields were traversed in zig-zag fashion, and a minimum of 40 cores (15 cm depth × 2.3 cm diameter) were taken per field. Samples were taken during the latter half of October in 1980, and on May 9th in 1983. The samples were air dried, and stones and recognizable plant remains removed by hand.

In May of 1980, bulk densities were determined at two sites on each of 5 fields. At each site, soil was removed from an area of approximately 20 × 20 cm to a depth of 15 cm; the precise volume of the displaced soil was determined by pouring measured volumes of coarse sand into the excavation. The soil sample was dried at 105°C and weighed.

Species composition of weed biomass

On most occasions when plant biomass was sampled, the relative abundance of weeds in the weed biomass was ranked by visual estimation after the crop had been removed from the quadrat. Weed species were ranked 1 for most abundant, 2 second in abundance and so on until an estimated 80% of the biomass was accounted for—generally four or fewer species accounted for most of the biomass. To arrive at an overall ranking of weed abundance, rank values for individual quadrats were transformed geometrically (1 = 8 points, 2 = 4 points, 3 = 2 points, 4 = 1 point), and values for all quadrats summed.

Within field variability studies

On June 4th, 1980, a study was carried out in an attempt to correlate the visually obvious variation in wheat growth with edaphic factors. Ten sites on field A1/A3 (treated as one field) were selected on a map of the field using random numbers; an additional 6 sites were selected visually to include very short wheat and very tall wheat. At each site, wheat and weeds were harvested from, and 15 soil cores (15 cm depth × 2.3 cm diameter) were taken within, a 35 × 35 cm quadrat. The soil samples were mixed, and stored in the fridge until the following day when subsamples were taken for measurements of phosphatase activity, soil mineralizable N, soil nitrate and phosphate.

On May 26th, 1983, measurements were made of heights of wheat plants, and of the soil suction (matric potential) during a saturating rainfall (it had been raining almost continuously for 3 days) on fields A2, A4 and B4. On each field 20 locations were chosen by traversing the field in zig-zag fashion and walking the last 10 paces before each site with eyes closed. The height of the tallest wheat plant at that point was measured and soil suction was measured by inserting a portable null-point tensiometer (Soil Moisture Equipment Corp., Santa Barbara, California) 3.5 cm into the soil so that the porous cup was just covered. Then 12 sites were selected where there were large variations in height of wheat within a short distance; at each of these "paired sites", wheat height and soil suction were measured for adjacent tall and short wheat. The measurements of soil suction were carried out by technical assistants who had no knowledge of the hypothesized relationship between height and soil suction.

Acetylene reductions assays of N_2 fixation

For acetylene reduction assays of fababeans on fields A2 and A4 in 1980, roots (plus nodules) were excised from 9 plants taken within the region of the field containing experimental blocks (described above under 1980 fields A2 and A4 fababeans); these were placed in 1 or 1.5 liter jars, with 3 plants to a jar. Acetylene, freshly generated from calcium carbide and water was added to give approximately 10% v/v acetylene in the jars, and the jars were buried in the soil. Gas samples for analysis of ethylene by gas chromatography (Hardy *et al.*, 1967) were taken after 30 minutes and stored in tubes closed with serum stoppers. Assays were conducted on 7 occasions between May 29th and August 27th. Total seasonal nitrogen fixation was estimated from the acetylene reduction data by assuming the rates observed applied over 18.6 h each day (Patriquin *et al.*, 1981) and by use of a 3 : 1 molar ratio of acetylene reduced to N_2 fixed (Hardy *et al.*, 1967).

For acetylene reduction assays of clover in 1979 and 1981, 4 to 6 plants collected within an area of approximately 0.1 ha were placed individually in jars and treated as above. Dry weights of foliage of each plant were determined, and areal rates of nitrogen fixation calculated by taking into account the per hectare biomass (estimated from quadrat sampling) and assuming (i) that acetylene reduction activities applied over 24 h for each day, and (ii) a 3 : 1 molar ratio as above. Estimates of total seasonal N_2 fixation in 1979 and 1981 are based on measurements on 4 (1979) and 8 (1981) separate dates between May 1st and June 29th.

Analyses of plant materials and manure for N and P

Total N was determined by a standard semi-micro Kjeldahl technique (Bremner, 1965a). N was determined on at least 2 separate samples of weeds, and an average value was calculated by weighting the percentages by the dry weights of the weed samples. N content of the crop was determined on a composite sample (plant material from 2 or more quadrats) or on 2 or more separate samples of the crop. For mature crops, N of reproductive and vegetative fractions was determined separately, and (as appropriate) an average value calculated for the whole plant. Ammonium in manure was determined by analysis of ammonium in 2N KCl extracts of the manure (10 : 1 v/w).

To determine phosphorus content of plant materials and of manure, duplicate 100 mg samples were digested in Kjeldahl flasks with sulfuric acid-water-SeO_2 (500 ml : 500 ml : 0.1 g) and additions of hydrogen peroxide. Phosphate was determined on dilutions of the digested sample by the technique of Strickland & Parsons (1972). At least 3 separate samples were analyzed for each class of materials. The Strickland & Parsons technique was also used to determine the phosphate content of water from tile drains.

Analyses of soils

Soil samples from the fall 1980 sampling were analyzed by the Woods End Laboratory, Temple, Maine, U.S.A., for pH (2 : 1 v/v water/soil, and in 0.1 M $CaCl_2$), organic matter by the Walkley-Black technique (Allison, 1965), humus stability by a chromatographic technique (Brinton, 1983), exchangeable acidity by summation of exchangeable Al (Hesse, 1971) and Woodruff H^+ (Woodruff, 1948), exchangeable cations in buffered (pH 4.8) NaOAc (Hesse, 1971), and available and reserve phosphate by the Bray I and II techniques (Bray & Kurtz, 1945). Samples taken in 1983 were analyzed in our laboratory for texture using hydrometer analysis, pH and organic matter as above, cation exchange capacity by ammonium/NaCl saturation and exchangeable bases by extraction with neutral NH_4Oac followed by atomic absorption spectrophotometry (Chapman, 1965), and bicarbonate extractable P according to Olsen & Dean (1965).

For measurement of soil nitrate, samples were frozen rather than air dried. Soil was thawed and 5 or 10 g samples were extracted with 50 or 100 ml aluminium sulphate solution and nitrate determined using an Orion specific ion electrode (Anonymous, 1978). For measurement of ammonium, 5 or ten grams of air dried or frozen soil were shaken with 2 N KCl for 1 h, and the ammonium concentration in the supernatant determined using an Orion ammonium electrode. When frozen samples were used, replicates were oven dried to determine fresh-to-dry weight ratios.

Soil phosphatase activity

Measurements of soil phosphatase activity were made on soil samples from the within-field variability studies (above), and on samples from experimental plots set up in field A5 in 1980 (above). Fifteen cores taken from each plot were mixed together and stored on ice during transit. Assays of phosphatase activity were conducted the following day. Subsamples were removed and dried for subsequent analyses of dilute acid extractable and bicarbonate extractable phosphate by the methods of Olsen & Dean (1965). For assays of phosphatase activity samples, 200 g fresh weight of soil were mixed with 800 ml water, and duplicate 5 ml aliquots removed from the slurry and assayed by the procedure of Tabatai & Bremner (1969). Subsamples from the plots in field A5 were air dried; after 4 months, 75 g from each subsample was placed in a 500 ml jar with 18 ml water, the top closed with polyethylene, and the bottle incubated in the dark at room temperature for 6 weeks. Then phosphatase activity of the incubated soil was assayed as above except that the slurry was prepared by adding 300 ml water; duplicate 1 g samples of the dried soil were also assayed at this time.

Nitrate and CO_2 production and microbial biomass in soils incubated in the laboratory

To examine the effects of different residue and soil types on production of nitrate, soils collected in April of 1980 were air dried for approximately 1 month and passed through a 2 mm sieve. 100 gram portions were mixed with 300 g coarse silica sand and 0.6 g of ground, oven dried manure or 0.5 g chopped (2 cm pieces) crop residue, or no residues were added; the whole mixture was then added to a 1500 ml jar to which 37.5 ml of deionized water had previously been added. The tops of the jars were closed with polyethylene film to allow aeration but restrict water loss (Bremner, 1965b). The jars were incubated at 30°C, and 25 g subsamples removed with a spatula at 2 week intervals and analyzed for nitrate as described above. There were three replicates for each treatment; the coefficients of variation were in most cases less than 10%. Measurements of available N reported for field A2 and A4 in 1980 were similarly conducted as were those for the within field variability study, except in the latter case, only one sample from each plot was examined.

A second experiment was conducted as above with the following modifications: soils were collected in the fall of 1983, each sample consisted of 150 g soil (+450 g quartz sand and 56 ml water) in a 1.5 liter jar, bottles were "preincubated" for 2 weeks prior to adding residues, and 10 g subsamples were removed for analyses of nitrate at 1, 2, 6, 14, 28, 56 and 98 days. Rates of CO_2 production were determined at 1, 2, 7, 14, 28, 42, 70 and 98 days; jars were opened, flushed with fresh air, closed and total CO_2 accumulation measured after 19 hours. Estimates of microbial biomass (Anderson & Domsch, 1978) were made for the same soil samples in July of 1984. Fifty grams of the dried, sieved soil were mixed with sand and water in the proportions above, and incubated at room temperature for 2 weeks. Then 1.2 g of previously mixed and ground talcum/glucose (1 g talcum to 0.2 g glucose) was mixed into the soils, and the bottles incubated at 22°C. Samples of the gas phase were removed by syringe at 1, 2, 3, 4, and 5 hours and analyzed for CO_2 using an infra-red gas analyzer. The lowest rate of CO_2 production over the 5 hour period was used to estimate microbial biomass using the conversion factor given in Anderson & Domsch (1978). Measurements were made on two samples of each soil; a separate study indicated that 0.2 g glucose/50 g soil was sufficient to give maximal CO_2 evolution.

RESULTS

1. Soil characteristics

All (14) fields were sampled in the fall of 1980, 4 years after the cessation of use of agrochemicals. The samples were analyzed by the Woods End Laboratory. The data (Table II) illustrate the following:

(i) The soils exhibited wide variation in color and texture reflecting the presence of at least 4 distinct soil series on this farm (Macdougall *et al.*, 1969).

(ii) Soil organic matter values were in the range characteristic of "good cropland" (2.5 to 4%; Koepf *et al.*, 1976), but values for 4 of the eleven field crop soils contained less than 3.8% organic matter or approximately 2% C, the "rule of thumb" level for moderate structural stability in English and Welsh soils (Greenland *et al.*, 1975).

(iii) Levels of available phosphorus were in the medium (16–30 ppm) to high (> 30) range (Thomas & Peaslee, 1973).

(iv) Levels of exchangeable K in four of the 11 field crop soils were below those suggested as required for maximum growth of field crops (170, 200 and 250 pp2m for sands and loamy sands, sandy loams and loams, and silt loams and clays respectively: Doll & Lucas, 1973).

(v) Except for soil A3, pH values were in the range considered suitable for field crops (5.8–6 to just above 7; Brady, 1974). Field A3 had the lowest pH and lowest base saturation. This is the most poorly drained field on the farm.

(vi) The "ideal" balance of cations has been suggested as: 65% Ca, 10% Mg, 5% K and approximately 20% H (Bear & Toth, 1948; Albrecht, 1975) or 75% Ca, 10% Mg and 2.5–5% K with yield little affected by Ca of 65–85%, Mg of 6–12% and K from 2–5% (Graham, 1959 in Mclean, 1973). On this basis the calcium contents are low, magnesium high, potassium adequate to marginal or low, and H adequate to high. The

TABLE II

Physical and chemical characteristics of soils. Samples were taken in the fall of 1980, except for bulk density (spring, 1980) and texture (spring, 1983)

Characteristic	Field													
	A1	A2	A3	A4	A5	A6	B1/2	B3	B4	C1	C2	G	H/V	P
Area (ha)	4.4	3.2	0.8	0.8	6.9	2.5	5.5	3.3	4.1	1.2	1.8	0.1	0.5	0.6
Crop-83[1]	C	W	C	W	F	C	O	O	W	C	F	G	G, A	cow
Color[2]	tan	tan	y-tan	y-br	y-br	g-br	m-br	g	m-br		br	g-br	g-br	br
Texture[3]	SCL	SCL	SCL	SL	SL	SCL	SL	SL	SL	LS	LS	SL	SL	SL
Bulk density[4]	1.36			1.18	1.11		1.20				1.30			
pH (1971)	6.1	6.5	5.7	5.9	5.8	6.4	6.2	6.2	5.9	6.1	6.2	6.5	6.2	5.5
pH (1980)	6.4	6.5	5.2	6.2	6.4	6.5	6.4	6.2	6.6	6.2	6.6	6.9	6.4	6.2
pH (1980-salt)[5]	5.8	5.9	4.4	5.6	5.7	5.8	5.7	5.8	5.9	5.4	5.8	6.3	5.7	5.7
O.M. (%)	3.8	2.9	3.8	3.8	3.8	3.5	4.1	4.1	7.1	3.0	2.8	2.8	3.4	7.3
Humus (%)	1.9	1.6	1.9	1.9	1.9	1.7	2.1	2.0	3.6	1.5	1.4	1.7	1.7	3.3
Humus stability[6]	M	M	ML	ML	ML	M	M	ML	ML	M	ML	MH	ML	ML
N rel. (kg/ha)[7]	51	39	45	51	51	51	56	54	98	39	39	39	45	96
CEC (meq/100g)	22.4	17.1	19.0	17.7	17.7	15.0	16.3	13.4	15.8	13.4	9.0	13.4	14.2	21.6
Exch H^+ (%)[8]	17	16	43	32	25	25	31	37	26	38	31	13	23	18
Exch Ca^{++} (%)[8]	55	54	37	43	46	51	46	38	49	38	44	67	50	63
Exch Mg^{++} (%)[8]	26	28	18	23	26	23	22	23	24	23	22	17	24	16
Each K^+ (%)[8]	1.8	1.2	1.6	1.7	2.3	2.7	1.8	1.5	1.3	0.7	3.3	3.7	4.2	2.8
Ca: Mg	2.1	1.9	2.1	1.9	1.8	2.2	2.1	1.7	2.0	1.7	2.0	3.9	2.1	3.9
K^+ (pp2m)	312	156	234	234	312	312	234	156	156	78	234	390	468	468
P Bray-1 (ppm)	28	25	50	62	29	28	56	23	24	24	43	119	53	45
P Bray-2 (ppm)	84	65	115	180	55	71	148	47	42	60	109	615	121	142

[1]C = clover, F = fababean, O = oats, W = winter wheat, G = garden, A = alfalfa.
[2]y = yellow, br = brown, m = marbled, g = gray. [3]S = sand, C = clay, L = loam. [4]Units are g/cm^3.
[5]pH measured in 0.01 M $CaCl_2$. [6]H = high, M = medium, L = low.
[7]Woods End Laboratory's estimate of N available to crops in one year.
[8]Values refer to percentage of exchange capacity occupied by respective cations.

low Ca/Mg ratios reflect the use of dolomitic limestone in the past. The highest ratios occurred in the Garden and Pasture soils, which have received only one dressing of 2.2 tonnes/ha lime in the last 20 years.

(vii) The garden soil, which has received chicken manure annually at a rate of 10–15 tonnes/ha over the previous 20 years, had high levels of P and K, the highest base saturation, the highest humus stability, and together with a sandy soil (C2), the lowest content of organic matter. The highest level of organic matter occurs in the pasture soil.

Ten fields, including all of those with field crops except for field Cl, were again sampled in the spring of 1983, and analyzed in our laboratory for organic matter, pH, CEC, exchangeable Ca, Mg, K and Na, and bicarbonate extractable P. Our (1983) estimates of pH and organic matter agreed closely with those of Woods End, and did not differ significantly as assessed by paired t-tests; the same techniques were used by both laboratories. Different techniques were used to estimate CEC and exchangeable cations. Their estimates of CEC were correlated with ours ($r = 0.723$) but averaged 1.25 times higher. The average calculated base saturation in our analyses was 0.95, and the average for the same fields in the Woods End analyses was 0.72. The latter are more consistent with what would be expected given the clay and organic matter contents and the pH values (Brady, 1974). Their measures of ammonium fluoride available-P were correlated with our measures of bicarbonate available-P ($r = 0.88$). Only one field (B4) of ten fields sampled in 1983 had low potassium judged by the criteria given above.

2. Historical changes in pH, Ca and Mg

Soil samples were taken from some or all of the fields by Mr. Aldhouse in several of the years prior to 1976, and in 1978. These were analyzed by the Nova Scotia Department of Agriculture. Their techniques for analyzing pH, Ca and Mg were the same as those we used in 1983, and that Woods End used in 1980 for pH. Woods End used a different extractant for Ca and Mg, but in non-calcareous soils both extractants should remove roughly the same (exchangeable) fraction, and the values be roughly comparable. Different sets of fields were sampled in the different years; except for 1971/1980 when all fields were sampled in both years. To make comparisons, for each field sampled after 1971 we calculated the ratio of the value for the year in consideration to the value for the same field in 1971, and then averaged the ratios for the particular year.

The data so compared (Table III) suggest that pH rose significantly after 1975. No fertilizer was applied to any of these soils after 1975 and no lime after 1976. (A total of 366 tonnes of 100–200 mesh dolomitic limestone was applied on the farm between 1964 and 1970. In 1971, 46 tonnes were applied to field A5, and a total of 34.5 tonnes was applied to fields A1, B1/2, B4 and C2 in 1976).

After 1976 calcium and magnesium in the surface horizons also appear to have increased by substantial factors, the magnesium more so than the calcium. These increases occurred even in soils which had not been limed since 1966–1969. The data suggest that pH, Ca and Mg declined between 1980 and 1983, but in 1983 were still well above the pre-1976 values.

TABLE III

Summary of comparable data from soil analyses, 1971–1983

Variable	Avg. value in 1971	Year					
		1971	1974	1975	1978	1980	1983
1. pH	6.06						
19XX value / 1971 value, avg.		1.0	0.964	0.959	1.02	1.04**	1.03
proportion of fields with pH < 6		5/14	5/7	7/11	0/5**	1/14*	1/10
2. Ca^{++}, meq/100g	6.41						
19XX value / 1971 value, avg.		1.0	1.08	0.952	1.23	1.29*	1.18**
proportion of fields showing increase over 1971			4/7	4/12	3/5	9/14	9/10**
3. Mg^{++}, meq/100g	2.08						
19XX value / 1971 value, avg.		1.0	1.15	1.19*	1.68	1.92**	1.52**
proportion of fields showing increase over 1971			6/7	9/12	4/4	14/14**	9/10**
4. Ca/Mg	3.35						
19XX value / 1971 value, avg.		1.0	0.954	0.820**	0.817	0.673**	0.781**
proportion of fields for which ratio decreased compared to 1971			4/7	10/10**	3/4	14/14**	10/10**

* ** 19XX values differ from 1971 values as determined by paired t-test, or proportion differs from 1971 proportion as determined by binomial theorem or proportion of fields in which there was an increase or decrease was higher than expected by chance as determined by binomial theorem (* =0.05; ** =0.01)

3. Effect of manure on soil phosphate status

In 1980, an experiment was conducted on field A5, a field with relatively low P (Table II), to test the effect of several treatments including use of superphosphate and manure, on oat plus weed production (described in Results section 8b), bicarbonate and acid extractable–P and soil phosphatase activity. It was expected that soil phosphatase activity would vary inversely with available–P (Spiers & McGill, 1979), and that soil phosphatase activity might be used to provide a short term biological (versus chemical) assay of soil phosphate status.

Manure increased the chemical measures of available–P by as much or more than did phosphate fertilizer. Only on the manure treated plots were the extractable phosphate values significantly different from those of control plots. Phosphatase values did not differ significantly between treatments (Table IV).

There was much more variation in acid or bicarbonate extractable–P between experimental blocks than there was between treatments but the same was not true of phosphatase activity (footnote a, Table IV). Acid extractable P was highly correlated with bicarbonate extractable P ($r^2 = 0.724$, $P < 0.01$). In contrast to what we had hypothesized, phosphatase values were not inversely correlated with either measure of inorganic phosphate. The phosphatase values in Table IV are for fresh soil samples. Phosphatase activity was determined on 12 of the 30 samples after they had been air dried, and after air dried soils were wetted and incubated for 6 weeks. Average phosphatase

TABLE IV

Effects of various additions on extractable phosphate and soil phosphatase activity in field A5, 1980. Values are means for 6 replicates. Treatments were set up on May 18, prior to seeding oats, and measurements were made on July 29

Treatment	P in addition (kg/ha)	Acid-P		HCO_3^--P (ppm)		P-ase (μmol p-nitrophenol per g dry soil per h)	
None	0	10.7	X[a]	14.0	X	9.05	X
Urea	0	9.1	X	14.7	X	10.7	X
Straw + urea	19	9.8	X	19.1	XY	9.67	X
P	182	14.3	XY	20.3	XY	8.24	X
Manure	88	17.5	Y	25.1	Y	8.23	X

[a] Within columns, means followed by different letters differ significantly ($\alpha = 0.05$), assessed by 2-way ANOVA followed by Duncan's Multiple Range test. Between block differences were substantial and significant for acid extractable P (block means 2.9 to 23.9), and bicarbonate extractable P (block means 9.8 to 45.6) but not for phosphatase activity (block means 3.63 to 5.55).

values for the fresh soil, dry soil, and incubated soils respectively were 8.42, 4.42 and 6.76 μmol per g dry soil. The incubated soil values, but not the fresh and dry soil values, were highly correlated with bicarbonate–P ($r^2=.621$; $P<0.01$) and acid–P ($r^2=0.431$; $P<0.05$). Evidently, phosphatase activity is strongly influenced by the level of inorganic phosphate under simplified, experimental conditions. The lack of correlation between fresh soil values and the soil P and the low variability of phosphatase compared to that for inorganic phosphate seem to suggest that the latter do not represent very well the real phosphate availability *in situ*.

4. Significance of incidental inputs of P, K, Ca and Mg

The observations above and others (Results sections 8a, 8b) suggested that levels of major mineral nutrients in the soil were generally adequate for field crops, and may even have increased after 1976 even though no fertilizers or lime had been applied since that time. Significant amounts of minerals could be entering the farm as "incidental inputs" in rain, purchased feed, feed supplements, and wood ash. To evaluate this possibility, inputs and outputs of P, K, Ca, and Mg to and from the fields were estimated and compared (Table V). Contents of P in crops, manure and in tile drain water were measured directly. Regional data were available for contents of P, Ca, Mg and K in rain water and wood ash. Contents of Ca, Mg, and K in crops and manure, and leaching losses of the same were estimated from data in the literature for similar situations. Net balances were calculated for (i) the farm from 1979–1982 when approximately half of the feed given to hens was grown on the farm, and (ii) the "farm at self sufficiency". For the latter, it is assumed that the removal of minerals from the field in grains would be equal to the estimated mineral content in the 91 tonnes of feed, including purchased and farm grown components, now fed annually to the birds.

Given no supplemental inputs of K to the barn, and only a small amount for Mg (6.3 kg/year in the vitamin-mineral supplement), the estimated amounts of K and Mg in manure should be close to or less than the amounts contained in feed (component 7, Table V). This is the case for K but not for Mg. Approximately 311 kg P is provided to hens in the dicalcium phosphate feed supplement, and approximately 1400 kg Ca enter the barn in ground oyster shell which is provided as "scratch". The estimated excess of P and Ca in manure compared to feed is therefore credible, and indicates that the barn is a net source of these elements for the fields. Because P is highly immobile (Brady, 1976) and leaching losses are very low (Table V), this results in a net positive balance for P in the fields. For the other minerals, which are much more mobile than P (Brady, 1976), field balances are negative, and would be so even if leaching losses were one-half of the values assumed in Table V. It

TABLE V

Estimated field balances for P, K, Ca and Mg

Component	P	K	Ca	Mg
		(kg/34.5 ha per year)		
ADDITIONS				
1. rain[a]	38	72	86	31
2. wood ash[b]	2	9	23	2
3. manure[c]	556	578	1029	200
REMOVALS				
4. straw[d]	1	10	4	1
5. leaching[e]	4	1922	6659	1380
6. Crop, 1979–'82[f]	174	331	36	62
7. crop, at self sufficiency[g]	367	660	93	127
AVERAGE GAIN OR LOSS		(kg/ha per year)		
1979–82	+12	–47	–161	–35
If self sufficient in feed	+6.5	–56	–163	–37

[a] Data for Nova Scotia from Freedman *et al.*, 1984.
[b] Ash from fuel wood: approximately 6 cords of mixed hardwood and softwood are harvested. Values are calculated assuming 1 cord contains 1900 kg dry matter (B. Freedman, personal communication), and P = 0.15%, K = 0.075%, Ca = 0.20%, Mg = 0.030% (Freedman *et al.*, 1981).
[c] Values are for 55 tonnes manure at 1.01% P, fresh weight basis (average for 3 samples); contents of other minerals calculated assuming Ca : P = 1.85, K : P = 1.04 and Mg : P = 0.36 (data for manure from laying hens in Flaig *et al.*, 1977). Three estimates of manure production are in the region of 55 tonnes per annum (fresh weight): (i) Manure production = Production of Manure–N × 100/ (%N in manure). Manure–N is 1.88% (fresh wt. basis) (Patriquin *et al.*, 1981). Production of Manure–N estimated from figures in Patriquin *et al.*, (1981) as (Feed–N + Straw Bedding–N) – (Egg–N + Dead Fowl–N + Volatilized N) = (2475 kg + 3 kg) – (384 kg + 26 kg + 1033 kg) = 1035 kg N/farm per year, and manure production is estimated as 55 tonnes. (ii) Manure production = production of Manure–P × 100/(%P in manure). Manure–P is 1.01% on fresh weight basis (avg. for 3 samples). Manure–P production = (Feed P + Bedding–P + Additive–P) – (Egg–P + Fowl–P) = (341 kg + 1 kg + 311 kg) – (42.2 kg + 55.8 kg) = 555 kg P and manure production is estimated as 55 tonnes. Feed–P and Bedding–P based on observed values. Additive–P is dicalcium phosphate supplied with feed at a rate of 30 lb/ton. P in eggs in assumed to be 0.11 g/egg (Anonymous, 1961) × 384000 eggs; Fowl–P is estimated as 500 birds × 1.8 kg/bird × 6.2% P (avg. P content for pulverized dead animals given in Roberts, 1897). (iii) From literature: Muller (1980) gives figure of 16.6 kg manure/bird per year for Rhode Island Reds, × 2000 birds = 33.2 tonnes dry manure or 51 tonnes fresh weight (Patriquin *et al.*, 1981), + 2 tonnes bedding = 53 tonnes.
[d] Two tonnes of wheat straw are removed from the field for bedding, the remainder of the straw stays in the field. Contents of K, Ca and Mg estimated using data in Russell (1973, p. 24).
[e] Fifteen samples of tile drain water taken over one year from field A1 contained an average of 40.1 parts per billion P (range: 14–104); leaching was estimated assuming 114 cm rainfall and a percolation factor of 0.25 (Patriquin et al., 1981). Data for K, Ca and Mg are those observed by Lyon *et al.* (1930) in lysimeter experiments in New York State; conditions were similar to those at Tunwath: rotation included cereals and legumes, manure was added 5 times in 15 years, no N fertilizer was used, soil was a silty clay loam, average rainfall was 82.6 cm.
[f] Calculated using average grain yields for 1979–1982 (combine data in Table X below), which were 1.9, 2.1 and 0.93 tonnes dry weight/ha for fababeans, wheat and oats respectively; P contents for the 3 grains were 0.60%, 0.28% and 0.32% respectively; contents of K, Ca and Mg were estimated from values given for these crops in Russell (1973).
[g] Values estimated for farm if it were completely self sufficient in feed exclusive of methionine and vitamin-mineral supplement. These were obtained by multiplying respective grain components in feed (Table I) by mineral contents refered to in (f), or for alfalfa, soybean meal and barley, by mineral contents given in Anonymous (1971). Total feed requirement is approximately 91 tonnes per year.

appears likely therefore, that incidental inputs of minerals to the farm combined with recycling could account for adequacy of P after 1976, but could not account for the increases in Ca and Mg in surface horizons after 1976, or for maintenance of adequate levels of K. The figures also suggest that achievement of self sufficiency in feed production, which would require roughly a doubling of crop production over the 1979–1982 values, would have relatively little effect on the net field balances.

5. Mineralization of N from soil and manure

5a. Field data

Soil nitrates were determined for several fields for all or part of three growing seasons (Fig. 3). Exchangeable ammonium was determined for 3 fields in 1979; values increased from less than 5 μg N/g soil on April 29th to 8 to 11 μg N/g soil in mid-May, and then declined by early June to values of less than 2 to 4 ppm and remained low for the rest of the season (data not shown). Except on field A4, nitrate values in vegetated soil did not exceed 5 μg N/g soil. Field A4 exhibited higher values and pronounced increases following cultivation. The section of this field included in the sampling was under orchard until 1970 and was in hay through most of the seventies. Mr. Aldhouse considered it to be the most fertile of his cultivated soils. The organic matter content for this section of field A4, 5.1%, is higher than that given in Table II (3.8%) for the whole field.

The amount of N accumulated in non-leguminous crops and associated weeds at harvest (Table VI) can be considered to provide reasonable estimates of "soil available N" given that (i) no fertilizer–N is used on the farm, (ii) soil nitrate values did not differ greatly between planting and harvest, and (iii) inputs of N from rain and asymbiotic nitrogen fixation and outputs due to leaching and denitrification are low and approximately balance one another (Patriquin *et al.*, 1981).

Excluding the 1984 oat fields and field B2 in 1982, N accumulation in oats and weeds in the absence of manure varied from 39 to 67 kg/ha. The mean value was 50.3 kg/ha. These values are similar to those estimated by the Woods End Laboratory (Table II) for soil available N. The calculated recovery of manure N in crops and weeds (total N in presence of manure minus total N in its absence divided by N applied in manure, ×100) on fields A2 and A4 was 40.5 and 11.4% respectively.

In manured wheat fields, N accumulated in wheat and weeds varied from 55 to 102 kg with a mean of 80.6 kg. For field B2 in 1981, recovery of manure-N is estimated as 23.6%; this estimate may be too low, as it does not allow for possibly lower percentages of N in wheat grown without manure. Assuming that 25 kg N are available from manure, the average soil-available N under wheat is 56 kg, a value similar to those calculated for oats.

The 1982 oat data are from a variety trial in which oats were planted in experimental plots in fields in different phases of the rotation (see Table XV, below). The very low amount of N available on field B2 was probably due to immobilization of N by wheat residues.

The N accumulated in oats and weeds in 1984 exceeded all previous values, and there was no apparent increase from adding manure. Other observations possibly related to this phenomenon are given in Results section 8b.

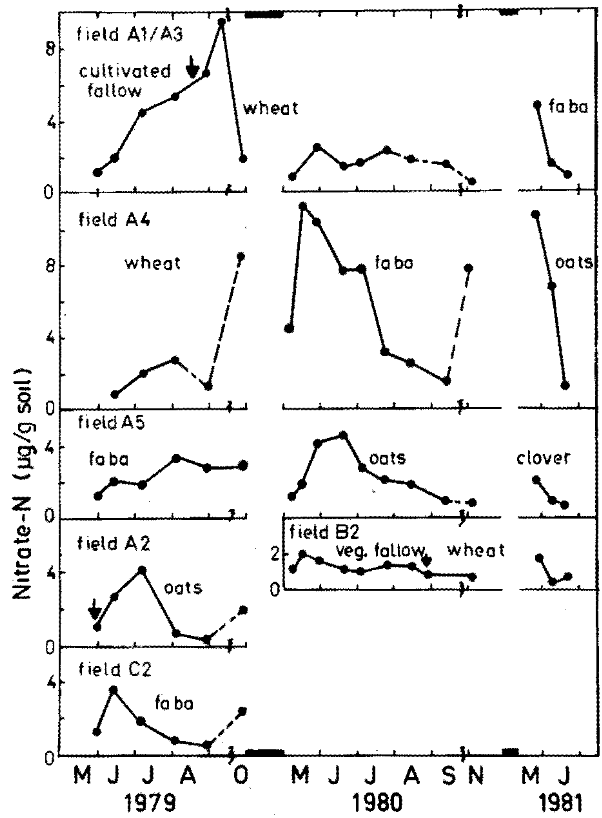

FIGURE 3 Soil Nitrate. Arrows indicate addition of manure. Veg-fallow refers to weed-covered soil (not regularly cultivated); cultivated fallow refers to soil regularly cultivated to reduce weed populations.

TABLE VI

Nitrogen accumulated in cereals and associated weeds at harvest

Crop & Year	Field	Manure-N† (kg/ha)	No. Quads.	Biomass Crop (kg/ha)	Biomass Weeds (kg/ha)	Total N (kg/ha)	Crop-N / Tot. N
OATS							
1979	A2	105	10	3110	230	67.2*	0.935
1980	A5	0	9	1160	3083	61.1*	0.292
1981	A2	0	6	4090	500	46.2*	0.861
	A2	155	6	4620	1265	109*	0.660
	A4	0	6	5080	490	45.8*	0.920
	A4	155	6	4620	505	63.6	0.928
1982	A1	0	18	552	4410	50.1	0.099
	A2	0	18	3120	1630	44.8	0.627
	A4	0	18	5100	1890	65.3	0.704
	A5	0	18	3080	1100	39.0	0.711
	B2	0	18	520	2290	28.1	0.167
1984	A5	0	8	5144	1306	105*	0.732
	A5	105	8	5215	1315	102*	0.715
	C2	0	7	4718	536	86.9*	0.834
	G	105	7	4710	1110	81.1*	0.695
WHEAT							
1979	A4	105	6	8660	1880	88.9*	0.787
1980	A1	105	9	7300	1703	95.0*	0.701
	A1	105	5	5420	605	55.0*	0.870
	A6	105	6	9630	340	78.8*	0.949
1981	B2	0	10	2269	2661	52.7	0.364
	B2	105	10	5379	2530	77.3	0.588
1982	A5	105	6	9873	380	88.2	0.946
	C2	105	6	7588	448	69.7	0.919
1983	A2	105	6	7293	1240	83.2*	0.806
	A4	105	7	8241	3082	102*	0.748
	B4	105	7	5065	2406	62.1*	0.600
1984	A1	105	7	6645	2454	87.0	0.645
	A6	105	7	2649	4593	80.2	0.278

†Input of manure-N was estimated from average values for manure-N and from the amounts of manure applied to the fields or experimental plots. Average N content of 7 samples of manure taken from conditions representative of manure when it is applied to the field was 1.88% on a fresh weight basis or 2.89% on a dry weight basis; of this total-N, an average of 31% was present as ammonium-N; farmer's field application rate was 5600 Kg/ha; losses of N by volatilization after incorporation of manure were small (details in Patriquin *et al.*, 1981).

*Asterisked values are based on measured N contents; others were calculated assuming N contents as follows. (1) For oats (grain and straw combined) and weeds respectively in the no manure treatments, 0.783 and 0.890 %N (avg. for 4 plots in 1981). Other values for 1981 were: with manure, oat-N = 1.23% and weed-N 1.68% N; grain/(grain + straw) ratios were 0.401 without manure, and 0.410 with manure, grain N was 1.18% without manure and 2.04% with manure. In 1984, half of field A5 was manured, grain/(grain + straw) ratio was 0.50 without manure, 0.47 with manure; grain-N was 2.01 and 1.89 without and with manure respectively; straw-N was 0.53 and 0.60 without and with manure. (2) For wheat: N content of wheat 0.704%, weeds in wheat 1.05% (avgs for 1979 and 1980 samples); averages for 1983 were 0.702 and 0.875 for wheat and weeds respectively. See Table XI for further details related to wheat. Total plant N values (tops + roots) were estimated by multiplying top values by 1.15 for oats (Williams, 1955), and associated weeds, and by 1.20 for wheat (Patriquin *et al.*, 1981) and associated weeds. Different values were used for weeds in the two crops because annuals predominate in the former and perennials in the latter, and annuals generally have a lower root biomass relative to tops than perennials (Abrahamson, 1979); the absolute values for N allocation to roots of weeds are within the ranges of values indicated by studies of Abrahamson (1979) and Abrahamson and Caswell (1982).

5b. Laboratory data

Residues that are incorporated in the soil shortly after harvest (i.e. those from fababeans, wheat and clover) and manure were examined for their nitrogen-immobilizing or -mineralizing properties in soils from three different fields. The soils and residues were mixed with sand and incubated in bottles at field capacity and 30°C (Fig. 4). Wheat straw (0.28% N) and fababean straw (0.99%) immobilized N initially, while clover (3.70% N) and manure (3.20% N) released N. The week to week fluctuations were probably associated with waves of microbial growth (consuming N) and turnover (releasing N) initiated when the dried soil was wetted, and may not be very representative of what goes on in the field. The calculated recovery of manure–N as nitrate–N

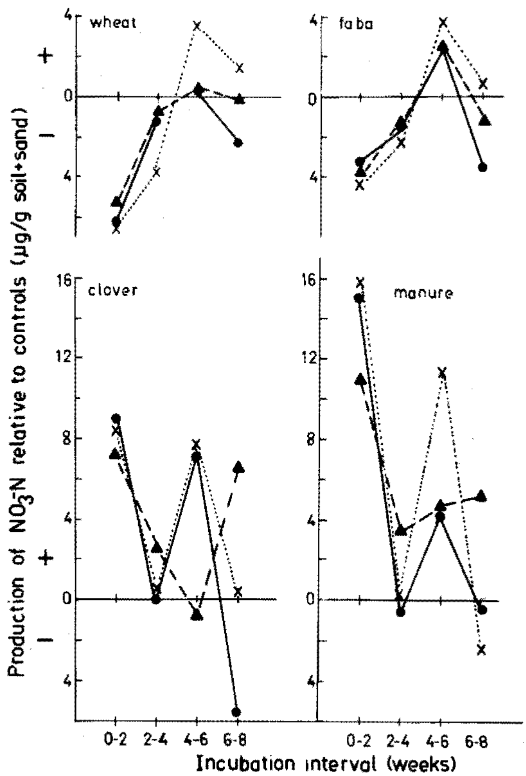

FIGURE 4 Production of nitrate–N in three soils to which four residue types were added compared with production in untreated soils. Rates are calculated for two-week intervals by subtracting nitrate production in untreated soils from that in treated soils. Values are means of triplicates. Soils were from A2 (●), A4 (×) and B2 (▲).

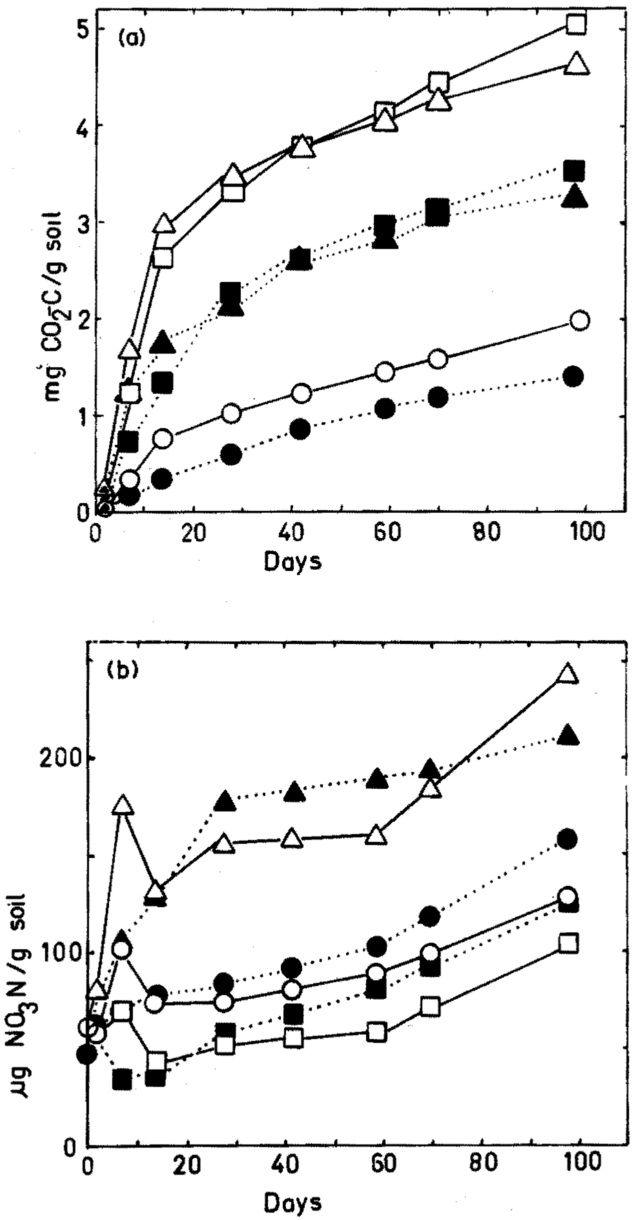

FIGURE 5 Time courses of (a) carbon dioxide and (b) nitrate production in soils incubated in bottles without and with residues. Soil from field A5 is represented by open symbols, soil from field A2 by closed symbols; (0 ●) = no additions, (□ ■) = with straw, (△ ▲) = with manure. Values are means of triplicates.

(nitrate–N in manured samples minus nitrate–N in controls/N in manure, × 100) at 2 weeks was 23–33% and at 8 weeks, 38–52% for the different soils; for clover it was 15 to 19% at 2 weeks and 23 to 33% at 8 weeks.

To further assess the effect of soil type on mineralization of soil N, soils from 6 different fields were incubated at field capacity for 2 weeks, oat straw (0.72% N) or manure (3.78% N) was added, and mineralization of C and N were followed for 98 days. Soils with added manure or straw exhibited high rates of CO_2 evolution during the first 2 weeks (designated phase I), followed by lower and gradually falling rates between 14 and 98 days (phase II). There were large amounts of ammonium–N, ranging from 38 to 80 μg/g soil, in manure amended soils at 2 days; most of this was present in the manure as ammonium when it was added to the soil (KCL extractable ammonium–N was 38.7 μg/g soil). By 2 weeks, ammonium fell to less than 4 μg/g and remained low in all soils and all treatments. Representative time courses for CO_2 and nitrate production are given in Figure 5. We have summarized the

TABLE VII

Production of carbon dioxide and nitrate from different soils incubated in jars at field capacity and 30°C with and without residues. Soils are listed in order of decreasing additional CO_2 in presence of straw. Values are means of triplicates

Field & interval (days)		Carbon Dioxide–C: Soil alone	Carbon Dioxide–C: Additional CO_2 in presence of straw	Carbon Dioxide–C: Additional CO_2 in presence of manure	Nitrate–N: Soil alone	Nitrate–N: Additional NO_3–N in presence of straw	Nitrate–N: Additional NO_3–N in presence of manure	Microb. Biomass (mg per 100 g soil)
		(μg CO_2–C or NO_3–N/g soil)						
B2	0–14	566	1920	2020	-0.3	–26	77	15.3[a]
	0–98	1422	3114**[b]	2624	59	–26	112	
A5	0–14	740	1866	2219	13	–32	56	17.7
	0–98	1985	3053**	2650	67	–24	116	
A4	0–14	926	1859	1961	18	–24	45	23.7
	0–98	2806	2812**	2880	143	–53	95	
C	0–14	354	986	1402	20	–40	52	13.0
	0–98	1408	2122	1884	101	–32	54	
A2	0–14	332	856	1178	20	–24	61	11.3
	0–98	1337	1946	1566	91	–35	68	
A1	0–14	330	834	1686	10	–7	80	15.1
	0–98	1324	1867	2282	109	–58	84	

[a]Microbial biomass was determined on a separate subsample after two weeks of incubation without residues (equivalent to the time at which residues were added)
[b]Asterisks indicate soils for which the amount of addition Co_2–C evolved in the presence of straw exceeded the amount of carbon added as straw (2250 μg C/g soil, estimated assuming straw is 45% C).

data by calculating production of CO_2 and nitrate for phase I alone, and both phases combined. These data illustrate the following (Table VII):

1. All soils exhibited net immobilization of N in the presence of straw. The amount of N immobilized was positively correlated ($r^2 = 0.693$, $P < 0.05$) with the amount of N produced in soil alone, presumably because microbial growth in the presence of straw was N limited.
2. The amount of "additional" N produced in the presence of manure (N in soil + manure minus N in soil alone) over 98 days was equivalent to 21.4 to 46% of the N added in manure (252 μg/g soil).
3. There were positive relationships between the additional nitrate produced in the presence of manure over 98 days and (a) CO_2 produced in soil alone over 0–14 or 0–98 days (probability for rank correlation, < 0.1), (b) CO_2 production in soil + straw or soil + manure over 0–14 or 0–98 days ($p < 0.05$), and (c) microbial biomass ($p < 0.05$).
4. Most of the variation in additional nitrate produced in the presence of manure was associated with differences in mineralization in phase II, when soils B2, A5 and A4 produced 35 to 65 μg N/g soil, and soils C, A2 and A1 produced only 2 to 7 μg additional N/g soil.
5. The additional CO_2-C produced in soils B2, A5 and A4 in the presence of straw exceeded the total amount of C added as straw indicating that straw had a primary effect on the breakdown of native organic matter in these soils. This suggests that the greater production of additional nitrate–N in the presence of manure in the same soils (B2, A5 and A4),. compared to other soils (C2, A2 and A1), could have been due to priming by manure of breakdown of the native organic matter in soils B2, A5 and A4, but not in soils C2, A2 and A1.
6. Production of nitrate in soil alone was highly variable, and not related in any simple way to CO_2 production, microbial biomass or to production of additional nitrate in the presence of manure. Also, the total production of nitrate (as opposed to additional nitrate) in the presence of manure bears little relationship to CO_2 production or microbial biomass. However it is notable that the A4 soil, taken from the lower part of the field which had been under hay until recently (referred to in the first paragraph of Results section 5), exhibited the highest total production of nitrate in the presence of manure and the highest production of nitrate in soil alone over 0–98 days, the highest CO_2 production in soil alone (0–14 and 0–98 days), and had the highest microbial biomass of the 6 soils examined.

6. Nitrogen fixation

Our observations permit 3 independent estimates of N_2 fixation in fababeans.

First, the total N in fababeans and associated weeds at harvest (Table VIII) may be compared with total N in cereals and weeds at harvest (Table VI). Excluding field C1 in 1981, where fababeans were planted for the first time and nodulation was sporadic, (fababean + weed)–N exceeded the maximum (cereal + weed)–N (105 kg), by 61 to 227 kg.

Secondly, for 4 fields, N_2-fixing activity was monitored by the acetylene reduction technique at bi-weekly or shorter intervals. Nitrogen fixation was estimated from the integrated values by use of the theoretical molar ratio of acetylene reduction to N_2 fixed of 3 : 1 (Hardy *et al.*, 1967). These values (Table VIII) increase in the same order as do the values for (fababean + weed)–N. N_2

TABLE VIII

N in legumes and weeds at harvest, and estimates of N_2 fixation

Year	Field	No. Quads.	Biomass (kg/ha) legume	weed	grain	Tot N (kg/ha)	Crop-N (% of total N)	N_2 fixation (kg/ha per yr or per day)
1978	B1[a]		9750		5250[b]	332*[c]		125/yr
1979	A5[a]		4560	1230	2543	197*	80	74/yr
1980	A4	7	4140	2390	1720	166*	75	53/yr
	A2	7	6530	639	2910	212*	93	80/yr
1981	A1	5	5990	1130	2750	210	89	
	A6	5	7010	566	3903	253	95	
	C2	5	1560	1240	745	75	66	
1983	A5	20	5110	1440	2965	209	86	
1984[d]								
CLOVER								
1979	B2	6	3730	2029		176*	76	13/yr, 0.11/d[e]
1981	A5	9	3889	1190		111*	73	98/yr, 2.15/d
1983	A1	9	988	3796		111	25	0.04/d
	A6	10	2286	1379		96	68	0.21/d

[a] See Patriquin *et al.*, (1981) for details

[b] Seed yields estimated by multiplying measured pod + seed values by 0.795, average value for 8 determinations (range 0.74–0.84) of seed/seed + pod ratio, samples from various fields and years.

[c] Asterisked values are estimated from measurements of standing crop and % N. Values without asterisks were estimated from the standing crop and assumed % N values. For beans, the assumed % N values were the averages of the two 1980 crops and were 1.29% 4.19% and 1.79% N for bean stems, pods + seeds, and weeds respectively. Root–N was estimated assuming 3.7 mg root N per g stem (Patriquin *et al.*, 1981). For clover the % N values were the averages between the values for 1979 and the 1980 observations; these were 2.14% for clover and 1.83% for weeds; for clover, root N was assumed to be equal to 34% of above ground N, which is an average value for red clover (Bowren *et al.*, 1968); root N in weeds was assumed to be 20% of above ground N, as for weeds in winter wheat (Table VI).

[d] In 1984, only seed yields were estimated. For A4, A2 and B4 respectively, these were 2675, 1891, and 557 kg. At both Tunwath and another farm, germination and early growth were highly erratic because of a prolonged cold spell in May and June.

[e] Daily estimate based on acetylene reduction assay at about 11 a.m. on one day in the interval June 15–22; 3 : 1 molar ratio of acetylene reduction to N_2 fixation assumed.

fixation estimated as (fababean + weed)–N minus 105 kg N exceeds the values estimated from acetylene reduction by an average factor of 1.39.

Finally, for two fields in 1980, N_2 fixation was estimated as the difference between N in fababeans and weeds and N in plots of weeds only or plots of a non-legume crop and associated weeds (Table IX). For field A2, N in sunflowers and weeds was 1.35 times that in weed only plots. The non-legume crop failed to germinate in field A4; however, we think that N accumulation in a non-N_2-fixing crop would not exceed that in weeds alone by as large a factor as it did in field A2 because there was a much larger weed seed bank in field A4 than in field A2 (Patriquin *et al.*, 1981), and growth of hemp nettle (*Galeopsis tetrahit*) was vigorous. Also, the ratio of (N in sunflowers + weeds in field A2)–to–(N in weeds only in field A4), 0.60, is close to the ratio, 0.61, for the values of mineralizable–N in these two fields (Table IX). N_2 fixation values estimated by difference (154 kg for field A2 and 69 kg for field A4) exceed the values of N_2 fixation estimated by acetylene reduction by an average factor of 1.61. If we assume that the difference method gives a more reliable absolute measure of N_2 fixation, then this indicates that the ratio of acetylene reduced to N_2 fixed is 1.86, a value which is similar to the value of 1.8 determined by Hudd *et al.* (1980) for laboratory-grown fababeans.

Taken together, these observations suggest that N_2 fixation in fababeans at Tunwath can be estimated with reasonable accuracy from acetylene reduction data using a molar ratio of 1.86, or from the total N in beans + weeds by subtracting 68 kg N/ha (average mineralizable N in fields A4 and A2). Using this ratio, the acetylene reduction data indicate N_2 fixation values of 85 to 202 kg N_2 fixed/hectare per year, with a mean of 134 kg (n = 4). N_2 fixation estimated as (total N – 68) for 7 fields varies from 98 to 264 kg with a mean of 158 kg.

TABLE IX

Nitrogen fixation by fababeans in fields A4 and A2 in 1980 estimated by difference and acetylene reduction techniques

Field	N accumulated in vegetation: Plots with *V. faba*: In V. faba (kg N/ha)	Plots with *V. faba*: In weeds (kg N/ha)	Plots with weeds only (kg N/ha)	Plots with sunflower & weeds (kg N/ha)	Difference (kg N/ha)	N_2 fix (C_2H_2) (kg N/ha)	Mineralizable N (ppm/4 wks)
A2	192 (22)[a]	13 (4.0)	37 (4.9)	51 (9.0)	168, 154	80	23 (3.9)[b]
A4	118 (18)	36 (14)	85 (23)		69	53	46 (2.8)

[a]Mean and standard error for 7 plots; standard error calculated from standard error for the biomass term (N accumulated = %N ×biomass).
[b]Mean and standard error for nitrate production between 2 and 6 weeks (parts nitrate–N per million parts dry soil for 3 replicates).

Values for total N in clover and weeds at harvest were substantially lower than those for beans + weeds (Table VIII). Assuming that soil available–N under clover, which grew as a winter annual, is similar to the average estimated for winter wheat above (56 kg), N_2 fixation under clover can be estimated as: (N in clover + weeds minus 56 kg N). The values so estimated for the 4 crops in Table VIII vary from 40 to 120 kg with a mean of 67.5 kg/ha. N_2 fixation estimated from acetylene reduction assays for two of those crops was 13 and 98 kg per year, the higher value corresponding to the lower value estimated by the difference method. Although the acetylene reduction data and total N data are not in good agreement for the individual fields, the figures concur in suggesting that N_2 fixation in clover averages about 60 kg/ha and is probably more variable than that in faba beans.

For both beans and clover there is evidence to suggest that some of the variability in N_2 fixation is related to variation in soil available–N. N_2 fixation measured in two fields with faba beans in 1980 was lower in the field with higher available–N (Table IX). For clover, acetylene reducing activity determined in mid-June varied inversely with the weed biomass (Table VIII) suggesting that N_2 fixation was suppressed where there was sufficient available N to permit good growth of non-legumes.

Seasonal patterns of N_2 fixation in fababeans (Fig. 13 below, and other data not shown) were similar to those described previously (Patriquin *et al.*, 1981) and for fababeans elsewhere (Sprent & Bradford, 1977) with a peak at flowering and a gradual decline thereafter. On all samplings in 1980, the per plant acetylene-reducing activity was higher in field A2 than on field A4. Nitrogenase activity in clover fields in 1979 (data not shown) and 1980 (calculated cumulative values of N_2 fixation are given in Fig. 10 below) increased during the period of rapid increase in clover biomass in May and June, reached a maximum in mid to late June when flowering occurred, and then declined rapidly. Similar patterns have been observed elsewhere (Rice, 1980).

7. Theoretical limits to grain production

Since nitrogen is usually the limiting nutrient for crop production in humid regions (Greenwood, 1982), it is reasonable to estimate the potential yields for this system from the N balance, i.e. to estimate the potential or maximum sustainable yields as the yields required to give equivalence of outputs of N from and inputs of N to the fields:

$$\text{OUTPUT–N} = \text{INPUT–N}$$

where OUTPUT–N = (leached–N + denitrification–N + manure–N volatilized after field application + harvested grain–N) and INPUT–N = (asymbiotic

N_2 fixation + rain–N + seed–N + manure–N + symbiotic N_2 fixation).

Assuming that (leached–N + denitrification–N + N volatilized after field application) is small and roughly balanced by (asymbiotic N_2 fixation + rain–N + seed–N) (Patriquin *et al.*, 1981)*, then the sustainable output of N in grains can be considered equal to the input of N to fields in manure and via legume N_2 fixation, i.e.:

FABABEAN–N + CEREAL GRAIN–N =
FABABEAN N_2 FIXATION + CLOVER N_2 FIXATION + MANURE–N

The input of manure–N to fields is estimated as 55,000 kg × 1.88% N = 1034 kg N (see Table V for the quantity and Patriquin *et al.*, 1981 for %N).

For simplicity we assume that the N balance for the fababean is zero, and that fababeans do not utilize any of the manure–N; so:

OUTPUT of FABABEAN–N = INPUT OF N VIA N_2 FIXATION

At 146 kg N fixed/ha (section 6), and 26% protein (4.16% N), the potential sustainable yield of fababeans is calculated as 3.5 tonnes/ha (14% moisture).

The sustainable output of cereal–N for the farm as a whole is then:

OUTPUT OF CEREAL–N = MANURE–N + CLOVER N_2 FIXATION

which is 1034 kg manure–N + 529 kg clover N_2 fixation (61.5 kg N/ha clover × 8.6 ha) = 1563 kg/farm or 90.9 kg N/ha of cereal. At 12% protein (1.92% N), this is equivalent to a yield of 4.7 tonnes/ha (14% moisture).

Because a large fraction of the feed, of the order of 40 to 50%, is now purchased, the fields are receiving a subsidy from outside of the farm in the form of manure produced from purchased feed. To what extent could that subsidy be relieved? The calculated total potential output of N from the fields in grains is 2818 kg (N_2 fixation in fababeans and clover + manure–N). This value exceeds the total N being fed to birds to produce manure, 2475 kg, indicating that the farm is potentially self sufficient in feed–N.

*Values in kg or g N/ha per year were: leaching, 9.2 kg (estimated from measurements of nitrate in tile drain water); denitrification, 1 kg (assumed to be similar to values measured under fababeans on a nearby farm where soil nitrate was between 4 and 6 $\mu g/g$ soil); volatilization after incorporation of manure, <0.5 g (based on measurements over 3 days after manure was incorporated); seed, 3.3 kg (average for the rotation); rain, 4.2 kg (regional data); asymbiotic N_2 fixation, 2.3 kg (literature values). The leaching and denitrification values are lower than those commonly estimated for conventional systems (Legg & Meisinger, 1982), but are consistent with other estimates indicating low losses of N via leaching for a similar crop rotation (not receiving N fertilizer) in a humid, temperate region (Lyon *et al.*, 1930), and indicating low rates of denitrification when soil nitrate values are less than 6 $\mu g/g$ soil (Ryden, 1983). Not included in these balances are various other losses and gains which in total probably add up to about zero, i.e. losses via runoff and erosion, and via volatilization from plants; or gains via dry deposition, via absorption of atmospheric ammonia (Legg & Meisinger, 1982), via N_2 fixation by leguminous weeds (vetches, black medic, white clover, volunteer Alsike clover) and via rhizosphere N_2 fixation in weeds such as *Plantago major* (Smith & Patriquin, 1978), and in crops (Dart, 1986).

8. Actual yields and limiting factors

Estimates of average actual yields were made from our quadrat data and from the farmer's records, as available, of the numbers of 100 bushel boxes taken from individual fields or from two or more fields combined. Grain yields of quadrat samples were calculated from total biomass values (Table VI, VIII) using observed or assumed harvest indices (see footnotes to Table X). These values were adjusted to 14% moisture and multiplied by 0.75 as overall yields for the fields might be expected to be about 25% lower than those indicated by quadrat samples. (Most of our experiments and observations were located at sites close to the edges of fields, and we deliberately excluded regions with chronic waterlogging or chronic perennial weed problems; see also combine yields and plot values in Patriquin *et al.*, 1981). To convert the farmer's bushel per acre to tonne per hectare values (14% moisture), bushel yields of oats were multiplied by 0.038, those of wheat by 0.067 (Bates *et al.*, 1980) and those of fababeans by 0.067 (Presber, 1972).

To give some indication of how yields at Tunwath stand in relation to other farms in the region, yields are expressed as percentages of reference values (Table X). For oats and wheat the reference values are the Nova Scotian provincial averages for the interval 1979–1983 which were 2.1 and 2.9 tonnes/ha respectively (calculated from Anonymous, 1984 using bushel-to-tonnes conversions as above). The reference value for fababeans is 3.0 tonnes/ha which is the approximate yield expected for this crop locally under conventional management (Langille & Hough, 1978).

The Tunwath averages for 1962 to 1975 were slightly above (fababeans & oats) to well above (wheat) the reference values (Table X). Provincial averages for wheat and oats from 1962 to 1975 were both equivalent to 83% of the reference values. The calculated potential sustainable yields (section 7) are 223, 162 and 116% of the reference values for oats, wheat and fababeans respectively.

Included in Table X are estimates of crop yields that would occur in the absence of weeds. To make these estimates, we assumed that crop yields are N limited and that in the absence of weeds, the crop would take up 90% of the total (crop + weed) N accumulated in the presence of weeds (Table VI).

8a. Winter wheat

Quadrat and combine data indicate that there was a substantial decline in yields of wheat between 1979–1983 and 1983–1985. The decline in values calculated for wheat in the absence of weeds suggests that overall fertility declined during this period, and the quadrat data indicate that weeds were relatively more abundant in 1983–84 compared to 1979–82. Actual yields and

TABLE X

Grain yields at Tunwath as percentage of those achieved or expected under conventional management (see text). (n) refers to the number of different fields in which quadrat sampling was conducted, or to the number of separate estimates for the combine (each estimate was for an entire field, or for two or more entire fields combined)

	Wheat[a]			
Interval	combine	(n)	quadrats (n)	calc. for no weeds
1962–1975	119	(20)		
1979–1982	85	(2)	76 (6)	84
1983–84	52	(1)	49 (5)	71
1985	51	(1)		
	Oats[b]			
Interval	combine	(n)	quadrats (n)	calc. for no weeds
1962–1975	111	(11)		
1979–1982	52	(4)	52 (5)	77
1984	100	(1)	91 (2)	106
1985	96	(1)		
	Fababeans[c]			
Interval	combine	(n)	quadrats (n)	calc. for no weeds)
1962–1975	106	(6)		
1979–1982	72	(2)	71 (6)	75
1983–84	72	(3)	59 (4)	
1985	100	(1)		

[a] Grain yields of wheat in quadrat samples were calculated from total biomass values (Table VI), using observed grain-to-total biomass ratios (1979, 1980 samples) or for the 1983 samples using observed head-to-total biomass ratios (Table XI below) and assuming a grain-to-head ratio of 0.80 (see footnote a of Table XI), or for the 1981 samples by using the average grain-to-total biomass ratio for 1980, 0.374, or for the 1982 and 1984 samples using the average grain-total biomass ratio for 1983, 0.269; values so calculated were adjusted to 14% moisture, and multiplied by 0.75 (see text).

[b] Grain yields of oats in quadrat samples were calculated from total biomass values (Table VI) using observed grain-to-total biomass values (1979, 1980, and 1984), or assuming a ratio of 0.44 (see footnote to Table VI); these values were adjusted to 14% moisture and multiplied by 0.75 (see text).

[c] Grain yields of fababeans taken from Table VIII, adjusted to 14% moisture and multiplied by 0.75 (see text).

the calculated yields in the absence of weeds for both periods were substantially below pre-1975 combine yields.

In 1980, yields of winter wheat on two fields exhibited a marked response to fertilizer–N (Table XI). Percent N values of grains from unfertilized and fertilized plots were very low in comparison to values considered to indicate adequacy of N (in the region of 2% N, Goos *et al.*, 1982). We conclude that yields of wheat were N limited in 1980 and probably in 1979 (Patriquin *et al.*, 1981, Fig. 3).

In contrast, in 1983 there was a substantial numerical (but statistically not significant) response to N on only one of the three fields. The total biomass values on N fertilized plots in 1983 were well below those for fertilized plots in 1980 and the % N values for grains in 1983 were well above those for 1980. These observations suggest that the lack of response to N in 1983 was due to operation of another limiting factor. There was no response to potassium in 1983 (Table XI). It seems unlikely that P would have been limiting, given the evidence that chicken manure is high in available P (section 4 above; note also lack of response to P in 1980, Table XI).

TABLE XI

Effects of fertilizers on wheat

Year	Field	Treatment	Biomass		Ratios		Nitrogen	
			Crop (g/m^2)	Crop+wds (g/m^2)	Crop to Crop+wds	Heads to total crop†	grain (%)	straw (%)
1980	A1	None	542 X*	602 X	0.883 X	0.494 X	1.43	0.21
		+N	1388 Y	1401 Y	0.988 X	0.515 X	1.50	0.23
	A6	None	963 X	997 X	0.984 X	0.475 X	1.43	0.27
		+N	1307 Y	1321 Y	0.988 X	0.435 X	1.62	0.24
		+P	728 Z	769 Z	0.959 X	0.461 X		
1982	A2	None	729 X	852 X	0.780 X	0.361	1.78	0.37
		+N	1089 X	1182 X	0.899 X	0.403	1.77	0.36
		+K	793 X	943 X	0.794 X	0.371		
	A4	None	824 X	1132 X	0.730 X	0.370	1.86	0.31
		+N	754 X	1010 X	0.754 X	0.412	2.00	0.28
		+K	768 X	1096 X	0.679 X	0.393		
	B4	None	506 X	747 X	0.630 X	0.278	1.93	0.24
		+N	524 X	900 X	0.589 X	0.274	2.16	0.58
		+K	492 X	727 X	0.665	0.264		

†In 1980 ratio of seeds to heads was 0.845, 0.850 for composite samples from N fertilized plots in A1 and A6 respectively, and 0.765 and 0.781 for samples from unfertilized plots in A1 and A6 respectively. Head to total crop ratios were determined for all samples in 1980, and for 2–4 samples from each treatment per field in 1983. The N content of chaff in 1980 was 0.34, 0.41, 0.26 & 0.25% for +N samples from A1 and A6 and unfertilized samples from A1 and A6 respectively.
*Within columns, and for each field considered separately, means followed by different letters differ significantly (α =0.05), assessed by 2-way ANOVA followed by Duncan's Multiple Range test.

The response of wheat in 1980 to application of N fertilizer was consistent and pronounced: within 2 weeks of its application in mid-May, all fertilized plots were readily distinguished by their greater height and darker shade of green in comparison to surrounding vegetation. At the same time, normal, unfertilized wheat exhibited noticeable variation in height, color and overall robustness. We hypothesized that this variation was related to variation in the supply of mineralizable-N in the soil.

To test this hypothesis, on June 4, 1980, sixteen sites in field A1/A3 were sampled for soil and plant characteristics. We included measures of soil phosphate and soil phosphate activity because Verstraete & Voets (1977) reported wheat yield to be correlated with soil phosphatase activity.

There was large variability in both soil and plant characteristics (Table XII) but there were no significant linear or rank correlations between the two.

A plot of total plant-N versus mineralizable-N (Fig. 6) suggests that the potential to accumulate N in the vegetation—represented by the broken line in Figure 6—was related to soil mineralizable-N, but that this potential was not realized at most sites because of the operation of other limiting factors (see Balandreau & Ducerf (1980) and Parnas (1975) for discussions of this sort of limiting factor analysis).

The only site at which the total N accumulated in vegetation exceeded that represented by the broken line (Fig. 6) was a plot within the wheat field that had been fertilized with urea 17 days earlier. This, and the uniform response of wheat on 5 other plots within that field to urea (Table XI), led us to conclude that whatever the limitation to wheat growth was on that field, it was relieved by application of fertilizer-N.

TABLE XII

Ranges of values of selected plant and soil characteristics for field A1/A3, June 4th, 1980

Characteristic	Range of values: *Randomly selected sites* ($n = 10$)	*Selected sites* ($n = 6$)
Wheat biomass (g/m^2)	109–445	57.9–1000
Weed biomass (g/m^2)	9.8–146	32.6–153
Total biomass (g/m^2)	207–454	93.0–1040
Wheat N (%)	0.90–1.39	0.93–3.45
Weed N (%)	0.96–1.78	0.70–3.63
Total (wheat + weed) N (g/m^2)	2.76–5.13	2.16–12.8
Soil NO_3–N ($\mu g/g$ soil)	1.66–4.46	1.21–11.9
Soil mineralizable N ($\mu g/g$ soil per 2 wks)	10.7–19.4	11.0–16.6
Soil acid-soluble P ($\mu g/g$ soil)	2.09–51.9	9.39–43.1
Soil bicarbonate soluble P ($\mu g/g$ soil)	15.1–52.0	11.5–44.3
Soil phosphatase activity (μmol p-nitrophenol per g soil per h)	1.69–8.41	2.23–5.03

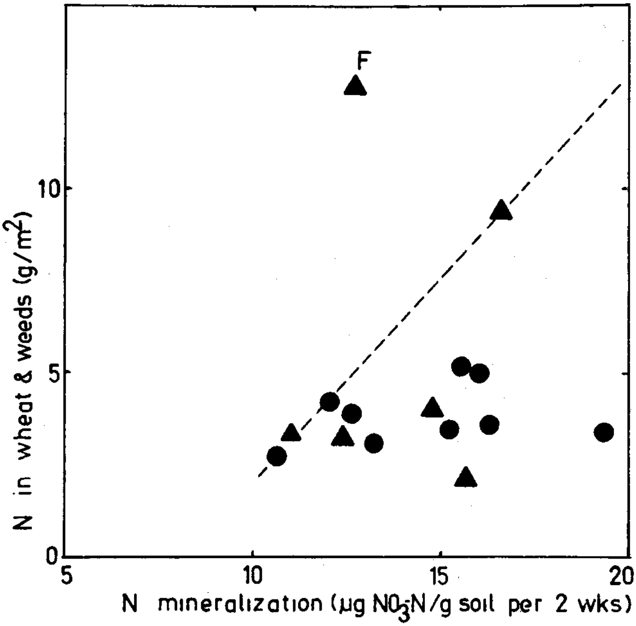

FIGURE 6 Relationship of total N in winter wheat and weeds to soil mineralizable N for field A1/A3 on June 4th, 1980. The point labelled "F" is for a nitrogen-fertilized plot; triangles represent selected sites and circles, randomly-chosen sites. The broken line is a boundary curve representing the relationship of total N to mineralizable–N when no other factors limit uptake of N; points below that curve represent situations in which uptake of N is limited by a factor other than mineralizable–N (Balandreau & Ducerf, 1980).

Efficiency of use of N fertilizer is reported to be affected by drainage. More N fertilizer is required to achieve a given yield in poorly drained situations (Armstrong, 1980). We suspected that variation in drainage could account for the apparent contradiction between the marked and uniform response of winter wheat to fertilizer–N, and the poor correlation of vegetation–N (most of which was in the wheat) with soil mineralizable–N.

In 1983, we examined the relation of wheat height to soil suction (matric potential) measured during a saturating rainfall, assuming that the better the drainage (and aeration), the higher would be the soil suction. In this survey we avoided obvious low spots. On each of the three fields 20 randomly selected sites, and 12 paired sites of adjacent tall and short wheat were sampled. There was no correlation between plant and height and soil suction for the randomly selected sites (r^2 value .0122 to .0946). However, for the paired sites, soil suction was higher in the tall wheat than in the short wheat at 8 of 12 ($P=0.120$), 10 of 12 ($P<0.05$) and 12 out of 12 ($P<0.01$) sites in fields B4, A2 and A4 respectively. Data for field A4 are given in Table XIII. This suggests that variation in drainage is responsible for much of the variation on a small scale (i.e. within distances of a few meters). The supply of mineralizable–N may be limiting at the better drained sites.

What is responsible for the variation in drainage? There was a general trend on these fields in 1983 for the areas of tall and short growth to be parallel and to be oriented in the same direction as harvesting, tillage and manure-spreading operations, and for the short growth to be in narrower bands separated by approximately the distance covered by both the manure spreader and the combine. Obvious straw residues were found in blocks of soil taken from underneath tall wheat at 3 sites, but not in those taken from adjacent short wheat. These observations suggest that the variation in drainage was related to the pattern of straw deposition behind the combine and/or the pattern of manure distribution and/or the pattern of compaction by machinery.

Pertinent to this phenomenon is Mr. Aldhouse's observation, with which we concur, that wheat growth is almost invariably superior in the one or two strips at the headlands of fields where wheat is planted perpendicular to that of the rest of the field. This is the region where vehicles turn during tilling/planting operations, and which therefore receive additional tillage at the end of the main operation, and are seeded parallel to the end of the field. Because of the additional tillage, weed control is enhanced but there is greater compaction than in the rest of the field (Schreiffer, 1984).

In summary, yields of wheat at Tunwath appear to be limited by a combination of excessive weediness, inadequate N, and by soil structural factors which affect drainage and aeration.

TABLE XIII

Soil suction values at adjacent stands of tall and short wheat, field A4, May 26, 1983

Short		Tall	
Height (cm)	Suction (centibars)	Height (cm)	Suction (centibars)
44	4.0	67	7.0
34	0.5	60	1.0
42	0.4	62	2.0
36	0.5	63	4.5
31	2.6	49	5.5
35	2.0	56	11.0
35	0.8	54	8.5
34	1.0	63	7.0
44	0.1	55	2.0
33	0.0	71	5.0
30	1.5	53	2.0
37	1.5	66	2.5

8b. Oats

The estimates of yields from combine and quadrat data (Table X) concur in indicating very low yields in the interval 1979–82, and marked improvement of yields in 1984 and 1985, which is a reversal of the trend seen for wheat. Quadrat data suggest that low yields in 1979–1982 were associated with both excessive weediness, and low total productivity (calculated yields without weeds are 1.5 × those with weeds, but are still only .77 × provincial average). Following is an account of the development of "the oat problem", and its solution.

Because our original N budget (Patriquin *et al.*, 1981) indicated that the output of manure was not sufficient to sustain application of 5600 kg/ha to both oats and wheat, Mr. Aldhouse did not apply manure to oats after 1979. He reasoned that wheat is the more valuable crop, and that oats are known to be "non-demanding" (see, for example Roberts, 1897, p. 356). Thus he would conserve manure until he found out just what was required and what he could afford to put on oats.

He also decided in 1979 to rotovate bean residues (prior to planting oats) in the spring, rather than in the fall, in order to maintain a good cover of the soil by weeds over the winter.

In 1980 field A5 was rotovated approximately two weeks before oats were planted. Germination of oats was poor and weeds predominated from very early in the season (Fig. 7). There were pronounced increases in total (weed+crop) biomass early in the season on plots where manure or N fertilizer was applied, but by harvest all treatments exhibited similar total biomass values (Table XIV). Because there had been a heavy growth of weeds on this field in the spring, we suspected that the poor performance of oats was due to the production of phytotoxic compounds during the initial breakdown of green residues (Russell, 1973). Mr. Aldhouse therefore decided to revert to the more traditional practice of fall cultivation. Studies conducted in the summer of 1980 indicated that fababean residues, once incorporated, would immobilize N initially (Results section 5b). Given that, and the fact that fababeans are harvested late in the year when temperatures are falling, we thought it likely that fall cultivation after a legume crop would not in this case result in excessive losses of N.

In 1981, oats planted on fields A2 and A4 following rotovation of these fields in the fall, exhibited good germination, and oats predominated over weeds (Table XIV). However, final yields were still low in relation to conventional yields (yields estimated from quadrat data were 51 and 63% of the reference values for fields A2 and A4 respectively). Responses to NPK and manure in plot experiments on those fields were similar to those observed for field A5 in 1980: there was a mid-season response, but little numerical and no statistically significant differences in yields between treatments at harvest.

However the percent N of manured oats was almost twice that of unmanured oats (see footnote, Table VI).

We were puzzled by these results (low yields, without response to fertilizer or manure). In 1982 two extensive experiments were conducted in an effort to determine whether they could be related to use of an inappropriate cultivar, or to deficiencies or gross imbalances in nutrients.

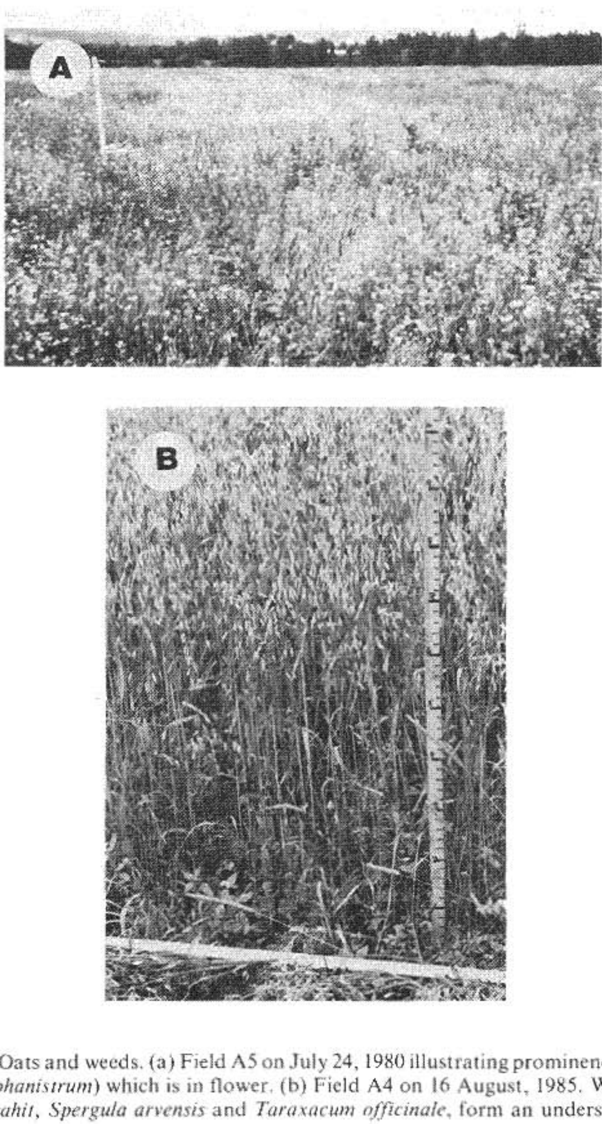

FIGURE 7 Oats and weeds. (a) Field A5 on July 24, 1980 illustrating prominence of wild radish (*Raphanus raphanistrum*) which is in flower. (b) Field A4 on 16 August, 1985. Weeds, including *Galeopsis tetrahit*, *Spergula arvensis* and *Taraxacum officinale*, form an understory.

TABLE XIV

Effects of various fertilizer treatments, and of herbicide on yields of oats and oats + weeds

Year, Field & Treatment	–Herbicide				+Herbicide			
	Preharvest		Harvest		Preharvest		Harvest	
	oats	total (g/m²)	oats	total	oats	total (g/m²)	oats	total
1980 A5								
None	83.4 XY*	289 XY	134 X	391 X				
Urea	104 XY	398 YZ	170 X	416 X				
Straw +N	166 Y	446 ZK	202 X	450 X				
Phosphate	54.5 X	260 X	145 X	477 X				
Manure	138 XY	533 ZK	90 X	405 X				
1981 A2								
None	290 X	377 X	411 X	476 X	275 X	349 X	407 X	442 X
NPK	442 X	556 Y	492 X	570 X	353 X	452 X	570 X	601 X
Manure	378 X	549 XY	438 X	613 X	552 Y	658 Y	487 X	564 X
1981 A4								
None	320 X	442 X	413 X	487 X	393 X	510 X	602 X	627 X
NPK	471 X	594 X	559 X	624 X	423 X	583 X	529 X	594 X
Manure	493 X	646 X	372 X	444 X	521 X	591 X	552 X	581 X

*Values are means of 6 replicates; for each field, means within columns followed by different letters differ significantly (α =0.05) as assessed by 2-way ANOVA followed by Duncan's Multiple Range test. 3-way ANOVA illustrated a significant effect of herbicide on weeds and crop only for the harvest data from field A4. There were no significant interactions (block × fertilizer × herbicide).

In the first experiment, 6 cultivars of oats were planted in 3 replicate plots on each of 5 fields including fields in all phases of the rotation. The cultivar effects will be discussed in section 9. There were pronounced field effects on total biomass, and on the proportion of the total biomass made up by oats (Table XV). The total biomass was exceptionally low on field B2 where the oats had been planted in place of beans, following winter wheat. The proportion of oats in the total biomass was exceptionally low on field B2 and on field A1/A3 for which oats was the normal crop, and followed fababeans.

In a concurrent experiment, 17 combinations of various minerals and manure were applied to one or two plots per treatment on each of two oat fields (Fig. 8). We were looking for factors that would approximately double the yields. In Figure 8, yields are expressed relative to average control values which were set at 100. As assessed by the rank sum test, treatments that included fertilizer–N had a positive effect on total biomass ($P<0.05$) but not on oats alone ($P>0.4$), while treatments that included manure had positive effects on both total biomass ($P<0.01$) and oats alone ($P<0.05$). Other treatments had little or no effect on yields (Fig. 8).

TABLE XV

Yields of oats tested on plots in five fields in various phases of the rotation†

Field	Normal Crop on Field	Avg. Biomass in Oat Plots						Ratio of Oat Biomass to Total Biomass	
		Crop		Weed (kg/ha)		Total			
A1/A3	oats	550	z*	4410	x	4970	y	0.142	y
A2	clover	3120	y	1630	yz	4750	y	0.667	x
A4	clover	5110	x	1890	yz	6990	x	0.715	x
A5	wheat	3080	y	1100	z	4180	y	0.722	x
B2	fababeans	520	z	2290	y	2810	z	0.205	y

†Values are means of 18 samples (3 replicates of each of 6 cultivars of oats on each field). Within columns, different letters indicate significant differences in the rank order of the mean values. (The Kruskal Wallace H-test indicated significant differences between fields in the rank orders for each of the biomass characteristics (α=0.001). Mann-Whitney U tests incorporating Ryan's procedures to fix the overall type I error at 0.05 or less were used to compare rankings of individual fields (Mendendenhall and Ramey, 1973).

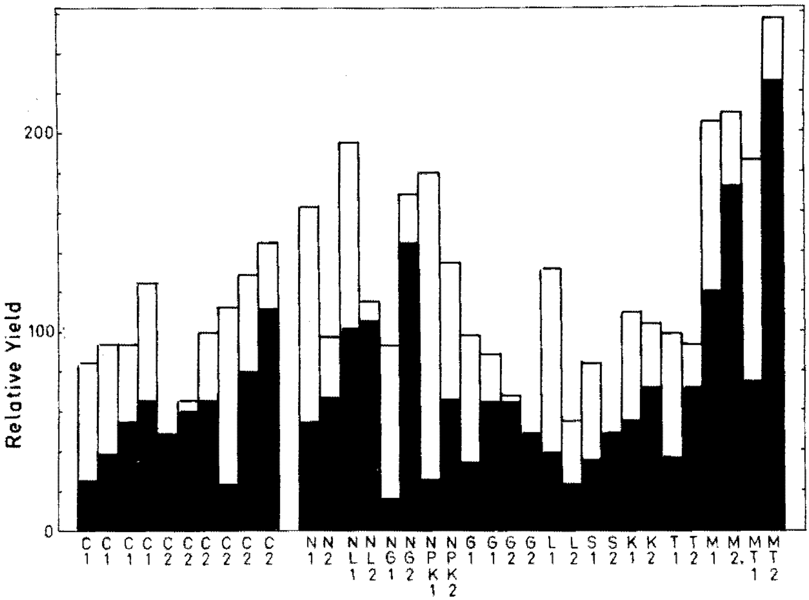

FIGURE 8 Yields of oats (shaded parts of bars) and weeds (open parts of bars) on individual plots receiving various fertilizer treatments. Numbers denote field (1=field A1, 2=field C1). Letters: C=control, N=nitrogen, L=dolomitic lime, G=gypsum, P=phosphorus, K=potassium, T=combined trace elements, M=manure. Values are: 100 × (observed yield/average control yield). Average control values for oats were 3123 kg on field A3 and 3655 kg on field C1. Data for plots in which trace elements (Zn, Cu, Mn, Fe, Bo, Mo) were applied individually are not shown.

We interpret these results as follows. Total yields in field B2 were very much lower than those in other fields because of immobilization of N resulting from incorporation of low N (ca. 0.25%) wheat residues in the previous year. Bean residues (ca. 0.9% N) incorporated in field A1/A3 in the previous fall did not exert a pronounced immobilization effect (weed + crop biomass was much higher than on field B2). However both bean and wheat residues were phytotoxic to oats resulting in a low proportions of oats in the total biomass on both fields.

Manure relieved the phytotoxic effects by feeding microbes which in turn broke down the phytotoxins. However, it is evident from Figure 8 and the other experiments (Table XIV) that manure could not be relied upon to consistently relieve the phytotoxic effects of fababean residues.

Mr. Aldhouse was not satisfied with the rotovation of residues because it leaves a fair amount of residue sticking up at the surface, and it leaves the surface flat (Fig. 9a). This results in slow drainage and slow warming of the soil in the spring. Following rotovation of bean residues on field A5 in the fall of 1983, he ridged the soil using a tool bar equipped with shanks and 3 inch

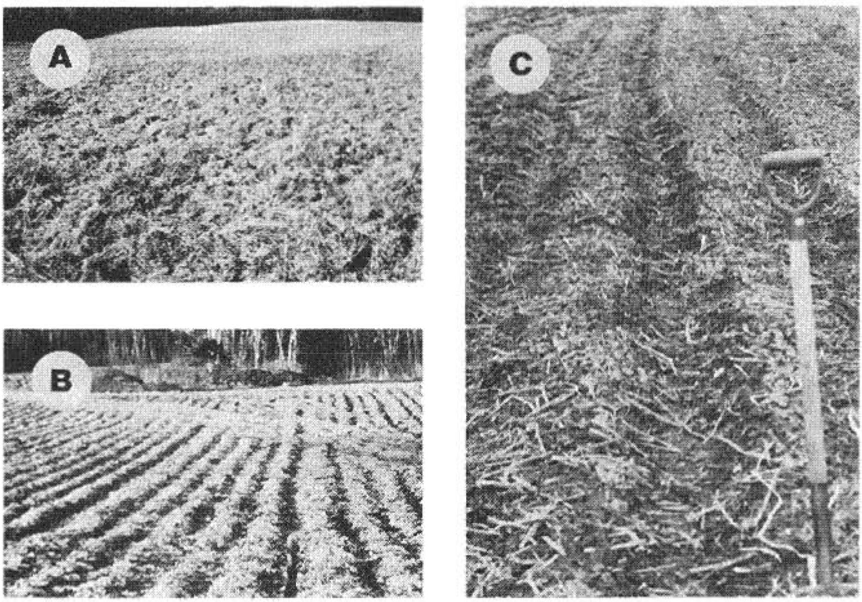

FIGURE 9 Fall tillage. (a) Field C2 after rotovation of wheat residues in fall of 1982. (b) Field A5, and (c) Field A4 in spring of 1984 and 1985 respectively, after rotovation of fababean residues and ridging of soil during the previous falls. In (c) note lighter color of ridges due to drying; residue pieces protruding from the soil act as wicks which assist in penetration of water (Schrieffer, 1984).

shovels; ridges were spaced at 28 inches and were of 6–8 inches (15–20 cm) elevation (Fig. 9b, c). In the same fall he also mouldboard–ploughed field C2 after harvesting beans; this was done because he felt that he would have to begin mouldboard–ploughing once in 4+ years to control perennial weeds. In May of 1984, manure was applied to one-half of field A5, and oats were planted in fields A5 and C2 and in a manured strip in his vegetable garden.

On June 21, oats on all fields looked better than had been observed at this stage at any time during the previous 5 years; on field A5 oats on the manured section were darker green and substantially larger and more robust-appearing than oats on the unmanured section. Final yields on all fields were better than any observed over the previous 5 years (Table VI, above) but no differences were evident visually or quantitatively in oat biomass, harvest index, N content or in weeds between the manured and non-manured sections of A5. Total N accumulated in oats and weeds in the absence of manure almost doubled in comparison to previous years (Table VI). Good yields of oats were again obtained in 1985 (Table X; Fig. 7b), when fields had again been ridged after rotovation.

In summary, from 1979 to 1983, productivity of oat fields was very low and the oats were very weedy. They appear to have been suffering from phytotoxicity induced by rotovation of fababeans residues. Introduction of a ridging operation following rotovation of fababean residues, or of mouldboard–ploughing (in place of rotovation and ridging), largely relieved these limitations.

8c. *Fababeans*

Because this crop did not exhibit the overt declines characterizing cereal crops following cessation of use of agrochemicals, Mr. Aldhouse was not particularly concerned about its performance. However, in retrospect, it appears that yields in the interval 1979–1983 were substantially lower than the pre-1976 yields (Table X). Mr. Aldhouse had noticed that he was not able to plant fababeans as early as he had generally been able to in the early 1970's, and in the fall of 1984 he followed rotovation of residues with ridging on fields on which fababeans were to be planted the following year, as well as on those to be planted in oats. Because Canada thistle had recently become obvious on field A4, he had also departed from his routine by mouldboard–ploughing that field in the fall of 1983, prior to planting fababeans in 1984. In 1985 the yield of fababeans increased in comparison to 1979–1983 (Table X) and in 1984, the only "reasonable good yield" of beans was that for field A4, the one field of the three planted (Table VIII) that had been mouldboard–ploughed.

Altogether, these observations and experiments suggest that tillage and soil structural factors limited yields of cereals and fababeans in the interval 1979 to

1983. It appears that introduction of the ridging practice relieved these limitations to a large extent for oats and fababeans. The nature of the limitations in wheat and the means of solving them remain poorly defined.

9. Weed—crop interactions

Growth of weeds where and when crops are not present conserves substantial amounts of N (Patriquin *et al.*, 1981). Weeds also reduce erosion and runoff losses (Weil, 1982), produce organic matter, fix N_2, and are probably a factor (Altieri, 1984) in the absence of significant pest problems on this farm. Thus it is desired to manage weeds in such a way that they can function as a "self-seeding cover crop" without at the same time reducing crop yields.

In this connection we wish to know how much control is necessary, how much is excessive, what type of control is appropriate, and what reduction in yield must be tolerated for the sake of maintaining a weed population?

Information relevant to such questions has been provided by (i) records of weed and crop biomass and species composition, (ii) seasonal observations on weed and crop biomass and N contents (iii) specific experiments involving hand or chemical control of weeds; (iv) an oat-fababean intercropping experiment, and (v) a study on seed banks and vegetation on four fields in 1979, and again in 1983 after one complete rotation of crops. The last mentioned is reported separately (Hill, Vander Kloet & Patriquin, in prep.)

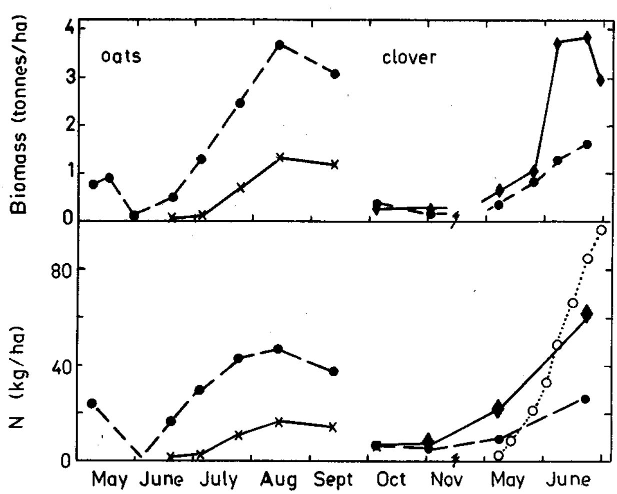

FIGURE 10 Seasonal changes in biomass and nitrogen content of successive oat (×) and clover (♦) crops, and of weeds (●) and calculated cumulative nitrogen fixation by clover (o) on field A5 in 1980/81.

TABLE XVI

Ranking of weeds making up the bulk (estimated 80%) of weed biomass. 1=most abundant. Nomenclature is after Roland and Smith (1969)

	Winter wheat[a]							Clover[b]			Fababeans[c]						oats[d]							
Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1. PERENNIAL GRASSES																								
ALL		2	1	1	1	1	4	1	1	1	1	1	1	2	1	3	2	2		1	2	4		2
Agropyron repens		2			3		1	1	3	3					1									
Phleum pratense			2	1	3	1	3		1	2				2		3								2
Poa pratensis			1		1	2			2	1												4		
2. PERENNIAL DICOTS																								
Apocynum androsaemifolium											2													
Cerastium vulgatum						4	2																	
Cirsium arvense		1	4																	4				
Plantago major		2						2							3		3		1			2		
Solidago graminifolia										4				3	4									
Sonchus arvensis													2							4				
Stellaria graminea				3																				
Taraxacum officinale					2			3			4					1		3				1		4
Trifolium spp.		4				3																		
Vicia cracca																4								
3. EQUISETUM SPP.		4	3						4															

4. WINTER ANNUALS & BIENNIALS																								
Daucus carota													4											
Rumex crispus											4			4										
Vicia tetrasperma		4		2				4																
5. SUMMER ANNUALS																								
Ambrosia artemisiifolia																			2					
Chenopodium album												3							2	3	3		1	1
Galeopsis tetrahit	2										3	1	4		2		4				1		2	
Oxalis stricta																		4						3
Polygonum hydropiper																2								
Polygonum persicaria																							3	
Raphanus raphanistrum	1											4		1			1	4	4		4			
Setaria glauca																				2				
Stellaria media																		1				3	3	

[a] 1=Field A1, October 28, 1979
2=Field A1, July 24, 1980
3=Field A1, July 30, 1984
4=Field A4, Aug. 1, 1979
5=Field A4, July 26, 1983
6=Field A2, July 26, 1983
7=Field B4, July 26, 1983

[b] 8=Field A5, June 22, 1981
9=Field A1, June 14, 1983
10=Field A6, June 14, 1983

[c] 11=Field A4, July 4, 1980
12=Field A4, Aug. 27, 1980
13=Field A2, Aug. 27, 1980
14=Field A5, July 10, 1979
15=Field A5, Aug. 21, 1979
16=Field A5, Sept. 24, 1983

[d] 17=Field A5, June 19, 1980
18=Field A5, Sept 12, 1980
19=Field A2, Sept. 9, 1979
20=Field A2, Aug. 19, 1981
21=Field A4, Aug. 19, 1981
22=Field A5, Aug. 30, 1984
23=Field G, Aug. 30, 1984
24=Field C2, Aug. 30, 1984


A
B
C

FIGURE 11 Winter wheat and weeds. (a) Field A1, Sept. 21, 1979; seedlings between rows of winter wheat are *Raphanus raphanistrum*, (b, c, and d): Sequence of photographs of the same region at the headland of field B2 (looking east). In (b), taken on October 12, 1984, winter wheat is completely covered by wild radish. In (c), taken on April 23, 1985, wild radish has died over the winter, and rows of wheat can again be seen; (d) illustrates wheat on July 29, just prior to harvest; at inflorescence level only a few heads of timothy can be seen but there is an understory of weeds. Fig. (e) illustrates a region of winter wheat field where wheat is sparse and small, possibly due to phytotoxicity of previously incorporated residues. Weeds are small but numerous. Most of the weed biomass is made up of mouse-eared chickweed (*Cerastium vulgatum*) with small white flowers; larger flowers are those of wild radish.

9a. General composition of the weed flora

Ranking of the weed species making up the bulk of weed biomass in different crops is given in Table XVI. In general, perennials and winter annuals or biennials predominated in the two long-season, winter annual crops (winter wheat and clover); summer annual weeds predominated in the short-season, summer annual crop (oats), and annuals and perennials were both abundant in the long-season summer annual crop (fababeans). This sort of general synchrony of life cycles of weeds and crops is well known (Bunting, 1959).

9b. Seasonal changes in crop & weed biomass and nitrogen

Seasonal changes in weed and crop biomass and N were monitored throughout the growing season of 1980, and for clover, of 1981.

Germination of oats in 1980 was exceptionally poor, probably because of phytotoxicty problems (discussed above). Weeds predominated at all times (Fig. 10), wild radish (*Raphanus raphanistrum*) in the early summer (Fig. 7a) and chickweed (*Stellaria media*) in the later part of the season (Table XVI, nos. 17, 18). Neither the resultant total biomass nor the total N accumulated in oats and weeds was exceptionally low (Table VI); this suggests that the potential productivity of the mixed weed population approaches or is equal to that of the introduced plants. Clover, undersown in the oats, exhibited little growth until after harvest of oats, and most growth occurred within a one month period in the following spring (Fig. 10). Biomass of clover then exceeded that of weeds at all times, illustrating that weeds had effectively substituted for oats as a nurse crop for clover.

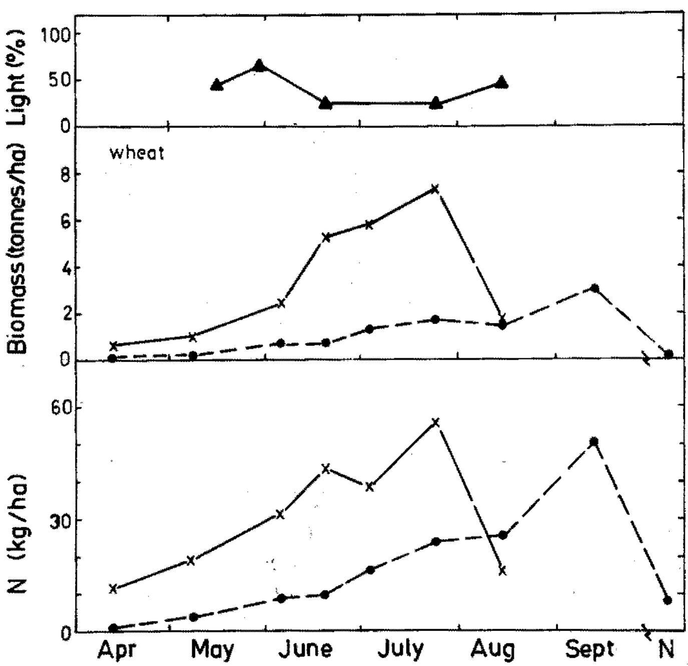

FIGURE 12 Seasonal changes in the percentage of light incident at the top of wheat that reaches the soil, and in wheat (×) and weed (●) biomass and N content on field A1/A3 in 1980.

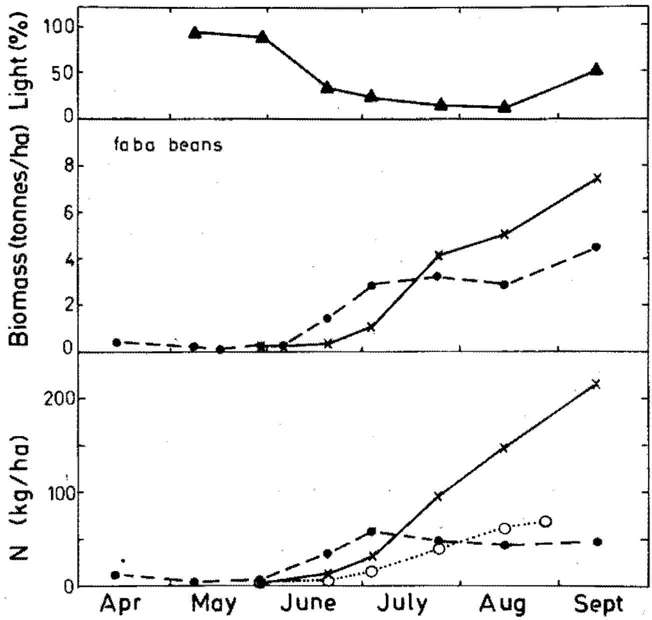

FIGURE 13 Seasonal changes in the percentage of light incident at the top of fababeans that reaches the soil, in fababean (×) and weed (●) biomass and N content, and in calculated cumulative N_2 fixation by fababeans (0) on field A4 in 1980.

Wheat planted in field A1/A3 in the fall of 1979 reached a biomass of 630 kg/ha, and weeds, 130 kg/ha by October 28 of 1979 (Patriquin *et al.*, 1981). Most of the weed biomass consisted of wild radish, *Raphanus raphanistrum* (Fig. 11). On April 13, 1980, wheat biomass was 618 kg and weed biomass, 25.3 kg/ha: all wild radish had been killed by the winter. Weeds were a rather minor component of the total biomass thereafter, but included a more substantial proportion of the total N (Fig. 12). After harvest, N in weeds increased by 27 kg within one month, of which 16 kg was in clover. The actual turnover of N within weeds was probably substantially higher because the combine cut weeds at 10 cm height.

Weed biomass in the fababean field (Fig. 13) exceeded that of fababeans during vegetative growth of the crop, remained more or less constant after canopy closure, and then increased again during podfill when the canopy began to open up. A similar pattern was observed in 1981 on field A1 (data not shown). Predominance of weeds during vegetative growth of fababeans was noted visually in other years, and on other fields (Fig. 14). Frequently, but not on A4 in 1980 (Table XVI), wild radish was the predominant weed in the


A
B
C

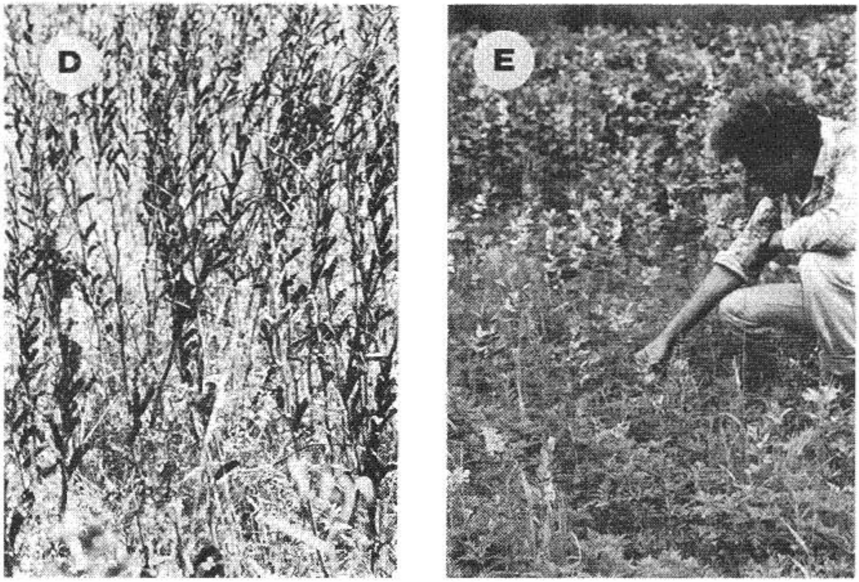

FIGURE 14 Fababeans and weeds on Field A1, 1985. No harrowing was done on this section of the field after seeding. The crop was planted May 1, but growth was delayed by cold wet weather during most of May. (a) June 14, early vegetative growth, weeds make up more than 50% of the biomass, species visible include *Taraxacum officinale, Raphanus raphanistrum, Cirsium arvense, Phleum pratense* and *Equisetum arvense*. (b) July 10; early reproductive stage, canopy has closed and weeds (including *Ambrosia artemiisifolia, Raphanus raphanistrum* and *Taraxacum officinale*) occur as an understory. (c) July 29; inflorescences of *Sonchus arvensis* stand above fababeans; this was the only weed which exceeded fababeans in height. (d) September 14, crop ready for harvest, most leaves have dropped, canopy has opened and biomass of weeds is increasing. (e) A patch in field where germination was erratic, and beans and weeds (mostly *Ambrosia artemiisifolia*) were stunted in comparison to most of field (normal growth of beans in the background).

early phase (Hill *et al.* in prep.) and fields were speckled with its yellow flowers just before canopy closure.

The fababean begins to fix N_2 early in its development (Sprent & Bradford, 1977; Patriquin *et al.*, 1981). We hypothesized that the apparent stimulation of weeds during vegetative growth of fababeans is due to release of recently fixed N. However, the magnitude of N_2 fixation in this period, estimated from acetylene reduction assays using a molar conversion factor calculated from data in Table IX, is not sufficient to account for the accumulation of N in weeds (compare N accumulation in weeds with N_2 fixation in Fig. 13). Rather than being due to stimulation of weeds, the predominance of weeds during vegetative growth of fababeans may be due to the relatively slow growth of fababeans during the period when nodule biomass and N_2 fixing activity is increasing (Fig. 13; Sprent & Bradford, 1977).

TABLE XVII

Parameters and statistics of linear regressions of % crop on total (weed + crop) biomass

Date	Field & treat	n	r^2	S.D./ mean Y	interc.	slope	F
FABABEANS							
Jul 18, 1979	A5 –[a]	9	62.1	25.9	-2.60	0.128	11.5
Aug 21, 1979	A5 –	9	72.3	14.3	8.34	0.111	18.3***[b]
	A5 +N	9	1.76	47.2	44.4	0.0106	0.125
Aug 27, 1980	A2 –	7	37.5	9.71	64.2	0.0357	3.002
	A4 –	7	0.92	25.5	58.0	0.00750	0.047
Sep 18, 1981	A1/A3 A6, C1	15	82.4	11.9	37.7	0.0639	60.8***
Sep 24, 1983	A5 –	20	36.8	13.1	51.9	0.040	10.5***
	A5 +oats	20	18.7	20.8	44.1	0.0345	4.14*
OATS							
Sep 9, 1979	A2 –	10	42.4	4.88	84.0	0.022	5.89**
	A2 N	5	33.1	49.9	22.7	0.116	1.49
Aug 27, 1979	Other	10	60.6	28.9	-6.33	0.133	12.3**
Sep 12, 1980	A5 all	30	4.04	62.2	18.4	0.0217	1.18
Aug 19, 1981	A2 –,M, NPK	14	27.7	10.2	77.8	0.0244	4.60*
	A4 –,M NPK	18	10.6	12.4	74.5	0.0210	1.89
Aug 27, 1982 A2, A4, A5 combined, cultivars as below							
	Fundy	9	24.7	11.8	67.7	0.0280	2.30
	Sentinel	9	38.1	41.5	109	-0.104	4.30*
	Cabot	9	9.00	21.7	55.9	0.0275	0.692
	Garry	9	27.9	17.5	50.2	0.0558	2.71
	Manic	9	12.3	30.7	38.0	0.0274	0.98
	QD89	9	10.2	17.4	62.7	0.0264	0.80
Aug 27, 1982 (all cvs)	A1	18	32.9	68.3	32.4	-0.0369	7.86**
	B2	18	19.1	55.6	34.1	-0.0473	3.78*
Aug 27, 1982	C1–	18	0.732	29.9	79.2	-0.00894	0.118
	A3–	16	0.004	38.4	41.4	-0.00074	0.001
Aug 30, 1984	C2–	7	76.3	3.79	76.3	0.0212	16.1**
	G M	7	5.20	5.56	77.5	0.00544	0.275
	A5–	8	46.0	9.36	57.7	0.0317	5.12*
	A5 M	8	51.2	12.1	46.1	0.0487	6.29*
WINTER WHEAT							
Aug 1, 1979	A4–,N	10	48.6	18.1	24.7	0.0480	7.55**
Jul 29, 1980	A1–,N	10	48.0	7.59	80.4	0.0126	7.40**
	A6–,N,K	18	41.0	1.61	93.0	0.00465	11.1***
Aug 2, 1981	B2–,M	20	50.6	26.5	13.8	0.0647	18.5***
Jul 27, 1982	A5–	6	10.6	10.9	82.9	0.0124	0.473
	C2	6	10.1	12.6	82.8	0.0132	0.449
Jul 26, 1983	A2–,N,K	21	6.17	20.7	61.0	0.0106	1.25
	A4–,N,K	18	46.8	21.1	37.2	0.0456	14.1***
	B4–,N,K	21	8.32	160	-74.8	0.216	1.72
Jul 24, 1984	A6–	7	12.4	40.9	-11.9	0.02879	0.710
Jul 30, 1984	A1–	7	1.97	14.3	66.1	0.00731	0.101
CLOVER							
Jun 14, 1983	A3–	10	33.8	85.3	-2.48	0.0396	4.091*
	A6–	9	40.7	41.4	-4.14	0.168	4.801

[a]Treatment: dash indicates no additions except those normally given by farmer; N, P, K refers to fertilizers and M to manure applied in plot experiments. Data from different treatments were combined except for the +/– N treatments in oats and beans in 1979; for these slopes and/or intercepts differed (α=0.1) between treatments as determined by the dummy variable method (Kleinbaum and Kupper, 1977)

[b]Asterisks indicate significant levels, * α = 0.1, ** α = 0.05, *** α = 0.01.

9c. Proportion of weeds and crop in the plant biomass

In previous studies (Patriquin *et al.*, 1981) we observed highly significant linear relationships between the proportion of crop in the total biomass at harvest—hereafter referred to as "% crop"—and the total (weed + crop) biomass. The higher the total biomass, the higher was the %crop (up to a value of 100%) and the lower the percentage of the sample made up by weeds.

We interpreted those regressions to mean that "increasing total biomass is related to increasing soil fertility and provided the crop has the initial advantage (given by seedbed preparation, optimal planting time etc.), higher soil fertility enables the crop to compete more effectively with weeds for available nutrients" (Patriquin *et al.*, 1981).

Linear regression characteristics for biomass data from 1979 to 1984 are given in Table XVII. Thirty-six out of 41 regressions have positive slopes, and 18 are significant at the 0.1 level of probability or better. Negative slopes were found only for some of the oat crops.

The effect of removing weeds

It could be argued that this relationship is the result of the crop growing better where there are fewer weeds. To test this, weeds were removed by hand from fababean plots until canopy closure, and yields of fababeans and weeds on these and on adjacent unweeded plots were determined at crop maturity (Table XVIII). There was a highly significant correlation between % crop values and total biomass in the unweeded plots (Table XVII, entry under Fababeans for September 18th, 1981). Overall, yields on unweeded plots were only 9.4% lower than those on weeded plots indicating that the relationship is not a result of crops growing better where there are fewer weeds. Weeds did not exert substantial inhibitory effects on crop growth at either low or high total biomass: at 5 out of 8 of the paired weeded/non-weeded plots with low total biomass, and at 4 out of 7 those with high total biomass, crop yields were higher on the unweeded plots. In this situation, weeds appeared to be filling in the spaces between crop plants rather than competing directly with them.

A similar experiment, but involving chemical control rather than hand control, of weeds was conducted with oats on fields A2 and A4 in 1981 (Table XIV). In these cases the r^2 values (Table XVII) were much lower than those of the beans cited above. Yields on chemically-treated plots were 8.4 and 20.2% higher than untreated plots for fields A2 and A4 respectively. The reductions in yield of weeds and increases in crop yields were statistically significant for field A4 but not for field A2.

Relative weediness of different fields and years

The % crop-total biomass relationship suggests that the proportion of weeds in the total biomass (Table XVII) and even the absolute mass of weeds (Table

TABLE XVIII

Effects of hand-weeding fababeans (experiment 1), overseeding fababeans with oats (experiment 2) and presence of Canada thistle (observation 3) on fababeans

Experiment/ Observation & treatment	Crops	Biomass Weeds (g/m²)	Oats	Total	% Crop	Ratio of pods & seeds to total crop biomass
1. low total[a] biomass (n=8)						
unweeded	241	121		361	60.4	0.596
weeded	323	34.3***[b]		357	86.3***	0.565
1. high total biomass (n=7)						
unweeded	764	72.2		836	90.8	0.639
weeded	777	30.0**		806	96.4**	0.613**
2. (n=20)						
No oats	511	144		655	75.3	0.732
+ oats	362**	110**	86.3	559	63.1***	0.675
3. (n=10)						
+ thistle	330	51+[c]		381		0.747

[a] "Low total biomass" includes data from plots in which the total biomass on unweeded plots was less than 600 g/m²; high total biomass data were the remainder (total biomass > 600 g/m²). For the combined data, only values for weed biomass and % crop differed significantly (α=0.01) between weeded and unweeded plots.
[b] Values differ significantly from those of the corresponding pair as assessed by paired t test, using 1-tailed tests to test differences in weed and crop biomass, and % crop, 2-tailed tests for total yields, and ratio of pods + seeds/total crop biomass. One, two and three asterisks indicate 0.1, 0.05 and 0.01 levels of significance.
[c] Refers to weight of thistle plants only, estimated from average weight for 15 plants and counts of plants per unit area.

XVIII) varies in a consistent manner with total (crop + weed) biomass. This variation needs to be taken into account when comparing "weediness" between fields, between treatments within a field, or between fields in different years. Plots of percent crop versus total biomass appears to provide a simple means of comparing weediness that takes into account this variation, and that is essentially independent of differences in the absolute biomass that might result from either real differences or from differences in sampling procedures. Given a % crop-total biomass relationship in one situation, deviations from that in a second situation indicate a shift in the weed crop relationship either in favor of weeds (lower % crop values at given biomass values) or in favor of the crop (higher % crop values at given biomass values).

Comparisons of this sort are described and discussed below for each crop. Regression parameters and statistics are given in Table XVII, and data are plotted in Figures 15–17. Weed species composition for certain of these is given in Table XVI.

Fababeans

(i) Fertilized versus unfertilized plots on field A5 in 1979. Data points for N-fertilized plots fall largely below the regression for the unfertilized plots (Fig. 15a) and the former exhibit a much weaker relationship between % crop and total biomass. Interestingly, the biomass of fababeans did not change in response to N (avg. +N = 399 g/m^2; avg. −N = 414 g/m^2) while weed biomass roughly doubled (from 146 on unfertilized to 346 on fertilized plots). Evidently, all of the advantage of adding N went to the weeds without inhibiting the crop.

(ii) Field A5 in 1979, mid season compared with end of season (entries for July 18th and August 21st, 1979, in Table XVII): although the absolute values differ, averaging 358 g/m^2 crop and 160 g/m^2 weeds on 2 July 18th, 414 and 146 g/m^2 for crop and weeds on August 21st, and the weed species composition differ (Table XVI, entries 14 and 15), the % crop-total biomass regressions for these two dates have almost identical parameters (Table XVII).

(iii) Field A5 1979 versus the same field in 1983 (after one complete cycle of the rotation): there was a marked change in the composition of weeds between these two years (entries 15 and 16, Table XVI) but not in the % crop-total biomass relationship (Fig. 15b). The parameters of the regression for 1983 differ substantially from those for 1979 (Table XVII). However the 1983 data include four very high total biomass values which clearly should not be included in the regression. If these are excluded, the regression parameters (intercept 24.1, slope 0.0903) are much closer to those for 1979.

(iv) Field A2 versus field A4 in 1980 (Fig. 15c). The data for field A4 fall largely below the data for field A2, suggesting that weeds had relatively more advantage in field A4. This might be related to the higher supply of soil N on this field (Table IX) giving more advantage to weeds relative to the legumes, and/or to the larger seedbank on field A4 (Patriquin *et al.*, 1981).

Wheat

(v) Fields A1 and A6 in 1980 and 1984: These fields had high percent crop values (few weeds) even at low total biomass in 1980, but were characterized by low % crop values in 1984 (Fig. 16a).

(vi) Field A4 in 1979 versus the same and other fields in 1983: regression parameters for field A4 in the two years were nearly identical (Table XVII). In 1983, fields A2 and B4 were much weedier at high total biomass values than field A4 (Fig. 16b); this is a reversal of the relative weediness cited for beans on fields A4 and A2 in 1980 (no. iv above).

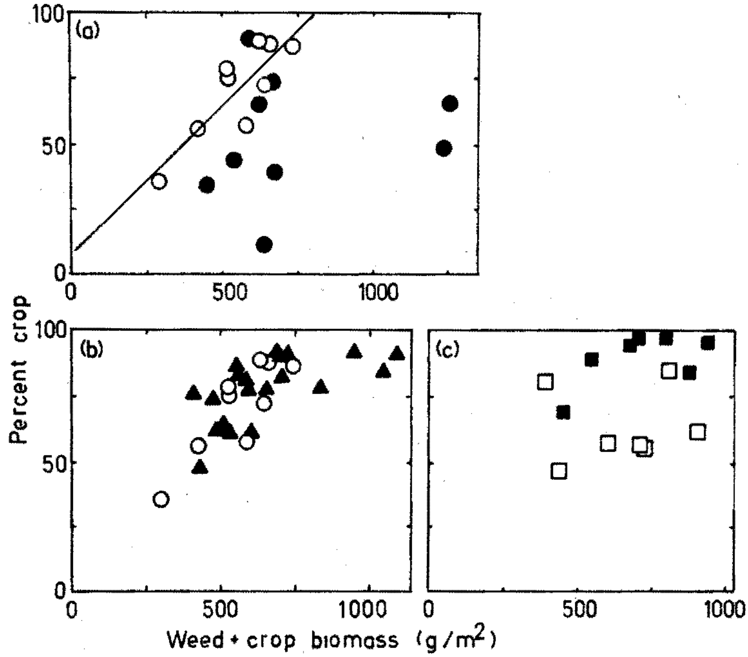

FIGURE 15 Plots of percentage crop versus total biomass of fababeans. Fig. 15a is for fababeans on A5 in 1979 without (0) and with (●) N fertilizer; regression line is given for the minus fertilizer data. Fig. 15b is for field A5 in 1979 (0) and again in 1983 (▲). Fig. 15c is for field A2 (■) and A4 (□) in 1980.

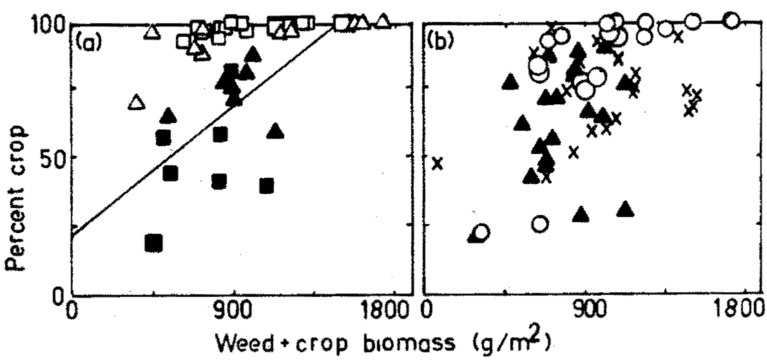

FIGURE 16 Plots of percentage crop versus total biomass for winter wheat. Fig. 16a is for field A1 in 1980 (△) and 1984 (▲) and field A6 in 1980 (□) and 1984 (■). The regression line is that for field A4 in 1979. Fig. 16b is for fields A2 (×), A4 (0) and B4 (▲) in 1983.

Oats

(vii) Oats 1979 field A2 and "other farm" oats in 1979 (Fig. 17a); there were significant correlations between % crop and total biomass for both fields, even though parameters of the linear regressions were quite different. Field A2 had a high positive intercept (i.e. there were few weeds at all levels of total biomass), which we suggested was related to reduction of the weed seed bank by intensive cultivation preceding planting of oats in 1979 (Patriquin *et al.*, 1981). The "other farm" data were for an oat field in which herbicide would normally be applied but was not in that year because of rain.

(viii) Oats in 1980 and 1982, compared to 1979: the 1980 data fell largely below both regression lines for 1979 (Fig. 17b) and are clearly indicative of the weeds having an advantage (see Fig. 7a). In 1980, tillage operations were conducted in the spring, and the freshly incorporated weeds and fababeans residues appeared to exert strong phytotoxic effects on the oats (cf. section 8b above). Chickweed (*Stellaria media*) predominated at harvest. According to Walters & Fenzau (1979), this species thrives in soils in which there is a lot of

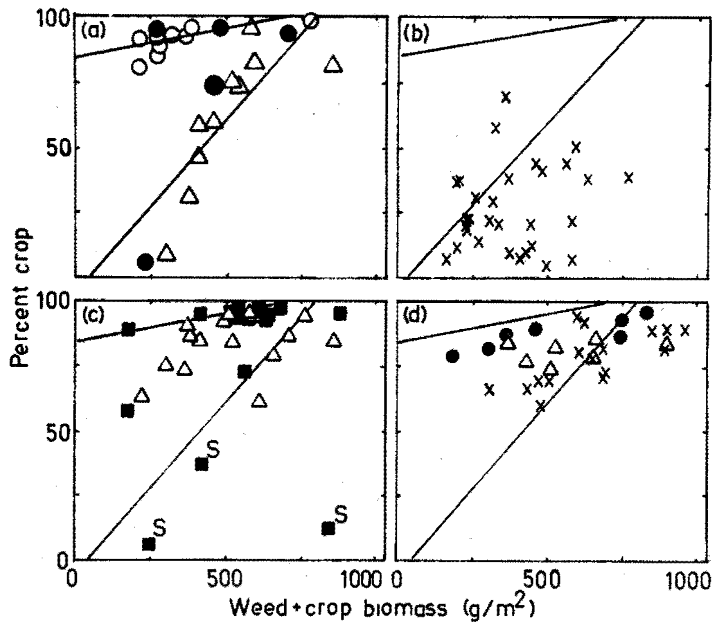

FIGURE 17 Plots of percentage crop versus total biomass for oats. Data and regression line in Fig. 17a are for field A2 in 1979 without fertilizer (0) and for another farm in 1979 (Δ); data for + fertilizer plots on field A2 are given by shaded symbols. The regression lines are redrawn in Figs. 17b, c and d. Data of Fig. 17b are for field A5 in 1980. Data of Fig. 17c are for fields A2(■) and A4 (Δ) in 1980 (S denotes perennial sow thistle). Data of Fig. 17d are for fields A5(×), C2(●) and the garden (Δ).

incompletely decomposed organic matter. Weeds also predominated at high total biomass on fields C1, A3, A1 and B2 (Table XVII) in 1982 which we attribute to phytotoxic effects of residues from the preceeding crops (wheat or beans). Regression slopes for these fields were all negative.

(ix) Oats on fields A4 and A2 in 1981: for both fields, the percent crop values fall largely between those of the two 1979 regression lines. The three highly disparate values (Fig. 17c) were for plots where there was a heavy infestation of perennial sow thistle (*Sonchus arvensis*).

(x) Different cultivars of oats on fields A2, A4 and A5 in 1982: these cultivars include 3 traditional types (Fundy, Cabot and Garry), and 3 modern selections (QD89, Manic and Sentinel). The % crop-total biomass plots (Fig. 18) illustrate 3 different patterns or trends in % crop-total biomass relationships for the different cultivars: (a) trends similar to the 1981 data, with positive slopes, and close to 100% crop at higher total biomass values (Fundy, Garry and QD89); (b) a trend of decreasing % crop at high total biomass (Sentinel cultivar); and (c) low % crop at all total biomass values (Manic). The Cabot cultivar appears to be intermediate between (a) and (c).

(xi) Oats on three fields in 1984 (Fig. 17d): for all fields, there were high Y intercept values, and the distributions of points approach the regressions for oats on field A2 in 1979 which was relatively "clean" following repeated cultivation; this indicates a marked reversal of the trend to greater weedines evident in preceding years. There were relatively more weeds on A5 than on the C and G fields, a difference possibly related to the prominence of two broad leaved perennials (*Taraxacum officinale* and *Plantago major*) on field A5.

Percent crop in relation to density of fababeans

Determination of biomass values for fababeans entailed counting the number of plants per square meter. There are significant correlations of % crop with

TABLE XIX

Values of r^2 for regressions of % crop on density of fababeans

Year and field	n	stems/m^2 mean	stems/m^2 range	r^2	F
1979 A5	9	29.0	10–63	31.7	3.25
1979 A5+N	9	26.0	5–52	83.1	34.4***
1980 A2	7	24.6	15–32	75.6	15.5**
1980 A4	7	19.4	8–34	32.1	2.37
1981 A1/3, A6, C1	15	32.3	26–44	0.02	0.003
1983 A5	20	28.6	16–37	23.5	5.33**
1983 A5+oats	20	27.9	13-36	38.5	11.4***

***Asterisks indicate significance level (**=0.05, ***=0.01).

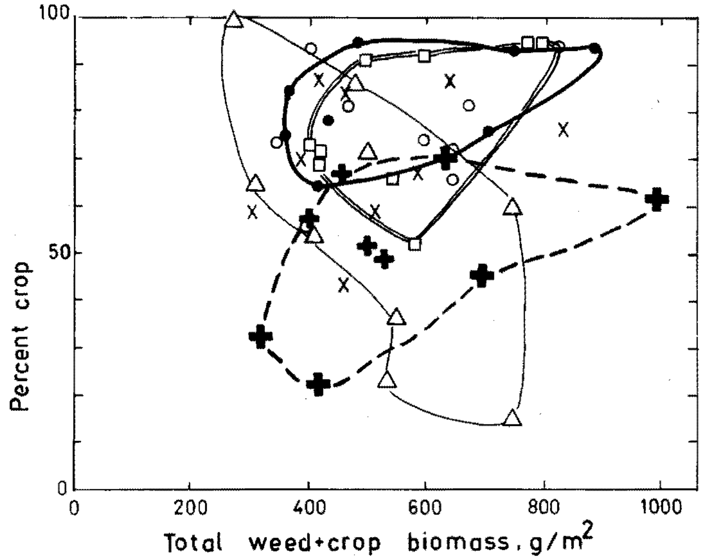

FIGURE 18 Plots of percentage crop versus total biomass for different cultivars of oats, in 1982. Cultivars are Fundy(●), Garry(□), Cabot(×), Sentinel(Δ), Manic(+) and QD 89(0). Envelopes enclose data for four of the cultivars separately.

plant density for years in which there were low plant densities in some plots (Table XIX). Correlation coefficients for multiple regressions of % crop with total biomass and stem density were not better than those for stem density or total biomass alone. Plots of % crop-stem density data (Fig. 19) suggests that crop-weed balance in the absence of fertilizer-N is related to stem density up to values of about 25 plants/m^2. In the presence of fertilizer-N, there is a much stronger correlation of % crop with plant density, and the number of plants required to give a certain crop density is higher than in the absence of fertilizer (Fig. 19a).

9d. Perennial weeds

Overall, the % crop-biomass data suggest that from 1979 to 1984 weediness of winter wheat increased, while there was little or no change in weediness of fababeans and there was a marked reduction in weediness of oats. The increased weediness of winter wheat was associated with greater abundance of perennial grasses that had always been common in winter wheat, and with more widespread distribution and greater abundance of dicotyledenous perennials including *Taraxacum officinale* and *Cerastium vulgatum* (Table XVI). *Taraxacum* also increased in prevalence and abundance (Table XVI) in

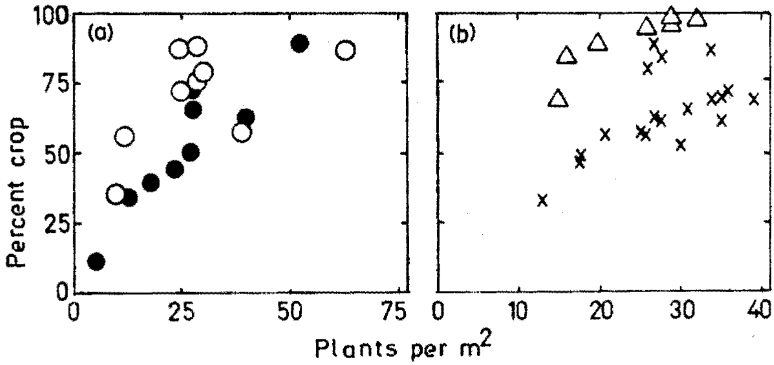

FIGURE 19 Plots of percentage crop versus density of fababeans for (a) field A5 in 1979, +N (●) and −N (0); (b) field A2 in 1980 (▲) and +oats plots on field A5 in 1983 (×).

other crops during this period, and patches of two perennial rhizomatous dicotyledons, *Cirsium arvense* (Canada thistle) and *Sonchus arvensis* (sow thistle) became more numerous. Patches of *Cirsium arvense* increased dramatically in size on fields A5 and A2, and new stands developed in all except the sandier fields (B and C fields). These changes are further documented by Hill *et al.*, (in prep.)

To gain some indication of how much infestations of Canada thistle may be reducing yields, fababeans were sampled in the densest thistle patch on field A5 (Table XVIII, no. 3) at the same time that they were sampled in a strip across the field selected without reference to thistle (entry for no oats under no. 2 in Table XVIII). Average densities of beans were similar (24.6 plants/m^2 in the thistle patch and 28.6 in the strip). Thistle plants averaged 14.8/m^2 in the thistle patch; none were recorded in the strip samples. Yield of beans in the thistle patch was 36% lower than the average yield for the strip. Thistle patches were estimated visually to occupy less than 10% of the field area. Thus a liberal estimate of the reduction in yield due to the presence of thistle is (10% of the area × 36% yield reduction)=3.6%.

9e. Fababeans-oats intercropping experiment

At the end of 1982, Mr. Aldhouse recognized that he had a chronic problem with oats and began to consider the possibility of a 3 course rotation: fababeans and oats intercropped—fallow—winter wheat; a short season green manure crop might be included in the fallow year if the field was not in need of recurrent cultivation to control perennials. As a preliminary test of

TABLE XX

Number of fababeans and wild radish (*Raphanus raphanistrum*) plants inside and outside of a strip of fababeans oversown with oats. Observations made on field A5, July 5th, 1983

Treatment	Fababean plants (avg. and range of no./m^2)		Wild radish plants	
None	33.2	(8–81)	111	(0–277)
+ Oats	30.9	(8–57)	62.1*	(0–269)

*Number differs significantly (α=0.05) from that for no oat plots, as determined by paired t-test (n=36).

fababean/oats intercropping, he overseeded a regular seeding of beans with a diagonally sown strip (3 seeder widths) of Sentinel oats. Sentinel is a long season variety, which our oat cultivar studies (above) suggested would not be highly competitive with the beans.

The oats germinated successfully, and exhibited good growth and dark green coloration during vegetative growth of the fababeans. The oat strip was readily distinguished during the flowering of the predominant weed in fababeans, *Raphanus raphanistrum*, by the sparsity of this weed's prominent yellow flowers in the oat strip in comparison to the rest of the field. Counts of *Raphanus* plants confirmed the visual impression that the presence of oats had suppressed germination or development of *Raphanus* (Table XX). There was no difference in the number of fababeans plants inside and outside of the oat strip, suggesting that oats had simply replaced weeds as the intercrop. However comparison of fababean yields at harvest illustrated that the oats had a large suppressive effect on the fababeans (Table XVIII).

10. Relative costs of Conventional and Biological Husbandry

In Table XXI, costs of applying fertilizer, lime and herbicide to crops at Tunwath under conventional management are compared with the costs of buying grain to make up for losses in yield under biological husbandry, plus costs of fertilizer to maintain major plant nutrients exclusive of N.

Yields that are currently achievable under biological husbandry are 6%, 12% and 57% lower than the previously attained yields for fababeans, oats and wheat respectively (calculated from data in Table X).

The long term requirement for lime is estimated as that required to balance the estimated annual removal of Ca from the fields (Table V). This is 161 kg Ca/ha per annum, or 423 kg limestone at 38% Ca.

The phosphorus budget (Table V) suggests there is already a net input of P to the farm, and soil analyses (Table II) indicated that levels in the fields are adequate. Therefore we consider that there is no requirement for phosphate fertilizer.

Assuming that approximately one-half of the field deficit in potassium (Table V) could be supplied by soil reserves (Cooke, 1977), we have estimated the requirement for K fertilizer as 25 kg/ha per annum.

TABLE XXI

Comparison of costs of chemicals for management of crops at Tunwath by conventional husbandry with cost of chemicals and additional grain required to make up for yield losses during the transition to biological husbandry

Crop		Conventional husbandry[a] Fertilizer		Herbicide		
	Yield (tonnes/ha)	amount (per ha)	cost (per ha)	amount (per ha)	cost (per ha)	Cost/crop (per ha)
FABA	3.2	506 kg 5-20-20	$177.10	Treflan 710 ml	$16.67	$193.77
WHEAT	3.5	300 kg 5-20-20	$132.00	MCPA 355 ml	$5.28	
		200 kg 34-0-0	$98.00			$235.28
OATS	2.3	350 kg 17-17-17	$154.00	MCPA 355 ml	$5.28	$159.28
					+ lime	$49.02
				Total for the 3 crops		$637.35

Crop	Biological Husbandry[b] Yield loss (tonnes/ha)	Value of crop per tonne	Cost of loss per hectare
FABA	0.2	$336.50	$67.30
WHEAT	2.0	$237.66	$475.32
OATS	0.3	$212.46	$63.74
		+ lime	$24.51
		+ potassium	$39.15
		+ clover seed	$6.60
		Total for the 3 crops	$676.62

[a]Yields taken from Table X. Quantities of chemicals are those recommended in local field crop guides (Ministries of Agriculture for the Maritime Provinces, AGDEX numbers 100, 100.32, 141, 541.100); costs are those cited by local merchants in March, 1984. Lime costs are based on an application rate of 2 tons/acre (0.9 tonnes/ha) every 5 years. This rate is one cited by a local dairy farmer who grows grains, puts manure on the fields and applies fertilizer at recommended rates.
[b]Yield reductions are based on currently achieved yields (Table X). Costs are those quoted by local merchants in March 1984. Lime requirement is calculated as that required to balance the current field deficit (Table V), which would be equivalent to approximately one half the lime application rate under conventional husbandry. The potassium requirement is estimated as 25 kg/ha per year (see text).

The calculated costs for producing grains by the two systems are nearly equal. The average reduction in grain yield in the biological system is 25% so it can be said that at the costs of grains and fertilizer in 1984, yields would have to be better than 75% of conventional to make the biological system relatively more profitable.

Equivalence of yields seems to be well within the potential of biological husbandry on this farm and requirements for minerals would change little at yield equivalence (cf results section 4). Therefore the farm is considered to be in a transition state, and the expected savings once equivalence is achieved are calculated as $189 (1984 Canadian dollars) per hectare of grain (total chemical costs under conventional husbandry minus costs of Ca, K and clover seed under biological husbandry). This comparison does not take into account possible differences in tillage requirements, costs of borrowing money *et cetera*, and the fact that in the biological system, a crop is not taken off the field one year in four.

DISCUSSION

In terms of basic understanding of biological farming systems generally, and of Tunwath in particular, we consider the most significant points revealed by this study to be the six discussed below. Using information from the literature, we explain our observations and results of experiments as best we can. In most cases, these explanations have the status of hypotheses. Their formulation is intended to clarify questions that might be profitably investigated in studies on other farms in transition to biological husbandry and is a logical step in the ongoing investigation of Tunwath by the hypothetico-deductive method. Farm management decisions constitute an integral part of this process, and are also discussed.

1. Increase in pH, Ca and Mg in the surface horizon

An increase in soil pH during transition to biological husbandry is often reported informally, but has not been formally documented. Pfeiffer's (1948) observations on a dairy farm during its transition to biodynamic agriculture are similar to ours at Tunwath: "Four years ago we started out with an average pH below 6.0, mostly 5.5 to 6.0. Last year 6 fields were better than 6.0. This year 18 fields out of a total of 24 tested are better than 6.0, ten of them better than 6.5."

One of the factors causing acidification in conventional systems is use of urea or ammonium fertilizer. Oxidation of these reduced species of nitrogen is accompanied by release of H^+; the latter is taken up again when nitrate is reduced by plants, but to the extent that nitrate is lost before being taken up, there is net acidification (Helyar, 1976). At Tunwath, the major inputs and outputs of N to and from the system are uncharged species (N_2 and NH^3, and there should not be a large input or output of H ions associated with N cycling, except for slight acidification associated with N_2 fixation (Nyatsanga & Pierre, 1973).

Also involved in the increase in pH may be increased recycling of cations leached into deeper horizons. Repeated application of limestone can result in substantial accumulations of Ca and Mg in subsurface horizons (Lowrance *et al.*, 1985). The increase in exchangeable Ca in the surface horizon at Tunwath between 1975 and 1978 was equivalent to roughly 20% of the Ca applied in limestone from 1964 to 1976 (calculated from data in Table II, III, and total limestone application, p. 87 above). Since there are negligible amounts of native carbonates in these soils (Macdougall *et al.*, 1969), the higher levels of exchangeable Ca and Mg after 1976 must have been due to a net influx of these cations from deeper horizons. Given a significant upwards movement of cations normally (via the evapotranspirational stream and through active uptake by deep-growing roots of winter wheat and legumes), a net influx to the surface horizon could have resulted from reduced downward movement and/or enhanced upward movement. Some possibilities are: (1) cessation of use of fertilizer-N likely reduced leaching of cations (Russell, 1973, p. 624); (2) the emphasis on reduced tillage after 1975 and more consistent cover of the soil between crops (by weeds) could have changed the overall dynamics of water movement in a direction favoring net transport of cations towards the surface; (3) increased abundance of deep rooted herbs, particularly dandelions (*Taraxacum officinale*) and associated earthworm activity could have enhanced upward movement of cations. Pfeiffer (1974) noted a close association of earthworms with *Taraxacum officinale*, and we have observed the same phenomenon (unpublished data). According to Russell (1973), "Most earthworms, including all larger species, need a continuous supply of calcium, and if they are feeding on a calcium-rich material will excrete calcium surplus to their requirement as calcite from special glands in their digestive tract." It appears possible that dandelions provided channels for earthworms to move deep into the soil, and the earthworms in turn transported calcium from deeper horizons to the surface.

Because different fields were sampled in different years, and at different times (in spring in 1983, fall in other years) and the extractant used in 1980 differed from that used in other years, we cannot make precise statements about the changes in Ca and Mg after 1978. Nevertheless the trends suggested by the data—a rapid increase in Ca and Mg between 1975 and 1978, continued but lower rates of increase between 1978 and 1980, and after 1980, declines—but at lower rates than under conventional husbandry—are what could be expected to occur as a new steady state is approached during transition from conventional to biological husbandry. Over two and one-half years, removal of Ca at a rate equivalent to the estimated field deficit (Table V) would result in 13.8% reduction of the area-weighted average Ca in 1980 (Table II). That figure is of similar magnitude to the area-weighted average decline estimated from soil analyses in 1980 and 1983, which is 10%.

2. Variation in Nitrogen fixation

Different species of legumes are frequently described as exhibiting certain levels or ranges of N_2 fixation, except in the presence of fertilizer-N when it is recognized that N_2 fixation is likely to be substantially reduced. We found that even in a situation where fertilizer-N_2 is not being used and native levels of nitrate or ammonium were low, fababean N fixation varied 3-fold and clover fixation, 7-fold. There was some evidence that this variation was related to variations in mineralization of soil-N. In a more extensive study, Rice (1980) observed almost the same absolute and relative variation in nitrogenase activity for Alsike clover that we did, and likewise attributed it to variation in mineralization of soil-N.

The amount of N_2 fixed may depend as much on cropping sequence as it does on legume species. It is probable that the higher and less variable N_2 fixation of fababean compared to clover at Tunwath is due to the former being grown following the incorporation of a large quantity of low-N (approx. 0.25%) wheat straw in the soil. This sequence was deliberately set up to stimulate N_2 fixation in fababean (Patriquin *et al.*, 1981). In contrast, clover follows oats which produce lower quantities of higher % N (approx. 0.6%) straw which is not immediately incorporated.

3. Interactions of phytotoxicity, soil structure and tillage

Because the symptoms of phytotoxicity are multiple and not unique, and because the conditions that result in production of phytotoxins may have other deleterious effects on crops, phytotoxicity can be difficult to diagnose. It is only recently that phytotoxicity has been implicated as a common problem associated with certain agricultural practices or systems, notably those involving minimum or no tillage. We believe that phytoxicity was the major factor responsible for low oat yields from 1980 to 1983. We suspect that it contributed to reduced fababean yields between 1980 and 1984, and that it is a factor in the poor wheat yields.

Symptoms of phytotoxicity include inhibition of germination, stunting, chlorosis, injury to roots, damaged nutrient absorption, wilting and death of plants (Patrick, 1971). The effects are caused in some cases by original constituents of plant residues but more commonly, it appears, by the transient accumulation of organic acids resulting from microbial metabolism of polysaccharides in the early phases of decomposition of plant residues under waterlogged conditions or in anaerobic microsites (Patrick, 1971; Lynch, 1983). Legume residues are reported to be more phytotoxic than cereal residues (Lovett & Jessop, 1982).

Lynch and coworkers found acetic acid to be the chief phytotoxic agent in decomposing cereal straw. Because it has a pK of 4.6, phytotoxicty of acetic acid increases markedly as pH falls. The potential to produce acetic acid was correlated with straw polysaccharide content. Production of acetic acid became negligible when polysaccharide content fell to 21%, and phytotoxic effects negligible when it fell below 50%. Acetic acid concentration fell sharply with distance from the source of the polysaccaride indicating that proximity of roots to straw particles is probably required for phytotoxic effects to be expressed. Incubation studies indicated that toxins produced in the fall could persist through the winter and exert phytotoxic effects in the spring (Lynch, 1983).

3a. Oats

Based on the above, we suggest the following explanation for the generally poor oats and excessive weediness in oats from 1980 to 1983, and for the marked response of oats to ridging or mouldboard plowing in 1983/84.

Oats follow fababean; fababeans are harvested in late September or early October and residues are rotovated just before the onset of very low temperatures. When rotovation alone was practiced the soil drained slowly in the fall, and drained and warmed slowly in the spring creating conditions favorable for production and preservation of phytotoxins. Their presence in the seedbed resulted in poor or delayed germination of oats, taking away one of the key advantages of the crop in the weed-crop relationship, and weeds predominated. In 1981, when weeds were not excessively favored but yields of oats were still low, phytotoxins may have accumulated after germination and exerted other more subtle effects on oats such as impairment of root growth.

Manure relieved the phytotoxic effects in the 1982 experiment by accelerating microbial growth at a critical point, resulting in faster breakdown of phytotoxins. The ridging operation conducted after rotovating on field A5 in 1983 resulted in better drainage and hence in less production of phytotoxins, faster warming in the spring accelerated breakdown of any produced. Mouldboard plowing of field C2 relieved phytotoxicity by incorporating residues below the depth of the seedbed, and also by improving surface drainage and warming in the spring.

3b. Fababeans

Limited observations suggest that ridging after rotovation, or mouldboard ploughing, resulted in improved growth of fababeans compared to rotovation alone. This conclusion is supported by observations of Simon & Skrdelta (1983) and others cited in their paper showing that yields of broad beans (same species as fababean, but a different variety or subspecies) are reduced in no-till compared to mouldboard ploughed soil.

The oat cultivar experiment, conducted on fields in different phases of the rotation, suggests that phytotoxins are produced after incorporation of wheat residues. There was no evidence of these having pronounced detrimental effects on fababeans, the crop normally following wheat in the rotation. This could be because the fababeans are planted at 7–8 cm, near the bottom of the depth to which most residue is placed. The large seed size of fababeans might also make this plant less sensitive to phytotoxicity. However, localized phytotoxicity might result in poor germination or poor early survival of individual plants within small areas, resulting in the low numbers of mature plants counted in one meter square quadrats in some fields or years (Table XIX). It is possible as well that there were other more subtle effects of phytotoxicity on growth of fababeans, and that part of the benefit that mouldboard ploughing or ridging conferred on fababeans was due to reduced production of phytotoxins.

3c. Winter wheat

We do not have direct evidence for phytotoxicity being a factor in the falling yields of wheat. However, there are several conditions that could be expected to be conducive to phytotoxicity, or are similar to conditions considered conducive to production of phytotoxins in continuous winter wheat culture (Lynch, 1983; Cannell, 1984):

(a) Large amounts of clover and weed residue are incorporated in the soil in the same season that wheat is planted. Between 1981 and 1984, Mr. Aldhouse began to work the residues into the soil in mid-July; wheat is planted in early September.

(b) During August, microbial activity is liable to be restricted by low moisture, so that much of the phytotoxic potential would still be present when wheat is planted in the fall.

(c) The soil is worked at least twice with a rotovator (once to incorporate clover, and once to incorporate manure) prior to planting winter wheat. Pulverization of soil accompanying rotovation (Wilkinson & Braunbeck, 1977) may result in poorer aeration and greater potential for phytotoxicity.

(d) Low, but above-freezing, temperatures and high rainfall in November may encourage production and preservation of potentially phytotoxic organic acids.

In addition, some of the features of the "wheat problem" are strikingly similar to those characterizing the oat problem prior to its solution:

(e) Yields of both crops declined after initiating the crop rotation in 1979/80; reasonably good wheat yields were obtained on fields A1 and A6 in 1980 but unlike the situation in subsequent years, these fields did not have clover on them in the spring and summer before wheat was planted and they were regularly cultivated over the entire summer before wheat was planted.

(f) Yields of oats (1980, 1981, 1982) and wheat (1983) failed to respond to fertilizer–N, but there was an increase in % N on fertilized plots.

(g) Both crops were (oats) or became (wheat) excessively weedy.

Finally, there are restricted areas which appear to be suffering from acute phytotoxicity (Fig. 11e).

Evidence presented in Results section 7a suggested that N limitation, soil structural factors, and weeds are responsible for the poor growth of wheat. That conclusion is not necessarily at variance with our suspicion that phytotoxicity is involved as there may be significant interactions between the various factors. For example rotovation could result in poor aeration which would reduce efficiency of N use by wheat, and also create conditions conducive to phytoxicity. Weeds might be favored by being less sensitive to poor aeration and phytotoxicity, and by poorer growth of wheat at critical stages; weeds might in turn suppress growth of wheat by competitive effects.

Because of the increasing prevalence of Canada thistle on the farm, Mr. Aldhouse decided in the fall of 1984 to institute a partial "summer fallow" prior to planting winter wheat in year III (discussed on p. 144, below). It is to be initiated in early June when clover has reached near maximum biomass and most of the nitrogen has been fixed. By incorporating residues at an earlier stage, and during a period of warm temperatures and generally high moisture, the partial summer fallow may also reduce the phytotoxic potential. In the fall of 1985, experiments were begun to determine if the rotovation operation could be replaced by discing or use of a minimum-tillage tool (Schriefer, 1984).

The Tunwath system may be much more sensitive than the more usual sort of biological farming systems to problems related to soil structure and phytotoxicity. In most biological farming systems, a substantial fraction of the land is under sod, and the manure is composted or contains much more carbonaceous material than hen manure; both of these conditions favor creation of good soil structure. Presence of cattle or other mammals also results in more straw being removed from the fields or consumed in the fields, and in lower phytotoxic potential. The poor value of hen manure as a humus building material is illustrated at Tunwath by the low organic matter of the garden which receives heavy applications of hen manure each year. Conversely, the high organic matter of the pasture, and good overall qualities of field A4 (which was under hay through most of the seventies), illustrate the benefits of including perennial phases in a crop rotation.

4. The proportion of weeds in the plant biomass

The correlations of % crop with total biomass suggest that it is "normal" or at least "usual" at Tunwath for weeds to make up a high proportion of the biomass at sites of low total biomass. The near equivalence of fababeans yields in the presence and absence of weeds, in a situation where there was a strong correlation of % crop with total biomass, suggests that weeds were not exerting substantial negative effects on the crop. In such situations, the low yield of crops at sites of low total production represents a fertility limitation rather than a weed problem—even though weeds may make up a large portion of the biomass and "look bad".

Weed-crop interactions of this sort can be described as "epigenetic" (Thomas, 1984). The crop has a potentially negative effect on weeds, and weeds have a potentially negative effect on the crop. In such a positive feedback loop, "the beginner is the winner". Preplanting tillage can be viewed as "forcing weeds to the starting position". Then a strong initial advantage is given to the crop by all of the factors that distinguish annual grain crops from wild annuals, e.g. large seed size and reserves of N (allowing them to be planted deeper in the soil, and making them initially less dependent on soil-N), planting by man at optimal times, uniform germination, large leaves and rapid canopy closure (compared to weeds planted at the same density).

Given an initial advantage, then the higher the site fertility, the faster the crop will grow resulting in earlier canopy closure, in less light reaching the weedy understory, and finally, in a lower proportion of weeds at harvest.

Similar regression parameters were obtained for fababeans at mid-season and end of season in 1979, and for field A5 in 1979 and 1983 although the predominant weeds differed in these situations. This suggests that the crop, probably in combination with the climatic-edaphic regime, is the fundamental determinant of weed biomass. The population dynamics of individual weed species determine which weed species are predominant, but do not determine their total production.

These sorts of crop-weed interactions are easily recognized in the field. Where there is a strong correlation between % crop and total biomass, weeds are shorter than crop plants (Figs. 7b, 14b), except during early stages of vegetative growth in fababeans (Fig. 14a), or sometimes in late fall in winter wheat (Fig. 11b); weeds are relatively abundant only where crop plants are small (Figs. 11e, 14e).

Marked deviations from this sort of relationship were associated with (i) certain cultivars of oats, (ii) phytotoxicity (Fig. 7a), (iii) application of N fertilizer, and (iv) presence of certain perennial weeds (Fig. 14c). Except for (iv), all are situations in which the initial advantages of the crop are reduced (e.g., phytotoxicity reduces immediacy of germination, fertilization reduces advantage of large reserves of N in the seed) and the initial advantage shifts to the weeds. Only situation (iv) represents one in which the weeds may have a real natural advantage over the crop and one that may need to be dealt with by ensuring that the particular species is removed from the system. The other situations are best dealt with by actions other than those aimed at eliminating the weeds.

These considerations suggest that the strategy for dealing with weeds, exclusive of certain perennials (next section) should emphasize (a) a clean seed-bed, (b) intensification of advantages for the crop (i.e. selection of cultivars, planting time, depth etc.) and (c) enhancement of biological fertility. Post-planting tillage (harrowing) might be regarded as a secondary strategy, most important to apply when some of the initial advantage for the crop was inadvertently lost—for example when seeding is delayed because of poor weather, or when the seedbed is weedy.

Increasing the seeding rate is commonly cited as one means of suppressing weeds (Walker & Buchanan, 1982). Our observations suggest that below 25 fababean plants/m^2, density rather than fertility is the prime determinant of the proportion of weeds in the total biomass. Although average densities were mostly above 25 plants/m^2, in 4 of 7 of the fields sampled there were some plots with lower values. At a seeding rate of 224 kg/ha, there should be of the order of 40 plants/m^2 (at 0.5 g/seed and 90% germination). This suggests that where low numbers occurred, these were the result of abbreviations in soil conditions rather than of too low a seeding rate. Studies conducted to determine whether the reduction in numbers occurs at the germination stage (e.g. as a result of localized phytotoxicity, or waterlogging) or during post-planting harrowing would aid in identifying the causes of the reduced numbers.

The relationship of yield and % crop to density and to fertility could be expected to vary with row spacing. Based on the arguments presented above, we suspect that closer row spacing (or perhaps broadcasting of seed) would be advantageous at lower fertility, but not advantageous and possibly detrimental at high fertility because of increased intraspecific competition.

We had hypothesized that intercropping oats with beans would displace some of the weeds, and like the weeds, exert only a small inhibitory effect on the beans. Some of the weeds were displaced, but the presence of oats also resulted in reduced yields of beans. We suggest that, unlike the weeds, the oats are a domesticated plant with many of the same initial advantages as the beans, and we should expect oats not to interfere with the beans only if the beans were planted at a lower density (i.e. something less than 25 plants/m^2).

Data on crop yields in the presence and absence of weeds from a variety of situations are required to confirm (or not) our interpretation of the crop-weed data and various hypotheses concerning the weed-crop interactions. A study conducted in Malawi concurs with many of our conclusions: Weil (1982) found that arrangement, density, cultivar selection and form of fertilization of maize had significant effects on losses due to the presence of weeds in unweeded maize. The combination giving the lowest loss resulted in only 11% loss (statistically non-significant) and the presence of weeds resulted in substantial reductions in runoff and erosion. Weil concluded that excellent yields could be obtained without weeding, and that the saving in labor and long term gains due to the presence of weeds outweighed the short term losses due to weeds. He expressed uncertainty about the possible long term effects of larger seedbanks; the same uncertainty applies to the Tunwath system.

5. Weeds: increase in perennials

Informal accounts commonly cite perennial weeds as a major problem encountered during the transition from conventional to alternative husbandries. Our observations suggest that perennial weeds increased in importance at Tunwath during the course of the first complete cycle of the rotation initiated in 1979/1980. More intensive observations on seedbanks and vegetation (Hill *et al.*, in prep.) confirm this suggestion and the changes have been visually obvious for certain species. Mr. Aldhouse was particularly concerned about the increasing size and number of thistle patches on fields A2 and A5, and the appearance of bigger and/or more thistle plants on other "A" fields. A pronounced increase in dandelions (*Taraxacum officinale*) was also apparent in these fields.

The increase in perennials at Tunwath is probably associated with the emphasis on reduced tillage. Over the first half of the 20th century, temperate agricultural systems exhibited the reverse trend, (increases in annuals and decreases in perennials), a trend related in part to the increasing frequency and intensity of tillage operations accompanying mechanization (Haas & Streibig, 1982). We attribute the increase in perennials at Tunwath to (i) elimination of mouldboard ploughing, (ii) reduction in length of fallows and (iii) multiplication of plants through fragmentation of rootstocks in rotovating and harrowing operations.

Analysis of % crop-biomass data suggests that overall, weeds have become relatively more abundant in winter wheat, and are probably competing with (inhibiting) that crop, perennial weeds being the most important. Neither perennial nor annual weeds appear to be having much effect on the summer annual crops, exclusive of thick patches of Canada thistle (*Cirsium arvense*) and of perennial sow thistle (*Sonchus arvensis*) on A fields, and possibly of dogbane (*Apocynum androsaemifolium*) which is restricted to field A4.

It is clearly desirable to greatly reduce if not eradicate Canada thistle. This weed is abundant only on the heavier soils (A fields) and appears to be gaining most rapidly on the fields of lowest overall fertility (Hill *et al.*, in prep.).

Canada thistle has been cited as "one of the most serious weeds of temperate regions . . . The obnoxious character of the weed is due mainly to the highly successful vegetative propagation carried on by the creeping horizontal roots which survive winter and continue to extend . . . giving rise to numerous aerial shoots" (Moore, 1975). The rootstocks accumulate carbohydrates and can survive long periods, and small fragments of rootstock will regenerate new plants.

We hypothesize that Canada thistle gains an advantage over other crops at Tunwath in situations where nutrients have leached below the levels which annuals can effectively exploit in one season, and that it is fulfilling a positive function by returning nutrients to the surface horizon. In ecological terms, the most sensible way of reducing thistle infestation would be to introduce a desirable species to do the same function. It is well known that several years growth of alfalfa combined with regular mowing can eliminate Canada thistle (Hodgson, 1958).

Since at Tunwath this option was not available, at least in the short term, Mr. Aldhouse decided to introduce a partial summer fallow in the third year. The fallow is to be initiated by deep rotovating in early June when clover has reached near maximum biomass, and when Canada thistle begins to flower. At this stage, sugar reserves in Canada thistle are at their lowest point (Welton *et al.*, 1929). Cultivation is to be repeated at approximately 21 day intervals until winter wheat is planted (usually September 3–10), giving 5 successive cultivations. Canada thistle and other perennials in temperate climates typically draw heavily upon their carbohydrate reserves during early vegetative growth and replenish those reserves as flowering is approached and/or after flowering (Smith, 1972). The object of allowing 21 day intervals between cultivations is to starve below-ground perennial organs by allowing plants to grow for a short period vegetatively, lowering the reserves, and then removing the photosynthetic part of the plant before the period of recuperation. Hodgson (1958) found that one season of cultivation at 21 day intervals resulted in 99% reduction of Canada thistle. We expect that the plant will not initiate new above ground growth in the fall because of low temperatures (it doesn't emerge in spring until the soil warms substantially) and by the following spring, new growth will be suppressed by the wheat. We are hopeful that N produced by mineralization during the fallow and leached to deeper horizons will be recovered by winter wheat, roots of which are known to grow to at least 1 m depth (Rothamsted Annual Report for 1984, p. 63).

As well as bringing Canada thistle under control, we expect that the partial summer fallow will reduce infestations of sow thistle and dogbane, whose habits are similar to those of Canada thistle, and which appear to compete effectively with crops where they become established. It will also serve as a regular check on other perennials and annuals which we think are not serious competitors now, but which in very high densities may become so.

6. Variation in the mineralization of soil and manure-N

In 1980, we considered that it would be possible to make a substantial improvement in the use of manure by taking into account variations between fields in the mineralization of soil and manure-N. While we think this may still be possible, subsequent field observations suggested that variation in other factors may have much more pronounced effects on mineralization.

Estimates of mineralization of soil N under crops from 1979 to 1983 were in the range 28 to 65 kg/ha for oat fields, 30 to 77 kg/ha for wheat fields (calculated by subtracting 25 kg N from the crop + weed N in manured fields) and in 1981 were 51 and 85 kg/ha for two bean fields. The estimated mineralization of soil-N on two unmanured oat fields in 1984, 87 and 105 kg/ha, exceeded all of these values. The good yields of oats in 1985 are indicative of similarly high levels of mineralization in that year.

When manure was added to soils in the laboratory, the additional nitrate produced was equivalent to 18 to 33% of the manure N after 2 weeks of incubation and to 21 to 52% after 8 to 14 weeks of incubation. Fifteen percent of manure-N was present initially as ammonium. Manure was dried in an oven for these experiments; in field manure an average of 31% was present initially as ammonium. Assuming that N not mineralized by 14 weeks is not likely to be available within one year, we could expect the gain in N in the field from addition of manure to be between about 35 and 65% of the applied manure-N. The gains estimated from differences in vegetation-N on manured and non-manured plots in wheat and oat fields ranged from 0 to 41% of the manure-N. In 1981, the gain of N in manured plots on field A2 was 40% and on field A4 was 11%; this is the reverse of what happened in two separate laboratory experiments (soil A4 produced more additional nitrate in the presence of manure than did soil A2). In 1984, in marked contrast to the increased mineralization indicated for unmanured soils, mineralization of N from manure in manured oats was estimated to be zero.

It is likely that the change in tillage practices in 1983–84 was a factor in the increased mineralization of soil N in 1984/1985. Several observations suggest that this was more than just a matter of improved physical conditions for mineralization, and provide a possible explanation for the lack of additional N in manured oats in 1984.

From 1979 to 1982, the yield of oats was low (52% of provincial average) and the % N in grains at harvest was low (1.18 in 1981). The total N accumulated by oats and weeds on unmanured soils was about 50 kg/ha. Fertilization with N or manure increased yields at mid-season, but not at harvest. The % N in grains was increased by manuring (to 2.04% in 1981).

In 1984, after rotovation and ridging or after mouldboard ploughing, there were good yields of oats (100% of provincial average), the % N in grains was high (2.01) and the calculated mineralization of soil N approximately doubled in comparison to previous years. As in previous years there was an early season but not an end of season yield response to manuring. Unlike 1981, however, there was no difference between manured and unmanured sections in the N content of oats or weeds at harvest. The additional N from manure that had been evident early in the season disappeared by harvest.

The improved growth of oats, doubling of the supply of soil–N and apparent disappearance of manure–N in 1984 is suggestive of a feedback relationship between the requirement of oats for N and the supply of soil–N, i.e. the supply of soil–N appears to be regulated to some degree by the oats.

There are known mechanisms, or at least some known components for such a relationship. Associations of plants with mycorrhizae (Ames *et al.*, 1983), *Azospirillum* (Lin *et al.*, 1983; Lethbridge & Davidson, 1983) and non-specific soil bacteria and protozoans (Clarholm, 1985) can enhance uptake of soil or fertilizer–N. The associations with or benefits of mycorrhizae (Hayman, 1975) and *Azospirillum* (reviewed in Patriquin *et al.*, 1983) may be suppressed or not evident at high levels of N. Phytotoxins may have direct inhibitory effects on beneficial plant-microbe associations (e.g. Rose *et al.*, 1983) or indirectly suppress those associations by encouraging growth of non-beneficial or pathogenic organisms (e.g. Gussin & Lynch, 1983; Elliot & Lynch, 1985).

We speculate that prior to 1984, phytotoxic compounds inhibited plant growth and the process of association of oats with beneficial microorganisms. This resulted in poor growth, low uptake of N in the absence of fertilizer or manure, and in enhanced uptake of N in the presence of manure or fertilizer–N. Introduction of the ridging practice eliminated the phytotoxicity problem, resulting in overall healthier growth of oats and in the establishment of beneficial associations with microorganisms. This in turn resulted in greater uptake of N in the absence of manure than prior to 1984, but in the presence of manure, the microbial-plant interactions were suppressed negating what would otherwise be a positive effect of manure on the total supply of N. The overall effect of this was to regulate the supply of N, above a certain background level (roughly the pre-1984 levels), according to the ability of the plant to use it.

CONCLUSION

Over the period 1979 to 1985, yields of two of the grain crops at Tunwath improved, and of one, declined. Yields of oats and beans now compare favorably with conventional farms in the region, while yields of winter wheat do not. The yields of winter wheat and oats that could be sustained by biological husbandry are well above present yields. For each crop, there is evidence that soil structural factors, or interactions between soil structure, phase of rotation, and tillage, contributed to low yields. Perennial weeds increased in overall abundance between 1979 and 1984 and may be a factor in the poor yields of wheat at present. It appears that weeds are not having substantial negative effects on yields of oats and fababeans. Weeds benefit the system by functioning as a self-seeding cover crop, and probably in other ways, for example by stimulating earthworm activity, and by creating a more diverse environment for insects. Nitrogen is not now a limiting factor for oats; it could become limiting for winter wheat once the other limitations are removed. With the possible exception of potassium on some fields, other mineral nutrients are probably not limiting for crop production at the present time. Inputs of potassium and lime will be required to maintain levels favorable for crops in the future. Use of coarse (Albrecht, 1975), low mangesium limestone, or of gypsum may be advisable in order to increase the Ca/Mg ratio. Inputs of P to the farm as feed supplement (dicalcium phosphate) are sufficient to sustain present levels of soil phosphate.

Introduction of the ridging practice appears to have relieved the major limitations to oat production, and probably those to fababeans. Solution of "the wheat problem" likewise appears to be a matter of developing or choosing an appropriate system of tillage. It is not yet clear whether improved conditions for growth of winter wheat would result in fewer problems with perennial weeds, or whether the levels of weeds must first be reduced for yields of wheat to improve. We also wonder whether improved growth of winter wheat would result in marked increases in mineralization of soil N as appears to have been the case with oats or whether oats are peculiarly "non-demanding" (Roberts, 1897).

The time commonly quoted for transition from conventional to biological husbandry is 3 to 7 years (Koepf *et al.*, 1977; Hanley, 1980; Brusco *et al.*, 1985). Tunwath is an unusual biological farm in that the commercial part of the farm consists only of annual crops, and does not include cattle or other mammals. The farmer's experience, and our observations and calculations suggest that inexperience and lack of analytical knowledge about such situations, rather than a low innate potential for biological husbandry, is the reason for the transition to biological husbandry taking longer than usual. New types of minimum tillage systems and equipment may prove especially valuable in extending biological husbandry to situations where it was previously difficult to practice. The use of the modified ridging system (Schrieffer, 1984) at Tunwath is one example; use of ridge-planting equipment and techniques in corn-soybean systems in the U.S. (Brusco *et al.*, 1985) is another.

There has been very little commitment to research on biological husbandry in the past, largely because it has not been viewed as economically viable (Russell, 1966, p. 468) or acceptably productive (Martin *et al.*, 1976, p. 165; Langley *et al.*, 1983) alternative to conventional husbandry. Our estimates of the relative costs of growing grains under conventional and biological husbandry concur with other studies (Berardi, 1978; Lockeretz *et al.*, 1981) in suggesting that in today's economic climate, savings in inputs under biological husbandry can be sufficient or more than sufficient to make up losses due to reduced yields. Further, it is probable that the maximum yields that could be sustained by biological husbandry are much higher than those currently achieved. Regardless of the pros and cons of biological versus conventional husbandry, we suggest that the study of biological farming systems offers unique opportunities for the advancement of agricultural science because (i) of the existence of organisms or relationships that are suppressed in conventional systems, yet might be profitably utilized in such systems, and (ii) because the effects of environmental factors (physical and biological) on crops are not masked by the presence of agrochemicals. Encouragement of farmers to experiment in biological husbandry and a serious commitment by scientific establishments to the study of these systems should be considered consistent with the goals of mainstream agricultural research.

SUMMARY

Tunwath is a mixed farm (laying hens-grains) located in the Annapolis Valley, Nova Scotia, in a cool humid temperate zone. It includes about 2100 laying hens, 35 hectares of field crops and additional garden, pasture, hay and woodland. Field crops were grown by conventional methods until 1976 when the farmer stopped using fertilizer, and pesticides. A regular rotation of crops was initiated in 1979/80: fababeans—oats underseeded with clover—clover (green-manure)—winter wheat. Most of our observations were conducted from 1979 onwards; some data on yields and soil chemistry were available from earlier years.

Soil analyses in 1980 and 1983 indicated no major deficiencies in minerals except for low K on some of the sandier soils. A pasture had the highest organic matter content, and a garden receiving regular applications of chicken manure, the lowest. Historical data indicate that pH, Ca and Mg in surface horizons rose substantially after 1975. Estimated field balances for P, K, Ca and Mg are +12, −47, −161 and −35 kg/ha per annum; the positive P balance is due to an input of dicalcium phosphate as a feed supplement. Chicken manure

increased chemical measures of phosphate more than did superphosphate. Mineralization of soil nitogen during crop growing seasons was estimated from vegetation–N to be in the range 28–85 kg/ha until 1984 when it rose to the region of 100 kg/ha following changes in tillage practices. The effect of manure on available N was highly variable in both laboratory and field studies; the additional N found in plants when manure was applied amounted to 0 to 41% of the manure–N. Nitrogen fixation by fababeans was estimated on average as 146 kg/ha and varied 3-fold; that by clover was estimated as 62 kg/ha and varied 7-fold. Inputs of N via N fixation and manure was sufficient to support cereal yields of 4.7 tonnes/ha, and a fababean yield of 3.5 tonnes/ha; these are 162% (wheat), 223% (oats) and 116% (fababeans) of reference yields (recent provincial averages for wheat and oats and cited expected yield for fababeans). Prior to 1976, yields of oats, wheat and fababeans averaged 111, 119 and 106% of the reference values. Between 1979 and 1985, yields of oats rose from about 50% to 98% of the reference value, fababeans from 72 to 100% while yields of wheat fell from 85% (1979–82) to 51% (1984/5) of the reference value. Various data indicate that oat yields had been depressed by residue-induced phytotoxicity and that initiation of the practice of ridging soil after fall rotovation relieved the phytotoxicity. Improvement in oat yields in 1984 was accompanied by an increase in the % N in grains; total N accumulated in oats (+weeds) in the absence of manure roughly doubled compared to previous years but manured oats (+weeds) did not accumulate more N than non-manured oats. It is suggested that healthy oats form a beneficial association with microorganisms which regulates the mineralization of soil–N, above a certain background level, according to the requirements of the crop. Limited observations suggest that ridging after rotovation, or mouldboard ploughing in the fall prior to planting fababeans benefited fababeans compared to rotovation alone. For wheat, there is evidence that yields are now limited by a combination of, or interactions between, the following factors: low available N, competition from perennial weeds, soil structural factors influencing drainage and aeration, and phytotoxicity (associated with rotovation of clover residues prior to planting winter wheat).

There is general correspondence between life cycles of weeds and those of the crops, with perennial weeds dominating in winter wheat, summer annuals in oats (short season summer annual), and a mixture in fababeans (long season summer annual). There is heavy growth of wild radish, a summer annual weed, in winter wheat fields in the fall but this plant is killed by the winter. Fababeans tend to be very weedy during early vegetative growth, probably because growth of fababeans is retarded when nodule growth is most active. For all crops, and in a variety of situations, there were positive correlations beween the percent of the total biomass made up by the crops at harvest, and the total biomass (made up of crops and weeds). One comparison of weeded and non-weeded plots of fababeans in a situation where this correlation was very high, indicated that the presence of weeds caused less than a 10% reduction in crop yield. These observations suggest that the presence of many weeds at sites of low total production is indicative of fertility limitations rather than weed problems. Plots of percent crop versus total biomass are used to compare relative weediness between different fields and years; these suggest that (i) weediness of oats decreased following introduction of the ridging practice in the fall of 1983, (ii) weediness of winter wheat increased between 1980 and 1984, and (iii) that there has been little change in the weediness of fababeans. The data for winter wheat, and other observations indicate an overall increase in perennial weeds between 1979 and 1984. This is attributed to the emphasis on minimum tillage. A comparison of six oat cultivars revealed a pronounced cultivar effect on the relative weediness of oats.

The costs of chemicals required for growing grains at Tunwath by conventional management were compared with the costs of purchasing additional grain to make up for shortfalls in yields during the transition to biological husbandry. The comparison suggests that yields under biological husbandry have to be 75% or better of those under conventional management for appreciable savings to be made. The saving that would be realized when yields under biological husbandry are equal to those under conventional husbandry, which appears to be well within the potential of biological husbandry, is estimated as $189 per hectare of grain (1984 Canadian dollars).

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