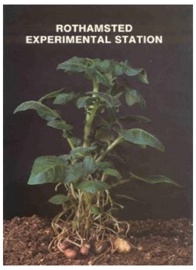
# Rothamsted Experimental Station Report for 1983



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# Rothamsted Garden Clover—Red clover grown continuously since 1854. Yields, crop and soil analyses 1956–82

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## Abstract

A series of tests made to the red clover in the Garden Clover experiment showed positive yield responses to N, K, Mg, aldicarb, benomyl and a variety resistant to *Sclerotinia trifoliorum*. The combination of all these treatments gave mean yields of 16 t $ha^{-1}$ dry matter, which exceeded those in the early years of the experiment.

The effects of the treatments on the offtakes of N, P, K and Mg in the harvested crop and on the amounts of nutrients in the soil are discussed.

## Introduction

Lawes and Gilbert failed in their attempts to grow red clover continuously on the Rothamsted farm. In 1854 they established a small plot for this purpose in the rich soil of what was then the kitchen garden of the Manor House. Because of its situation the area was known as the Garden Clover. It is small (2·1×3·0 m) and experimental treatments were limited; it has therefore received less attention than most of the other Classical experiments.

Reports by Gilbert (1895) and Gilbert (1901) gave details of results until 1901. Garner (1957) summarized the whole period from 1854 to 1956. The main features of the first 100 years of the experiment were (all yields and applications of materials here and elsewhere in this paper are on a 'per hectare' basis):

(i) An initial 10-year period with an average annual yield of 10 t dry matter (with a maximum of 16·9 t in the second year) in which only one re-sowing was necessary.
(ii) A further 30-year period with an average of 5 t dry matter with frequent re-sowing.
(iii) The remainder of the period in which yields continued to decline and in the last 30 years gave an average of only 1·2 t dry matter, frequent re-sowing being necessary.

Lawes and Gilbert attributed the very good yields in the initial period to the exceptionally rich soil. They were uncertain of the reasons for declining yields. Attempts to restore them by incorporation of mineral fertilizer to a depth of 45 cm in 1896, by 'microbe-seeding' garden soil extract in 1897 and by disinfecting with carbon disulphide in 1898 (to control the recently identified fungus *Sclerotinia trifoliorum*) were unsuccessful. No further treatments or basals were applied until 1956.

## Treatments and basal applications 1956–82

Details of treatments and basal applications for each period are given in Appendix Table 1. Because %K in the crop in 1954 was low, and readily soluble K in the soil had declined substantially during the experiment, this was the first nutrient tested, from 1956 to 1966. The K was applied annually and cumulatively to the same plot. Thereafter the whole area received potassium, with an extra application, 437 kg K, to the plot given none previously. This dressing was calculated to give the same level of exchangeable K in the soils of both plots—see section on soil analysis. From 1967 to 1979 part of the basal potassium depended on the number of cuts taken and the total per year varied accordingly.

Molybdenum, as sodium molybdate, was tested in 1960 and 1961 and a formaldehyde drench in 1965; neither was beneficial and they were not included in later years.

Nitrogen was tested from 1967 to 1972 (Gilbert held the view that the initial very large yields could be related to the initial large amounts of nitrogen in the soil) and magnesium from 1968 to 1972 (following analyses of the 1967 crop which showed only 0·097%). From 1973 both nitrogen and magnesium have been applied basally plus extra magnesium, 500 kg Mg, in 1973 to the sub-plot given none previously.

Phosphate was not tested, as the decline in amounts in the soil was much less than for potassium, but a basal dressing, 33 kg P, has been applied since 1968 to ensure that a deficiency does not develop. Ground chalk was applied at intervals from 1961, the dressings ranging from 1·2 to 7·5 t, to maintain a pH above 6·0.

No tests were made from 1973 to 1975, to ensure that the site returned to reasonable uniformity, thereafter all tests were biological, directed towards control of *Sclerotinia trifoliorum* and the root cyst nematode *Heterodera trifolii. S. trifoliorum* has been known to be present on the site since 1897 but its importance as a cause of crop death during the winter may have been underestimated. *H. trifolii* was first identified on the site in 1969 in damaging numbers (60 cysts per 100 g of soil, 21 eggs $g^{-1}$ of soil).

From 1976 to 1978 the variety Hungaropoly, believed to be resistant to *S. trifoliorum,* was compared with the standard susceptible variety S.123 both varieties being grown with and without aldicarb to control *H. trifolii.*

From 1979 the whole site was given aldicarb and sown to Hungaropoly. Because this variety was less resistant to *S. trifoliorum* than expected and because Jenkyn (1975) had shown winter sprays of benomyl to give effective control, this treatment was tested for the crops harvested in 1980, 1981 and 1982.

In most years since 1956 the crop either failed completely or partially during the winter and was either completely re-sown or patched in spring by sowing seed between surviving plants. When complete re-sowing was necessary the root stumps and crowns were removed from the site.

## Yields

Between one and five cuts were taken each year, most commonly three, depending on productivity which varied considerably between years (Appendix Table 1). The effect of potassium in the years 1956–66 (Table 1) was to double the mean annual total yield from 2·2 to 4·6 t but this yield was still less than half that recorded in the first 10 years of the experiment. Molybdenum tested in 1960 and 1961 lessened the yield substantially both in the presence and absence of K; the effect of formalin in 1965 was inconsistent (Table 2).

The mean effect of nitrogen, 125 kg N per cut, for the years 1969–72, was a small increase from 4·2 to 4·7 t, that of magnesium, 110 kg Mg, 1969–72, an increase from 4·0 to 5·0 t (Table 3). The crop grown with basal NPKMg from 1973 to 1975 gave yields of 5·5, 4·9, 1·2 t respectively.

**TABLE 1**

*Garden Clover: Effect of potassium on yield (DM t $ha^{-1}$)*

| | Year | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | Mean |
| Potassium* | 0·5 | 6·5 | 8·5 | 2·6 | 3·4 | 3·6 | 1·6 | 8·5 | 8·3 | 3·6 | 3·5 | 4·6 |
| None | 0·2 | 3·5 | 5·8 | 0·9 | 1·7 | 1·1 | 0·7 | 3·2 | 2·5 | 1·0 | 3·1 | 2·2 |
| Difference | +0·3 | +3·0 | +2·7 | +1·7 | +1·7 | +2·5 | +0·9 | +5·3 | +5·8 | +2·6 | +0·4 | +2·4 |

* 125 kg K $ha^{-1}$ except 1961, 250 kg

**TABLE 2**

*Garden Clover: Effects of molybdenum and formalin on yield (DM t $ha^{-1}$)*

| | None | | Potassium* | |
|---|---|---|---|---|
| | None | Molybdenum† | None | Molybdenum† |
| 1960 | 1·7 | 0·7 | 3·4 | 1·7 |
| 1961 | 1·1 | 0·2 | 3·6 | 2·6 |
| | None | | Potassium* | |
| | None | Formalin‡ | None | Formalin‡ |
| 1965 | 1·0 | 2·4 | 3·6 | 3·1 |

* 125 kg K $ha^{-1}$
† 1·1 kg Sodium molybdate $ha^{-1}$
‡ 3000 litre 38% (w/v) formaldehyde $ha^{-1}$

**TABLE 3**

*Garden Clover: Effects of nitrogen and magnesium on yield (DM t $ha^{-1}$)*

| | None | | Nitrogen* | |
|---|---|---|---|---|
| | None | Magnesium† | None | Magnesium† |
| 1967 | 4·7 | (1) | 5·3 | (1) |
| 1968 | (2) | 4·4 | (2) | 4·0 |
| 1969 | 3·1 | 2·4 | 3·2 | 3·0 |
| 1970 | 4·0 | 4·9 | 3·6 | 5·5 |
| 1971 | 4·7 | 7·1 | 6·4 | 6·8 |
| 1972 | 3·1 | 4·6 | 3·6 | 5·5 |
| Mean (1969–72) | 3·7 | 4·8 | 4·2 | 5·2 |

* 125 kg N $ha^{-1}$ per cut
† 110 kg Mg $ha^{-1}$
(1) Not tested
(2) Yield omitted, rabbit damage to first cut

**TABLE 4**

*Garden Clover: Effects of cultivar and aldicarb on yield (DM t $ha^{-1}$)*

| | S.123 | | Hungaropoly | |
|---|---|---|---|---|
| | None | Aldicarb* | None | Aldicarb* |
| 1976 | 2·1 | 3·7 | 3·0 | 4·6 |
| 1977 | 1·3 | 4·4 | 2·8 | 6·4 |
| 1978 | 3·1 | 6·1 | 2·9 | 7·9 |
| Mean | 2·2 | 4·7 | 2·9 | 6·3 |

* 10 kg $ha^{-1}$ aldicarb in spring

From 1976 to 1978 the mean yields without aldicarb were: Hungaropoly 2·9 t, S.123 2·2 t. Aldicarb was beneficial to both varieties, with a mean increase for S.123 of 2·5 and for Hungaropoly of 3·4 t (Table 4).

The crop of Hungaropoly sown in 1979 yielded 6·9 t that year, and was maintained without resowing for the next three years. Very large yields were obtained, a mean of 15·7 t without benomyl, of 16·6 t with (Table 5). In both 1981 and 1982 the largest yields from this experiment were recorded.

### TABLE 5

*Garden Clover: Effect of benomyl on yield of Hungaropoly (DM t ha$^{-1}$)*

| | None | Benomyl* |
|---|---|---|
| 1980 | 12·8 | 14·6 |
| 1981 | 15·5 | 17·4 |
| 1982 | 18·7 | 17·8 |
| Mean | 15·7 | 16·6 |

*0·6 kg ha$^{-1}$ benomyl on five occasions during the preceding winter

## Nutrient concentrations and offtakes

All nutrient concentrations are given on a dry matter basis and offtakes on a per hectare basis. The first and second cuts of clover in 1954 contained only 1·47 and 1·66% K in dry matter. Such small amounts were a reason for testing K, the first dressing being given in May 1956. This had little effect on either yield or %K at the first cut in July, but by the second, in September, both yield and %K were substantially increased. Meaned over all cuts during 1956–66 the effect of K was to increase %K from 1·10% to 1·99% as well as to double yields. In the absence of fertilizer K dressings, %N and %P were always a little larger (3·25% N, 0·351% P) than in crops given fertilizer K (3·13% N and 0·323% P).

Nitrogen fertilizer, aldicarb, benomyl and variety affected yield but caused no appreciable change in %N, P or K. The test of Mg, 110 kg, increased %Mg both in the presence and absence of N. Without magnesium fertilizer, %Mg was 0·152 and 0·172% without and with N; with magnesium fertilizer, %Mg increased to 0·289 and 0·307% respectively.

Some of the annual offtakes of N, P, K, Mg, Ca and Na are given in Tables 6–9 in the chronological order of the various tests. During 1956–66, when test K was applied, annual offtake of NPCaMg was almost twice that in the absence of K because of the

### TABLE 6

*Garden Clover: Effect of potassium on the mean annual offtake of N, P, K, Ca, Mg and Na, 1956–66 (kg element ha$^{-1}$)*

| | Offtake | | | | | |
|---|---|---|---|---|---|---|
| Treatment | N | P | K | Ca† | Mg | Na† |
| None | 55 | 6·1 | 22 | 39 | 3·9 | 2·8 |
| Potassium* | 110 | 11·4 | 80 | 77 | 7·2 | 2·9 |

*125 kg K ha$^{-1}$ except 1961, 250 kg K
†1956–65 only

### TABLE 7

*Garden Clover: Effects of nitrogen and magnesium on the mean annual offtake of N, P, K and Mg, 1968–72 (kg element ha$^{-1}$)*

| | | Offtake | | | |
|---|---|---|---|---|---|
| Treatment | | N | P | K | Mg |
| None | None | 126 | 9·9 | 114 | 5·4 |
| | Magnesium† | 148 | 11·6 | 143 | 12·8 |
| Nitrogen* | None | 142 | 10·6 | 128 | 6·5 |
| | Magnesium† | 156 | 13·0 | 143 | 14·2 |

*125 kg N per cut
†110 kg Mg per year
All given basals at 250 kg K (187 kg 1968) and 33 kg P per year

TABLE 8

*Garden Clover: Effects of variety and aldicarb on the mean annual offtake of N, P, K and Mg, 1976–78 (kg element ha$^{-1}$)*

| Treatment | | Offtake N | Offtake P | Offtake K | Offtake Mg |
|---|---|---|---|---|---|
| S.123 | None | 79 | 6·4 | 67 | 7·1 |
| | Aldicarb* | 170 | 14·5 | 162 | 15·2 |
| Hungaropoly | None | 104 | 8·6 | 97 | 9·6 |
| | Aldicarb* | 221 | 19·0 | 232 | 19·3 |

*Aldicarb at 10 kg ha$^{-1}$
All given basals at 125 kg N per cut and 312 kg K (250 kg 1976), 33 kg P, 110 kg Mg per year

TABLE 9

*Garden Clover: Effect of benomyl on the mean annual offtake of N, P, K and Mg, 1980–82 (kg element ha$^{-1}$)*

| | | Offtake N | Offtake P | Offtake K | Offtake Mg |
|---|---|---|---|---|---|
| None | 1980 | 536 | 46·8 | 530 | 35·6 |
| | 1981 | 501 | 52·7 | 592 | 37·2 |
| | 1982 | 498 | 53·2 | 600 | 42·7 |
| Mean | | 512 | 50·9 | 574 | 38·5 |
| Benomyl* | 1980 | 584 | 51·7 | 578 | 40·4 |
| | 1981 | 556 | 58·7 | 618 | 43·5 |
| | 1982 | 487 | 52·0 | 539 | 41·9 |
| Mean | | 542 | 54·1 | 578 | 41·9 |

*Benomyl at 0·6 kg ha$^{-1}$ on five occasions during the preceding winter. Variety Hungaropoly, all given basals at 125 kg N per cut and 125 kg K, 33 kg P and 110 kg Mg per year plus aldicarb at 10 kg each spring

two-fold difference in yield (Table 6). Without fertilizer K, the annual offtake was 22 kg K, about equal to that in the mixed herbage growing on K-deficient soils on the Classical Park Grass experiment. With fertilizer K nearly four times as much, (80 kg K), was taken off because both yield and %K were increased. Sodium offtakes were very small but equal, suggesting that to the extent to which Na was available it substituted for K, in the K-deficient plants. However, these K-deficient plants probably had to divert some carbon assimilate to maintain cell turgor (Leigh and Wyn Jones, 1983) and therefore less was available for dry matter production.

In the subsequent periods K offtakes ranged from 67 kg (Table 8) to 618 kg in 1981 (Table 9). Only in the three years 1980–82 did annual offtake, 576 kg, exceed the fertilizer dressing, 125 kg, and this had an appreciable effect on exchangeable K levels in the soil as discussed later.

In general, K and N offtakes each year were closely related, in the approximate ratio 1:1. In 1981–82 the K/N ratio increased to about 1·2 to 1·0 with substantially increased yields, despite the decrease in basal K dressings from 1979 onwards.

Average annual N offtakes were small, 55 kg, in the absence of K during 1956–66 but were increased to 110 kg where K was given. In the subsequent periods average N offtakes ranged from 79 kg (Table 8) to 542 kg (Table 9) with the largest individual offtake of 584 kg N from five cuts, given a total of 625 kg N, in 1980. Larger yields in 1981–82 did not remove more N probably because only four cuts were taken and therefore only 500 kg N as fertilizer was applied. Offtakes in 1980–81 were slightly greater than the 500 kg N applied suggesting either some fixation by *Rhizobium* or uptake from soil.

The range in Mg offtakes was from 3·9 kg, in 1956–66, with neither K nor Mg applied, to 41·9 kg in 1980–82 with both. In 1968–72 crops given Mg removed twice as much as those given none (Table 7). Subsequently the amount removed never exceeded that applied in the basal application. The ratio of K to Mg offtakes remained at about 10 : 1 except in 1980–82 when it was 14 : 1.

Calcium offtakes were calculated but are not given in detail. They ranged from 39 kg (Table 6) to 276 kg (1980–82) and except in this last period were often very similar to the K offtakes. Equivalence of K and Ca offtakes is common with clover, but grass normally contains much less Ca than K.

Annual phosphorus offtakes, in crops grown on this soil well supplied with P ranged from 6 kg (Table 6) to 54 kg (Table 9). Only in 1980–82 did P offtakes exceed the P dressing, 33 kg, which was applied each year from 1967.

## Soil analysis

The situation of the experiment, in the lawn of the formal garden at the Manor, appears to disagree with the statement that the experiment was laid down on a rich garden soil (Gilbert, 1899). However, the formal garden was extended at some time after 1854 and the experimental plot surrounded by the present lawn. When the soils were sampled in detail in 1961 it was noted that the depth of topsoil above yellow clay subsoil was shallower, (20–23 cm) on the south side of the plot than on the north (26–29 cm). There was a thin layer of ashes, about 6 mm, uniformly across the site just above the clay or at about 23 cm, suggesting that in the course of trenching by hand ashes had been put in the trench bottom. About 46–50 cm from the south side there was a narrow band of stones at about 20 cm depth along the full length of the site. The depth of the stones was not determined but was at least a further 10 cm and may have been part of a drainage system. The subsoil was wetter near this drain.

Lawes and Gilbert sampled the soil in 1857, 1879 and 1896. We sampled it in 1956 and at various times subsequently (Appendix Table 2) by either halves or quarters except in 1961 when the area was divided into sixteenths, each of which was sampled separately. The depth of sampling was usually 0–23 cm, occasionally the 23–46 cm depth was sampled.

**Soil weights.** Lawes and Gilbert used rectangular boxes, open at both ends, driven into the soil to 23 cm to take cubes of soil to determine soil weights per unit area (Dyer, 1902). We used a 15×15×23 cm sampler in 1983. This method works well in autumn on ploughed and conventionally cultivated arable soils which are at maximum compaction after harvest. However, like Lawes and Gilbert, we found that after the box had been driven into this soil, the level inside was below that outside, signifying that the soil was very loose. Soil weights for 1857, 1879 and 1896, taken from old records, and our recent values were:

| Year | 1857 | 1879 | 1896 | 1983 |
|---|---|---|---|---|
| Weight of dry soil (t) | 2075 | 2118 | 1922 | 2015 |

It might have been expected that soil weight would have increased as soil organic matter declined. This has not happened, probably because the soil was not subject to compaction because of hand cultivation.

**Soil reaction.** The pH in water of the pre-1900 soil samples varied little, 6·9–7·0. A few dressings of gypsum were applied at various times during the period but the calcium ions were most likely to have been lost by leaching with the sulphate. The lack of change in pH is remarkable. It suggests that most of the nitrogen mineralized from the organic matter was taken up by the crop leaving little nitrate to be lost by leaching. This presupposes that the availability of mineral N decreased $N_2$ fixation by the clover; we have calculated that the soil initially lost 82 kg ha$^{-1}$ per year whilst Gilbert calculated offtake in the crop was 180 kg. In addition enough calcium may have been released from the declining amount of organic matter to meet the requirement for Ca to maintain electrical neutrality of the drainage water.

In 1956 the pH was 6·6 but by 1961 some of the 16 surface soils had a pH of 6·0 and a first dressing of ground chalk was applied. These dressings were repeated periodically (Appendix Table 1) and were intended to keep the pH about 6·3. This was achieved (Appendix Table 2) except in 1978 when pH had fallen to 5·6, probably as a result of much fertilizer N being applied during the previous six years, little was removed in the crop and therefore much Ca was leached out with nitrate. In 1961 subsoil pH ranged from 6·6 to 7·5 (mean 7·0) suggesting that subsoil acidity was not one of the causes of poor yields in earlier years.

**Nitrogen and carbon.** Gilbert (1899) stated that the soil had received 'excessive' dressings of farmyard manure (FYM) while part of the kitchen garden. Some confirmation for this comes from comparing soil weights to 23 cm and total N in the 1857 samples with values given by Jenkinson and Johnston (1977) for the FYM plot on the Hoosfield Continuous Barley Classical experiment. By 1975 approximately 4200 t FYM ha$^{-1}$ had been applied to the Hoosfield experiment since 1852; comparative soil weights and total N contents were:

| Experiment and date sampled | Weight of fine soil 0–23 cm t ha$^{-1}$ | Total N in topsoil t ha$^{-1}$ |
|---|---|---|
| Garden Clover 1857 | 2075 | 11·76 |
| Hoosfield FYM plot 1975 | 2290 | 7·68 |

Gilbert (1899) reported 0·5095 and 0·3634% N in the Garden Clover topsoils in 1857 and 1879 respectively, values which were changed subsequently to 0·5876 and 0·4232% respectively (Dyer, 1902, Table 92). We have searched old records and found that Gilbert's analyses were done by the soda-lime method which gave lower values than the Kjeldahl method by a factor of 0·96 (Dyer, 1902). However, Dyer appears to have reported analyses done by a dry combustion method using copper oxide which, on highly organic soils, would give erroneously large values due to the inclusion of methane in the nitrogen gas which was collected and measured. We found results in the old records for all three years obtained by the Kjeldahl method in 1897; for the 1896 samples they were the values given by Dyer (1902). These old values for %N in soil and those for our recent reanalyses of the old samples, were:

| Year | | | 1857 | 1879 | 1896 |
|---|---|---|---|---|---|
| Depth | 0–23 cm | Old | 0·567 | 0·428 | 0·380 |
| | | New | 0·510 | 0·434 | 0·384 |
| | 23–46 cm | Old | — | 0·272 | 0·238 |

Our recent analysis of the 1857 soil gives an appreciably lower value than that found in the records and a somewhat lower value than that, 0·530, obtained by correcting Gilbert's soda-lime value by the factor 1·04. We are therefore inclined to accept that the soil in 1857 contained about 0·520% N.

An interesting feature of these results is that the subsoils contained more than twice as much N as is now found in the topsoils of many of our arable experiments given only inorganic fertilizers for the last 140 years.

To study how soil nitrogen content changes with time it is necessary to allow for changes in bulk density and calculate N content at each date in a fixed weight of soil. To do this here we have had to assume that soil weight changes linearly with depth and that soil N did not change appreciably in the 2 cm below 23 cm. Using these assumptions, and also that the soil weight in 1956 was the same as in 1983, we have calculated the soil N content in 2075 t ha$^{-1}$ of soil on five occasions to be:

| Year | 1857 | 1879 | 1896 | 1956 | 1983 |
|---|---|---|---|---|---|
| kg N ha$^{-1}$ | 10790 | 8900 | 7373 | 5048 | 4514 |

Thus in the first 23 years, 17% of the N was lost, at an average rate of 82 kg ha$^{-1}$ per year and by 1983 about 60% had gone.

Recently-determined carbon contents on the pre-1900 soil samples gave %C as 5·26, 4·98, 4·61, in 1857, 1879 and 1896 respectively with C/N ratios of 10·3, 11·5 and 12·0. From 1966, %C changed little in 17 years ranging from 3·60 to 3·95% C and with an apparent increase in C/N ratios in this period to a mean value of 17·4 : 1. This widening of C/N ratios is probably an artefact; Lawes and Gilbert made vigorous efforts to remove charcoal and ash from their samples, we did not and our wider C/N ratios are caused by elemental carbon in the soil.

**Phosphorus.** Lack of P was never considered a cause of poor crop growth because ample was supplied by the prior dressings of FYM. Recent analyses for bicarbonate-soluble P gave values of 268, 201 and 161 mg P kg$^{-1}$ in the 1857, 1899 and 1896 samples respectively. In 1961 there was more $NaHCO_3$-soluble P in the subsoil than in the topsoil, 116 and 77 mg P kg$^{-1}$ respectively, suggesting that much P had leached down from the surface soil. Leaching of P from arable soils does not occur at Rothamsted and Woburn when fertilizer P alone is used but does if much FYM has been applied (Johnston, 1975 and 1976). Unusually large amounts of P appear to have leached into the subsoil in this experiment, probably as a result of the large dressings of FYM given. It is probable that even larger amounts of bicarbonate-soluble P accumulated in the topsoil and these, rather than the subsoil P, were used by the crops during 1857–1967.

Bicarbonate-soluble P has been determined on all soil samples since 1961 (Appendix Table 2) when it was 77 mg kg$^{-1}$. This value remained nearly constant until the start of basal P dressings in 1968 which caused a slow increase. Offtakes were larger than additions in 1980–82 but this negative balance was too small to affect the slight positive change in soluble P recorded between 1978 and 1983.

The net P balance during 1968–83 was 190 kg P ha$^{-1}$, and bicarbonate-soluble P increased by 40 mg kg$^{-1}$, accounting for 81 kg P (soil weight 2015 t). Thus about 43% of the balance remained bicarbonate soluble, much more than would have been expected (about 10%) from other data on Rothamsted arable soils with less organic matter. This may be because either much P is held on organic matter with low bonding energies or because much P was already held on high energy bonding sites as a consequence of adding large dressings of P.

**Potassium.** Before 1860 FYM may have contained as little as 4 kg K t$^{-1}$ (Warren & Johnston, 1962) but the large dressings of FYM added much K and, when recently determined, the exchangeable K content of the 1857 sample was 593 mg K kg$^{-1}$. At the

## TABLE 10

*Garden Clover: The changes in exchangeable potassium in surface soil in relation to the balance caused by differences between potassium applications and offtake in the crop*

| | | Exchangeable K (kg ha$^{-1}$) during the period | | | | |
|---|---|---|---|---|---|---|
| Period | Treatment | At start | At end | Difference | K balance (kg ha$^{-1}$) | Change in exchangeable K as a percentage of K balance |
| 1956–66 | None | 171 | 194 | +23 | −246 | — |
| | Potassium* | 171 | 431 | +260 | +617 | +42 |
| 1967 | Balancing dressing applied† | 194 | 338 | +144 | +432 | +33 |
| 1968–78 | Potassium‡ | 375 | 1065 | +690 | +1667 | +41 |
| 1979–83 | Potassium§ | 1065 | 502 | −563 | −1494 | −38 |

* 125 kg K ha$^{-1}$ except 1961, 250 kg K

† 437 kg K ha$^{-1}$

‡ 187 kg K ha$^{-1}$, 1968 and 75, 250 kg K ha$^{-1}$ 1969–74 and 1976, 312 kg K ha$^{-1}$ 1977–78

§ 125 kg K ha$^{-1}$

next two sampling dates, 1879 and 1896, this value had declined to 216 and 163 mg K respectively.

By 1956 exchangeable K was only 85 mg kg$^{-1}$, about the same as in Broadbalk soil given no K since 1843. In 1961 Garden Clover soil given K since 1956 contained 200 mg kg$^{-1}$ whilst that given none had 103 mg kg$^{-1}$. The subsoil contained 100 mg kg$^{-1}$ suggesting very little K enrichment from the FYM.

It is possible to relate the K balance in various periods to the changes in soil analysis (Table 10). During 1956–66 only 246 kg K was removed by the small crops grown without K and exchangeable K was very little changed, the K requirements having been met from non-exchangeable K reserves. Where K was added in this period and in 1967 when the balancing K dressing was given, and from 1968 to 1978 when large basal dressings of K were applied, the K balance was always positive but the increase in exchangeable K ranged only from 33 to 42% of the K balance. After 1978 the combination of decreased basal K dressings, dramatically increased yields and K offtakes resulted in a negative K balance, only 38% of which was met by a decrease in exchangeable K. This evidence for the retention of K in non-exchangeable forms and its subsequent release when soils are stressed to supply K is similar to that given by Johnston and Poulton (1977) for soils growing cereals.

**Magnesium.** This was tested between 1968 and 1972 when the total test dressing was 550 kg Mg. In autumn 1967 exchangeable Mg was 50 mg kg$^{-1}$ on the plot without Mg and this declined during the period to 38 mg where no Mg was given. This decrease, equivalent to 24 kg Mg ha$^{-1}$ was 80% of the 30 kg Mg removed in the crop. On the plot which received Mg the exchangeable Mg increased from 54 to 236 mg kg$^{-1}$ equivalent to 367 kg ha$^{-1}$. The magnesium balance in this period was +483 kg, i.e. the increase in exchangeable Mg accounted for 76% of this balance. These data for magnesium, which show that both negative and positive Mg balances in the range tested can be largely accounted for by changes in exchangeable Mg in soil, are in marked contrast to the data for K.

**Benomyl.** Because much benomyl was used in the winter tests (a total of 3·0 kg in each of the winter periods preceding 1980, 1981 and 1982) and because its breakdown product, carbendazim, can persist (Austin & Briggs, 1976) soil samples were taken in October 1982. In the top 2·5 cm of soil an amount equivalent to 0·09 kg ha$^{-1}$ of carbendazim was found and in the next 2·5 cm an amount equivalent to 0·03 kg, none was found below this depth. Clearly on this soil benomyl may be used at this rate with little risk of accumulating residues.

### Discussion

A crop can be grown successfully in monoculture if the nutrients required are maintained, pests and diseases do not progressively increase and soil structure does not deteriorate. The Rothamsted soil, developed over clay-with-flints, has a robust structure and none of the classical cereal monoculture experiments has been noticeably affected by structural decline. With cereals, pests and particularly diseases, although increasing in the early years of monoculture, eventually achieve a balance which allows acceptable yields to be maintained if nutrition is also adequate. The supreme example is the classical wheat on Broadbalk where the yield from wheat in monoculture is only 10% less than the yield from a rotation of one wheat in three years (Dyke *et al.*, 1983).

For other crops, in the absence of chemical control, pest or disease attacks increase until the crop is so severely damaged that it is unable to support further increase. Potatoes and field beans *(Vicia faba)* are good examples, because attempts to grow these in monoculture in the classical experiments in the nineteenth century at Rothamsted were unsuccessful.

The Garden Clover results suggest that Lawes and Gilbert's failure to grow red clover continuously on farm soil was caused by winter-kill attributable to *Sclerotinia trifoliorum,* which was probably more abundant last century when its shared host, the winter form of *Vicia faba,* was commonly grown. A substantial population of *Heterodera trifolii* was unlikely on farm soil but would have been favoured by the monoculture of the experiment. It was likely to have been particularly damaging to establishing seedlings. The initial success of monoculture in the Manor Garden probably resulted from the initial absence of both *S. trifoliorum* and *H. trifolii* aided by exceptionally fertile soil; later progressive failure being caused by the introduction of these organisms and a progressive depletion of soil potassium. Control of these two soil-borne problems together with the restoration of an ample nutrient status led to strikingly increased yields. They slightly exceeded even the very large yields in the early years of the experiment, probably because of greater potential from the modern variety used and because of effects of the pesticides used on other less-damaging pests and diseases, e.g. *Sitona* weevils and mildew, *Erysiphe trifolii.* Large yield increases from pesticides have also been found on white clover (McEwen *et al.*, 1984) and it is clear that clovers are subject to damage by a wide range of organisms. Further research is clearly justified to devise strategies for safe and economic use of pesticides on clovers in farming situations.

An unexpected feature of the results in the period 1980–82 was the very large yields from sub-plots not given benomyl. Because complete re-sowing became an annual event between 1967 and 1976 and root stumps were removed each autumn, it may be that the inoculum of *S. trifoliorum* had thereby been greatly lessened. It is also possible that benomyl was splash-dispersed by raindrops from treated to untreated areas, because the area is so small the maximum distance needed for dispersion is only one metre.

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## APPENDIX TABLE 1

*Garden Clover: Treatments, basal applications and yields ($t\ ha^{-1}$ of dry matter)*

| | Treatments and yields | | | | | | | Basal applications |
|---|---|---|---|---|---|---|---|---|
| Year | | — | | | | K2 | | |
| 1956 | | 0·2 | | | | 0·5 | | — |
| 1957 | | 3·5 | | | | 6·5 | | — |
| 1958 | | 5·8 | | | | 8·5 | | — |
| 1959 | | 0·9 | | | | 2·6 | | — |
| | — | | Mo | | K2*Mo | | K2* | |
| 1960 | 1·7 | | 0·7 | | 1·7 | | 3·4 | — |
| 1961 | 1·1 | | 0·2 | | 2·6 | | 3·6 | Ca4 |
| | | — | | | | K2 | | — |
| 1962 | | 0·7 | | | | 1·6 | | — |
| 1963 | | 3·3 | | | | 8·5 | | — |
| 1964 | | 2·5 | | | | 8·3 | | |
| | — | | F | | K2F | | K2 | |
| 1965 | 1·0 | | 2·4 | | 3·1 | | 3·6 | — |
| 1966 | 3·1 | | | | | | 3·5 | — |
| | | — | | | | N | | |
| 1967 | | 4·7 | | | | 5·3 | | Ca3,K2‡ |
| | — | | −Mg2 | | N− | | NMg2 | |
| 1968 | † | | 4·4 | | † | | 4·0 | P,K3 |
| 1969 | 3·1 | | 2·4 | | 3·2 | | 3·0 | P,K4 |
| 1970 | 4·0 | | 4·9 | | 3·6 | | 5·5 | P,K4 |
| 1971 | 4·7 | | 7·1 | | 6·4 | | 6·8 | P,K4 |
| 1972 | 3·1 | | 4·6 | | 3·6 | | 5·5 | P,K4 |
| 1973 | | | | 5·5 | | | | CA§,N,P,K4,Mg** |
| 1974 | | | | 4·9 | | | | N,P,K4,Mg2 |
| 1975 | | | | 1·2 | | | | N,P,K3,Mg2 |
| | S− | | SA | | H− | | HA | |
| 1976 | 2·1 | | 3·7 | | 3·0 | | 4·6 | N,P,K4,Mg2 |
| 1977 | 1·3 | | 4·4 | | 2·8 | | 6·4 | N,P,K5,Mg2 |
| 1978 | 3·1 | | 6·1 | | 2·9 | | 7·9 | N,P,K5,Mg2 |
| 1979 | | | | 6·9 | | | | H,A,Ca5,N,P,K2,Mg1 |
| | | — | | | | B | | |
| 1980 | | 12·8 | | | | 14·6 | | H,A,Ca1,N,P,K2,Mg1 |
| 1981 | | 15·5 | | | | 17·4 | | H,A,Ca1,N,P,K2,Mg1 |
| 1982 | | 18·7 | | | | 17·8 | | H,A,Ca1,N,P,K2,Mg1 |

*=K4 in 1961
†=yields omitted because of rabbit damage to first cut.
K2, 3, 4, 5=125, 187, 250, 312 kg K ha$^{-1}$ as muriate of potash or from 1968 partly as (0:14:28)
Mo=1·1 kg sodium molybdate ha$^{-1}$
F=3000 litre 38% (w/v) formaldehyde ha$^{-1}$
N=125 kg N ha$^{-1}$ as 'Nitro-Chalk' per cut
Mg1, 2=50, 110 kg Mg ha$^{-1}$ as Epsom Salts
P=33 kg P ha$^{-1}$ as (0:14:28)
Ca1, 2, 3, 4, 5=1·25, 1·7, 2·5, 3·7, 7·5 t chalk ha$^{-1}$
H=Hungaropoly, variety resistant to *Sclerotinia*
S=S.123, variety susceptible to *Sclerotinia* (other varieties grown before 1976 were all susceptible)
A=10 kg aldicarb ha$^{-1}$ in spring
B=0·6 kg benomyl on five occasions during the preceding winter
‡=plus 437 kg K ha$^{-1}$ to plot previously given none
§=plus 0·8 t chalk ha$^{-1}$ to plots previously given N
**=plus 500 kg Mg to plots previously given none

## APPENDIX TABLE 2

### *Garden Clover: Soil Analyses*

| Date of sample | Fertilizer treatment* | Bicarbonate soluble-P mg $\text{kg}^{-1}$ | Exchangeable cations mg $\text{kg}^{-1}$ | | | | pH in $H_2O$ | %C | %N |
|---|---|---|---|---|---|---|---|---|---|
| | | | K | Ca | Mg | Na | | | |
| March 1956 | — | | 85 | | | | 6·6 | | 0·244 |
| Jan 1961 | K2 | 80 | 180 | | | | 6·6 | | |
| | K2 | 77 | 220 | | | | 6·5 | | |
| | — | 74 | 99 | | | | 6·3 | | |
| | — | 76 | 107 | | | | 6·2 | | |
| Aug. 1966 | K2 | 72 | 201 | 3990 | 48 | 16 | 6·4 | 3·67 | 0·216 |
| | K2 | 77 | 226 | 3700 | 55 | 8 | 6·4 | 4·34 | 0·230 |
| | — | 72 | 89 | 3820 | 54 | 10 | 6·4 | 3·80 | 0·217 |
| | — | 74 | 104 | 3870 | 58 | 12 | 6·4 | 3·70 | 0·213 |
| Dec. 1967 | — | 82 | 191 | 4140 | 47 | 9 | 6·6 | 3·44 | 0·216 |
| | — | 82 | 218 | 4060 | 53 | 12 | 6·5 | 3·89 | 0·224 |
| | —† | 80 | 175 | 4030 | 55 | 8 | 6·6 | 3·35 | 0·208 |
| | —† | 81 | 160 | 4000 | 53 | 11 | 6·5 | 3·74 | 0·213 |
| Autumn 1972 | — | 92 | 320 | 3480 | 39 | 14 | 6·3 | 3·44 | 0·217 |
| | N | 94 | 349 | 3690 | 36 | 8 | 6·2 | 3·56 | 0·232 |
| | Mg | 94 | 336 | 3320 | 260 | 17 | 6·3 | 3·58 | 0·207 |
| | Mg N | 100 | 328 | 3390 | 212 | 19 | 6·0 | 4·15 | 0·225 |
| Spring 1975 | —‡ | 99 | 323 | 3070 | 237 | 17 | 6·3 | 3·56 | 0·207 |
| | —‡ | 101 | 362 | 3070 | 216 | 6 | 6·3 | 4·14 | 0·228 |
| | — | 92 | 329 | 2950 | 224 | 14 | 6·3 | 3·78 | 0·205 |
| | — | 97 | 307 | 3300 | 207 | 13 | 6·5 | 4·11 | 0·209 |
| Oct. 1978 | — | 110 | 520 | 2350 | 247 | 8 | 5·7 | 3·54 | 0·215 |
| | — | 117 | 596 | 2520 | 271 | 7 | 5·7 | 3·94 | 0·225 |
| | — | 102 | 476 | 2200 | 254 | 7 | 5·5 | 4·02 | 0·220 |
| | — | 110 | 522 | 2460 | 257 | 8 | 5·6 | 4·29 | 0·229 |
| Sept. 1983 | — | 113 | 230 | 3380 | 181 | 5 | 6·4 | 3·57 | 0·214 |
| | — | 124 | 272 | 3770 | 178 | 5 | 6·5 | 3·87 | 0·221 |
| | — | 122 | 216 | 3180 | 191 | 5 | 6·4 | 3·56 | 0·218 |
| | — | 124 | 279 | 3360 | 183 | 13 | 6·3 | 3·86 | 0·220 |

*For treatments and basal applications see Appendix Table 1
†Balancing K applied spring 1967
‡Balancing Mg applied winter/spring 1973