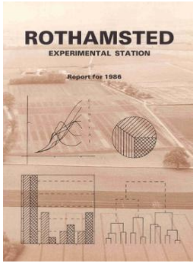
ROTHAMSTED RESEARCH

Rothamsted Experimental Station Report for 1986



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A. E. Johnston

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Saxmundham Experimental Station 1899–1986
A review of the achievements during 1965–1986

A. E. JOHNSTON

Abstract

Increased arable cropping, especially with autumn-sown crops on the heavier textured soils, has featured prominently in the changing patterns of farming since the early 1950s. This review summarizes work done during 1965–86 on a Chalky Boulder Clay soil in East Anglia. The topics studied include: the relationship between yields and both long-term release of potassium from soil and sodium bicarbonate-soluble P in soil, factors limiting yields of cereals, the effect of poor soil structure and inputs from atmospheric depositions and losses of nutrients in drainage water.

Yields of most crops increased appreciably during the 20 years as a result of growing cultivars with a high yield potential, controlling pests and diseases where possible and recognizing the potential for soil-borne disease to diminish yield. Learning how and when to cultivate the land was important because good seedbeds made timely drilling possible and a finer tilth allowed better control of weeds by pre- and post-emergence weed killers. More timely nitrogen applications decreased nitrogen loss either by denitrification or leaching. The soil was found to release much K over long periods and levels of sodium bicarbonate-soluble P above which yields of winter wheat, spring barley, potatoes and sugar beet did not increase were defined.

Introduction

Since 1965 Rothamsted staff working at Saxmundham Experimental Station in Suffolk have investigated, among other topics, the long-term release of potassium from this sandy clay loam, the relationship between yields and sodium bicarbonate-soluble P in soil and the effects of adding new P and increasing amounts of fertilizer N. Factors limiting yields of cereals including amounts of nitrogen and the timing of the dressing, pest and disease control and crop rotation have also been studied. The effect of poor soil structure has been measured. Inputs from atmospheric depositions and losses of nutrients in drainage water have been monitored, whilst weather data collected each year have been published annually in the *Rothamsted Report*. Now financial stringency has meant that, for the present at least, the site has had to be 'mothballed' and it is appropriate to extend and enlarge a summary of results given by Cooke (1975). The Appendix Table summarizes the experiments conducted since 1965. The list of published papers includes all those publications containing results from Saxmundham which it has been possible to trace.

The Classical Rotation I and II experiments (see later) were started by the Education Committee of East Suffolk County Council in 1899 and occupied most of the site (Fig. 1) although only four-tenths of Rotation II remained in 1964 when Rothamsted accepted responsibility for the experimental programme on behalf of the ARC (now AFRC). The ARC took over from NAAS (now ADAS) who had had the site since 1947. The history of the site has been summarized by Cooke (1975) who also listed earlier references which contain historical detail.

The soil, a sandy clay loam, pH 6·5 to 7·2, developed in drift over Chalky Boulder Clay has been described in detail (Hodge, 1972) and is classed as Beccles series (Corbett & Tatler, 1970). This, and closely related series, are widespread in eastern England, occupying 2000 km^2. As continuous arable cropping, especially with autumn-sown crops, has extended on to such soils the results at Saxmundham have assumed greater relevance.

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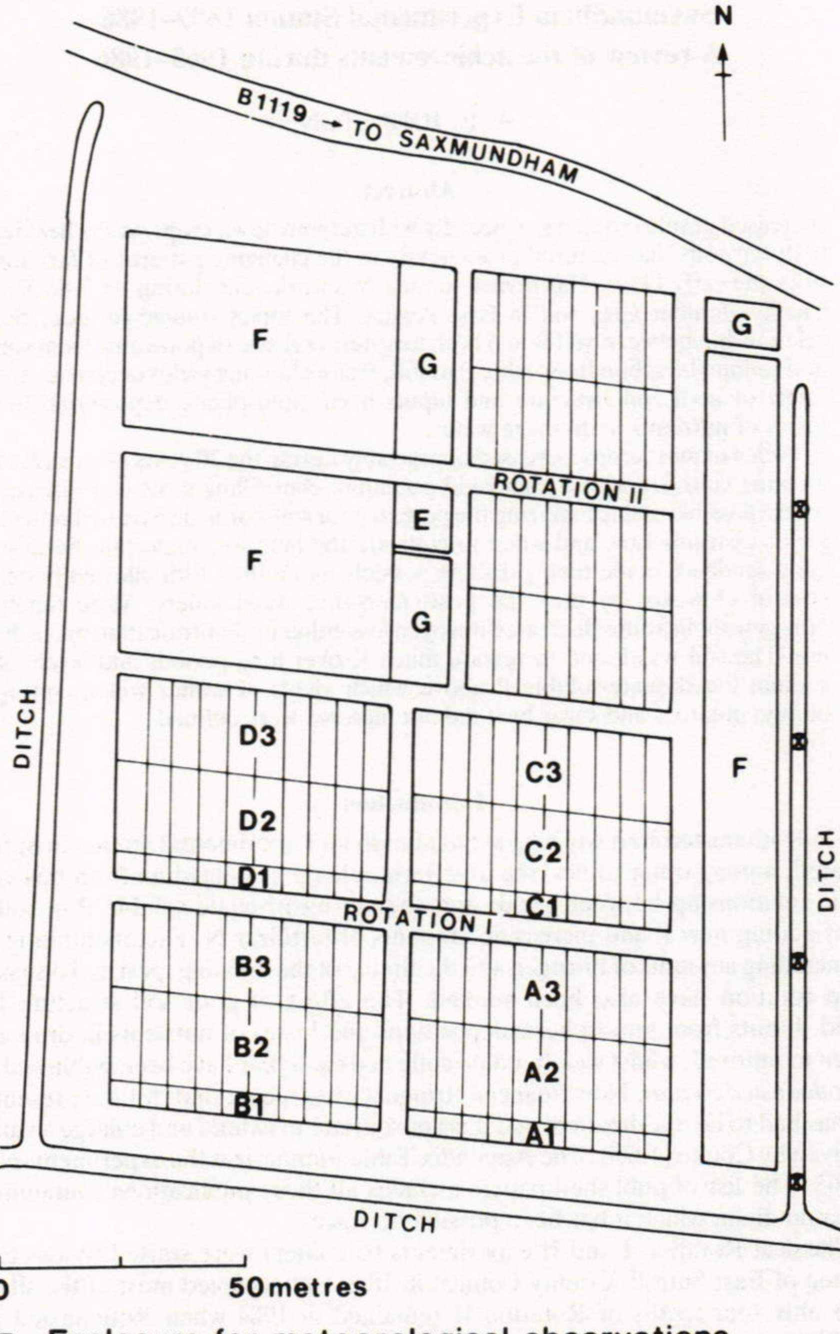

E Enclosure for meteorological observations
F Sites for wheat and barley experiments
G Sites for herbage experiments
⊗ Outlets for land drains, installed 1972, from which drainage water was collected for analysis.

FIG. 1. Saxmundham Experimental Station 1965–86.

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Yields

Winter wheat, winter barley, winter beans, spring barley, potatoes, sugar beet, grass leys given nitrogen fertilizer and grass-clover and lucerne leys have all been grown regularly, but not all crops in each year. Throughout this paper cereal and bean yields are for grain at 85% dry matter; herbage crop yields are of dry matter and potatoes and sugar beet are fresh tubers and roots respectively. All yields are expressed as t ha^{-1}.

Winter wheat. The best yield from fertilizer-treated plots was only 2·6 t ha^{-1} during 1940–61. When applications of N fertilizer were increased during 1966–69 yields increased to 4·4 t ha^{-1}, and in the favourable year of 1974, Cappelle-Desprez yielded 6·8 t ha^{-1}. Subsequently yields rose dramatically and since 1980, 10 to 11 t ha^{-1} have been grown each year and in 1984, again a favourable season, many plots gave yields in excess of 12·5 t.

Winter barley was not grown at Saxmundham until the late 1970s. It was then grown for three years both on Rotation I and in a series of experiments testing amounts and timing of nitrogen and other factors. Best yields were about 9·0 t ha^{-1}.

Spring barley yields on the best plots of Rotation I averaged 2·5 t ha^{-1} during 1940–61 and with improved nitrogen manuring these were increased to 3·8 t ha^{-1} during 1966–69. Changing to varieties which responded to extra N increased yields on Rotation II to 5·1 t ha^{-1} during 1970–73 and 6·0 t ha^{-1} in 1977. It has not been possible to raise yields much above 6·5 t ha^{-1}.

Sugar beet replaced mangolds as the root crop in the traditional four-course rotation on this soil because of both its greater profitability and the fact that stock keeping on similar soils declined. From 1956–65 on Rotation I yields were 25 t ha^{-1} and these were increased to 39 t ha^{-1} with better manuring in the period 1966–69. During 1969–74, best yields on Rotation II were much larger, 55 t ha^{-1}, probably because of earlier sowing and better weed control. Sugar beet was not grown subsequently.

Potatoes were not grown in the Classical Rotation experiments because the soil is not suited to this crop. However, their responsiveness to both P and K made it worthwhile to grow them for a few years in both Rotation I and II. Although seedbeds were not easy to prepare, many plot yields in wetter years were between 50 and 55 t ha^{-1}.

Beans were grown frequently as the legume crop in the third year of the traditional rotation; yields were only about 3·2 t ha^{-1}. In recent years best yields have approached 4·5 t ha^{-1} after it became possible to control both aphids and chocolate spot with suitable sprays.

Herbage crops. During 1971–75 best average yields from grass-clover leys were 5·0 t ha^{-1}, whilst grass leys with nitrogen and lucerne often gave yields in excess of 10 t ha^{-1}.

The Classical Experiments

The Rotation I and II experiments, started in 1899, each consisted of four blocks so that the four crops of a typical Norfolk four-course rotation, roots (mangolds or sugar beet), spring barley, a legume (peas or beans) and winter wheat could be grown each year. Blocks had ten plots, each 40×5·5 m, for the different manurial treatments. On Rotation I these were a factorial test of N, P and K fertilizers and on one plot bone meal, and another 15 t ha^{-1} farmyard manure (FYM); all treatments were applied cumulatively each year. Rotation II sought to determine how a total of 25 t ha^{-1} FYM, 190 kg ha^{-1} sodium nitrate and 950 kg

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ha^{-1} superphosphate could best be distributed during the four years of the rotation to improve both yields and profitability. The results of Rotation I were summarized by Trist and Boyd (1966) and those of Rotation II by Boyd and Trist (1966).

Rotation I. The small fertilizer dressings originally tested in 1899 remained unchanged until 1964. The yields showed that phosphorus was essential for all crops because in its absence there was little response to N, and the rate of release of potassium from soil reserves was adequate, K fertilizers giving only small increases in yields of K-sensitive crops even at the end of the period. In 1965 the manuring was changed (Williams & Cooke, 1971). Plots not previously given P received twice the annual dressing applied to P-treated plots. The P residue from this double-rate application was sufficiently large to increase bicarbonate-soluble P rapidly and yield differences between the two P treatments quickly diminished. N dressings were much increased and results over the next four years were given by Williams and Cooke (1971). The soil continued to release much K, only wheat and beans gave small increases in yield with fresh K fertilizer; barley and beet did not respond.

The lack of, or only small response to K after 70 years without K manuring was of considerable importance to the correct use of K fertilizers on these and similar soils and it was decided to study this in greater detail. In 1970 the plots were divided into three (Fig. 1). The smallest area, (A1–D1), 30·25 m^2, continued to receive the classical manuring and was sown to grass and later oversown with white clover. The remaining 187 m^2 was divided into two and one half (A2–D2) sown to a timothy-meadow fescue ley given fertilizer N, the other (A3–D3) to lucerne not given N. During 1971–74 yields from both leys were similar. Lucerne yields then began to decline because of an increasing infestation of crown wart of lucerne (*Urophlyctis alfalfae*) (Macfarlane, 1975, 1976). Spread of this spore-borne disease was apparently encouraged by the frequency with which surface water stood on the plots, in part attributed to the increasing compaction of the surface soil. The lucerne was reseeded in 1975 but failed and was sown again in the spring of 1976 but grew poorly in the dry, hot summer.

It was decided to plough up the lucerne on blocks C and D (Fig. 1) in autumn 1976 and grow arable crops to see whether they would respond to fresh fertilizer K now that much K, 520 kg ha^{-1}, had been removed by the lucerne from soils given no K since 1899. The crops grown were winter wheat, winter barley, spring barley, beans and potatoes. Of these only three were grown each year and each tested a fresh dressing of fertilizer K, 52 kg ha^{-1} for cereals and beans, 208 kg ha^{-1} for potatoes. On plots not given K since 1899 yields of winter wheat, winter barley and spring barley were 8·49, 7·58 and 5·68 t ha^{-1} respectively. These yields were not increased further by giving fresh fertilizer K or by growing the crops on soils which had received K in each year since 1899. On the impoverished soils beans yielded 2·52 t ha^{-1} and this was increased to 3·60 t ha^{-1} by giving fresh K; yield was even larger, 4·42 t ha^{-1} on plots given K each year, but was not further increased with fresh K. Similarly with potatoes, on soils without K yield was 28·8 t ha^{-1} and fresh K increased this to 39·6 t ha^{-1}, but this was less than the yield, 43·1 t ha^{-1}, on soils with K applied each year. Giving fresh K on this soil further increased yield to 44·0 t ha^{-1}. Thus on K-depleted soils, K-sensitive crops responded to K but the yields were not increased to equal those on soils which had been enriched with K residues over many years.

The large cereal yields and continued lack of response to fresh K on soils without K manuring for more than 75 years was intriguing. Grass had continued to be grown on section 2 of each block and yields and K offtakes in two seven-year periods could be compared. On soils to which no K had been added yields in the second period were 90% of those in the first but K offtake had declined by 50%. Release of soil K reserves was not matching possible offtake. It was decided to see whether the large amount of K, 1500 kg ha^{-1}, which had been removed by the grass had decreased soil K reserves to such an extent that yields of cereals

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would be affected. Sufficient grass was ploughed each autumn, first on blocks C and D and then on blocks A and B (Fig. 1) to grow beans and then wheat. In this way a first wheat after beans was grown in three successive years, 1983–85. Rather than test fresh K, four rates of N, 120, 160, 200, 240 kg ha^{-1} were tested. Yields of winter wheat grown on soils without K ranged from 8·70 to 9·16 t ha^{-1}; there was no readily defined response curve to nitrogen although the highest yield was given by the largest amount of N applied. On soils to which K had been given each year maximum yield, 10·48 t ha^{-1}, was given by 160 kg N ha^{-1}. Thus after more than 80 years without K manuring best winter wheat yields were decreased by about 15% but were still over 9 t ha^{-1}.

Lucerne continued to be grown on blocks A and B until 1978 but yields were small and the lucerne was replaced by a grass-clover ley. In 1980 the ley was ploughed to start a test of subsoil loosening and enrichment with P and K (Johnston & McEwen, 1984). Winter wheat grown in 1981 and 1982 yielded well, 9·8 and 8·0 t ha^{-1} respectively but in 1983 yields of spring barley grain were disappointing, 4·6 t ha^{-1}. Rates of N and P to the topsoil affected yield but there was no interaction with either of the subsoiling treatments. Effects of deep lossening were very small but were nearly always positive.

Rotation II. Treatments applied from 1899 to 1964 had given soils with a range of bicarbonate-soluble P values of 3 to 40 mg kg^{-1} (Mattingly, Johnston & Chater, 1970) and this range was extended to 3 to 67 mg kg^{-1} by applying large dressings of superphosphate and farmyard manure singly and in combination to four of the eight plots in each of the two blocks (Fig. 1). Relationships between these soluble P values and yields of potatoes and sugar beet during 1969–74 and cereals during 1970–77 were assessed. Responses by potatoes and sugar beet to freshly applied superphosphate were also determined at each level of soluble P. Residual effects of these dressings and responses to fresh superphosphate between 1974 and 1976 were measured by barley. Two amounts of N were tested on spring barley in 1976 and 1977 and two cultivars of winter wheat were grown in 1977 and yields related to soluble P. Relationships between yields and soluble P were described by an asymptotic regression equation; this model represented the measured yields well for all crops except barley in one four-year period. The asymptotic model was used to estimate plateau yields each year and soluble P values at which yields were less than plateau values by one standard error. Average plateau yields, and associated soluble P values were: potatoes, 43 t ha^{-1} and 25 mg P kg^{-1}; sugar (from sugar beet) 6·8 t ha^{-1} and 20 mg P kg^{-1}: spring barley, given 63 kg N ha^{-1}, 4·7 t ha^{-1} and 25 mg P kg^{-1}; barley given 94 kg N ha^{-1}, 5·3 t ha^{-1} and 33 mg P kg^{-1}; winter wheat 6·5 t ha^{-1} and 20 mg P kg^{-1}. The model was further used to estimate responses to dressings of superphosphate at three levels of soluble P, 9, 15 and 25 mg kg^{-1}, in the soils. Yield responses to 55 kg P ha^{-1} were 3·9, 2·1 and 1·8 t tubers ha^{-1} and 1·1, 0·3 and 0·0 t sugar ha^{-1} for potatoes and sugar beet respectively, at the three levels of soluble P. On impoverished soils (soluble P less than 10 mg kg^{-1}) even the largest fresh applications of broadcast superphosphate did not raise yields to those achieved on enriched soils (soluble P larger than 25 mg P kg^{-1}) in the absence of fresh phosphate. Soluble P in the soil accounted for much of the within-year variation of yields and estimated reliably and quantitatively the value of phosphate residues derived from both superphosphate and farmyard manure which had been applied in varying amounts and at different times between 1899 and 1976 (Johnston *et al.*, 1986).

From 1978 to 1985 wheat yields were related to soluble P at each of four levels of fertilizer N using the same asymptotic regression equation. Above about 15 mg P kg^{-1} the approach to the asymptote was linear for each of the four curves, one for each level of N. These linear parts of the relationship were parallel and were increasing at the rate of 0·25 t ha^{-1} grain for each 10 mg P kg^{-1} increase in soluble P between 15 and 35 mg kg^{-1}. This suggests that the

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response to N was independent of the level of soil P and extra P did not have to be applied to achieve the extra yield potential available from the use of additional N fertilizer.

Having created the eight levels of soluble P by 1968, some plots on each of the main strips were subsequently cropped without further addition of P, and P offtake and the change in soluble P monitored over the next 16 years. The total P removed in the harvested crop was much larger than the decline in soluble P, expressed in kg ha^{-1}. The change in soluble P, expressed as a percentage of that removed in the crop, ranged from 8% on soils with least soluble P to 46% on soils with most soluble P. Thus, even on the latter plots the soluble P fraction was well buffered by P reserves which were not initially soluble in the sodium bicarbonate extractant.

For each of the eight treatments soluble P values were plotted against time. Visual inspection of the curves suggested that they could be brought into coincidence by suitable horizontal shifts and this proved to be so. It was then possible to fit an exponential decay model to the data which showed that it would take approximately 50 years for soluble P values to fall from 60 to 3 mg P kg^{-1} and that the half-life was about nine years. Thus, in the event of any restraint to using fresh P we now know how long soluble P values might take to fall to those given above, where yield losses become important.

Experiments with cereals

Winter wheat. Partly in response to the observation that many farmers on similar soils in East Anglia were beginning to grow more and more autumn-sown crops, work on cereals at Saxmundham tended to concentrate on winter wheat. In 1965 the challenge was to see whether, on these calcareous boulder clay soils, wheat yields could be as large as those (6 t ha^{-1}) which were then becoming common on silty clay loams at Rothamsted and whether take-all (*Gaeumannomyces graminis* var. *tritici*) and eyespot (*Pseudocercosporella herpotrichoides*) were as damaging to winter wheat grown after wheat as they could be at Rothamsted. The results (Slope, Etheridge & Williams, 1973) were disappointing. Yields were very small, less than 4 t ha^{-1} in 1969 and 1970 following a non-cereal break, and little affected by root diseases, and these yields were not related to the incidence of foliar pathogens.

Explaining these poor yields was crucial and during the next three years (1971–73) sowing rates, row widths and three amounts of nitrogen were tested to see whether better crop distribution enhanced yield. Number of ears, leaf area, yield and nutrient content showed little benefit from increasing or decreasing seed rate around that normally sown. Rows 15 cm apart gave the largest yield independent of nitrogen because they produced most ears. There was no difference in yield between the second and the eighth continuous wheat, 100 kg N ha^{-1} was sufficient (Widdowson, Johnston & Penny, 1980).

From 1974–6, two cultivars of different yield potential, Cappelle-Desprez and Maris Huntsman, the growth regulator chlormequat chloride (CCC), and three amounts of N as single or divided dressings in spring were tested. The springs and summers of 1975 and 1976 were unusually dry and the summer of 1976 exceptionally hot, which explains why mean grain yields for the three years did not exceed 6 t ha^{-1}. In this comparison of cultivars, where wheat had been grown continuously for between seven and 11 years, Maris Huntsman outyielded Cappelle-Desprez by only 4·5%, about the same percentage increase was given by CCC. Divided N dressings increased yield by only 2·2%. The mean increase in yield from adopting all three improvements was 0·5 t ha^{-1} or 11%. Yields of the tenth and eleventh consecutive wheats declined in the later years of the period probably because blackgrass (*Alopecurus myosuroides*) became abundant and was difficult to control despite the use of residual and translocated herbicides (Widdowson, Johnston & Penny, 1980).

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The main thrust of the work on winter wheat continued during 1980–3 with cultivars of increased yield potential, in factorial experiments following beans to minimize foot and root rots. The effect of these diseases was measured in 1980, and again in 1982 and 1983 when wheat following wheat was also grown. In all years seedbed N, amount and timing of the spring-N application and sprays to control aphids and diseases were tested. Additional factors included were sowing date (1980 only) and, during 1981–3, cultivars; in 1981 these were Avalon and Virtue, in 1982–3 Avalon and Norman. Yields of grain were greatly increased by N given during April and by sequential sprays with fungicides and aphicide; these two factors interacted so that responses to N were larger with the sprays than without. Yield responses to seedbed N, although small, were greater than the benefits from applying divided instead of single N dressings in spring. Largest yields were 10·14 t ha^{-1} in 1980 and 10·91 t ha^{-1} in 1981 when N was given in spring at 160 and 200 kg ha^{-1} respectively, and the crops were sprayed with pesticides.

In 1982 and 1983 yields were larger after beans than after wheat mainly because the number of ears and the weight of a thousand grains were greater. This may have been because take-all was less severe where wheat followed beans. Previous cropping also interacted with variety; Avalon yielded slightly less than Norman where take-all was slight but much less where take-all was severe. Where N was given the mean loss in grain yield from growing Avalon rather than Norman in the two years was 2·47 t ha^{-1} after wheat, and 0·37 t ha^{-1} after beans. The take-all disease ratings of Norman and Avalon after wheat were 132 and 197 respectively. Yields of grain were greatly increased by N given during April especially of wheat following wheat and where the crop was protected with sprays; the average mean yield was only 2·79 t ha^{-1} without N, but was increased to 8·78 with 235 kg N ha^{-1}. Where wheat followed beans yields were 6·89 t ha^{-1} without N and 11·07 t with 175 kg ha^{-1}. Applying N to the seedbed increased yield slightly, and again by more than by dividing the dressing of nitrogen in spring (Widdowson, *et al.,* 1985).

During 1984–6 the cultivars Galahad and Moulin were grown as the first and also as the second wheat after beans. A test was made of 60 kg N ha^{-1}, as urea, applied early (February in 1984, March in 1985 and 1986) and of none and four amounts of N, as calcium ammonium nitrate, applied in April. More N was applied in April after wheat than after beans because the soil contained less residual NO_3-N. A combined treatment of fungicides and aphicide was again tested.

When given N, Galahad yielded *c.* 1 t ha^{-1} more grain than did Moulin over the three years. Unlike 1982 and 1983 (when Norman and Avalon were grown) previous crop did not interact consistently with variety. The superiority of Galahad over Moulin was not influenced by previous crop in 1984; it was larger after beans in 1985 but after wheat in 1986. Early-applied N was consistently beneficial for wheat grown after wheat but for wheat after beans, only where none or the smallest amount of April N was applied. Although April N increased yields more after wheat than after beans, yields were always larger after beans; April N also increased yields more where protective sprays were given. With these sprays the mean yield after wheat was 3·96 t ha^{-1} without April N and 8·86 t ha^{-1} with 260 kg N ha^{-1}. After beans, yields were 7·59 t ha^{-1} without April N and 10·48 t ha^{-1} with 150 kg N ha^{-1}. With April N, the protective sprays were slightly more beneficial, 1·02 t ha^{-1}, on the larger crops after beans than on those after wheat, 0·87 t ha^{-1}.

Supplementary experiments on winter wheat during 1974–79 investigated various factors in more detail than could be done in the experiments described above. During 1974–76 there was a test of applying 50 kg N ha^{-1} as a late foliar spray and a broad spectrum fungicide, benomyl and maneb with mancozeb, on winter wheat given 0, 50, 100, 150 kg N ha^{-1} as calcium ammonium nitrate in spring. The results (Penny, Widdowson & Jenkyn, 1978) showed that foliar pathogens varied from year to year and the efficiency of their control depended on correct timing of the fungicide application. Mean yields were again affected by

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two dry years, but were increased by increasing levels of nitrogen. Yields were increased, on average by 9%, by the late foliar-applied N in 1974 and 1975 but % N was increased in all three years. Fungicides increased the response to liquid N fertilizer only in 1974. With slight modifications these experiments were continued during 1976–79 (Penny, Widdowson & Jenkyn, 1983).

The above is only a brief summary of work on winter wheat. Cooke (1975) had stressed the poor yields of this crop:

'wheat after wheat yielded more in 1967 and 1968 than wheat after beans in 1969 and 1970. It seemed that wheat yields as Saxmundham were more affected (*compared with those at Rothamsted*) by weather and soil conditions than by take-all and eye spot diseases'.

A subsequent review showed that yields of wheat grown continuously at Saxmundham during 1971–6 were slightly larger than those of similarly treated wheats at Rothamsted (Widdowson, Johnston & Penny, 1980). Root studies by P. J. Welbank and P. J. Taylor in both 1972 and 1973 showed that the amounts and general pattern of root distribution were similar at both sites, and a test of irrigation at Saxmundham in the same years showed that adding water decreased, rather than increased, wheat yields. All this suggested that when like was compared with like yields at Saxmundham were little different from those at Rothamsted with one major exception: yields of wheat following a break crop were much smaller at Saxmundham (Slope, Etheridge & Williams, 1973).

From the late 1970s yields of winter wheat at Saxmundham increased dramatically, and after a break they were often larger than those at Rothamsted. For some cultivars yields of the second wheat after beans at Saxmundham have been appreciably less than those of a first wheat. This is often because of take-all, a disease which was not thought to be so damaging there in the earlier years when wheat was grown continuously.

Winter barley, grown during 1979–81 as part of a series of seven experiments at Rothamsted and Saxmundham, measured the effects of several amounts of nitrogen applied at different times in spring, a growth regulator applied in spring, and fungicide sprays. N applied in February was less effective than N applied in March and both were less effective, in terms of grain yield, than N applied in April. Divided dressings were best applied in February and April, or March and April; effects on percentage N in grain followed the same pattern and so, therefore, did the efficiency of uptake of fertilizer nitrogen. The growth regulator consistently reduced the length of the straw and diminished lodging; it increased yields in five of the seven experiments in which it was tested. Responses to fungicides were inconsistent from year to year (Penny, Widdowson & Jenkyn, 1986)

Spring barley. The effects of the fungicide benodanil on three cultivars given three amounts of nitrogen at two times were measured in 1973 and 1974 (Widdowson, Jenkyn & Penny, 1976) whilst during 1975–78 amounts and times of granular N fertilizer, late sprays of liquid N fertilizer and fungicides to control powdery mildew (*Erysiphe graminis*) and brown rust (*Puccinia hordei*) on two cultivars were tested (Widdowson, Jenkyn & Penny, 1982). In the first series, benodanil was sprayed in June and again in July to control brown rust, which was more severe on Midas, a susceptible cultivar, than on Julia and Mazurka, less susceptible cultivars. In 1973, there was more brown rust where all or part of the nitrogen was applied in May, but in 1974 the reverse was true, probably because dry weather limited uptake of N. Benodanil spray much decreased brown rust and increased grain yield in both years. In 1973, a year of ample rainfall in spring and summer, grain yield was increased more by giving nitrogen in May than in March, but not in 1974 when the March nitrogen dressing increased yield more because there was little rain until July.

In the second series of experiments, spring barley yields in 1975 and 1976 were small, because, like those of winter wheat, they were affected by the scarcity of summer rainfall;

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yields were larger in 1977 and 1978. Mildew was most severe in 1975 and least in 1978, brown rust was most severe in 1975 and 1978 but practically absent in 1976. The mildew fungicides increased yields by about 0·25 t ha^{-1} in 1975 and 1977 but decreased them in 1976. They had little or no effect on percentage N in grain but increased grain size in 1977. The rust fungicide benodanil, increased grain yields each year and especially in 1978, 0·37 t ha^{-1}. It had no effect on percentage N in grain but consistently increased grain size and so enhanced grain yield and, therefore, N uptake. Granular N fertilizer was better applied to the seedbed than as a topdressing in all years whether or not foliar diseases were controlled. Late sprays of liquid N fertilizer increased yield less than equivalent amounts of seedbed N but increased percentage N in grain more.

Herbage crops

All-grass leys receiving 125 kg N ha^{-1} for each cut and grass-clover leys without fertilizer N were compared during 1969–76. Tests of P (125 kg P_2O_5 ha^{-1} per year) and K (250 kg K_2O ha^{-1} per year) were also included. The best combination of treatments gave, on average, 5·0 and 8·9 t ha^{-1} per year from the grass-clover and all-grass leys respectively. The effect of P was small, ranging from 0·18 to 0·40 t ha^{-1} on soils initially containing 14 to 26 mg kg^{-1} bicarbonate-soluble P. The effect of K was only 0·36 t ha^{-1} on the grass-clover sward but more, 1·17 t ha^{-1} on the all-grass ley. Exchangeable K at the start of the experiment was 120 to 180 mg kg^{-1}. There was no simple relationship between yield and rainfall. Irrigation in 1972 and 1973, 252 and 210 mm respectively, increased yield of the grass-clover ley by 20% and of the all-grass ley by 26%. There was no interaction between watering and additions of P and K fertilizer. The amounts of nutrients removed and the changes in soluble P and K in soil were given by Johnston, Poulton and Williams (1979).

Atmospheric deposition and losses of nutrients in drainage water

The concentration of Na, K, Ca, Mg, NH_4-N, NO_3-N, PO_4-P, Cl and SO_4-S together with conductivity and pH of rain and drainage have been measured since 1970 and 1968 respectively. A comparative study with similar data collected at Rothamsted, Woburn and Broom's Barn has continued since 1968–69.

Atmospheric deposition. Saxmundham is in a rural situation only 13 km from the coast. Precipitation has recently become less acid and is currently pH 5·0. Precipitation chemistry is controlled chiefly by sea-salts (Na Mg Cl) which comprise 65% of the total salt deposition. However, deposition of non-sea Cl and SO_4-S has been increasing markedly and each year some 50–60 kg ha^{-1} of Cl and 25–35 kg ha^{-1} SO_4-S are presently deposited. Amounts of NH_4-N and NO_3-N are at present 10–15 and 5–10 kg ha^{-1} respectively (Goulding & Poulton, 1985; Goulding *et al.*, 1986).

Land drainage water. When the new system of tile drains covering the whole of the field was installed in October 1972 (see next section) every effort was made to seal all old tiles, which were cut through by the tile laying machine, before the trenches were backfilled. Williams (1976b) summarized data collected before the installation of the new drains and that from the two years following. Unfortunately the remaining data has still to be published. From December 1972 to March 1974 the two drains at the northern end of the field collected water from land under arable crops whilst the two at the southern end collected water from land under grass or lucerne on Rotation I (Fig. 1). Williams showed that the composition of drainage under the old system for the period 1968–70 and 1970–72 was very similar although rainfall during the first of these two periods was greater. Once the new system was installed there were interesting differences between the mean concentration of ions (mg l^{-1}), conductivity and pH of drainage from land under arable and herbage crops. Na, K, Mg were little

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altered but more Ca was lost from the arable sections. Concentrations of PO_4-P, SO_4-S and NH_4-N were also similar from all four drains. There was much more Cl and NO_3-N lost from the arable soils and presumably this explains the greater loss of Ca from these soils as the Ca maintained the electrical neutrality of the leachate. The conductivity of the drainage from the arable land was larger than that from the grassland soil but the pH was the same.

Losses of NO_3-N have varied appreciably from year-to-year. Between 1968 and 1976 these losses ranged from 3 to 32 kg N ha^{-1} during the winter drainage period. Widdowson, Johnston and Penny (1980) were able to show that these estimates of nitrate loss related well with variations in yield and N uptake between years because large losses of N in drainage were associated with small uptakes of N by the wheat and hence with smaller yields.

Soil structure and cultivations

Cooke and Williams (1972) described experiments made to improve soil structure. Differences between the easier-working soil at Rothamsted and that at Saxmundham were attributed to differences in particle size distribution, mainly in the coarse and fine sand and silt fractions. Any improvements in soil structure at Saxmundham, like those which resulted from growing leys, were often short-lived.

Subsequently discussing the results obtained between 1965 and 1973 Cooke (1975) concluded:

> 'The soil is difficult to cultivate and structure problems often occur, accentuating the effects of bad weather. Wet autumns make cultivations especially difficult, the seedbeds are cloddy, adversely affecting establishment and early growth of autumn-sown crops. Heavy rain after applying N fertilizer in spring may cause much leaching. Drought in summer can be very damaging because roots of annual crops do not penetrate deeply and the relatively small amount of available water which the soil holds (Salter & Williams, 1969) is soon exhausted'.

The field at Saxmundham was originally in ridge and furrow and ploughing depth was probably not greater than 15 cm. The plots of the Classical experiments were 18 feet or 5·5 m wide which was one 'land', the distance between furrow bottoms. This system of setting up soil each year was intended to facilitate surface water removal although it was often combined with some form of tile drainage. When the field was tile drained to current specifications for grant-in-aid schemes in October 1972 the remains of three separate tile drainage systems were found. These had failed because the tiles had become filled with fine soil particles; there were no remains of any backfill.

The new system had tile drains 7·5 cm diameter, 0·8 m deep and approximately 43 m apart with permeable backfill to plough depth. After installing the tiles the field was mole drained at 3 m centres, the moling was repeated in 1981.

The field was not set up in 'lands' after 1963 and was level ploughed in 1964 to 20 cm depth. The depth of ploughing was increased to 25 cm between 1964 and 1966 (Mattingly, Johnston & Chater, 1970) to improve drainage and allow rain, especially in spring, to drain rapidly from the surface soil at a time when mostly spring-sown crops were being grown and surface dryness controlled the time of spring cultivation.

Deeper ploughing all in one operation was, with hindsight, a mistake. In October 1976 pinboard samples of soil to 30 cm depth from Rotation I, which by then had been in continuous grass for seven years, revealed large clods of unweathered subsoil in what had been the cultivated layer since 1965 (Williams & Johnston, 1977). Mattingly, Johnston & Chater (1970) also showed how such deep cultivation had diluted various nutrients and organic matter.

Gradually we came to recognize that success with autumn-sown crops, especially winter wheat, depended on early cultivation following harvest. Crops like beans, potatoes and

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especially sugar beet because of their later harvest, delayed ploughing, which put at risk timely seedbed cultivations when the soil was reasonably dry. Also ploughing depth was decreased so that soil with a greater root residue remained near the surface; this appeared to improve workability. The larger cereal yields of recent years probably left more stubble and crown for incorporation than in any previous period; straw was always removed. Following early ploughing early autumn showers provided sufficient moisture for seedbeds to be prepared by a power-driven harrow for sowing winter wheat, usually in the last two weeks of September.

Although we increased yields of sugar beet and got good yields of potatoes, increases in spring barley yields were not as large as might have been anticipated. This was probably because the soil remained too wet in spring for the early cultivation and drilling required for barley. It was, therefore, not possible to lengthen the growing season for spring barley as was done for winter wheat.

Methods of primary cultivation other than ploughing have never been tested because there was not sufficient land available, and dates of drilling were only tested in one year because later drilling invariably led to problems with wet seedbeds.

One other problem of under-drained soils relates to the timing of N applications. If N is applied when the soil is at or near field capacity, nitrate may be readily leached by subsequent rainfall and removed from the field via mole- and tile-drains. In soils which are not so drained there is the possibility that crops like winter wheat may recover some of the nitrate leached to depth. At Saxmundham, 144 kg N ha^{-1} was applied as ^{15}N-labelled fertilizer on April 21 and 15 in 1981 and 1982 respectively. In 1981, 38% of the applied nitrogen was unaccounted for at harvest, in 1982 the amount was only 11%. Rainfall in the three weeks following fertilizer application was 114 and 12 mm respectively in the two years (Powlson, private communication).

Conclusions

It is difficult to rank those factors which have contributed to increased yields. For winter wheat growing cultivars with a high yield potential and controlling foliar pathogens have both played a major part, as has the recognition of the effect that soil-borne diseases, like take-all, can have on yields. Learning how and when to cultivate the land has also been important. Good seedbeds made timely drilling possible and a finer tilth allowed better control of weeds by pre- and post-emergence weed killers. Equally important as the control of pathogens has been the realization that all, or the major part of, the spring nitrogen application could be delayed until the middle two weeks of April when risk of loss of N by leaching or by denitrification was much diminished.

The fact that this sandy clay loam soil can release large quantitites of potassium is now well documented and levels of sodium bicarbonate-soluble P above which yields of winter wheat, spring barley, potatoes and sugar beet are unlikely to respond to further increases in soluble P can be defined.

For those farming similar soils this information plays an important part in giving advice on management practices which are likely to maintain yields and profitability.

Staff

The responsibility for the experimental programme at Saxmundham since 1965 has been largely with members of the Chemistry Department (until 1977) and then Soils and Plant Nutrition with joint sponsorship of appropriate experiments by members of Plant Pathology; most appear as authors of papers in the publications list. It is appropriate here to thank all those who have helped with field work, sample handling, chemical and physical analyses of crops and soils and with the statistical analysis of the data.

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Finally, it is with much pleasure that I and my colleagues at Rothamsted acknowledge the very considerable help and expertise given by Mr. V. C. Woolnough, resident foreman, who joined the Rothamsted staff in 1965 but who had worked at Saxmundham since 1948. We were all delighted by the official recognition of Mr. Woolnough's contribution to the success of Saxmundham when in 1974 he was awarded the British Empire Medal in the Queen's Birthday Honours List. We wish him well in his retirement.

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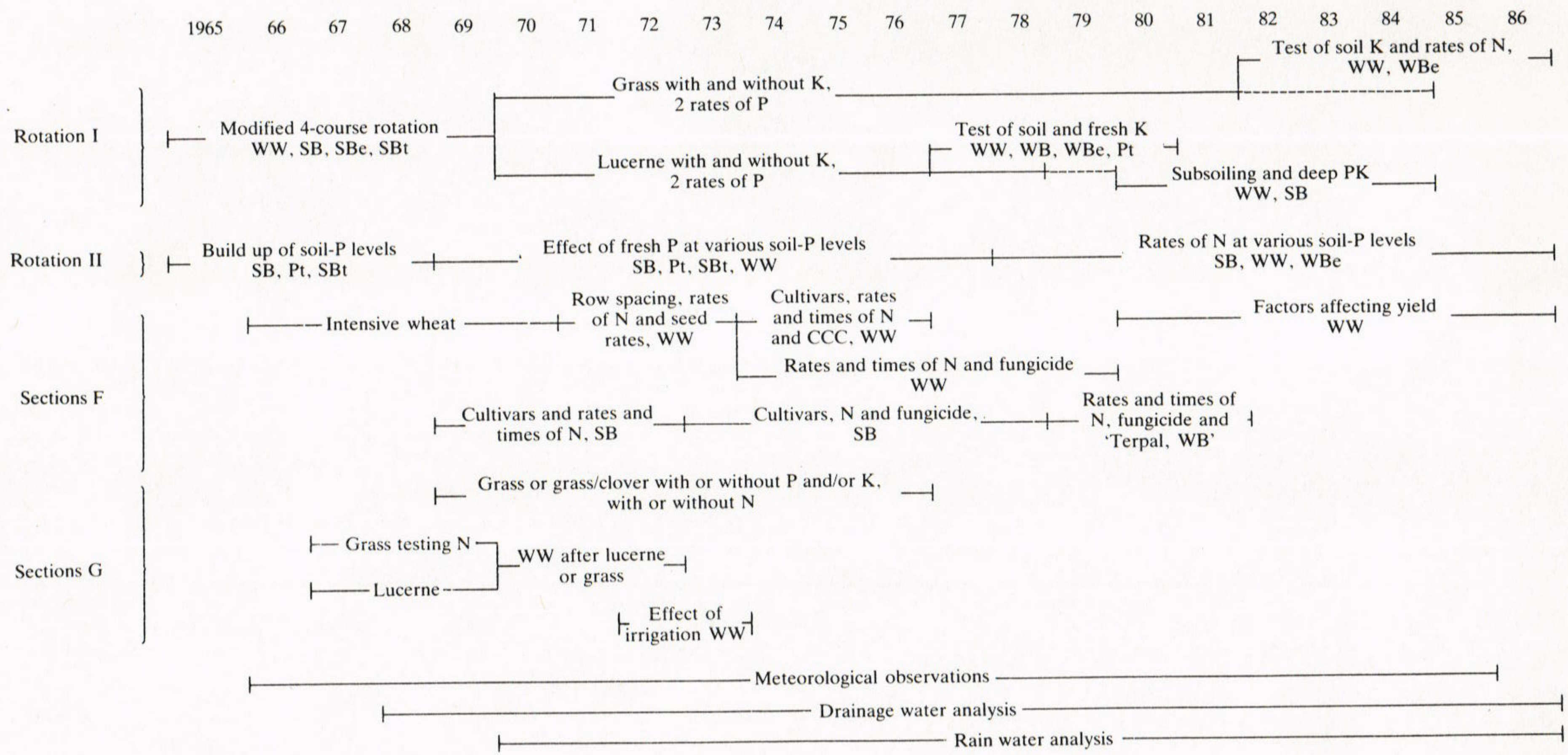
Appendix Table. *Experiments at Saxmundham 1965–1986*



WW, winter wheat; SB, spring barley; WB, winter barley; SBe, spring beans; WBe, Winter beans; Pt, potatoes; SBt, sugar beet; Additionally a small number of annual experiments, especially those on soil structure, were made.