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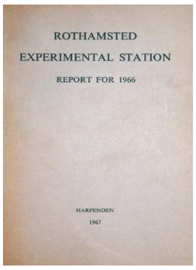

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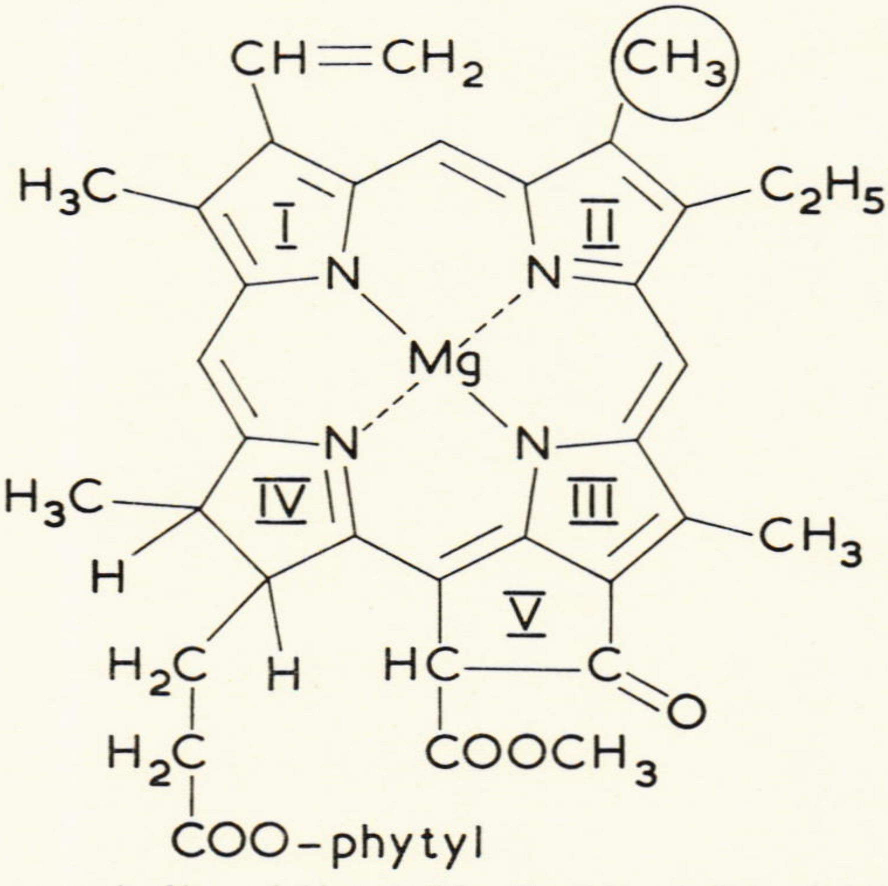
SPECIAL REVIEWS

THE BREAKDOWN OF CHLOROPHYLL

MARGARET HOLDEN

The ability of flowering plants, conifers, ferns, mosses and algae to photosynthesise depends on two green pigments, chlorophyll *a*, whose structure is shown in the figure, and chlorophyll *b*, which differs from *a* in having the CH_3 group that is ringed in the figure replaced by CHO. Quantitatively, chlorophyll *a* is the more important, because there is usually three times as much of it as of chlorophyll *b*. The chlorophylls break down in living tissues as part of normal physiological processes when leaves age or fruits ripen. Both also break down and thus diminish photosynthesis, because of many different adverse conditions, ranging from attacks by various pathogens to exposure to intense light, from deficiencies of nutrients to keeping in darkness and from lack of carbon dioxide to poisoning by various chemicals. Yellowing of leaves, the external sign of chlorophyll breakdown, is the commonest and often the first indication of ill health in plants.



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THE BREAKDOWN OF CHLOROPHYLL

Although chlorophyll breakdown in living cells is such a common occurrence, little is known of its biochemistry, partly because it is difficult to study it in conditions where chlorophyll is perhaps also being synthesised. To gain information about the kinds of change chlorophyll may undergo, and the mechanisms that may be involved in its degradation, the reactions that take place in pieces of leaf and in plant extracts have been studied in detail. Three known products formed by small changes in the chlorophyll molecule are pheophytins, chlorophyllides and pheophorbides. Pheophytins are formed by removing the magnesium; this occurs when dilute acid is added to plant extracts and during prolonged heating of leaves. Pheophytins are brown or grey and are responsible for the unattractive colour of overcooked green vegetables. Chlorophyllides are formed when the phytyl side chain of the chlorophylls is removed by the enzyme chlorophyllase. This produces no colour change, because chlorophyllides have the same absorption spectra as chlorophylls. When acidified, chlorophyllides form pheophorbides, which are similar in colour to the pheophytins.

Separation of the chlorophylls and their coloured breakdown products. Methods for separating chlorophylls *a* and *b* and some of their coloured degradation products have been much improved by the use of chromatographic techniques, and were recently reviewed by Holden (1965a). Chromatography on columns of adsorbents is the obvious choice for preparing large amounts of pigments, and the introduction of powdered polyethylene for this purpose makes it possible to separate pigments occurring mixed in crude extracts. For separating small amounts, chromatography on paper (Holden, 1962) has now been largely superseded by thin-layer chromatography (TLC). Bacon (1965) described a method for separating the chlorophylls themselves, pheophytins, pheophorbides and chlorophyllides on thin layers of cellulose. Using this method, Bacon & Holden (1967) also separated a range of "changed" chlorophylls and pheophytins that are probably oxidation products.

Enzymes concerned with the breakdown of chlorophyll

Chlorophyllase. The first stage in the breakdown of chlorophyll *in vivo* might be the removal of the phytyl side-chain, a change catalysed by the enzyme chlorophyllase. A study of the properties of this enzyme seemed therefore to be the obvious starting-point for research on the enzymic degradation of chlorophyll. Chlorophyllase was discovered more than 50 years ago by Willstätter & Stoll, but little work had been done on it, and none at all using modern methods of enzyme chemistry. Sugar-beet leaves proved to be an excellent source of the enzyme, and soluble preparations were made and considerably purified (Holden, 1961, 1963) from acetone-powders of these leaves. The most noteworthy property of the enzyme is its stability, particularly in the presence of large concentrations of organic solvents. When leaves of most species are suspended in aqueous acetone (50–60%) for a few hours much of the chlorophyll is converted into chlorophyllide. Chlorophyllides are also formed by chlorophyllase action when leaves are heated at temperatures between about 45° and 80° C, but higher temperatures inactivate the enzyme and prevent chlorophyllides being formed.

Chlorophyllase is widely distributed (flowering plants, gymnosperms, ferns, mosses, algae and purple bacteria), and its presence is readily demonstrated by its hydrolytic activity on chlorophyll *in vitro*, but there is little evidence that it is directly involved in the breakdown of chlorophyll *in vivo*. The last stage in the biosynthesis of chlorophyll is the attachment of the phytyl group to the porphyrin ring system, and the enzyme responsible for this has also been called chlorophyllase, but whether this is the same enzyme that removes the phytyl group *in vitro* is not known.

A lipoxidase in seeds. Holden (1965b) described an enzyme system from legume seeds that converts chlorophyll into colourless compounds. In this system long-chain fatty acids are peroxidised by lipoxidase and other enzymes, and the hydroperoxides are then broken down by a lipoperoxidase leading to free-radical formation and the oxidation of the chlorophylls. The nature of the chlorophyll breakdown products is now being studied. As there is no reason for supposing that this is the only, or even the usual, way in which chlorophyll is broken down *in vivo*, other enzymes that will catalyse the degradation of chlorophylls are being sought.

A lipoxidase in leaves. While investigating the behaviour of chlorophylls in leaf tissue kept in aqueous organic solvents, Bacon & Holden (1967) observed that most of the green colour disappeared from a suspension of chopped barley leaves in 50% acetone kept at room temperature in the dark overnight. Boiled suspensions remained green, suggesting that the bleaching was enzymic, and it seemed possible that these leaves contained a different chlorophyll-decomposing system. However, further work shows that a lipoxidase–lipoperoxidase system is again implicated (Holden, 1967). About 50 species were examined for chlorophyll bleaching by suspending leaf discs or strips in 50% aqueous acetone overnight; a few of them showed no loss of chlorophyll, but most lost some, and about one-third behaved like barley leaves and lost up to 80% of their green pigments. All these species were found to contain an active lipoxidase, although previously this enzyme was thought to be confined almost entirely to legume and cereal seeds. However, this lipoxidase differs in some of its properties from the one in legume seeds.

Glycollate oxidase. Kolesnikov (1948, 1949), who studied the oxidation of chlorophyll in suspensions of chloroplasts from barley leaves, found that when glycollic acid was added to suspensions kept in the dark the amount of chlorophyll oxidised was greatly increased. He suggested that oxidation was caused by organic peroxides of glyoxylic acid that were formed in the extracts. When the accumulation of peroxides was prevented by ascorbic acid or phenols the chlorophyll was not oxidised. However, he also observed that when carbonyl compounds were not formed a large amount of peroxide could accumulate without chlorophyll being oxidised. This suggests that a mechanism similar to the one in legume seeds was operating, with chlorophyll being bleached during breakdown of peroxides rather than by the peroxides themselves.

Tolbert & Burris (1950), who confirmed that chlorophyll in the sap from barley seedlings was bleached when glycollic acid was added, isolated two yellow pigments formed from chlorophylls *a* and *b* during glycollate oxidation. Bacon & Holden (1964) also confirmed that some chlorophyll is bleached during the enzymic oxidation of glycollate by barley and pea seedlings, but did not isolate any breakdown products.

Bleaching of chlorophyll by hydrogen peroxide. Noack (1943) found that fresh leaves turned white within 6 hours when treated with 3% H_2O_2 whereas boiled leaves remained green for more than two days. Pretreatment of the leaves with 4% diethyl ether prevented the chlorophyll bleaching, but in 3% H_2O_2 + 4% ether the loss of pigment was the same as with fresh leaves. Other compounds, such as phenylurethane, sodium bisulphite and 10% KNO_3 also inhibited bleaching by H_2O_2.

Noack did some *in vitro* experiments on chlorophyll bleaching using chlorophyllides made by chlorophyllase action. He found that chlorophyllides, unlike chlorophylls, were readily bleached by H_2O_2 in the presence of either $Fe(OH)_3$ or montmorillonite as a catalyst. He attempted to identify the colourless breakdown products, and with a short reaction time found methylethylmaleinimide, ammonia and oxalic acid. When the reaction was allowed to proceed for a long time he assumed total oxidation, with carbon dioxide, ammonia and water as the end products.

Noack envisaged that the breakdown of chlorophyll in ageing leaves took place in the following way: (1) accumulation of H_2O_2 because of a decrease in catalase activity; (2) breakdown of chloroplast protein; (3) splitting off of chloroplast iron as $Fe(OH)_3$; (4) activation of chlorophyllase and the conversion of chlorophyll to chlorophyllide; (5) oxidative breakdown of chlorophyllide by H_2O_2 with $Fe(OH)_3$ as catalyst. As all the reactions would take place simultaneously, intermediates would not accumulate.

This ingenious theory has not been confirmed, and although peroxides are involved in some *in vitro* reactions in which chlorophyll is broken down, there is no evidence as yet for such a mechanism *in vivo*.

Oxidation of chlorophyll by quinones. Keegel (1958) suggested that, during the fermentation of tea leaf, chlorophyll is oxidised to a brown pigment by quinones formed when catechins of the leaf are oxidised by polyphenoloxidase. When the magnesium in the chlorophyll is replaced by copper, which is said to be possible when tea bushes are sprayed with a copper fungicide against blister blight, the chlorophyll does not oxidise during fermentation and the leaf does not assume the colour of properly fermented tea.

Formation of "changed" chlorophylls. Strain (1954) described the formation of green oxidation products of the chlorophylls when chopped leaves were allowed to stand with alcohol or acetone in the presence of air. Chlorophyll *a* gave a pigment that was adsorbed more strongly on a column of sugar and hardly separated from chlorophyll *b*, which also gave a more strongly adsorbed pigment. Strain thought that these pigments were formed by enzyme action. Both these altered chlorophylls had absorption maxima at similar wavelengths to those of the pigments from which they were derived. Bacon & Holden (1967) found that two major "changed" pigments and some minor ones were formed from each of the chlorophylls when boiled leaves were kept in an aqueous alkaline medium and also when unheated leaves were kept in aqueous organic solvents. Bacon (1966) showed that these "changed" pigments are identical with pigments formed as artefacts on silica-gel chromatograms.

Loss of chlorophyll in senescing and detached leaves. In the chloroplast the chlorophylls are firmly attached to both protein and lipid, and until this linkage is broken the pigments are apparently not vulnerable to enzymic attack. *In vitro* the link can be broken by treatment with organic solvents such as acetone and alcohols or by heating. *In vivo*, concurrent breakdown of chloroplast protein seems to be necessary for chlorophyll degradation to occur. Several workers have correlated the disappearance of chlorophyll and protein in leaf tissues. Breakdown of lipid may be related even more closely than protein breakdown to chlorophyll degradation. Evidence to support this would be obtained if it could be shown that a mechanism involving peroxidation of lipids is actually responsible for the degradation of chlorophyll in some conditions.

The rate at which chlorophyll breaks down in detached leaves kept in the dark at room temperature depends on the species and age of the leaf and on the humidity. It also depends on pre-treatments such as freezing or boiling to which the leaves are subjected. Hoyt (1964) found that 90% of the chlorophyll was lost from Italian rye-grass after 4 days in a moist atmosphere, whereas in dry air chlorophyll degradation stopped after 2 days when the moisture content of the leaves had fallen from 76 to 33% and about half the chlorophyll still remained. Holden (1967) studied a wide range of species and found that leaves of purple sprouting broccoli lost 87% of their chlorophyll in five days under moist conditions. Most other species lost chlorophyll more slowly and, at the other end of the scale, Willow-herb (*Chamaenerion angustifolium*) lost only 5% in 10 days and *Paeonia* leaves none at all. Boiling or freezing of the leaves before keeping them in a moist atmosphere prevented chlorophyll breakdown. It is not unexpected that boiling should inactivate the chlorophyll-breakdown system, but it is of interest that freezing should also do so, because many enzymes can be frozen without loss of activity. However, it fits the observation that leaves of deciduous shrubs that are killed by a hard frost often remain green for a long period.

Detached leaves of about 30 plant species were kept moist and dark, and extracts were examined by TLC for the presence of coloured degradation products. Traces of chlorophyllides and pheophorbides were occasionally found, but usually only chlorophylls *a* and *b* in diminishing amounts were detected with no other coloured porphyrins. There is obviously a rapid conversion to colourless compounds without the accumulation of coloured intermediates.

Goodwin (1958) found that the remaining chlorophylls in autumn leaves of some deciduous trees, although having similar chromatographic properties to chlorophylls *a* and *b*, had different absorption spectra. The *a* pigment had a maximum in light petroleum at 652 mμ instead of 662 mμ and the *b* pigment at 635 mμ instead of 644 mμ. In samples of leaves taken from June to October the ratio of chlorophyll *a* to chlorophyll *b* remained nearly constant. Samples taken in November that contained only the altered chlorophylls had a much smaller ratio because the *a* derivative disappeared faster than the *b* pigment. So far we have been unable to confirm the formation of altered chlorophylls of this type in autumn leaves.

The effect of growth substances, herbicides and pesticides. Bruinsma (1965) reviewed the effect of growth-regulating substances, herbicides and a range of pesticides on the chlorophyll content of plants. Many compounds, e.g. the herbicide 3-amino-1,2,4-triazole, affect the chlorophyll content by interfering with its biosynthesis in young tissue rather than by accelerating its degradation. However, substances such as thiouracil and chloramphenicol, which are inhibitors of protein synthesis, accelerate the breakdown of chlorophyll. By contrast, compounds such as kinetin (Richmond & Lang, 1957) and benzimidazole (Person, Samborski & Forsyth, 1957) delay senescence and the yellowing of detached leaves by maintaining protein synthesis in the tissues. The use of benzylaminopurine as a spray or dip for improving the keeping qualities of some horticultural crops has been suggested (Salunkhe, Dhalival & Boe, 1962).

Gibberellic acid delays the development of autumn colours in the leaves of many deciduous trees (Brian, Petty & Richmond, 1959), and the senescence of leaf discs of various species (Fletcher & Osborne, 1966).

Humphries (1967) found that (2-chloro-ethyl)trimethylammonium chloride, which diminishes the rate of shoot growth of dwarf-bean plants, enables the primary leaves to retain their nitrogen longer, and so delays both protein hydrolysis and chlorophyll breakdown.

The effect of some other substances on chlorophyll is more complicated and less well defined than with the examples given above. It depends on the species of plant, on its stage of development and also on various other factors. Even kinetin, which usually delays senescence, was found by Bruinsma (1966) to stimulate chlorophyll breakdown when potato-leaf discs were kept in the light instead of in the dark.

Some herbicides seem to have a specific effect on chlorophyll. Oxidation of chlorophyll has been postulated as the mechanism by which substituted urea herbicides act as plant poisons (van Overbeek, 1964). The herbicide apparently blocks the usual photosynthetic path by which electrons in chlorophyll are replaced, and the chlorophyll is therefore damaged by being irreversibly oxidised. Herbicides like diquat and paraquat are thought to act by their ability to pick up single electrons leading to the formation of free radicals (Cronshey, 1961). These in turn may give rise to peroxide radicals that damage the chlorophyll and other cell constituents (Calderbank, 1966).

Chlorophyll breakdown in soil. Hoyt (1964) reviewed the few papers on the degradation of chlorophyll in soils. He measured the amount of chlorophyll-type compounds in leaves, farmyard manure and other materials that are commonly deposited on or in soils. He then studied the rate at which chlorophyll decomposes in plant materials when added to soil, and found that the activity of soil micro-organisms speeds its decomposition. Chlorophyll *a* was more susceptible than *b* to the action both of tissue enzymes and of soil micro-organisms. In acid soils chlorophyll was quickly converted into pheophytin. In water-logged soil leaf enzymes were inactivated, and because conditions were also unsuitable for micro-organisms chlorophyll breakdown was very slow. When dried, ground rye-grass leaves were added to various Rothamsted soils in the laboratory only about 5% of chlorophyll-type compounds remained after 90 days.

In field experiments chlorophyll decomposed much faster in fresh tissues than in dried plant material in which the enzymes had been inactivated. At Rothamsted 90% of the pigments had disappeared from dried material after 150 days, but at Woburn only 50%. Chlorophylls *a* and *b* were still detectable 72 days after the materials were incorporated into the soil. At the final sampling (150 days) only pheophytin was detected.

All the soils Hoyt examined contained chlorophyll-type compounds (0·5–3 lb/acre). The top 2 in. of old grassland and woodland soils contained much more than topsoil of arable land, but lower down the profiles the amounts were similar in various types of soil.

Soils more acid than pH 4 had more chlorophyll-type compounds than alkaline soils, and the microbiological degradation of chlorophyll in acid soils was very slow.

Chlorophyll derivatives in sediments and oil deposits. It is clear that in living tissues the porphyrin ring system of chlorophyll is broken easily, and colourless degradation products are formed. By contrast, in dead tissues, provided that the ring was intact when the plant died, it is remarkably stable, and coloured compounds are then found. Marine and fresh-water sediments up to 100,000 years old contain coloured degradation products of chlorophyll. Pheophytin, pheophorbide and chlorophyllide have all been found in sediments from Little Round Lake, Ontario (Vallentyne, 1960). Several factors seem to be responsible for preserving the porphyrin ring in wet sediments, of which lack of oxygen is one of the most important and others are lack of light, cold and the insolubility in water of the compounds in their natural state.

Petroporphyrins. The presence of porphyrins in oil deposits many million years old provides further evidence for the great resistance of the porphyrin ring to degradation. Thirty years ago Treibs described the separation of porphyrins from various bituminous materials, including oil, shale and coal. He identified etioporphyrin III (Etio) and deoxyphylloerythroetioporphyrin (DPEP) and put forward a degradation scheme by which hemin could be converted into Etio and chlorophylls *a* and *b* into DPEP. Six types of reaction were implicated: (1) removal of the metal; (2) saponification; (3) reduction; (4) aromatisation; (5) decarboxylation;

(6) chelation with a metal such as vanadium. More recent work has in general confirmed Treibs' ideas, but mass spectrometry shows that there are many homologues present of both the deoxyphyllo and etio series and also small amounts of rhodoporphyrins. Baker (1966) suggested that yet another type of reaction must also be involved to account for the many products found. This might be transalkylation via an ionic or free-radical mechanism.

Chlorophyll breakdown in animals. In animals during the digestion process chlorophyll is mainly converted into pheophytin and pheophorbide, but phylloerythrin is also formed by bacterial action. In phylloerythrin the phorbin ring is still intact, but the phytyl side-chain, magnesium and the two hydrogen atoms on ring IV have been lost, the vinyl group on ring I has been reduced to ethyl and the methoxy carbonyl group on the cyclopentanone ring has been replaced by hydrogen. Phylloerythrin is responsible for one type of photosensitisation reaction in animals. Its effectiveness as a photosensitiser may depend on its conversion to an activated form, possibly with a free-radical structure (Slater & Riley, 1966). It is usually absorbed from the gut and excreted by the liver, and is not concentrated enough in the blood to cause photosensitisation unless the liver is damaged in some way. A disease of cattle in South Africa, called Geeldkoppe, is a phylloerythrin photosensitisation caused when a poisonous fodder plant *Tribulus* damages the liver.

Conclusion

Work on the enzymic breakdown of chlorophyll was started in the hope that it would explain the processes by which chlorophyll disappears from leaves as they age or suffer from various infections and deficiencies. The experimental conditions used for studies *in vitro* are, of necessity, somewhat artificial, and chlorophyllase and the lipid-peroxidising enzymes may function differently *in vivo*. It is, however, clear that the activity of these enzymes *in vitro* is not correlated with the activity of chlorophyll loss in detached leaves. Other enzyme systems, yet to be found, may be involved, or other factors, such as the effect of light on chlorophyll when the linkages between it and either protein or fat are broken.

One of the most obvious effects of many virus infections is mottling and yellowing of leaves. Synthesis and breakdown seem to be affected, depending partly on the age of the tissues. We do not know whether virus infections affect chlorophyll biosynthesis and degradation in a specific way or whether the processes are upset because of the general derangement of metabolism.

With mineral deficiencies chlorophyll may disappear from mature tissues or fail to be formed in young leaves. In young leaves the effect is clearly on biosynthetic processes, and this may also be true in mature leaves. In these the synthesis of chlorophyll may not be able to keep up with the breakdown because one or more of the enzyme reactions may require the mineral that is deficient.

Fungal infections also often cause yellowing, but whether the breakdown by leaf enzymes is stimulated or whether the pathogens themselves contain chlorophyll-splitting enzymes remains to be discovered.

There is no reason to assume that the same mechanisms operate when chlorophyll disappears from leaves subjected to different forms of stress. Some progress has been made in elucidating the changes that take place in killed tissues, but much more information is needed before the processes that control the disappearance of chlorophyll from the living plant can be explained.

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HOOSFIELD CONTINUOUS BARLEY

R. G. WARREN and A. E. JOHNSTON

The Classical barley experiment on a 2½-acre site in Hoosfield was started by Lawes and Gilbert in 1852. The design of the main part of the experiment is similar to Barnfield. There are four Strips (1–4) with mineral manures (O, P, KNaMg, PKNaMg), and across these are Series treatments with nitrogen, none (O), ammonium sulphate (A), sodium nitrate (AA), sodium nitrate + sodium silicate (AAS) and rape cake (C) (now castor meal). Beyond the west end of the Strips are four plots, 1/N, 2/N (N as sodium nitrate), 5/O (PK fertilisers) and 5/A (NPK, N as ammonium sulphate). Two other plots, 6 and 7, were sited next to the south-east corner of the Strips. Ashes, which were mixed with the fertilisers to assist spreading, were tested on one half of plot 6, the other half was unmanured. Farmyard manure (FYM) was applied on all of plot 7 until 1871, but to only one half since. The AA and AAS plots with their present treatments started in 1868. Tables 1 and 2 give details of the manurial treatments and history of the plots.

Lawes and Gilbert described the results for the early years, 1852–83. In three papers entitled "The Rothamsted Field Experiments on Barley, 1852–1937", Russell and Watson examined the results exhaustively and compared them with those from other experiments with barley at Rothamsted, Woburn and other farms. They discussed the effects of N, P and K fertilisers and FYM on yield, composition and quality of barley grain. Variations in yields in different seasons, the influence of rainfall, sowing-date and the deterioration in yield of barley grown continuously are other subjects they treated fully. Their comprehensive account includes results of specialised studies on the Hoosfield experiment by Fisher, Frew, Hall and Morison, Mackenzie, "Mathetes", Wishart and Mackenzie and Yates and Watson. Hall *et al.*, Dyer, Keen and Haines, Ziemiecka, and Warren used the soils from the plots for various investigations, and Watson studied the effect of nutrient supply on net assimilation rate and leaf area.

As Russell and Watson dealt so thoroughly with results up to 1936, we shall only review work since then.

Recent crops

Only the crops for the most recent years, 1964–66, are discussed in detail here, but Table 3 includes the yields of grain, 10-year means, for 1852–1963 together with full period means for straw for reference. Table 4 gives yields for 1964–66. After the period dealt with by Russell and Watson (1852–1936) several of the ammonium sulphate plots became very acid, with serious effects on the crops from the early 1940s to the early 1950s. To neutralise the acidity and prevent future acidity a liming scheme was introduced in 1954–55 (Table 2).

HOOSFIELD CONTINUOUS BARLEY

TABLE 1

MANURIAL HISTORY OF THE HOOSFIELD BARLEY PLOTS, 1852–1966

Plot	Treatment	
GAUGE or *STANDARD SERIES* starting 1852 (so called by Lawes and Gilbert)		
6/1	Unmanured	(10 bushels ashes in 1872)
6/2	Ashes	1852–1932 (except 1928–29) none since
7/1	FYM	1852–71 none since
7/2	FYM	
NO NITROGEN GROUP starting 1852		
1/0	Unmanured	
2/0	P	
3/0	K Na Mg	
4/0	P K Na Mg	
5/0	P K	(N also in 1852 only)
AMMONIUM-N GROUP starting 1852		
1/A	N_1	
2/A	N_1P	
3/A	N_1 K Na Mg	
4/A	N_1P K Na Mg	
5/A	N_1P K	(N_2PK in 1880 only)
NITRATE-N GROUP starting 1868		
Previously received ammonium-N 1852–57 at rate N_2: 1858–67 at rate N_1		
1/AA	N_1	
2/AA	N_1P	
3/AA	N_1 K Na Mg	
4/AA	N_1P K Na Mg	
Starting 1864 plots AA were halved, the half next to the C Series received silicates (1862, 1863 only the quarter plot nearest the C Series received silicates).		
1/AAS	N_1 Si	
2/AAS	N_1P Si	
3/AAS	N_1 K Na Mg Si	
4/AAS	N_1P K Na Mg Si	
Starting 1853, manured in 1852 with PK		
1/N	N_1	
2/N	N_2 1853–57	N_1 1858–1966
CASTOR MEAL GROUP starting 1852		
1/C	C	
2/C	P C	
3/C	K Na Mg C	
4/C	P K Na Mg C	

Plot M The triangular piece of ground to the West of plots 5/O 2/N 1/N received P Na Mg 1855–93 and plot then abandoned because of weeds.

TABLE 2

DETAILS OF MANURES, CULTIVATIONS AND CROPPING, HOOSFIELD BARLEY, 1852–1966

Fertilisers and FYM applied annually.

Rates per acre*

NITROGEN

Ammonium sulphate at 210, 420 lb. These rates (N_1, N_2) supplied 43 and 86 lb N.

Before 1917 a mixture of equal weights of ammonium sulphate and ammonium chloride was used (except 1887, ammonium sulphate only). In 1901 the mixed salts were compared with ammonium bicarbonate on half of plots 1/A, 2/A, 3/A, 4/A.

Sodium nitrate at 275, 550 lb. These rates (N_1, N_2) supplied 43 lb and 86 lb N.

1964–66 N_2 rate given to Maris Badger, N_1 as usual to Plumage Archer.

PHOSPHORUS

Superphosphate containing 29–30 lb P, 66–69 lb P_2O_5 (366 lb 18·5% P_2O_5 superphosphate).

From 1852 to 1887 superphosphate was made on the Farm from 200 lb calcined bone dust and 150 lb sulphuric acid (sp. gr. 1·7). From 1888 it was supplied ready made and the weight adjusted to give the same amount of phosphorus as in the first period. 1898–1902 basic slag (400 lb) used instead of superphosphate.

POTASSIUM

Potassium sulphate *1852–1857* 300 lb containing 120 lb K (145 lb K_2O)
1858–1966 200 lb containing 80 lb K (96 lb K_2O)

Potassium dressings omitted 1917, 1918.

SODIUM

Sodium sulphate *1852–1857* 200 lb containing 28 lb Na
1858–1966 100 lb containing 14 lb Na

MAGNESIUM

Magnesium sulphate 100 lb containing 10 lb Mg

Magnesium dressings omitted 1917, 1918.

SODIUM SILICATE

1862–1867 200 lb sodium silicate + 200 lb calcium silicate
1868–1966 400 lb sodium silicate

Analyses of sodium silicate: the chemical composition of the mixed silicates is not known, the sodium silicate used since 1904 was a water-soluble powder with a weight ratio $SiO_2 : Na_2O$ of approximately 3.

FARMYARD MANURE

14 tons

ASHES

1852–1916 20 bushels of the clay and weed-ashes as used to mix with the mineral manures to aid their distribution
1917–1932 sifted ashes from the Laboratory furnace

CASTOR MEAL

1852–1857 2,000 lb rape cake (probably supplied 98 lb N)
1858–1940 1,000 lb rape cake except 1917–20 (none available)
1941–1954 1,000 lb castor meal
1955–1966 weight per acre adjusted for analysis so that total nitrogen applied equalled 43 lb N (1964–66, 86 lb N for Maris Badger)

* Plot Areas. The sizes of the plots were decreased in 1893 when paths between Series were widened and new paths between Strips were made; to maintain the rates of nutrients per acre the manures applied per plot were correspondingly smaller.

TABLE 2—continued

LIMING

To correct acidity that had developed on plots of strips 3 and 4 including 5/O, 5/A, ground chalk (5 tons $CaCO_3$/acre) was applied in winter 1954–55. To prevent further acidity developing a scheme of quinquennial chalk applications was introduced, the amount based on the acidifying effect of the ammonium sulphate (100 lb $CaCO_3$ for every 14 lb N as ammonium sulphate) and the castor meal (50 lb $CaCO_3$ for every 14 lb N as castor meal). First dressing in spring 1955.

CULTIVATIONS

PLOUGHING AND FERTILISER APPLICATIONS. Previous crop stubble usually shallow ploughed in autumn. 1852–1915 plots again shallow ploughed usually in March *after* fertiliser and FYM applied. Since 1916 FYM applied between September and January and plots then reploughed, tractor ploughing since 1921. Fertilisers then applied usually in March and worked in during seed-bed preparation, discing, spring tining, harrowing. Fertilisers applied by manure distributor since 1917 except N applied by hand. 1898–1902 the N was applied as a topdressing instead of to the seed-bed. Plots usually drilled in March.

WEED CONTROL. Up to 1915 the plots were hand hoed in some years when badly infested with weeds. 1929–32 plots were drilled with 18-in. rows to allow inter-row cultivation. Since 1944 spring spraying used to control weeds, 1944–56 DNOC, since 1957 various selective weedkillers. In 1958, 1959, 1961, stubble sprayed in autumn with 2,4-D to check coltsfoot (*Tussilago farfara*), and in 1962–64 dalapon was used in autumn to attempt to kill perennial grass weeds. To control wild oats (*Avena fatua*) much of the green crop on each plot was cut and carted, leaving only a small area for yield estimates in 1948, 1952, 1954, 1955, while in 1953 the whole field was cut green and the produce removed. In recent years wild oats have been kept in check by hand pulling.

HARVESTING. Plots were originally cut by hand, they were first cut by machine in 1910 and then from 1915 to 1957. Sheaves from each plot were stooked on that plot, carted in a large hessian sheet, stored and then threshed during the winter. Since 1958 plots harvested by combine-harvester, yield estimated by weighing 1 or 2 cuts only, rest cleared as discard.

FALLOWING. All plots were bare fallowed in 1912, 1933, 1943 to help weed control. In 1912 the plots were ploughed and subsoiled in a N–S direction, i.e. across the strips. On each fallowing occasion there were a number of ploughings and many cultivations both landwise and across the plots.

CROPPING

Except when fallowed the plots carried barley each year. (In 1906 and 1929 small areas of each plot grew swedes.) Seed rates varied from 1¾ to 3 bushels/acre.

Varieties	*1852–1880*	Chevalier
	1881–1890	Archers Stiff Strawed
	1891–1897	Carters Paris Prize
	1898–1916	Archers Stiff Strawed except 1902–5 Halletts Pedigree Chevalier
	1917–1966	Plumage Archer, 1927–32, except 1928, Spratt Archer also grown, 1964–66 Maris Badger also grown.

In 1908 the seed was treated with formalin and in 1928 with Corvusine. From 1936 seed treated each year with various seed dressings.

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TABLE 3

Hoosfield Barley yields 1852–1963

Plot	Treatment	10-year means (grain, cwt/acre) 1852–61	1862–71	1872–81	1882–91	1892–1901	1902–11	1912–21 (1)	1922–31	1932–41 (2)	1942–51 (3)	1952–61 (4)	Means 1852–1963 Grain (cwt/acre)	Straw (cwt/acre)
No nitrogen group														
1/0	Unmanured	11·4	8·8	6·8	6·2	5·3	5·2	6·5	3·7	6·9	9·3	7·4	7·0	7·9
2/0	P	13·9	11·8	9·0	9·6	7·1	9·3	10·2	6·7	11·6	11·7	10·6	10·1	9·7
3/0	K Na Mg	12·5	10·2	7·8	6·0	4·8	5·5	7·5	3·8	9·0	11·7	7·6	7·8	8·9
4/0	P K Na Mg	15·3	12·4	8·8	8·2	6·6	8·4	10·9	6·4	13·5	15·8	10·9	10·5	11·6
5/0	P K	12·3(*b*)	10·9	7·5	7·4	6·2	6·9	7·3	4·8	10·9	15·0	8·9	8·8	10·0
6/1	Unmanured	12·6	9·6	6·9	7·7	5·6	5·4	8·2	3·4	8·7	10·3	6·9	7·7	8·7
6/2	Unmanured	12·1	10·2	7·7	8·2	6·1	7·1	9·9	4·4	8·9	9·8	8·7	8·4	9·3
7/1	Unmanured (after FYM till 1871)			17·4	13·0	10·6	9·7	11·0	7·0	13·4	15·1	11·7	12·0	13·6
Ammonium-N group														
1/A	N	17·0	15·8	13·2	12·0	8·8	10·7	11·2	5·4	10·4	11·5	10·8	11·5	13·1
2/A	N P	22·9	24·7	20·4	18·0	15·5	16·1	16·2	11·8	18·8	15·9	16·8	17·9	19·4
3/A	N K Na Mg	17·8	17·8	15·0	12·4	11·8	11·0	11·3	6·0	13·2	14·4	13·4	13·1	15·8
4/A	N P K Na Mg	23·2	23·8	20·9	20·0	18·0	20·1	18·2	13·1	20·9	17·8	18·9	19·6	22·3
5/A	N P K	21·7	23·1	19·8	15·0	14·1	15·2	16·1	10·9	19·5	14·2	19·8(*c*)	17·3	21·9
Nitrate-N group (*a*)														
1/AA	N		16·0	14·2	14·0	11·6	12·6	12·3	7·1	12·1	13·0	12·9	12·3	15·5
1/AAS	N Si		18·7	17·7	17·1	16·0	14·9	14·9	8·6	16·4	16·1	17·0	15·5	18·3
2/AA	N P		24·0	21·1	21·0	19·4	20·3	19·7	14·7	22·0	18·5	20·2	19·8	22·5
2/AAS	N P Si		24·6	22·3	22·2	20·3	19·5	19·7	14·9	21·4	20·4	22·9	20·6	23·4
3/AA	N K Na Mg		16·5	15·1	14·2	12·8	11·6	12·1	6·3	14·4	15·9	13·9	13·0	16·8
3/AAS	N K Na Mg Si		21·5	19·4	17·5	16·7	15·5	14·2	8·4	16·7	17·3	18·3	16·3	19·8
4/AA	N P K Na Mg		24·0	21·6	20·1	18·5	19·8	18·9	13·3	21·8	21·4	19·9	19·7	22·8
4/AAS	N P K Na Mg Si		25·5	23·6	22·1	20·2	21·4	17·9	14·1	23·1	22·5	23·3	21·2	24·6
1/N	N	19·0	18·8	15·6	15·6	14·1	13·5	11·5	6·2	14·1	14·6	12·1	14·0	17·2
2/N	N	18·0	20·5	17·9	17·0	16·8	16·8	14·8	9·4	17·5	18·1	15·9	16·5	19·5
Organic-N group														
1/C	C	23·4	22·5	19·8	17·5	16·0	17·5	13·5	11·4	18·4	15·6	17·2	17·6	19·9
2/C	C P	23·9	23·7	21·2	19·1	17·1	18·3	14·6	14·8	21·3	20·9	19·5	19·5	21·3
3/C	C K Na Mg	22·1	22·4	19·0	16·8	15·1	17·4	12·2	10·0	17·6	21·1	17·0	17·4	20·0
4/C	C P K Na Mg	23·8	24·4	21·3	17·8	16·6	19·9	13·0	14·0	21·6	23·7	20·0	19·7	22·3
7/2	FYM	22·7	26·7	25·7	23·7	22·9	23·6	18·6	15·0	26·1	26·7	28·0	23·7	28·6

(1) Omitting 1912. (2) Omitting 1933. (3) Omitting 1943. (4) Omitting 1953.
(*a*) Started 1868, except 1/N, 2/N, yields from 1853 1/N, 1858, 2/N. (*b*) Omitting 1852. (*c*) Omitting 1954.

TABLE 4

Yield of Plumage Archer (PA) and Maris Badger (MB) Hoosfield Barley

cwt/acre, mean 1964–66

Plot	Treatment	Grain PA	Grain MB	Straw PA	Straw MB
No Nitrogen group					
1/0	Unmanured	8·2	8·3	4·6	3·2
2/0	P	11·3	11·1	5·9	4·4
3/0	K Na Mg	8·2	7·5	4·6	3·5
4/0	P K Na Mg	12·4	9·4	6·9	3·8
5/0	P K	11·6	9·3	7·2	5·7
6/1	Unmanured	7·2	5·7	4·3	2·7
6/2	Unmanured	9·9	7·2	5·3	4·1
7/1	Unmanured	13·3	8·6	8·7	5·4
Ammonium-N group					
1/A	N	12·2	14·5	8·8	9·1
2/A	N P	22·4	25·6	15·3	20·3
3/A	N K Na Mg	18·2	26·3	15·2	19·4
4/A	N P K Na Mg	26·8	39·8	18·4	28·4
5/A	N P K	30·0	38·2	24·0	32·6
Nitrate-N group					
1/AA	N	12·2	13·0	9·7	11·6
1/AAS	N Si	20·4	20·2	17·5	17·3
2/AA	N P	25·6	32·3	20·4	28·8
2/AAS	N P Si	26·4	30·2	20·4	24·8
3/AA	N K Na Mg	15·5	21·2	15·0	18·4
3/AAS	N K Na Mg Si	21·1	32·0	18·2	25·4
4/AA	N P K Na Mg	26·0	38·7	20·6	36·9
4/AAS	N P K Na Mg Si	29·6	39·3	23·3	34·5
1/N	N	10·5	8·2	12·0	14·4
2/N	N	17·8	23·6	13·4	18·7
Organic-N group					
1/C	C	22·7	34·2	15·6	21·3
2/C	C P	25·5	38·6	16·7	25·1
3/C	C K Na Mg	23·5	36·6	15·6	23·8
4/C	C P K Na Mg	27·6	38·7	19·4	27·3
7/2	FYM	36·6	39·8	28·6	30·7

A change from the old variety, Plumage Archer, to a more productive one was thought desirable, and in 1964 the plots were halved to compare Plumage Archer and Maris Badger. The amounts of N applied, including castor meal, were increased from 43 to 86 lb N/acre for Maris Badger, but otherwise the manuring was unchanged.

In 1964–66 the yields of Plumage Archer were exceptionally good, even when compared with 1932–41, one of the best 10-year periods (Table 5). The NPK plots gave 4–6 cwt more grain/acre and the FYM plot 10·5 cwt more, but the plots without nitrogen yielded about the average for 1932–41.

Table 6 shows that Maris Badger, with more fertiliser N, yielded 10–13 cwt grain/acre more on the NPK plots than Plumage Archer, but only 3 cwt more on the FYM plot, where both varieties received the same amount of manure.

Maris Badger yielded less than Plumage Archer on plots not given nitrogen (Series O) and on plot 7/1, which contains residues from the FYM applied during 1852–71. After 1871 yields on plot 7/1 soon diminished, but Russell and Watson reported that, even after 65 years, it still yielded 3–5 cwt grain/acre more than a plot unmanured since the

TABLE 5

Yield of Plumage Archer, Hoosfield Barley

Grain, cwt/acre

Plots with NPK	1932–41 mean	1964–66 mean
4/A	20·9	26·8
4/AA	21·8	26·0
4/AAS	23·1	29·6
Plot with FYM		
7/2	26·1	36·6
Plots without N		
1/0	6·9	8·2
2/0	11·6	11·3
3/0	9·0	8·2
4/0	12·5	12·4

experiment began. They could offer no explanation of this long-lasting effect of FYM residues. Warren showed that the soil of plot 7/1 contained (in 1946) much organic residue from FYM applied last century and that this decomposed very slowly. Of the organic N (1,500 lb/acre) in the residues, only about 10 lb N was mineralised each year. Some 6 lb entered the crop; the rest probably mineralised too late to be used by barley and was lost from the soil in drainage water. The FYM residues also contained available P and K, and Warren concluded that FYM had such an enduring effect because mineral N is released so slowly from the residues, which also contain available P and K.

Table 7 shows that these residues increased the yield of Plumage Archer but not of Maris Badger in 1964–66. There is no true control for plot 7/1 because it contains small residues of readily soluble PK from the FYM, but Table 8 shows that the amounts are small and nearer those in plot 1/O than plot 4/O. On plot 7/1 Plumage Archer took up more NPK than on 1/O and 4/O, but Maris Badger did not, probably because N was lacking. Tables 7 and 8 show that Maris Badger on the Exhaustion Land, where amounts of PK residues are the same as on Hoosfield (7/1), used the extra P and K and produced more grain and straw when given enough fertiliser N. The mineralised N from the FYM residues is probably

TABLE 6

Difference in yield between Maris Badger (MB) and Plumage Archer (PA), Hoosfield Barley

Grain, cwt/acre, mean 1964–66

	Series				
Strip	0	A	AA	AAS	C
1	0·1	2·3	0·8	−0·2	11·5
2	−0·2	3·2	6·7	3·8	13·1
3	−0·7	8·1	5·7	10·9	13·1
4	−3·0	13·0	12·7	9·7	11·1

Plots

6/1	6/2	7/1	7/2	1/N	2/N	5/O	5/A
−1·5	−2·7	−4·7	3·2	2·3	5·8	2·3	8·2

TABLE 7

Effect of old residues of FYM on yield and composition of barley

Grain and straw, cwt/acre; NPK, lb/acre

Hoosfield Barley, mean 1964–66

Plot Manuring	1/0 none	4/0 PKNaMg	7/1 FYM 1852–71	7/1 excess over 1/0	 4/0
Plumage Archer					
Grain	8·2	12·4	13·3	5·1	0·9
Straw	4·6	6·9	8·7	4·1	1·8
In crop					
N	13·2	18·3	21·6	8·4	3·3
P	2·6	5·3	4·9	2·3	−0·4
K	6·1	13·5	14·2	8·1	0·7
Maris Badger					
Grain	8·3	9·4	8·6	0·3	−0·8
Straw	3·2	3·8	5·4	0·6	1·6
In crop					
N	14·6	13·1	13·0	−1·6	−0·1
P	2·8	4·1	3·1	0·3	−1·0
K	6·3	9·2	7·8	1·5	−1·4

Exhaustion Land, mean 1964–66

Plot Manuring 1876–1901	1 none	3 FYM	3 excess over 1
1964–66	78 lb N/acre/year		
Maris Badger			
Grain	13·2	34·2	21·0
Straw	14·0	26·0	12·0

TABLE 8

Effect of old residues of FYM on readily soluble P and K in soil

Experiment		Hoosfield		Exhaustion Land	
Plot	1/0	4/0	7/1	1	3
Manuring	None	PKNaMg	FYM 1852–71	None	FYM 1876–1901
		P soluble in 0·5*M*-NaHCO$_3$ mg/100 g			
	0·5	12·6	1·2	0·4	1·6
		K soluble in 1*N*-ammonium acetate mg/100 g			
	8·7	43·3	12·1	8·6	11·6

produced too late in the season for Maris Badger, and this also restricts the uptake of P and K.

The failure of Maris Badger to measure the available nutrients from the FYM residues is relevant to the immediate future of plot 7/1. No information will be obtained from the plot when the new variety of barley is grown. The plot could be omitted from the experiment and used to study the residues in detail. Kale and sugar beet would probably make more use of the N released later from the residues, and it would be interesting to see whether adding an energy source to the soil would increase the mineralisation of the organic nitrogen.

Maris Badger, a stiffer-strawed variety than Plumage Archer, is better suited for larger amounts of fertiliser N. Table 4 shows that, given PK also, 86 lb fertiliser N/acre increased its yield by 30 cwt grain/acre, Plumage Archer increased its yield by only 15 cwt when given 43 lb N/acre. Table 9 shows the increases from P and K fertiliser. Because the amounts of fertiliser N differed, the figures do not give a quantitative comparison of the responsiveness of the two varieties to P and K, but it seems that Maris Badger used fertiliser K more effectively for producing grain. With the same quantity of fertiliser K and twice the fertiliser N the increase in Maris Badger from K fertiliser was four times greater than in Plumage Archer; for P the difference was only 50%.

TABLE 9

Increase in barley yield from PK fertilisers

Means of A and AA series, Hoosfield Barley
grain, cwt/acre, mean 1964–66

	Plumage Archer (43 lb N/acre)	Maris Badger (86 lb N/acre)
Increase from		
P (in presence of K)	9·6	15·5
K (in presence of P)	2·4	10·4

Sodium silicate is a treatment of special interest in the Hoosfield experiment. In 1964–66 its effect on yield was shown most convincingly by Maris Badger. Table 10 compares the yields of the two varieties with sodium nitrate alone (Series AA) and with sodium silicate (AAS).

TABLE 10

Effect of sodium silicate, Hoosfield Barley

(Maris Badger (MB) Plumage Archer (PA))
grain, cwt/acre, mean 1964–66

		Series					
		AA (sodium nitrate)		AAS (sodium nitrate + sodium silicate)		Increase from sodium silicate	
Strip	Fertiliser	MB	PA	MB	PA	MB	PA
1	0	13·0	12·2	20·2	20·4	7·2	8·2
2	P	32·3	25·6	30·2	26·4	−2·1	0·8
3	K Na Mg	21·2	15·5	32·0	21·1	10·8	5·6
4	P K Na Mg	38·7	26·0	39·3	29·6	0·6	3·6

Yield of Maris Badger was increased greatly by silicate only where superphosphate was not given, and this interaction was less evident with Plumage Archer. To account for the effect of sodium silicate, Lawes and Gilbert suggested that it made some of the phosphorus locked up in the soil available to barley. However, Hall and Morison decided that the action of the silicate was on the plant, not the soil, and that the silicate facilitates the uptake of phosphorus. Fisher examined further plant analyses for P and supported Lawes and Gilbert in concluding that the silicate acted on the soil to make more phosphorus available, but proof based on soil analyses was still lacking.

Table 11 shows the percentage of P and the total content of the two varieties in 1964 and 1966. Little or no effect is expected from silicate on

TABLE 11

Effect of sodium silicate on the phosphorus percentage and content, Plumage Archer and Maris Badger, Hoosfield Barley

% P in grain dry matter, 1964 and 1966

		AA		AAS		Increase from silicate	
Strip	Manuring	1964	1966	1964	1966	1964	1966
		Plumage Archer					
1	None	0·328	0·310	0·375	0·356	0·047	0·046
2	P	0·408	0·372	0·407	0·371	−0·001	−0·001
3	K Na Mg	0·333	0·306	0·369	0·360	0·036	0·054
4	P K Na Mg	0·382	0·383	0·392	0·404	0·010	0·009
		Maris Badger					
1	None	0·304	0·266	0·314	0·329	0·010	0·063
2	P	0·385	0·414	0·386	0·390	0·001	−0·024
3	K Na Mg	0·288	0·258	0·335	0·366	0·047	0·108
4	P K Na Mg	0·404	0·381	0·408	0·401	0·004	0·020

P content of crop, mean of 1964 and 1966
lb element/acre

PA — Plumage Archer
MB — Maris Badger

		AA		AAS		Increase from silicate	
		PA	MB	PA	MB	PA	MB
1	None	3·9	4·2	7·9	7·2	4·0	3·0
2	P	10·6	14·4	11·8	13·2	1·2	−1·2
3	K Na Mg	5·1	6·0	7·8	11·6	2·7	5·6
4	P K Na Mg	10·0	17·2	12·6	18·3	2·6	1·1

plots given superphosphate each year. For the plots without superphosphate, the two results, (1) extra yield of grain, and (2) the increase in P per cent in the grain, *taken together* provide good evidence that sodium silicate increases the amount of available P, but direct evidence from soil studies is preferred.

N, P, K, Na, Ca, Mg were measured in the 1964 and 1966 crops of both varieties from all plots. Table 12 shows the amounts of the elements removed in the crops from plots of Series O, A, AA, AAS, C on Strip 4 and from 7/2 only. Given the same quantity of FYM (plot 7/2), the two varieties contained almost identical amounts of the elements (mean yields 1964, 1966 were Plumage Archer 36·6; Maris Badger 39·8 cwt grain). Where Plumage Archer received 43 lb N and Maris Badger 86 lb N/acre, the form of nitrogen, ammonium sulphate or sodium nitrate, did not affect the uptakes of N. The recoveries of fertiliser N in the crops were Plumage Archer, 58%; Maris Badger, 69%. Lawes and Gilbert found 40% of the added N was recovered in the crop; Russell and Watson reported values between 1919 and 1923 of 40%, and between 1924 and 1928 of 29%, when yields were also smaller.

Most of the nitrogen in castor meal is mineralised quickly in the soil, and the amount taken up by the crop equals that from ammonium sulphate and sodium nitrate with 43 lb N/acre, but is a little less with 86 lb N. The effect of residues from rape cake measured in the Hoosfield and Barnfield experiments, 1917–21, were small.

On the fertiliser plots Maris Badger, with the extra N, removed about

TABLE 12

Amounts of N, P, K, Na, Ca, Mg removed in crops of Plumage Archer and Maris Badger, Hoosfield Barley

Grain + straw, mean of 1964 and 1966. lb element/acre

PA, Plumage Archer, 43 lb N/acre/year
MB, Maris Badger, 86 lb N/acre/year

		N		P		K	
Plot	Treatment	PA 43 lb N	MB 86 lb N	PA	MB	PA	MB
4/0	P K Na Mg	18·3	15·1	5·3	4·1	13·5	9·2
4/A	NH_4–N P K Na Mg	44·3	73·8	11·2	17·5	30·4	49·4
4/AA	NO_3–N P K Na Mg	42·2	74·5	10·0	17·2	28·0	47·4
4/AAS	NO_3–N P K Na Mg Si	47·1	72·8	12·6	18·3	34·7	53·2
4/C	Org–N P K Na Mg	43·7	68·4	11·8	18·4	32·2	48·7
7/2	FYM	67·8	70·1	17·6	18·3	61·0	58·7
		Na		Ca		Mg	
4/0	P K Na Mg	0·5	0·3	2·4	1·5	1·8	1·4
4/A	NH_4–N P K Na Mg	1·2	1·5	6·3	10·2	3·9	6·2
4/AA	NO_3–N P K Na Mg	2·3	5·1	5·5	10·6	3·4	6·0
4/AAS	NO_3–N P K Na Mg Si	4·3	9·9	7·1	12·0	4·6	6·8
4/C	Org–N P K Na Mg	1·1	1·6	5·8	9·4	4·1	6·8
7/2	FYM	2·2	1·7	10·0	10·0	5·5	6·0

6 lb more P and 19 lb more K per acre than Plumage Archer. The figures for the other elements are: Na 3–6 lb, where sodium nitrate and sodium silicate were given (but none otherwise), Mg 2 lb, Ca 5 lb. The uptakes of Na from sodium nitrate and sodium silicate were small, and the Na in them (74 and 60 lb/acre respectively) did not significantly lessen the uptake of K, which is in accord with the results of Barnfield and Park Grass.

The soil

The soils at Rothamsted are mainly derived from "Clay-with-Flints" which overlies chalk at various depths. The soil carrying the barley experiment on Hoosfield belongs to the Batcombe Series (undifferentiated) as classified by the Soil Survey of England and Wales. The field is on a level plateau where the "Clay-with-Flints" is thick and the soil has a flinty silt loam or loam surface. Like several of our other old arable fields, Hoosfield was given a large dressing of chalk in the early part of the last century, when the practice was to dig out the underlying chalk and spread it on the arable land. Detailed surveys for pH and $CaCO_3$ of Broadbalk and Hoosfield, made around 1954, suggested that these early large dressings were not applied uniformly, confirming, for Hoosfield, Russell and Watson's surmise from a few measurements of pH made in 1932.

The amount applied lessened with increased distance from one side or corner of the field, so that some parts had 10–15 tons more chalk per acre than others. This difference would not affect the yield of crops in the early years, but parts of the field with the smallest reserves of $CaCO_3$ to replace calcium lost in drainage water and removed in crops would become acid soonest. The onset of acidity would be hastened by ammonium sulphate and to a lesser extent by rape cake or castor meal. Table 13 shows the $CaCO_3$ contents of soils of the plots of the Barley experiment in 1946, and indicates that the early chalking was not uniform. Most $CaCO_3$ (0·8–1·7%) was within the O, A, AA and AAS Series of Strips 1 and 2. Beyond this in the direction of the C Series and towards Strips 3 and 4 $CaCO_3$ content diminishes abruptly. More detailed soil sampling and analysis done in the 1950s showed that sharp changes did not coincide with the boundaries between Series C and AAS and between Strips 2 and 3, ammonium sulphate and castor meal had, as expected, increased the irregularities. In 1946 the centres of plots 3/A, 4/A and 5/A (all receiving ammonium sulphate) were already acid.

TABLE 13

Percentage $CaCO_3$ in surface soils, 0–9 in., Hoosfield Barley, 1946

		(*5/A*)0·04	(*5/0*)0·08	(*2/N*)0·10	(*1/N*)0·09	Series
		0·01	0·00	0·04	0·17	C
		0·16	0·34	1·17	0·80	AAS
		0·17	0·38	1·70	1·48	AA
(*7/2*)0·48	(*6/2*)0·07	0·00	0·06	1·11	1·34	A
(*7/1*)0·14	(*6·1*)0·08	0·20	0·14	1·02	1·55	0
		4	3	2	1	
			Strip			

A second irregularity in the soils has come about since the experiment began by movement of soil across plot boundaries during cultivations. More such movement on Hoosfield than on the other Classical experiments probably reflects the intensive cultivations given during the early fallows before weeds could be controlled with chemicals. Cultivations were done both along and across the plots. That much soil had moved in this way became apparent in 1949, when the crop in the centres only of three of the five ammonium sulphate plots (3/A, 4/A, 5/A) were poor and discoloured from acute soil acidity. Crops were normal on the other two plots given ammonium sulphate (1/A, 2/A), where there were reserves of $CaCO_3$. In the early 1950s soil samples were taken, closely spaced (about 1 ft), in lines across the plots of the O and A series and several other plots to measure the extent of soil movement. Table 14 shows the changes in pH and total P across an ammonium sulphate plot (4/A). There were about 50 samples across each plot, and the results of analysis when plotted gave surprisingly smooth curves. For ease of presentation the results are condensed to 12 values for each kind of analysis. The paths between the strip treatments are fortunately wide, about $5\frac{1}{4}$ ft (8 links); they are cultivated but uncropped and unmanured since 1893. The figures for pH show that some of the slightly calcareous soil of the paths has been drawn into the plot. We cannot be sure that the centre has not been disturbed,

TABLE 14

Change in pH and Total P across Plot 4/A Hoosfield Barley, 1954

Surface soils 0–6 in.

	Path	Plot 4/A										Path
pH (in water)	7·0	6·0	5·4	5·1	4·9	4·8	4·9	5·1	5·8	6·9	7·5	7·7
Total P mg/ 100 g	88	110	118	122	125	126	125	120	110	90	70	63

but if it has the amount is likely to be small, because the pH over the central third of the plot changes little (0·2 pH unit). The figures for total P suggest the same amount of soil movement as do the pH values. Much P has been taken from the outside thirds of the plot into the paths (P contents of the undisturbed paths should be 40–50 mg P/100 g). Also, soil analysis showed extra P for a distance of several yards into the no P plots (6/2, 3/A) on either side of 4/A. The other plots examined showed approximately the same amount of soil movement. It must be stressed here that, for many years now, precautions have been taken to minimise the carry-over of soil; cross cultivations are avoided where possible, and ploughing is done so that the soil is turned in opposite ways on successive occasions. The results in Table 14 suggest that satisfactory soil samples could be obtained from the central third of the plot, that is by discarding 7 yd on each side and at the ends of the plots. When the 1946 soil samples were taken a surround of about 5 yd was discarded; the analyses of these samples are therefore probably subject to errors of a few per cent.

Because of the acute acidity on some of the ammonium sulphate plots

TABLE 15

Soil reaction and organic carbon and nitrogen content of Hoosfield Barley soils, 1965

Surface soils 0–9 in.

Plot	Treatment	pH in water	Organic carbon (%)	Total N (%)
No nitrogen group				
1/0	Unmanured	7·9	0·81	0·101
2/0	P	7·8	0·82	0·097
3/0	K Na Mg	7·8	0·91	0·107
4/0	P K Na Mg	7·2	0·97	0·110
5/0	P K	7·1	0·96	0·108
6/1	Unmanured	6·1	0·97	0·111
6/2	Unmanured	6·2	0·96	0·109
7/1	Unmanured	6·6	1·32	0·139
Ammonium-N group				
1/A	N	8·0	0·86	0·108
2/A	N P	7·7	0·90	0·107
3/A	N K Na Mg	7·5	0·90	0·106
4/A	N P K Na Mg	6·7	0·90	0·100
5/A	N P K	6·2	1·03	0·113
Nitrate-N group				
1/AA	N	8·1	0·92	0·110
1/AAS	N Si	8·1	0·91	0·108
2/AA	N P	7·9	1·01	0·114
2/AAS	N P Si	7·9	0·98	0·110
3/AA	N K Na Mg	8·0	0·93	0·108
3/AAS	N K Na Mg Si	8·1	0·89	0·102
4/AA	N P K Na Mg	7·5	1·02	0·109
4/AAS	N P K Na Mg Si	7·5	0·90	0·101
1/N	N	6·8	1·02	0·115
2/N	N	7·8	1·03	0·117
Organic-N group				
1/C	C	6·9	1·17	0·129
2/C	C P	6·5	1·10	0·117
3/C	C K Na Mg	7·1	1·08	0·114
4/C	C P K Na Mg	6·9	1·10	0·118
7/2	FYM	7·8	3·37	0·304

and slight acidity elsewhere, a scheme of liming was introduced. In the winter 1954–55, 5 tons chalk/acre were applied to Strips 3 and 4, including plots 5/A and 5/O. Regular chalk supplements were prescribed for all plots receiving ammonium sulphate or castor meal; these were 100 lb $CaCO_3$/14 lb N as ammonium sulphate and 50 lb $CaCO_3$/14 lb N as castor meal. Ten years later in 1965 the soil reaction of the chalked plots was still satisfactory, except plot 5/A (pH 6·2). Table 15 shows the pH values for all plots in 1965. Plot 5/A requires an extra dressing of chalk, and several other plots (e.g. 6/1, 6/2, 7/1), which did not need liming when the 1954–55 scheme began, are now slightly acid. It is therefore time to start a new scheme for liming at regular intervals.

Surface soil samples, 0–9 in., were taken in 1965 from within the least disturbed area at the centre of the plot. Tables 15, 16 and 17 show pH, content of organic carbon and total N, and the amounts of soluble P (by four methods), soluble K (three methods) and soluble Na (one method). Total P was not determined.

TABLE 16

Readily soluble phosphorus in the surface soils, Hoosfield Barley, 1965

		P soluble in			
Plot	Treatment	0·01*M*-$CaCl_2$ (g mols/litre × 10^{-6})	0·5*M*-$NaHCO_3$ (mg/100 g)	0·3*N*-HCl (mg/100 g)	Acetic acid–sodium acetate pH 4·8 (mg/100 g)
No nitrogen group					
1/0	Unmanured	0·2	0·5	0·6	0·2
2/0	P	5·4	7·8	39·4	16·6
3/0	K Na Mg	0·3	0·9	1·1	0·2
4/0	P K Na Mg	21·2	12·6	38·1	8·6
5/0	P K	18·4	12·8	27·5	5·5
6/1	Unmanured	0·3	0·6	0·3	0·1
6/2	Unmanured	0·3	0·7	0·6	0·1
7/1	Unmanured	0·4	1·2	1·1	0·2
Ammonium-N group					
1/A	N	0·2	0·4	0·6	0·2
2/A	N P	6·2	8·2	44·0	15·3
3/A	N K Na Mg	0·2	0·4	0·2	0·1
4/A	N P K Na Mg	14·4	10·3	24·3	3·6
5/A	N P K	11·4	11·9	21·6	2·5
Nitrate-N group					
1/AA	N	0·2	0·4	0·7	0·2
1/AAS	N Si	0·2	0·4	1·1	0·4
2/AA	N P	6·2	8·6	41·6	14·6
2/AAS	N P Si	4·5	5·9	47·4	19·2
3/AA	N K Na Mg	0·1	0·4	0·7	0·2
3/AAS	N K Na Mg Si	0·4	0·4	1·0	0·3
4/AA	N P K Na Mg	19·1	11·0	29·8	7·8
4/AAS	N P K Na Mg Si	11·4	7·2	34·1	12·5
1/N	N	0·2	0·5	0·5	0·1
2/N	N	0·3	1·3	1·1	0·2
Organic-N group					
1/C	C	0·4	1·5	1·1	0·3
2/C	C P	24·6	11·7	34·5	4·9
3/C	C K Na Mg	1·0	1·9	1·6	0·4
4/C	C P K Na Mg	22·0	11·5	32·8	5·5
7/2	FYM	25·4	10·2	33·3	15·0

TABLE 17

Readily soluble potassium and sodium in the surface soils, Hoosfield Barley, 1965

		K mg/100 g soluble in			Na mg/100 g soluble in
Plot	Treatment	1*N*-ammonium acetate	0·01*M*-$CaCl_2$	0·3*N*-HCl	1*N*-ammonium acetate
No nitrogen group					
1/0	Unmanured	8·7	1·1	5·7	5·1
2/0	P	7·1	0·8	4·4	4·7
3/0	K Na Mg	49·6	16·1	38·8	5·1
4/0	P K Na Mg	43·3	14·3	35·4	4·5
5/0	P K	42·4	13·9	34·7	4·6
6/1	Unmanured	10·1	1·9	6·3	4·2
6/2	Unmanured	8·8	1·6	5·5	4·1
7/1	Unmanured	12·1	2·0	7·4	4·8
Ammonium-N group					
1/A	N	7·2	1·0	4·8	7·3
2/A	N P	6·2	0·7	3·9	6·0
3/A	N K Na Mg	43·0	14·9	34·3	5·3
4/A	N P K Na Mg	36·2	12·1	29·4	6·9
5/A	N P K	40·6	11·6	31·8	3·8
Nitrate-N group					
1/AA	N	6·8	0·9	4·6	9·4
1/AAS	N Si	7·0	0·7	4·3	17·1
2/AA	N P	6·7	0·8	4·1	10·1
2/AAS	N P Si	6·3	0·6	3·6	15·5
3/AA	N K Na Mg	45·8	14·0	35·9	12·3
3/AAS	N K Na Mg Si	44·4	14·8	34·6	10.2
4/AA	N P K Na Mg	41·0	14·7	34·2	15·2
4/AAS	N P K Na Mg Si	35·8	12·4	31·8	16·0
1/N	N	7·1	1·1	4·5	16·4
2/N	N	8·4	1·2	4·9	13·1
Organic-N group					
1/C	C	10·2	1·9	6·6	4·8
2/C	C P	8·3	1·5	5·3	4·9
3/C	C K Na Mg	41·4	14·9	34·6	4·0
4/C	C P K Na Mg	38·4	12·3	36·2	11·1
7/2	FYM	75·8	28·8	60·5	5·2

Total N and organic matter. Table 15 shows the N content of the unmanured plot is the same as for many years past at about 0·10% N, and the NPK fertiliser plots contain the usual small extra amount (0·01% N). The N in the FYM plot (7/2), however, increased during the past 20 years more than was expected (total N in 1946, 0·27%; 1965, 0·30%), probably because the extra cultivations in the early 1930s and the intensive cultivations during the fallow year, 1933, oxidised more organic matter than when the field is cropped. A similar extra loss was noted on Broadbalk after the fallowing scheme was introduced in 1926. The organic residues from FYM applied last century on plot 7/1 continue to decrease slowly: between 1946 and 1965 the mean annual rate of loss of N was the same as between 1913 and 1946. There is a similar slow decomposition on the old FYM plots of the Exhaustion Land.

Potassium and sodium (Table 17). The potassium analyses show the expected effects, large accumulations from K fertilisers, much larger from

FYM and little or none from castor meal. Table 18 shows the amounts of K soluble in *N*-ammonium acetate for the Series treatments O, A, AA, AAS and Strips 1–4. As was found by analysis of the Barnfield soils, the Na (74 lb/acre) in sodium nitrate (Series AA) has not conserved soil K any more than has ammonium sulphate (Series A). Even the extra amount of Na in the sodium silicate (60 lb Na/acre) given to Series AAS has not affected removal of soil K. Soil not given K on Hoosfield has only about half the soluble K as corresponding soils on Barnfield. Where K has been applied the amounts of readily soluble K in the soil are much the same, but the greater amount of K given on Barnfield, 200 lb (Hoosfield 80 lb), has either been removed by the crop or fixed in non-exchangeable forms. The plots on both fields given only FYM receive the same amount each year, but the one on Hoosfield now has 50% more soluble K than the one on Barnfield.

TABLE 18

Effect of sodium on the readily soluble K in the surface soils, Hoosfield Barley, 1965

K soluble in 1*N*-ammonium acetate, mg/100 g

			Series			
		N as	O	A $(NH_4)_2SO_4$	AA $NaNO_3$	AAS $NaNO_3$
					Sodium silicate	
					Without	With
Strip	Treatment	Na lb/acre/year	0	0	74	134
1	Unmanured	0	9	7	7	7
2	P	0	7	6	7	6
3	K Na Mg	14	50	43	46	44
4	P K Na Mg	14	43	36	41	36

As on Barnfield, smaller amounts of Na than K are retained in an exchangeable form in the soil. On Hoosfield the sodium soluble in *N*-ammonium acetate ranges from 4·0 to 17·1 mg/100 g soil. On Barnfield the range is 0·4–5·8 mg/100 g. On both fields the increase on the plot given only FYM is about the same, 0·6 mg/100 g. It is not known why soils on Hoosfield have more exchangeable Na than on Barnfield when Na is added as fertiliser, the root crops on Barnfield may have removed most of the available Na, whereas barley takes up much less.

Phosphorus. Table 16 shows the amounts of soluble P determined by four methods that have been widely used to measure the P status of soils. The soils of the current Classical experiments contain either very small or large amounts of P, so are not suitable for testing empirical methods of analysis used to give advice on phosphate manuring. The larger amounts in the Classical experiments should, however, be an advantage in studies of the effects of manurial treatments and variable soil factors on the phosphate residues in the soil. It is reasonable to suppose that such effects would apply to the soils with small to medium amounts of P on commercial farms, and the information gained from the rich soils would be useful. The analyses for P in the soils of the five Series (O, A, AA, AAS, C) on Strips 1–4 are arranged in Table 19 to show how differences in

$CaCO_3$ content of the Hoosfield soils affect the amount of soluble P. The $CaCO_3$ content of the soils, shown in Table 13, are used to divide the plots into the two groups used in Table 19. No precise percentages $CaCO_3$ are set as the limits of the two groups, because during the long period phosphate accumulated in the soil the $CaCO_3$ content gradually decreased by losses of Ca. A difference in $CaCO_3$ like the one indicated must have existed between the two groups of plots for many years. The four plots of each Series except C are divided equally between the two groups; all plots of Series C are in the group with little or no $CaCO_3$. As expected, the soluble P in all plots without superphosphate (Strips 1, 3) is so little that the chances of detecting an effect of $CaCO_3$ are negligible. In contrast, there are large effects on soluble P in all plots with superphosphate (Strips 2, 4). With two of the methods of analysis (0·01*M*-$CaCl_2$ and 0·5*M*-$NaHCO_3$), the extra $CaCO_3$ in Strip 2 has decreased the solubility in $CaCl_2$ to one-third and in $NaHCO_3$ to three-quarters. Soluble

TABLE 19

Effect of $CaCO_3$ and sodium silicate on readily soluble P in the surface soils, Hoosfield Barley, 1965

Strip	1	2	3	4
P fertiliser	0	P	0	P
$CaCO_3$	*1–1·5%*		*small or none*	
Series	P soluble in 0·01*M*-$CaCl_2$ g mol P/litre × 10^{-6}			
O	0·2	5·5	0·3	21
A	0·2	6·0	0·2	14
AA without silicate	0·2	6·0	0·1	19
AAS with silicate	0·2	4·5	0·4	11
Mean	0·2	5·5	0·2	16
$CaCO_3$	*small or none*			
C	0·4	25	1	22
	P soluble in 0·5*M*-$NaHCO_3$ mg P/100 g			
O	0·5	7·5	1·0	13
A	0·5	8·0	0·5	10·5
AA without silicate	0·5	8·5	0·1	11
AAS with silicate	0·5	6·0	0·5	7
Mean	0·5	7·5	0·5	10·5
C	1·5	11·5	2·0	11·5
	P soluble in acetic acid-sodium acetate pH 4·8 mg P/100 g			
O	0·2	16·5	0·2	8·5
A	0·2	15·5	0·1	3·5
AA without silicate	0·2	14·5	0·2	8·0
AAS with silicate	0·4	19·0	0·3	12·5
Mean	0·2	16·5	0·2	8·0
C	0·3	5·0	0·4	5·5
	P soluble in 0·3*N*-HCl mg P/100 g			
O	0·5	39	1·0	38
A	0·5	44	0·2	24
AA without silicate	0·5	42	0·5	30
AAS with silicate	1·0	47	1·0	34
Mean	0·5	43	0·7	32
C	1·0	34	1·5	33

P in the two acid solvents show effects in the opposite direction; twice as much P was dissolved by acetic acid–sodium acetate from soils of Strip 2 and 1·3 times as much by 0·3*N*-HCl. On Series C, because the plots on Strips 2 and 4 both have little or no $CaCO_3$, there is no difference in soluble P by any of the methods. No chemical explanation of these $CaCO_3$ effects can be deduced from these simple tests, but the effects merit further study, especially with respect to: (1) soils with small P residues; (2) the adverse effect of over-liming and irregular distribution of liming materials on P soluble in calcium chloride and sodium bicarbonate; (3) the improvement of simple methods of soil analysis designed to give information on phosphate manuring. One other result of interest in Table 19 is the effect of past acidity on plot 4/A. The change to less-soluble phosphate (in weak acids) during the period of acute acidity has not been fully reversed during the 10 years since chalking in 1954–55. The soluble P in the two acid solvents is appreciably less (acetic acid–sodium acetate, 3·5; 0·3*N*-HCl, 24 mg P/100 g) than for the plots of other Series (O, AA, AAS) on strip 4.

Sodium silicate has increased the yield of barley on the plots without P, but not on those given superphosphate, since it was first applied in 1862. It seems that the silicate increases the availability of the small amount of P in the plots not given any. It is not expected that simple methods for measuring soluble P would detect any change with certainty, but again it is reasonable to expect that the silicate would also react with the larger amounts of P in the superphosphate plots. Soluble P measurements on these would be therefore more rewarding. Any increase in available P on these plots would not alter barley yields, because a generous dressing of superphosphate is given to the crop each year. Table 19 shows the effect of silicate on soluble P, measured by the same four methods used to detect the effect of $CaCO_3$. As was noted on the effect of $CaCO_3$, the methods divide into the same two groups by showing differences in opposite directions for the effect of silicate. With 0·01*M*-$CaCl_2$ and 0·5*M*-$NaHCO_3$, the amounts of soluble P are much less for silicate plots (AAS) than for others (AA). With acid solvents, the soluble P is significantly more for the silicate plots. As with $CaCO_3$, no chemical explanation can be given of the sodium silicate effects from these simple tests, but they do establish that sodium silicate alters the solubility of soil phosphate.

The effects on soluble P by $CaCO_3$ and sodium silicate reported here are not because of differences between the total P content of Strips 2 and 4. Although total P has not been determined recently, the differences were small in 1946 and cannot have changed much since.

Extending the use of the Hoosfield Barley Experiment. Even with the more productive modern variety of barley, the experiment on Hoosfield was not expected to give much new information. Changes have therefore been proposed. Part of the site will have a rotation of different crops, and provision will be made for testing soil sterilants. These changes will allow barley grown continuously to be compared with barley after other crops, and allow losses from soil-borne diseases and pests to be estimated. To improve the continuous-barley section, several different amounts of fertiliser N will be tested. The area under a crop rotation includes part of the sodium silicate plots, so that effects on crops other than barley will be forthcoming.

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ESTIMATING TRENDS IN FERTILISER USE

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In no other country is so much known as in Great Britain of how farmers manure their crops and of how their practice has changed with the years. This detailed information comes from two main sources. Since 1953 the Ministry of Agriculture has provided annual statements of the amount of fertiliser nutrients applied in each county, based on farmers' claims for subsidy payments. However, as these claims are made for a farm as a whole, the county totals, although useful in many ways, do not show how the manuring of individual crops is changing, information valuable both to the fertiliser industry as a guide to long-term planning and to advisory and research workers. Detailed information of this kind can be collected satisfactorily only by personal interview with farmers, as in the Survey of Fertiliser Practice.

Started 25 years ago, the main purpose of the first war-time surveys was to determine how far farmers were making proper use of their fertiliser ration, when lack of shipping made necessary a choice between imports of fertilisers and imports of food; the results also helped advisory workers by drawing their attention to instances of farm practice not in accordance with their recommendations. From the start the surveys were done by the Regional Soil Scientists of the National Agricultural Advisory Service (formerly the Provincial Soil Chemists); the Statistical Department at Rothamsted planned the surveys, selected the samples of farms and analysed the results, which were reported jointly. However, as the information was of interest not only to research and advisory workers but also to the fertiliser industry, additional fieldmen for large-scale surveys in 1957/8, 1962 and 1966 were provided by the Fertiliser Manufacturers' Association Ltd. The sample is now selected by the Agricultural Census Branch of the Ministry of Agriculture at Guildford. Since 1956, surveys on similar lines have been done by the Scottish Agricultural Colleges and the A.R.C. Statistics Unit, formerly at Aberdeen and now at Edinburgh.

Survey methods. In contrast with many farm surveys, the policy in the Survey of Fertiliser Practice is to survey small districts (counties or part-counties) chosen to be reasonably homogeneous with respect to soil or farming type. For example, in Shropshire the mixed arable and dairy farms on the lighter-textured Triassic drifts in the east and south-east of the county were surveyed separately from the more typical dairy farms on soils derived from boulder clays in the north. The districts are chosen partly for their special interest to the Regional Soil Scientist, and the sample may then be restricted to farms on a particular soil series or to other groups of related soils on which investigations, such as a series of fertiliser experiments, are being made. In South Shropshire and the adjoining area of Herefordshire, for example, farms on the Bromyard and

Munslow Series were surveyed. However, in years when a national survey is planned, the most important consideration is that the surveyed districts as a whole shall be representative of the main farming types in England and Wales. Thus a national survey yields detailed information for many widely scattered districts, each sampled intensively, in preference to sampling all parts of the country evenly but comparatively thinly. Such national surveys were made in 1954, 1957/8, 1962 and 1966; as the main purpose is to find out how practice is changing, some districts were included in more than one survey, though with a different sample of farms.

Despite the many soil and farming types in England and Wales, comparatively few surveys are needed to obtain reasonably accurate estimates of how fertiliser use is changing in different parts of the country. Although farmers' ideas of how crops should be manured may differ greatly, large groups of farmers facing similar problems tend to make similar decisions. Thus each major farming type has its own pattern of fertiliser use as well as of cropping. Moreover, changes in the pattern occur at about the same time on most farms of the type, regardless of the part of the country where they occur.

The farms to be visited in each district are selected systematically from the four size-groups, 20–50, 50–150, 150–300 and over 300 acres of crops and grass, and the allocation of the sample of farms between these groups is approximately proportional to the total areas in each group. In the earlier surveys only 30–40 farms per district were visited, but for the last 10 years the sample has been about 60 farms, except in 1962 when it was 90 farms per district. A fieldman needs about 6 weeks to visit 60 farms. The fieldwork is usually done in summer or early autumn, by members of the staff of the Regional Soil Science Departments of the N.A.A.S., representatives of fertiliser firms and by agricultural students. The survey information is obtained solely by interview with the farmer, usually in his house or office, and the surveyor is not expected to walk the fields. Sometimes soil samples are taken from a random sample of the fields on each farm; this usually entails a separate visit by someone from the Regional Soil Science Department.

National trends in fertiliser consumption. The continuing demand for

TABLE 1

Total fertiliser consumption in England and Wales

(per acre of crops and grass)

(cwt/acre) × 100

Year	N	P_2O_5	K_2O
1944–45	(12)	(21)	(7)
1953	15	22	14
1954	16	22	16
1956	19	23	19
1958	21	24	23
1960	27	28	28
1962	33	30	28
1964	38	29	28
1966	40	27	28

Source: 1953–66 Ministry of Agriculture based on subsidy claims. The figures for 1944–45 are estimated from the total consumption in the United Kingdom.

surveys has arisen in part from the interest of the fertiliser industry in discovering how the different crops, and in particular grassland, have contributed to the large changes in total consumption shown by the official estimates. Table 1 shows that during the period 1953–66 the amount of P/acre of crops and grass increased by one-quarter, K doubled and N almost trebled. After the war the consumption of N increased slowly at first, but faster in the 1950s, no doubt because the change in fertiliser subsidies favoured nitrogen use. There was a further sharp increase in the early 1960s and consumption is still increasing steadily, but more slowly, and reached 0·4 cwt N/acre in 1966. In the 1950s the increases in K were similar to those for N, but subsequently the average amounts of K remained steady at just under 0·3 cwt K_2O/acre. Having decreased slightly after the war, consumption of P increased to 0·3 cwt P_2O_5/acre by 1962, but is now a little less.

Trends in fertiliser practice for different crops. For comparison with changes in total use Table 2 shows trends in fertiliser used for individual crops; the estimates for 1966 are provisional, based on the 14 districts so far analysed. Increases in the use of nitrogen on cereals and leys have been greater than the average, those for permanent grass less. In the 1950s the area treated with P fertiliser increased rapidly, but this was offset by a decrease in the average amounts applied per treated acre, associated with combine-drilling of cereals, and, on grassland, with the use of compound fertilisers in place of basic slag. On the average, the amount of P and K used on cereals has gradually increased, mainly because more of the crops

TABLE 2

Trends in fertiliser practice in England and Wales 1950–66

(cwt/acre) × 100

		N	P_2O_5	K_2O
Wheat	1950–52	21	24	11
	1957	36	25	26
	1962	57	31	35
	1966	(66)	(33)	(35)
Barley	1950–52	16	26	16
	1957	24	27	31
	1962	43	30	38
	1966	(54)	(30)	(35)
Potatoes	1950–52	80	88	114
	1957	91	92	143
	1962	118	111	183
	1966	—	—	—
Temporary grass	1950–52	14	28	9
	1957	19	26	16
	1962	37	32	23
	1966	(50)	(29)	(24)
Permanent grass	1950–52	5	18	3
	1957	8	15	6
	1962	16	21	11
	1966	(18)	(17)	(10)

Note: The 1966 figures are provisional.

are dressed; in some arable districts rates of K have declined since 1962. From 1957 to 1962 more P and K were used on leys and permanent grass, but, since 1962, changes in the amounts of K used have been small, while amounts of P have decreased.

Differences between types of farm. From the first, the surveys showed that arable farmers, accustomed to manuring generously cash crops such as potatoes and sugar beet, usually applied fertiliser liberally to cereals and grass also, whereas the wartime grassland farmer, unaccustomed to giving more than an occasional dressing of basic slag to his grassland, often attempted to grow arable crops with little or no fertiliser. On average, arable farmers still use more fertiliser than dairy farmers, although the difference is much less than formerly, and stock farmers have been particularly slow to turn from basic slag to compound fertilisers containing all three nutrients. Thus surveys in four Midland counties in 1957/58 showed that grassland on dairy farms received much more N and K than grassland on stock farms (Table 3); P fertiliser was also used more frequently on dairy farms, but the amounts applied per acre were less, because most dairy farmers used a compound fertiliser, whereas the stock farmers relied on an occasional large dressing of basic slag. How far these differences persist will be revealed by the 1966 survey, for which an analysis will be made by farming type, as well as by districts.

TABLE 3

Grassland manuring on dairying and stock farms (1957/58)

	Percentage of acreage receiving:			
	N	P	K	FYM
Leys mown:				
Dairy farms	56	43	26	11
Stock farms	37	37	19	4
Leys grazed:				
Dairy farms	46	40	26	12
Stock farms	23	30	14	6
Permanent grass:				
Dairy farms	24	21	9	8
Stock farms	12	16	6	4

As there is no up-to-date map of farming types for England and Wales to bring out the differences between arable and grassland farms, and, among the grassland farms, between dairying and other livestock farms, the surveyed districts were grouped according to their acreage of tillage expressed as a percentage of their total area of crops and grass; the "A" groups have at least 60% of their area in tillage, "AG" between 40 and 60% in tillage and the "G" and "U" groups being mainly in grass. Regional subdivision within the "AG" and "G" groups gives a further broad differentiation of farming types (Table 4). The changes in the past 12 years in the use of N on spring barley and grazed leys for these groups are shown in Tables 5 and 6, which include the results of surveys in 85 districts in England and Wales, many of which have been surveyed several times.

TABLE 4

Grouping of surveyed districts

Group ref.	Tillage area* (% crops and grass)	Farming type	Counties and districts included
Arable districts			
A0	>80	High-value cash crops	Peat, silt and warp soils
A1	60–80	Mainly cash crops (cereals)	East Anglia (excluding Fens)
A2	60–80	Mainly cash crops (cereals)	Parts of Yorks, Notts, Lincs. (excluding warp soils)
AG1	40–60	Cash crops (substantial dairy side)	Arable areas of southern England
AG2	40–60	Cash crops (less dairy and more sheep and cattle)	Remaining arable areas of E. Midlands and North
Lowland grass districts (England)			
G1	30–40	With substantial diary side	Home Counties grassland areas
G2	30–40	With less diary and more sheep and cattle	E. Midlands and N. England
G (N.W.)	<30	Mainly dairying	Dairy grasslands of N.W. Midlands
G (S.W.)	<30	Mainly dairying	West Midlands, W. and S.W. England (excluding moorlands)
Wales and English uplands			
U	<20	Various livestock enterprises	Uplands of S.W. and N. England; Wales

* The percentages are for the period 1957–62; from 1962 to 1966 the tillage area of England and Wales increased from about 37 to 42% of the total crops and grass.

TABLE 5

Use of N on spring barley

(cwt/acre) × 100

Group of districts	1954	1958	1962	1966
A1	22	36	44	57
A2	21	30	45	58
AG1	24	35	51	64
AG2	14	26	42	54
G2	13	23	37	51
G (N.W.)	9	15	33	44
G (S.W.)	11	16	34	—
U (Wales)	5	8	17	—

TABLE 6

Use of N on grazed ley

(cwt/acre) × 100

Group of districts	1954	1958	1962	1966
A1	28	39	57	62
A2	17	26	33	—
AG1	23	34	50	65
AG2	13	22	41	48
G2	12	19	31	37
G (N.W.)	16	26	44	60
G (S.W.)	10	18	32	—
U (Wales)	—	7	12	—
U (N.)	—	13	25	—

In the early 1950s spring barley grown in the arable areas* of the country received twice as much N as in the grassland areas and about four times as much as in Wales and the uplands of south-west and northern England. The large and fairly constant annual increases in nitrogen use seem to have begun rather sooner in the arable districts and were least and most belated in Wales. Bearing in mind that the 1966 figures are provisional, it seems that in lowland England the use of N for barley has increased at an almost constant rate in all parts of the country.

The use of nitrogen on grazed leys shows similar differences. Again the increases have been almost linear over the whole period: those parts of the country where most nitrogen was used on leys in the early 1950s have continued to use most, although many are now using three times as much as formerly. The order of the groups is somewhat different from that of Table 5, the dairy grasslands of the north-west Midlands using more, whereas the east Midlands and Yorkshire have somewhat lagged behind in nitrogen use on grassland, perhaps because in these districts there is less dairying and more sheep and cattle grazing.

Using approximate crop areas for each group of districts, estimates of fertiliser consumption from the survey can be checked against the national totals from subsidy payments. Comparisons for 1957/58 and 1962 are given in Table 7. The survey estimates were very similar to the official figures.

TABLE 7

Official and survey estimates of fertiliser use in England and Wales

(cwt/acre) × 100

	N		P_2O_5		K_2O	
Year	Official	Survey	Official	Survey	Official	Survey
1957–58	20	21	24	25	22	23
1962	33	34	30	30	28	27

Changes revealed by the 1966 survey. The 1966 survey will give the most comprehensive information on trends in fertiliser use on individual crops since 1962. All the results are not yet in, but those for 14 districts give some indication of current trends in most parts of the country, although the grassland areas of west and south-west England and of Wales are each represented by only one district.

Cereals. The amount of N applied for winter cereals (Table 8) continued to increase in all the districts for which there are comparable results for 1962; the increases were slight for the two fen soils, but averaged about 0·1 cwt N/acre elsewhere. N.W. Norfolk, growing about 25,000 acres of winter wheat, seems the first district to record an average dressing of more than 100 units on a cereal crop (winter wheat). In most districts the area of spring barley is much greater than in 1962, partly replacing other arable crops but mainly leys and permanent grass. For spring cereals also,

* In referring to arable areas we must exclude the peat, silt and warp soils where barley almost always follows a heavily manured potato or other root crop; even in these districts, however, the barley crop participated in the general increase in nitrogen use in the latter part of the period.

TABLE 8

Manuring of winter cereals

(cwt/acre) × 100

Group	District	N			P_2O_5			K_2O		
		1957–58	1961–62	1966	1957–58	1961–62	1966	1957–58	1961–62	1966
A	Isle of Ely (peat)	15	14	16	12	11	16	14	7	7
	Holland (silt)	—	31	36	—	3	3	—	3	4
	N.W. Norfolk	30	—	99	27	—	34	36	—	39
AG	Berkshire (Chalk)	48	65	74	32	28	36	38	33	38
	Glos. (Cotswolds)	42	66	83	25	36	40	31	42	39
	Dorset (Chalk)	37	56	65	29	29	31	37	40	38
	N.E. Northants.	31	56	70	31	40	46	22	33	39
	N.E. Leicestershire	30	45	64	23	36	35	21	43	34
G	Hereford (Bromyard)	26	43	53	32	34	39	22	37	37

the amounts of N continued to increase, but, whereas in many arable districts the rate of increase was similar to that before 1962 (an average rate of 0·7 cwt/acre was reached in some districts), information for two western grassland areas (the Fylde district of Lancashire and the Bromyard district of Herefordshire) shows a much smaller increase, possibly because much of the additional area now under barley was formerly grassland. For winter cereals there were small increases in the use of P since 1962, related to the increase in N. There was a large increase on winter cereals in Berkshire because more of the crop received fertiliser (66% in 1962, 96% in 1966).

The average change in use of K was small. However, in the arable districts (but not in other areas) less K was applied to spring cereals in 1966 than in 1962; the decrease was particularly large on the chalk soils of Berkshire and Dorset. Excluding the Fenland districts, the range of the average rates of application per district decreased from 0·21–0·38 cwt/acre in 1957/58 and 0·30–0·42 in 1962, to 0·34–0·39 cwt K_2O/acre in 1966. When the recently-introduced "High-N" compounds become more familiar to farmers, amounts of K for cereals are likely to decrease further.

Potatoes. The information on trends in potato manuring is very limited, but includes two important groups of fenland farms, peat farms in the Isle of Ely and silt farms in Holland (Lincs.). The N.A.A.S. has made many manurial trials in both Fenland areas; those on peaty soils (Pizer *et al.*, 1961) are already the basis of advice to farmers, and those on silt soils are now being written up. Farmers on peat soils were recommended to apply 100–120 units N, 180–200 units P_2O_5 and 150–200 units K_2O/acre for maincrop potatoes; these amounts were for fertilisers applied over the ridges or placed, and more would be needed when broadcast "on the flat".

Potato-growers have often been criticised for taking little account in their manurial policy of the kind of soil they farm. Although crop requirements differ greatly from one soil to another, average fertiliser use in different parts of the country was surprisingly uniform. The 1966 survey results (Table 9) are of special interest in showing that growers of potatoes

TABLE 9

Manuring of potatoes

(cwt/acre) × 100

District	Soil type	N 1957–58	N 1961–62	N 1966	P_2O_5 1957–58	P_2O_5 1961–62	P_2O_5 1966	K_2O 1957–58	K_2O 1961–62	K_2O 1966
Isle of Ely	Peat	102	116	134	125	148	186	158	182	206
Lincs. (Holland)	Silt	—	130	132	—	134	130	—	174	197

on peaty soils seem to have rapidly adapted their manuring to advisory recommendations by substantially increasing their P and K dressings. This change of practice is in sharp contrast with that of potato growers on the nearby fen silt soils, who used much the same dressings as in the previous survey in 1961.

Sugar beet. The only available information on sugar-beet manuring is for three districts of East Anglia and shows no large or consistent trend (Table 10). The small ratio of P (80 units/acre) to N and K (150 units/acre) in N.W. Norfolk is interesting.

TABLE 10

Manuring of sugar beet

(cwt/acre) × 100

District	N 1957	N 1962	N 1966	P_2O_5 1957	P_2O_5 1962	P_2O_5 1966	K_2O 1957	K_2O 1962	K_2O 1966
Isle of Ely (peat soils)	79	68	74	75	108	114	106	137	126
Holland (silt soils)	—	106	112	—	96	96	—	140	167
N.W. Norfolk	114	—	149	84	—	78	194	—	146

Leys. As indicated in Table 6, the trends to increased N manuring of grazed leys have continued with little change, and in many districts the average dressing exceeded 0·60 cwt/acre in 1966. Some fields received much more than this: for five of the districts surveyed in 1966 there is information on the manuring of strip-grazed fields, and of fields that were both mown and strip-grazed; the average dressing on strip-grazed fields was 1·04 cwt N/acre and on fields both mown and strip-grazed, 1·24 cwt N/acre.

The changes in nitrogen use on mown leys were similar to those of grazed leys, but average dressings were 0·10–0·20 cwt N/acre larger. As with grazed leys, the available information suggests that the rate of increase in the average amount used on treated fields was much the same as in earlier years. However, the increase in nitrogen use on grassland in the early 1960s resulted from more fields being dressed, as well as from the changes in the amounts applied on these fields. In many districts almost all the leys now receive some nitrogen, so the average increase may in future be less rapid.

Although some districts of west and north-west England used P fertiliser very generously on leys—average dressings were about 0·6 cwt P_2O_5/acre in the Fylde district of Lancashire and in central Cheshire—most other parts of England applied only about 0·3 cwt/acre. Average amounts of potassium, ranging from 0·3 to 0·5 cwt/acre, seem to have

TABLE 11

Manuring of leys 1957–66

(cwt/acre) × 100

		N			P_2O_5			K_2O		
Group	District	1957–58	1961–62	1966	1957–58	1961–62	1966	1957–58	1961–62	1966
A1	N.W. Norfolk	59	—	88	12	—	30	40	—	30
A2	E. Durham	—	—	64	—	—	35	—	—	29
AG1	Dorset (Chalk)	26	39	73	20	22	33	27	27	34
	Berkshire (Chalk)	37	55	64	23	38	33	29	46	30
	Gloucestershire (Cotswolds)	16	36	53	21	19	29	12	15	20
AG2	N.E. Northants.	14	32	47	30	35	21	9	15	12
G2	S. Warwickshire	—	20	40	—	33	42	—	8	13
	E. Leicestershire	24	42	58	23	47	17	8	17	19
G (N.W.)	Lancashire (Fylde)	22	46	87	33	29	64	29	43	49
	C. Cheshire	—	—	84	—	—	38	—	—	33
G (S.W.)	Hereford (Bromyard)	10	29	30	36	44	29	7	19	21
U	W. Carmarthen	10	—	48	33	—	52	10	—	23
	N. Lancashire	—	—	61	—	—	41	—	—	34

changed little in the last 4 years. It is interesting that the strip-grazed fields mentioned above received no more P and K than other grazed or mown fields in the same districts.

Permanent grass. Although fertiliser use on leys was similar to that on barley, the 10m. acres of permanent grass in England and Wales still

TABLE 12

Manuring of permanent grass

(cwt/acre) × 100

		N			P_2O_5			K_2O		
Group	District	1957–58	1961–62	1966	1957–58	1961–62	1966	1957–58	1961–62	1966
A1	N.W. Norfolk	18	—	65	7	—	15	10	—	19
A2	E. Durham	—	—	36	—	—	26	—	—	16
AG1	Dorset (Chalk)	12	20	31	5	10	11	7	11	10
	Berkshire (Chalk)	17	29	25	9	13	16	13	15	12
	Gloucestershire (Cotswolds)	5	12	22	13	11	10	5	7	7
AG2	N.E. Northants.	4	13	14	5	24	10	2	7	5
G2	S. Warwickshire	—	6	14	—	18	21	—	1	4
	E. Leicestershire	6	18	19	14	19	10	2	9	9
G (N.W.)	Lancashire (Fylde)	15	28	39	28	30	33	18	31	33
	C. Cheshire	—	—	50	—	—	23	—	—	24
G (S.W.)	Hereford (Bromyard)	5	12	13	18	25	15	3	9	9
U	W. Carmarthen	6	—	25	28	—	28	6	—	15
	N. Lancashire	—	—	24	—	—	33	—	—	20

Notes (Tables 8, 11 and 12): S. Warwickshire: the first survey was in 1960.
N.E. Leicestershire: the area surveyed in 1966 differed from that of the previous surveys.
C. Cheshire: this survey was done in 1965.

receive little fertiliser, no more than was used on leys 10–15 years ago. Even on the intensive dairy farms of Lancashire and Cheshire, less than two-thirds of the grazed and mown permanent grassland received nitrogen in 1966, and the average amount applied on the treated fields was only about 0·6 cwt N/acre. Nor was permanent grass more generously treated in the arable districts: in the Cotswolds and West Berkshire only 40% of the permanent grass acreage received N at an average of about 50 units per treated acre. In the surveyed areas of the east and west Midlands, covering parts of the counties of Hereford, Leicester, Northampton and Warwick, average amounts of N ranged only from 0·11 to 0·17 cwt/acre on grazed fields and from 0·17 to 0·27 cwt/acre on mown fields.

These small dressings might indicate that many farmers, particularly those producing fat sheep and cattle from grass, are still relying on clover-N, but this is not borne out by the use of P fertiliser on permanent grass, which shows fairly consistent decreases on grazed fields, and except in some arable districts, on mown fields also.

Little potassium fertiliser was used except in arable and dairying districts; amounts were similar to 1962. These results suggest that grassland farmers, particularly sheep and cattle graziers, have reacted to unfavourable prices by restricting expenditure on fertilisers for permanent grass.

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