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# The Book of the Rothamsted Experiments

BY A. D. HALL, M.A. (OXON.), F.R.S.

LATE DIRECTOR OF THE ROTHAMSTED EXPERIMENTAL STATION, FIRST PRINCIPAL  
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REVISED BY E. J. RUSSELL, D.Sc., F.R.S.

DIRECTOR OF THE ROTHAMSTED EXPERIMENTAL STATION

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## PREFACE TO THE SECOND EDITION

IN this edition I have carried on the tables for a further decade, and made the necessary alterations in the text. Some of the deductions drawn in the first edition have required modification, but no great change has been made: the picture is essentially as Mr Hall painted it. Two new chapters have been added: one by Mr Hall, on the secondary effects of manures on the soil, gives a connected account of the important investigations he carried out here on this very difficult and important subject. The other chapter, by myself, contains a summary of the investigations made during the past ten years, and still continuing, on the biochemical processes in the soil.

I hope when conditions become more normal that it will be possible to arrange for a proper statistical survey of the mass of valuable data accumulated at Rothamsted. The greatest pains are taken to ensure the reliability of the data, and I cannot help thinking that the application to them of modern statistical methods would yield information of high value both to the man of science and to the practical agriculturist. We have not yet learnt anything like all the lessons the Rothamsted fields can teach us.

E. J. R.

HARPENDEN, 1917.

## PREFACE TO THE FIRST EDITION

IN writing this account of the Rothamsted Experiments—the sixty years' work of two men, Lawes and Gilbert, whose names have become familiar in every part of the world where agriculture is something more than a matter of tradition and custom—I am of necessity acting as an external demonstrator, describing from the outside, as it were, what seem to be the chief lessons conveyed by the experiments which I have now the honour to conduct. Lawes and Gilbert are dead, and with them passed away many observations of value and many notable generalisations which they had found no opportunity of giving to the world, nor had I the personal contact with either which would enable me to report even such portions of their experiences as might have been conveyed by conversation. But though these losses cannot be repaired, and though nothing can replace the instinctive knowledge that comes of having seen a thing grow year after year, yet the position of an outsider has some advantages, especially when drawing up an account which, like the present, is addressed to the general student of the subject.

In the first place, the outsider approaches the consideration of each experiment without any of the prepossessions arising from too exclusive a recollection of the purpose with which the experiment was originally framed. Readers of the *Rothamsted Memoirs* will know how certain ideas, *e.g.*, the source and function of the nitrogen in vegetation, occupied the minds of Lawes and Gilbert from the very beginning of their experiments until the end. In consequence, the papers on specific investi-

gations often tend to be less accounts of the experiment as a whole than discussions of such of its results as bear upon the dominant idea with which Lawes and Gilbert were then engrossed.

The outsider, again, who has any knowledge of his subject cannot fail to bring some ideas of his own which he can find illustrated and elucidated in the work done at Rothamsted. For here comes the particular distinction of the Rothamsted Experiments; the plots exist to-day as they have been for the last fifty years or so, and records of the most astonishing completeness remain of their past history, so that as soon as one looks closely into the material there is hardly any part of the science of the nutrition of the plant on which it cannot be made to throw light. Indeed only a portion of the story of the Rothamsted Experiments has yet been told, for new matter will be discovered in them as our knowledge grows and fresh lines of investigation are opened up. Accordingly, in planning this account I have tried to look at each experiment from as general a point of view as possible, and to set out what information it can afford both to the student of agricultural science and to the man more occupied with practical problems. I have endeavoured to summarise under the head of each crop the mass of information that has already been published in the long series of *Rothamsted Memoirs*, and to add other facts and deductions arising out of the experiments which the original investigators had not hitherto been able to publish.

As to the purpose of the book, that is best dealt with by discussing the purpose of the Rothamsted Experiments themselves. They are, above all, attempts to obtain knowledge—to ascertain the conditions under which the plant grows and the soil supplies it with nutriment. And as the attainment of knowledge is the prime object, practical considerations are put on one side in framing the scheme of the experiments. For example, on one of the Rothamsted fields wheat has been grown for the last sixty years, year after year, on the same plots of

land with the same manures. As the British farmer never grows wheat continuously on the same land, and rarely uses any kind of manure for it, the whole experiment is from one point of view hopelessly unpractical; indeed many men might consider that to grow wheat at all nowadays is unpractical. But the aim of the experiments is to find out *how the wheat plant grows*, and the scheme of manuring and management adopted is the most practical method of solving that problem. Experiments which only aim at ascertaining how to derive the greatest monetary return from a given crop, however necessary they may be, are only of value for a short time and for the particular soil and locality where they are carried out. During the period the Rothamsted wheat field has been under experiment the price of wheat has been as high as 75s. and as low as 23s. ; any conclusions reached as to the most paying system at the former price would have to be altogether revised at the lower rates. There is, of course, every probability that price and other economic conditions may fluctuate just as much in the future as they have done in the past, but the one thing that will for ever remain unchanged is the manner in which the crop draws its nutrition from the air, the water, and the soil. Hence the farmer who best knows how this process takes place will, other conditions being equal, be the one best fitted to continue to derive a profit under the changing conditions.

The great object, then, of the Rothamsted Experiments is to obtain knowledge that is true everywhere, and to arrive at principles of general application, leaving the farmer himself, through his more immediate advisers, to adapt these principles to his own practical conditions and translate them into pounds, shillings, and pence. Thus the farmer who visits Rothamsted must not expect to see demonstrations of the most profitable means of growing this or that crop, but rather to obtain information as to its habits and requirements which on reflection he can make useful under his own conditions. Some of the work also that is going on may seem to deal with problems little connected with practice; so remote, in fact, that

they never can have any bearing upon the business of farming. There are, however, many matters in which the actual farmer will always have to rely upon the advice of scientific experts, and as a rule the unpractical-looking experiments are devised to settle this or that point on which the scientific man must have information in order to form a correct judgment for the guidance of the practical man.

Agricultural science involves some of the most complex and difficult problems the world is ever likely to have to solve, and if it is to continue to be of benefit to the working farmer, the investigations, as far as their actual conduct goes, must very quickly pass into regions where only the professional scientific man can hope to follow them. However, it is not with such research that the present volume deals; here, I trust, there is nothing that the farmer with an intelligent interest in his profession cannot appreciate and find useful. The book is intended, firstly, for any man concerned with the management of land, whether farmer or market gardener, land-owner or agent, who wants to learn something of the processes going on in the growing crop and in the soil, as they have been elucidated by the most complete set of field experiments the world has yet seen. Secondly, the book is intended for the agricultural student; it will furnish a running commentary on a very large portion of the information he finds in his text-books on agriculture and agricultural chemistry. It is of great importance to the student that he should from time to time get in touch with the sources of the statements and conclusions he reads in his text-books or hears in lecture, since he obtains thereby some idea of the extent to which these statements can be trusted to apply to working conditions. Lastly, the book is intended for the agricultural teacher and expert, for whom it will provide a certain amount of unpublished matter concerning Rothamsted, and will also serve as a guide to the very extensive series of reports issued by Lawes and Gilbert. To this end references have been added at the close of each chapter to the original papers dealing with the subject.

Throughout I have kept the teacher in view, and have endeavoured to supply him with the summaries and illustrations which will be useful in his class work.

Of course, in many respects the book covers the same ground as the summary of the Rothamsted Experiments drawn up by Gilbert for his lectures in America, which were published both by the United States Department of Agriculture and by the Highland and Agricultural Society of Scotland in 1895. The American lectures were, however, in the main intended for the reader who was already equipped with a considerable knowledge of agricultural science; on the one hand, they did not deal with all the Rothamsted work, and on the other, they went into much greater detail than is here attempted. In the present book I have endeavoured to make matters plain to the non-technical reader and to elucidate the subject by diagrams and simplified tables, leaving the specialist to consult the original papers for fuller information.

By the kind permission of Mr R. Warington and the Council of the Royal Society, I have been permitted to reprint Mr Warington's account of Lawes and Gilbert from the Obituary Notices of the Royal Society, and this forms the best introduction to the history of the Rothamsted Experiments and the personality of their founders.

In the Appendix will be found a bibliography of all the more important papers issued by Lawes and Gilbert, together with others which deal with Rothamsted material by independent investigators. A list will also be found of previous books which have given a general account of the experiments, including Dr Fream's little book published in 1888, which, though dealing only with wheat, barley, and grass, has formed for so many readers their introduction and guide to the Rothamsted investigations.

Although by the terms of the trust deed no teaching may be done at the Station, accommodation may be provided for persons capable of assisting in research; these are welcomed and are given all facilities for carrying out special

investigations with the material in which the Station is so rich.

In this book little has been said of the work now in progress ; speaking generally, the old plots as described are being continued without essential change, but the current investigations deal chiefly with the composition of the crops produced and with the soil. The bacterial life of the soil forms indeed the unknown territory which promises the greatest reward to the explorations of the agricultural chemist of to-day.

In the preparation of the book, I have to thank Dr N. H. J. Miller for most of Chapter II., and both him and Mr J. J. Willis for much detailed information and many facts that have never been recorded. Dr H. T. Brown, F.R.S., and Dr J. A. Voelcker have been good enough to read the proof-sheets and make many suggestions. Particularly I have to thank Mr G. T. Dunkley for the great trouble and care he has taken over the preparation of the tables and diagrams ; without the help of his knowledge of the past history and his familiarity with the records, I should have found it impossible to prepare this account of the Rothamsted Experiments.

A. D. HALL.

THE ROTHAMSTED EXPERIMENTAL STATION,  
HARPENDEN, *March* 1905.

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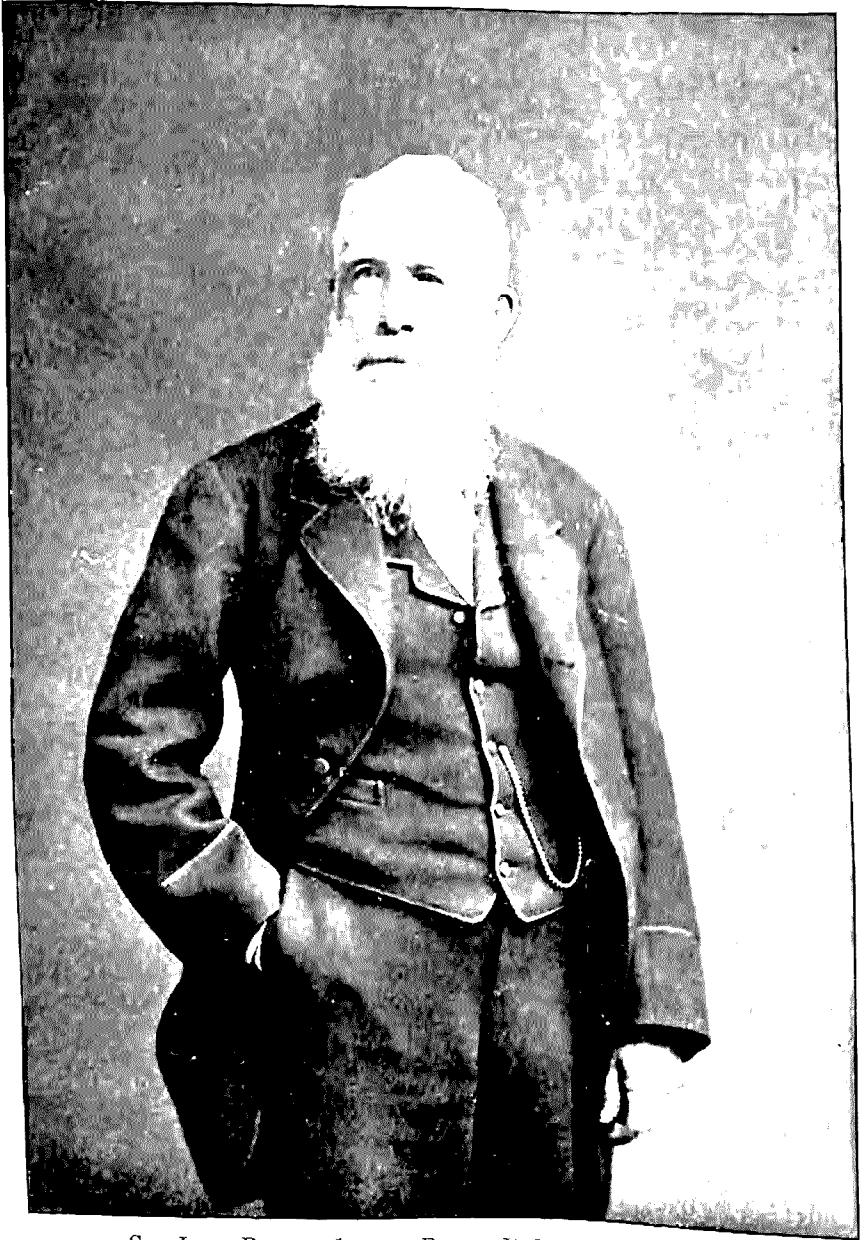
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SIR JOHN BENNET LAWES, BART., D.C.L., LL.D., F.R.S.

## BIOGRAPHICAL INTRODUCTION\*

SIR JOHN BENNET LAWES, BART., 1814-1900

THE manor-house of Rothamsted, situated in the parish of Harpenden, Herts, was the birthplace of John Bennet Lawes, and the Rothamsted farm became, in subsequent years, the scene of the great work of his long life. So far-reaching have been the results which he achieved, that the name of Rothamsted is now a household word wherever the science of Agriculture is studied.

The ancestors of Sir John Lawes had occupied Rothamsted for many generations. Jaques Wittewronge came to England from Flanders in 1564, owing to the religious persecution then prevailing. The manor of Rothamsted was purchased in 1623 for his grandson, John Wittewronge, who was then a minor. John Wittewronge was knighted by Charles I., and afterwards created a baronet by Charles II. In consequence of the failure of male heirs, the manor passed to the Bennet family by the marriage of Elizabeth Wittewronge with Thomas Bennet, and finally to the Lawes family by the marriage of Mary Bennet (great-granddaughter of James Wittewronge) with Thomas Lawes. His son, John Bennet Lawes, was the father of the John Bennet Lawes of whom we have to speak, who was born at Rothamsted on December 28, 1814.

John Bennet Lawes was an only son. He lost his father when eight years old, and owed much to his mother's bringing

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\* Largely reprinted from the Obituary Notices of the Royal Society, by the late R. Warington.

up. He seems to have led the life of a country boy, and his studies he afterwards described as being "of a most desultory character." Experiments in chemistry, made at home, seem to have been one of his favourite occupations. He was sent successively to Eton, and to Brasenose College, Oxford, which he entered in 1832. While at Oxford he attended some of the lectures of Dr Daubeny, the professor of chemistry. He left the University without taking a degree.

In 1834 Mr Lawes entered on the personal management of the home farm at Rothamsted, then of about 250 acres; he at the same time threw himself heartily into chemical investigations. He tells us: "At the age of twenty I gave an order to a London firm to fit up a complete laboratory, and I am afraid it sadly disturbed the peace of mind of my mother to see one of the best bedrooms in the house fitted up with stoves, retorts, and all the apparatus and reagents necessary for chemical research. At the time my attention was very much directed to the composition of drugs; I almost knew the Pharmacopœia by heart, and I was not satisfied until I had made the acquaintance of the author, Dr A. T. Thomson. The active principle of a number of substances was being discovered at this time, and, in order to make these substances, I sowed on my farm poppies, hemlock, henbane, colchicum, belladonna, etc. Some of these are still growing about the place. Dr Thomson had suggested a process for making calomel and corrosive sublimate by burning quicksilver in chlorine gas. I undertook to carry out the process on a large scale, and wasted a good deal of time and money on a process which was, in fact, no improvement on the process then in use." At this time Dr Anthony Todd Thomson, Professor of Materia Medica at University College, London, was his chief instructor and adviser. An old barn at Rothamsted was transformed into a laboratory, and here the calomel was afterwards made; this laboratory remained in active use till 1855.

The researches of De Saussure, on the nutrition of plants, seem to have first called Mr Lawes' attention to the relations

between chemistry and agriculture. In 1837 he commenced experiments in pots with agricultural plants, the manures made use of supplying various elements of plant food. These experiments were continued on a larger scale in 1838 and 1839. Spent animal charcoal was then a waste product, and Mr Lawes was asked by a London friend if it could be turned to any use. He therefore employed it as a manure in his pot experiments, and discovered that if previously treated with sulphuric acid its efficacy as a manure was greatly increased. Apatite and other mineral phosphates were soon treated in a similar manner, and the "superphosphate of lime," thus prepared, was found to be most effective as a manure, especially for turnips. The new superphosphate was employed on a large scale for crops on the Rothamsted farm in 1840 and 1841, and the results were so satisfactory that in 1842 Mr Lawes took out a patent for the manufacture of superphosphate.

The application of sulphuric acid to bones had been practised before the date of Mr Lawes' patent; the novelty of his patented invention consisted in the treatment of mineral phosphates in this manner. The supply of bone available for farmers is but small, but the supply of apatite, coprolite, and of the various rock phosphates discovered in recent years, is almost unlimited. These mineral phosphates are usually too insoluble to have any practical value as manure, but by treatment with a limited quantity of sulphuric acid, a mixture of monocalcic phosphate, phosphoric acid, and gypsum is produced. The phosphates in this compound are almost entirely soluble in water, and far more efficacious as manure than the phosphates of raw bone. The enormous influence which the introduction of superphosphate has had on the development of agriculture may be gathered from the quantity now annually employed by farmers. The annual manufacture of superphosphate in Great Britain amounts at present to about 1,000,000 tons, while the total manufacture in the world is about six times this amount. If Sir John Lawes had done

nothing more than introduce the manufacture of artificial manures, he would still rank among the greatest benefactors to agriculture.

The life of Sir John Lawes divides at this point into two parts. He became from the date of his patent a chemical manufacturer, carrying on an extensive London business, and as prosperity increased he embarked in a variety of enterprises. While, however, obliged to spend two days of every week in London, his devotion to agricultural research continued to increase, and the profits yielded by commerce were employed for the creation and maintenance of a large experiment station at Rothamsted. The experiments in the fields had already, at the date of his patent, reached a stage at which the continuous services of a trained chemist were urgently needed. On the recommendation of Dr A. T. Thomson, Mr Lawes engaged a young chemist who had studied under Liebig—Dr J. H. Gilbert. Dr Gilbert entered upon his work at Rothamsted in June 1843, and continued actively occupied in the scientific superintendence of the agricultural experiments during the whole of his long life. For fifty-seven years Lawes and Gilbert worked together on a great variety of agricultural problems; of these labours and their results we shall give a brief account, after completing our sketch of the life of each worker.

Mr Lawes married, in 1842, Caroline Fountaine, daughter of Andrew Fountaine, Esq., of Narford Hall, Norfolk. He enjoyed her society for more than fifty years, and her artistic power was not unfrequently employed in providing illustrations of the investigations in progress. As the commencement of manufacturing operations made great demands on his capital, Mr Lawes at this period let Rothamsted House, and for some years resided either in London or Devonshire.

His first factory for the manufacture of superphosphate was erected at Deptford Creek in 1843. The business rapidly extended, and in 1857 about 100 acres of land were purchased at Barking Creek, and a larger factory erected, including an

extensive plant for the manufacture of sulphuric acid. In 1866 Mr Lawes purchased the tartaric and citric acid factory at Millwall. The purchase was unwillingly made, but the new work was taken up with his accustomed energy and enterprise, many economies and improvements were introduced, and the factory became the most important of its kind in this country. In 1872 he sold the whole of his manure business for £300,000; he retained the tartaric and citric acid factory till his death. Mr Lawes had also a large sugar estate in Queensland: the low price of sugar and the lack of cheap labour prevented, in this instance, a commercial success.

The investigations at Rothamsted made rapid progress. In 1843 were commenced the systematic field experiments on turnips and wheat; the wheat field has grown wheat without intermission ever since. In 1847 the field experiments on beans commenced, and in 1848 those on clover, and on a four-course rotation. In 1851 the rotations of wheat and fallow and wheat and beans were started. In 1852 the field experiments on barley commenced. In 1856 those on grass land. In all about 40 acres were brought under experiment. Of all these crops complete chemical statistics were obtained. Experiments on sheep-feeding with various foods commenced in 1848. The whole bodies of ten animals—oxen, sheep, and pigs—of various ages and conditions as to fatness, were analysed between 1848 and 1850. In 1850 an extensive series of pig-feeding experiments was made.

The extent of the work undertaken, its thoroughness, and the practical value of the results obtained, gained the admiration of both scientific and practical men. At a meeting of Hertfordshire farmers at St Albans, on December 24, 1853, it was resolved to present Mr Lawes with a testimonial. The circular issued states: "It was considered that Mr Lawes has for many years been engaged in a series of scientific and disinterested investigations for the improvement of agriculture generally, which have been carried out to an extent, with an attention to accuracy and detail, and at a cost, never before

undertaken by any individual, or even by any public institution." The proposal was soon enlarged, and became national in its character. The subscriptions received amounted to about £1160. At Mr Lawes' desire, the greater part of this sum was spent in the erection of a new laboratory, which was opened at a gathering of distinguished agriculturists on July 19, 1855, the Earl of Chichester presiding on the occasion. The speeches made by Mr Lawes, Dr Gilbert, and others, have fortunately been preserved. Mr Lawes, on this occasion, paid a warm tribute to the work done by Dr Gilbert. Besides the gift of the laboratory, Mr Lawes received a handsome silver candelabrum, bearing a suitable inscription. In later years the laboratory was found too small for the preparation and storage of the numerous samples, and additional buildings were erected.

Mr Lawes was elected a Fellow of the Royal Society in 1854, and in 1867 one of the Royal medals was awarded to him and Dr Gilbert for their systematic researches upon agricultural chemistry. Seven papers by Lawes and Gilbert have been published in the Society's *Philosophical Transactions*.

The connection of Mr Lawes with the Royal Agricultural Society was naturally a close one. He became a member of the Council in 1848, and was afterwards a vice-president and trustee. In 1893 the presidency of the Society was offered to him, but declined on account of his advancing years. In the *Journal of the Society* the greater number of the reports on the Rothamsted agricultural investigations have been published; forty-six reports had thus appeared before the year 1900. In 1876 he took an active part in arranging for the commencement of the field experiments conducted by the Society at Woburn, in Bedfordshire. These experiments consisted in repetitions of the experiments at Rothamsted upon the continuous growth of wheat and barley with known manures, the experiments in this case being made upon a purely sandy soil; they also included rotation experiments designed to test the manurial

value of cattle foods. These experiments were conducted on the Duke of Bedford's estate, and at his expense.

The relations of Mr Lawes with the Chemical Society were also intimate. He became a Fellow in 1850, and was elected to the Council in 1862. The chief part of the chemical work done in the Rothamsted laboratory was communicated to this Society, and about twenty-two lectures and papers by Lawes and Gilbert, and other Rothamsted workers, appear in the *Journal and Transactions*.

Mr Lawes was a member of the Royal Commission appointed in 1857 "To inquire into the best mode of distributing the sewage of towns, and applying it to beneficial and profitable uses." Two members of this Commission, Lawes and Way, conducted for several years important experiments on sewage irrigation at Rugby. The investigation dealt with the quantity and composition of the grass receiving varying amounts of sewage, and its value as food for fattening oxen and milking cows, including the composition of the milk obtained. The effluent waters from the irrigated fields were also analysed, and the formation of nitrates in large quantities was demonstrated. The final report was published in 1865.

The aid of Rothamsted was again sought by the Government in 1863, the object in this case being to ascertain whether the malting of barley resulted in any increase of its value as a food. A considerable bulk of barley was divided into two lots, one of which was malted, and the loss in dry matter ascertained; feeding experiments were then made, in which the nutritive effect of a given weight of barley was compared with that shown by the quantity of malt which could have been produced from it. The trials with oxen, sheep, and pigs were made at Rothamsted, and those with milking cows at Rugby. The full report was presented to Parliament in 1866.

While the formal reports on the Rothamsted investigations were to a large extent the work of Dr Gilbert, Mr Lawes was himself an active writer on agricultural subjects. In middle

life he was a frequent contributor of short papers to agricultural newspapers and periodicals, both English and American; he also lectured from time to time to agricultural associations. His writings were always marked by great originality, they were also very practical in character. When bringing forward the results of recent scientific enquiries, he would avoid as far as possible the use of scientific language, and speak as a farmer to farmers. The fertility of the land and its relation to landlord and tenant, and the manure value of foods, with the compensation due to an outgoing tenant for unexhausted manures, were subjects which he made peculiarly his own. For many years he sent annually to the *Times* newspaper, in the early autumn, an estimate of the quantity of wheat yielded by the preceding harvest in this country. This estimate was based on the produce of the standard plots in the experimental wheat field at Rothamsted; as the produce here was over or under the average, so it was assumed would be the general produce of the country. The estimates thus made proved generally to be near the truth.

For his great services to agriculture Mr Lawes was created a baronet by the Queen in 1882. The degree of LL.D. was conferred on him by the University of Edinburgh in 1877; D.C.L. by Oxford in 1893; and Sc.D. by Cambridge in 1894. He received the Legion of Honour from Napoleon III.; he was also a Chevalier du Mérite Agricole. He was elected a corresponding member of the Institute of France in 1879. In 1863, he received a Gold Medal from the Russian Government. In 1881, the German Emperor awarded a Gold Medal for Agricultural Merit to Lawes and Gilbert.

Sir John Lawes early conceived the idea of perpetuating the Rothamsted investigations by placing the laboratory and fields in the hands of trustees with a permanent endowment for their maintenance. He first spoke of this in his speech at the opening of the new laboratory in 1855. In 1872 he publicly announced that he had set aside £100,000 for this purpose. By deeds executed by him in February 1889, the

laboratory and experimental fields were leased to Sir John Lubbock, William Wells, Esq., and Sir John Evans, as trustees, for ninety-nine years at a peppercorn rent. To the same trustees he covenanted to pay the sum of £100,000, the interest on which was to be applied to the maintenance of agricultural investigations under the direction of a Committee of nine persons, of whom four were to be nominated by the Royal Society, two by the Royal Agricultural Society, one by the Linnean Society, and one by the Chemical Society, the owner of Rothamsted being always a member of the Committee. The appointment of new trustees when required was vested in the Royal Society. The Managing Committee were at once appointed. They consisted of Sir John Evans, Dr Hugo Müller, Sir Michael Foster, and Sir W. T. Thiselton Dyer, nominated by the Royal Society; Sir John H. Thorold, and Charles Whitehead, Esq., nominated by the Royal Agricultural Society; William Carruthers, Esq., nominated by the Linnean Society; Prof. H. E. Armstrong, nominated by the Chemical Society; with Sir John Bennet Lawes. Under this Committee, with but few alterations in their constitution, the direction of the work at Rothamsted has since proceeded.

The Jubilee of the Rothamsted Experiments was celebrated on July 29, 1893. The organisation of this celebration originated with the Royal Agricultural Society. At a meeting on March 1, presided over by H.R.H. the Prince of Wales, it was resolved: "That some public recognition should be made of the invaluable services rendered to Agriculture by Sir John Lawes and Dr Gilbert." A subscription list was opened, and with the contributions received a large boulder of Shap granite was erected in front of the laboratory, bearing the following inscription:—"To commemorate the completion of Fifty Years of continuous experiments (the first of their kind) in agriculture, conducted at Rothamsted by Sir John Bennet Lawes and Joseph Henry Gilbert. A.D. MDCCCXCIII." A large and distinguished gathering was held in front of the laboratory on the afternoon of July 29, the Rt. Hon. Herbert Gardner,

M.P., President of the Board of Agriculture, presided. The Duke of Westminster, as President of the Royal Agricultural Society, presented to Sir John Lawes his portrait, painted by H. Herkomer, R.A., and to Dr J. H. Gilbert, a silver salver. He also presented congratulatory addresses to both Lawes and Gilbert from the subscribers to the fund, each address being signed by H.R.H. the Prince of Wales. The presentation of a large number of addresses from English and Foreign Societies then followed, including one from the Royal Society. Sir John Lawes and Dr Gilbert then replied. A few of the words spoken by Sir John Lawes must be quoted. "That afternoon he had to return thanks to that distinguished and brilliant assembly for their kind congratulations to himself and Dr Gilbert upon the work that they had been carrying on for the last fifty years. When two people were joined together in marriage they could not part, because they were bound together by very solemn ties. But with regard to himself and Dr Gilbert the case was quite different, Dr Gilbert could have left him, or he could have left Dr Gilbert. Their connection, however, had lasted for more than fifty years. What was the cause? Nothing less than mutual love of the work they had been engaged in. He (Sir John) had delighted in the work from the beginning. All the time he could spare in the midst of many other responsibilities and duties he had given to the work. But with Dr Gilbert it had been the work of his life. If it had not been for Dr Gilbert's collaboration their investigations would have been in a very different state to what they were then."

Shortly after the Jubilee celebration Dr Gilbert received the honour of knighthood. In September of the same year the Liebig Silver Medal was awarded to Sir John Lawes and Sir Henry Gilbert by the curators of the Liebig Foundation of the Royal Bavarian Academy of Sciences. In the following year, 1894, the Albert Gold Medal of the Society of Arts was presented to Lawes and Gilbert by H.R.H. the Prince of Wales, "for their joint services to scientific agriculture, and

notably for the researches which, throughout a period of fifty years, have been carried on by them at the Experimental Farm, Rothamsted."

Something must now be said as to the personality of the remarkable man whose life's work we have attempted to describe. He possessed an extremely vigorous constitution, and when past 85, exhibited but few of the infirmities of old age. His holiday was always spent in Scotland, and deer stalking and salmon fishing were then his chief occupations. At home, all his leisure time was spent on the farm. He was a keen observer, and knew the experimental fields better than anyone else. His interest in agricultural problems never tired, he was continually finding fresh subjects for inquiry. While gifted with a full share of the scientific imagination, he was thoroughly practical in his conclusions. His long experience as a farmer, and the careful attention to economy learnt in business, were of great use to him when he brought the results of scientific investigation before the agricultural world. He took a broad, statesman-like view of all agricultural questions, and was looked up to by the English farmer as his safest guide and his highest authority.

Sir John Lawes seldom took part in public functions, he was not seen at meetings of scientific societies, and took no active part in politics; excepting the hours unavoidably spent on his London business, he lived as far as possible a country life. It was, however, in no sense a secluded life; his correspondence was very large, and the visitors to the Rothamsted experiments were extremely numerous and of all nationalities. They found at Rothamsted a genial host and a ready guide to the fields, where the lessons taught by the experimental crops were described in brief and pithy sentences by one who knew thoroughly the whole history of each plot.

Sir John Lawes by no means confined his attention to science, agriculture, and business; he was a man of active benevolence. The agricultural labourers of Harpenden found in him their best friend. He began to provide allotment

gardens in 1852, and before his death the number had reached 334. In 1857 he built a club room in the gardens. Various co-operative schemes were started for the labourer's benefit; one of these has been immortalised by Charles Dickens, who visited the club room in April 1859, and afterwards gave an account of what he saw in the first number of *All the Year Round*. The welfare of his workmen at his various factories was equally considered. He exercised a wide private benevolence, and in his own parish was never appealed to in vain for any good work.

Sir John Lawes' life was prolonged to an unusual period; he lived and worked and taught through two successive generations. His health remained very good till within about a week of his death. He died at Rothamsted on August 31, 1900, in his 86th year, and was buried at Harpenden. His only son, Sir Charles Bennet Lawes, who has assumed the additional name of Wittewronge, succeeds to the Rothamsted estate.

#### SIR JOSEPH HENRY GILBERT, 1817-1901

JOSEPH HENRY GILBERT was born at Hull on August 1, 1817. He was the second son of the Rev. Joseph Gilbert, a Congregational Minister, who had previously held the position of Professor of Classics at the Divinity College, Rotherham. His mother belonged to a well-known literary family, and under her maiden name of Ann Taylor, was a popular authoress of poems for children. The family removed in 1825 to Nottingham, and it was here that the boyhood of Joseph Henry Gilbert was spent. He was first sent to an elementary school taught by a blind lady of great intelligence, and afterwards to a school kept by Mr Long at Mansfield. In 1832, while at Scarborough, he met with a serious gunshot accident, which permanently deprived him of the sight of one eye, and considerably damaged the other; his general health suffered much from the



SIR JOSEPH HENRY GILBERT, M.A., Ph.D., LL.D., F.R.S.

shock, and it was some years before he was able to resume his studies. During this interval he in 1838 paid a visit to St Petersburg. In the autumn of 1838 he became a student at the University of Glasgow; here he devoted nearly a year to the study of analytical chemistry in the laboratory of Prof. Thomas Thomson. *Materia-Medica* was studied under Dr J. Couper, and botany under Sir W. J. Hooker. He came to London in the autumn of 1839, and continued his studies at University College, where he attended the chemical lectures and practical classes of Prof. T. Graham, and worked for a short time in the laboratory of Prof. Anthony Todd Thomson. He also studied natural philosophy under J. Sylvester, anatomy under Dr Grant, and botany under Lindley at Chiswick, and made some progress in the German language. In 1840 he went to Germany, and spent a summer session at Giessen, in the laboratory of Prof. Liebig. Here he took the degree of Ph.D.; two other English students, J. Stenhouse and L. Playfair, afterwards to become celebrated as chemists, took their degrees at the same time. On returning to England, Dr Gilbert renewed his studies at University College, and became class and laboratory assistant to Prof. A. T. Thomson during the winter and summer sessions of 1840-41. In 1842 he left London and became consulting chemist to Mr Burd, a calico-printer in the neighbourhood of Manchester. The turning point of his life soon arrived. Mr Lawes had already made his acquaintance in the laboratory of Prof. A. T. Thomson, and being in want of a trained chemist to assist in the agricultural investigations he had commenced at Rothamsted, he, on the recommendation of Prof. Thomson, engaged the services of Dr Gilbert. On June 1, 1843, Dr Gilbert entered on his work at Rothamsted. The connection between Lawes and Gilbert thus commenced continued till the death of Sir John Lawes in 1900, a period of fifty-seven years.

The rapid development of the agricultural investigations at Rothamsted after the year 1843 has been already noticed in the preceding account of the life of Sir John Lawes. The value of

the work done was largely due to the unremitting labours of Dr Gilbert. At the opening of the new laboratory in 1855, Mr Lawes said, "I should be most ungrateful were I to omit this opportunity of stating how greatly I am indebted to those gentlemen whose lives are devoted to the conduct and management of my experiments. To Dr Gilbert more especially, I consider a debt of gratitude is due from myself and from every agriculturist in Great Britain. It is not every gentleman of his attainments who would subject himself to the caprice of an individual, or risk his reputation by following the pursuits of a science which has hardly a recognised existence. For twelve years our acquaintance has existed, and I hope twelve years more will find it continuing." The testimony borne by Sir John Lawes to his colleague at the end of fifty years of their joint work has been already quoted in the preceding account of Sir John Lawes.

We must now attempt to give some idea of the special part taken by Sir Henry Gilbert in the Rothamsted investigations. The two leaders of the work were in almost daily consultation, Sir H. Gilbert spending, as a rule, an hour at Rothamsted every day that Sir John Lawes was at home. The plans for new experiments, the results obtained from day to day, and the drafts of the reports in preparation, were thus all discussed by them together. Sir John Lawes directed the agricultural operations in the experimental fields; the execution of the remainder of the work was in the hands of Sir Henry Gilbert. Sir John Lawes contributed to the joint work a thorough knowledge of practical agriculture. His original mind was stored with facts learnt by keen observation and study in the field. A born investigator, he seemed to be continually occupied in the study of agricultural problems. His enterprising and practical spirit impressed its character on the whole of the Rothamsted work. Sir Henry Gilbert supplemented in a remarkable manner the qualities of his chief. His training as an analytical chemist, and his acquaintance with foreign languages and literature, were naturally of great value in

research work. His knowledge of colloquial German enabled him in after years to describe the results of the Rothamsted investigations to many foreign visitors. His special mental characteristics also eminently fitted him for the work subsequently carried out. He was both cautious and painstaking to a remarkable extent, desiring to accumulate a great mass of facts before coming to any certain conclusion upon them. His mode of work was also extremely methodical, and the method once adopted, after full consideration, was continued through many subsequent years, thus giving rise to long series of results obtained in a perfectly similar manner. The continuation of the same field experiments for more than fifty years, and the important results which subsequently followed from an examination of the soils so long under definite cultivation, may be cited as examples of Gilbert's method. Under his care, samples of the grain and straw from each experimental plot, in each year were preserved in the laboratory, and also samples of the ash yielded by each. In later years, when samples of the soils and *subsoils of each plot were repeatedly taken, large portions of each sample were also preserved.* At his death the number of *samples stored for future reference in the laboratory and in the adjoining building exceeded 50,000.* The bulk of tabulated records prepared by the clerks at the laboratory was correspondingly large. He thus laid the foundation of much solid work. The same characteristics appeared in his reports. These usually contained a great bulk of numerical statements, set forth in an orderly manner, with not unfrequently only a small proportion of illuminating theory. The recording of observed facts seemed often to satisfy his object as an investigator. When, however, a definite conclusion had been arrived at it was tenaciously held, and if attacked was vigorously defended. Sir Henry Gilbert was an antagonist who never tired. His controversies with Liebig, on the subject of his mineral theory, and, in later years, with other German investigators, on the source of fat in the animal body, will be well remembered by his contemporaries.

The life work of Sir Henry Gilbert will chiefly be found in the published reports of the Rothamsted investigations, which, at the time of his death, had reached ten volumes; the subjects of these investigations will be briefly noticed at the close of this biography. His work, however, frequently extended beyond the sphere of the Rothamsted Experiments. He was Mr Lawes' scientific adviser, and as such he played an active part in the trials which took place in the Law Courts respecting the alleged infringement of Mr Lawes' patent. He made reports on deposits of phosphates at home and abroad. He superintended the experiments relating to the disposal of sewage at the time when Mr Lawes was a member of the Royal Commission of 1857. Other important undertakings will be mentioned presently.

Dr Gilbert was married in 1850 to Eliza Laurie, daughter of the Rev. G. Laurie. His wife died in 1853. He married a second time, in 1855, Maria Smith, who survived him. Sir Henry Gilbert owed much to his second wife's untiring assistance. The feeble condition of his eyesight obliged him to rely a good deal on clerical help. Both foreign and English papers were read to him by Lady Gilbert, while the greater part of his own work was dictated to an amanuensis. His great pluck and determination, with the assistance thus rendered, enabled him to accomplish a very large amount of work notwithstanding the serious difficulties under which he laboured.

Sir Henry Gilbert was an active member of many scientific societies, a regular attendant at their meetings, and a member of many scientific committees. The Rothamsted investigations undoubtedly gained by the intercourse thus obtained with other investigators, though the time occupied by visits to London was often considerable. Sir Henry Gilbert was elected a Fellow of the Royal Society in 1860. He was the author, with Sir John Lawes, of seven papers in the Philosophical Transactions. In 1867 he received, with Sir John Lawes, one of the Royal Medals for the work done at Rothamsted. He served on the Council in 1886-8. Sir Henry Gilbert joined the

Chemical Society in 1841, a few weeks after its formation, became a member of the Council in 1856, and a Vice-President in 1868. In 1882 he was elected President of the Society. Sir Henry Gilbert delivered four lectures before the Society, and was the part author of several other papers. In 1898 a memorable dinner was given by the Society to six Past-Presidents, all of whom had been members of the Society for more than fifty years : of these Past-Presidents Gilbert was the eldest. The President concluded his address to him by saying : "The Rothamsted results will be for ever memorable : they are unique, and characteristic of the indomitable perseverance and energy of our venerated President, Sir Henry Gilbert."

Of the Linnean and Meteorological Societies Sir Henry Gilbert was also a Fellow, and occasionally read papers at their meetings. He was also a member of the Society of Arts. He became a member of the Scientific Committee of the Horticultural Society in 1868, and for many years regularly attended its meetings.

In his summer holidays the meeting of the British Association for the Advancement of Science was generally attended ; his attendance commenced in 1842, and during many years he scarcely missed a meeting, and frequently read a paper describing some of the Rothamsted results. In 1880 he was President of the Chemical Section, and gave as his address, "A Sketch of the Progress of Agricultural Chemistry." A tour on the Continent generally formed part of the summer holiday ; agricultural laboratories and experimental stations were then visited, and the Naturforscher Versammlung, and other scientific gatherings, were often attended and papers read before them. In 1871, and the following year, the details of sugar-beet culture were studied in Germany, Austria, and France, preparatory to the commencement of experiments on this subject at Rothamsted.

Three visits were paid to the United States and Canada. In 1882 he attended the meeting of the American Association for the Advancement of Science, at Montreal, and brought

before them the recent determinations of nitrogen in the experimental soils at Rothamsted. A tour of nearly three months was afterwards made in the United States. In 1884 he was again at Montreal, at the meeting of the British Association, and afterwards made a second extensive tour through North America. The last visit was paid in 1893, after the celebration of the Rothamsted jubilee, for the purpose of delivering a course of lectures on the Rothamsted experiments, in accordance with a provision of Sir John Lawes' trust deed. Sir Henry Gilbert first attended the Agricultural Congress held in connection with the World's Fair at Chicago; here he had a splendid reception, all present rising and cheering for some time. To this Exhibition at Chicago a large collection of diagrams had been sent from Rothamsted, and for these a medal was afterwards awarded. Sir Henry Gilbert then gave a course of seven lectures at the State Agricultural College at Amherst, Mass., taking as his subject the chief results relating to the crops ordinarily grown in rotation, with those relating to the feeding of animals, obtained at Rothamsted during the previous fifty years. These lectures, in an enlarged form, were afterwards published by the United States Department of Agriculture, and were reprinted, with an introductory account of the Rothamsted Experiments, in the *Transactions of the Highland and Agricultural Society of Scotland* for 1895.

In 1884 Dr Gilbert was elected Sibthorpeian Professor of Rural Economy in the University of Oxford, and held this office for six years, the full term allowed by the statute. He delivered during this time over seventy lectures on the results of the Rothamsted investigations; these lectures he hoped to publish, but the intention has remained unfulfilled.

In 1885 Dr Gilbert became an Honorary Professor of the Royal Agricultural College at Cirencester, and delivered an annual lecture during six years; the lectures were published in the *Agricultural Students' Gazette*. They treat in a condensed form of some of the subjects previously discussed at Oxford

The transfer of the laboratory and experimental fields to the management of a committee appointed under Sir John Lawes' trust deed of 1889 has been already mentioned. After this date the virtual direction of the experiments continued to remain in the hands of Lawes and Gilbert during their joint lives. For the information of the new committee Sir Henry Gilbert drew up a brief report on the investigations hitherto conducted, showing to what extent the results obtained had been already published, and making suggestions as to future work. This report was printed in 1891 for the use of the committee.

The celebration of the jubilee of the Rothamsted Experiments in 1893 has been already described in the notice of Sir John Lawes, with the numerous honours subsequently conferred on both Lawes and Gilbert. Dr Gilbert received knighthood from the Queen on August 11 of that year.

Sir Henry Gilbert was a member of the committee appointed by the Government in 1896 to take evidence and report on the materials used in the manufacture of beer. The committee presented their report to the Treasury in 1899.

He received many honorary degrees. The University of Glasgow made him LL.D. in 1883; Oxford, M.A. in 1884; Edinburgh, LL.D. in 1890; Cambridge, Sc.D. in 1894. He was a life governor of University College, London; a Corresponding Member of the Institute of France; a Chevalier du Mérite Agricole; and an honorary member of many agricultural societies at home and abroad.

With a life so filled with many labours it need hardly be said that Sir Henry Gilbert was possessed of a robust constitution. He, however, suffered at times from over-brainwork, and his frequent excursions abroad were really needed to maintain a healthy tone. In later years he suffered much at times from internal pain, the precursor, probably, of his last illness. The death of Sir John Lawes in 1900 was naturally a

great shock to him. He was fairly vigorous, however, during the next summer, but was taken seriously ill during a visit to Scotland, and returned home with difficulty. He died at Harpenden on December 23, 1901, in his 85th year.

## CHAPTER I

### THE SOURCES OF THE NITROGEN OF VEGETATION

To arrive at a proper understanding of the scheme of the Rothamsted Experiments it is necessary to reconstruct a little the state of the knowledge of agricultural science at the time they were begun in 1843. In many respects it was a period of considerable activity in matters agricultural ; the whole landed interest were making great efforts towards the improvement of land and stock and of methods of cultivation ; great areas of the country were being tile-drained and rendered for the first time suitable for arable cultivation, other poor sandy land was being reclaimed by marling and claying. A sign of the times was the establishment of the Royal Agricultural Society in 1838, and in its earlier volumes, particularly in the writings of Dr Daubeny on the scientific side, and those of Philip Pusey on the practical side, a good idea may be formed of the point of view of the intelligent farmer of that date. The science of the time had just reached a point which enabled a general theory of the nutrition of both plant and animal to be formed. In the latter part of the eighteenth century the researches of Priestley, followed up by Ingenhousz and Senebier, had settled the fundamental fact that green plants in sunlight decompose the carbonic acid of the atmosphere, setting free the oxygen and retaining the carbon, this being the source of the carbon which makes up the bulk of the dry matter of plants. A little later De Saussure, who published

## 2 SOURCES OF THE NITROGEN OF VEGETATION

his *Recherches Chimiques sur la Vegetation* in 1804, confirmed the above-mentioned discoveries and gave them a coherent shape. He then proceeded to discuss the mineral or ash constituents of plants, made a series of analyses of the ashes of various plants, and pointed out the importance of these substances in the nutrition of the plant. Davy, whose lectures on Agricultural Chemistry to the Board of Agriculture were published in 1813, though he did not advance the subject much by his own investigations, yet did much service in presenting to the agricultural public the science that was then available. He laid more stress than before on the importance of the ash constituents and the use of manures to supply them, but he appears still to have considered that much of the carbonaceous matter of plants was directly derived from the humus of the soil, and that the assimilation of carbon from the atmosphere was of minor importance.

Boussingault's memorable work began in 1834, and in 1838 he published the result of the enquiries he had been making on his farm into the principles underlying the rotation of crops. He analysed both the manures applied and the crops removed from the land, and thus demonstrated statistically that the source of the enormous quantities of carbon removed annually can only be the carbonic acid of the atmosphere, not the soil nor the manures applied. In 1840 appeared Liebig's famous report to the British Association on "Organic Chemistry in its applications to Agriculture and Physiology." Here, building upon the foundations laid by De Saussure and by Boussingault (for in this direction Liebig was not an original investigator), and illuminating these facts by the light of his own recent discoveries in organic chemistry, Liebig drew out a convincing scheme of the nutrition of the plant. Green plants by the aid of sunlight derive their whole substance from carbonic acid, water, ammonia present in the atmosphere and produced by decaying matter in the soil, and the simple inorganic salts which are afterwards found in the ash when the plant

is burned. From these simple substances the plant elaborates those compounds of carbon and nitrogen, such as starch, sugar, fat, and the proteins, which the animal requires for its food, and thereby reconverts into the original simpler materials. Liebig's brilliant essay excited universal attention and roused the interest of both the scientific and practical men of all civilised countries in the subject, so that to a very large extent we can date modern agricultural science from this stimulating publication. Henceforward we may take it that the source of the carbon of vegetation was no longer regarded as doubtful; it came from the atmosphere, and the humus of the soil practically contributed nothing to it.

The origin of the nitrogen was however by no means so settled: De Saussure had concluded that plants were unable to assimilate the free nitrogen of the atmosphere, but obtained it from the nitrogenous compounds in the soil and from the small amount of ammonia which he showed to be present in ordinary air. Boussingault took out statistics of the nitrogen as well as the carbon supplied in manures and recovered in the crops; in 1838 he also published an account of experiments in which plants were grown in pots and supplied with known amounts of combined nitrogen, so as to ascertain if the growing plant did assimilate atmospheric nitrogen. While the crop statistics seemed to show in certain cases a considerable surplus of nitrogen removed in the crops during a rotation over that supplied in the manure, his direct experiments, made as accurately as the chemistry of the time would permit, indicated that plants drew nitrogen only from the soil or manure.

The arguments of De Saussure and of Boussingault were adopted by Liebig in his first publication; he considered the source of the nitrogen of vegetation was ammonia derived from the decay of the previous generation of plants or brought down from the atmosphere by the rain. In his later editions Liebig somewhat shifted from this point of view and began to minimise

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the importance of any supply of combined nitrogen to the plant; provided that the soil were supplied with the mineral constituents removed by the crop, he argued that it would be able to grow luxuriantly and obtain for itself all the nitrogen necessary. It is difficult now to estimate exactly the positions held by controversialists of more than half a century ago, but there can be little doubt that Liebig overestimated the amount of ammonia which could be obtained from the atmosphere, and that he and his followers, arguing from general grounds as to the origin of the original stock of combined nitrogen in the world, were disposed to believe that some, if not all, leafy plants could assimilate and fix free atmospheric nitrogen.

Some little time before the publication of Liebig's report, Lawes had begun his experiments on a small scale; as early as 1835 he was making trials in pots at Rothamsted, and these were year by year extended to the fields on the home farm, until in 1843 the scale had so far increased that he secured the co-operation of Gilbert and the Rothamsted Experiments as we now know them began.

Curiously enough, at this very time (1842) Dr Daubeny, some of whose lectures Lawes had attended at Oxford, was writing in the new *Journal of the Royal Agricultural Society* about the necessity of systematic experiments to ascertain the value of manures: "I know not how such experiments can well be instituted, except it be on an experimental farm, established for the purpose, and placed under scientific hands. Productive of no immediate advantage to the land on which they are tried beyond what could be equally well attained by a much inferior expenditure of labour, they are not likely to be taken up by any private individual who combines practical experience and pecuniary resources with the requisite scientific skill; and even if such a person were to present himself, what guarantee can we offer to the world that he possesses the requisite qualifications?" For it should be remembered that

this was the period of the first introduction of what we now call artificial manures; the virtue of bones had long been known, and at Liebig's instigation their phosphoric acid was being made soluble by acid, and dissolved bones were becoming an article of commerce. Lawes had followed up Henslow's discovery of coprolites by converting them into mineral superphosphate, and setting up the earliest manufactory of artificial manures. The first importations of Peruvian guano had been made, and nitrate of soda was also beginning to find its way into the country.

With these and many other substances Lawes had been experimenting on a small scale, and the results of his trials and all his farming experience went to show that a supply of combined nitrogen in some form or other was not only necessary to the crop, but on the whole determined its yield to a far greater extent than the supply of ash constituents. Yet Liebig's argument in the second (1843) edition of his report all inclined to represent the mineral manures as fundamental, and a supply of combined nitrogen as unnecessary, or at least of secondary importance. This question of the value or otherwise of nitrogenous manures supplied the main guiding principle in the design of all the earlier field experiments at Rothamsted, as will be evident when the individual fields come to be considered, and the controversy which arose with Liebig on the publication of the first reports from Rothamsted endured for more than a generation. Indeed the source and fate of the nitrogen of vegetation remained in one form or another the dominant interest in the Rothamsted Experiments up to the death of Lawes and Gilbert.

The evidence from the field experiments that farm crops require a supply of combined nitrogen will be considered elsewhere, as also the results of the determinations made of the amounts of ammonia and other nitrogenous compounds brought down by the rain; in neither case was there evidence that a normal vegetation could supply itself with the necessary

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nitrogen from atmospheric sources only. Attempts had also been made to grow plants in artificial media with a known supply of nitrogen, which could be compared with the amount of nitrogen found later in the fully grown plant. Boussingault, to whom the first experiments of this nature were due, soon found that very elaborate precautions must be taken to obviate the influx of nitrogen either in dust or as ammonia in the atmosphere and in the water employed, hence in all his later experiments the plants were grown in closed cases fed with air from which all ammonia had been withdrawn by acid. Boussingault's conclusions were against the fixation of any nitrogen, but they were not accepted universally; in particular, Ville brought forward other similar experiments, in which the plant showed a distinct gain of combined nitrogen. In 1857 the subject was taken up at Rothamsted, and a most elaborate series of experiments were carried out by Dr Evan Pugh, at that time working in the Rothamsted laboratory. The experimental plants were grown under glass shades, and every precaution was taken to ensure the freedom from ammonia of the air entering the shades, and also of the other materials—the burnt earth, the pots, the water, the manures—employed in the experiment.

The experiments were made with wheat, barley, oats, clover, beans, peas, and buckwheat, and the trials were repeated, in the one case with no manure in the pots, and in the other with the supply of a small quantity of sulphate of ammonia. The soils employed were made up from either ignited pumice or ignited soil, and the glass shades under which the plants were grown rested in the groove of a stoneware vessel, mercury being used as a lute. The air, previously passed through sulphuric acid and sodium carbonate solution and washed, was forced into the apparatus, so as always to maintain a greater pressure inside than out, thus minimising all danger of unwashed air leaking in; carbonic acid was also introduced as required. Under these rigorous conditions the following results were obtained:—

TABLE I.—*Summary of the Results of Experiments made at Rothamsted to determine whether Plants assimilate Free Nitrogen.*

			Nitrogen—Gram.			Ratio of Nitrogen recovered to Nitrogen supplied.
			In Seed and Manure if any.	In Plants, Pot, and Soil.	Gain or Loss.	
<i>With no combined Nitrogen supplied beyond that in the Seed sown.</i>						
Gramineæ .	1857 {	Wheat .	0·0080	0·0072	- 0·0008	0·90
		Barley .	0·0056	0·0072	+ 0·0016	1·29
		Barley .	0·0056	0·0082	+ 0·0026	1·46
	1858 {	Wheat .	0·0078	0·0081	+ 0·0003	1·04
		Barley .	0·0057	0·0058	+ 0·0001	1·02
		Oats .	0·0063	0·0056	- 0·0007	0·89
1858 {	Wheat .	0·0078	0·0078	...	1·00	
	Oats .	0·0064	0·0063	- 0·0001	0·98	
Leguminosæ .	1857 {	Beans .	0·0796	0·0791	- 0·0005	0·99
	1858 {	Beans .	0·0750	0·0757	+ 0·0007	1·01
Peas .		0·0188	0·0167	- 0·0021	0·89	
Other Plants .	1858	Buckwheat	0·0200	0·0182	- 0·0018	0·91
<i>With combined Nitrogen supplied.</i>						
Gramineæ .	1857 {	Wheat .	0·0329	0·0383	+ 0·0054	1·16
		Wheat .	0·0329	0·0331	+ 0·0002	1·01
		Barley .	0·0326	0·0328	+ 0·0002	1·01
		Barley .	0·0268	0·0337	+ 0·0069	1·25
	1858 {	Wheat .	0·0548	0·0536	- 0·0012	0·98
		Barley .	0·0496	0·0464	- 0·0032	0·94
		Oats .	0·0312	0·0216	- 0·0096	0·69
	1858 {	Wheat .	0·0268	0·0274	+ 0·0006	1·02
		Barley .	0·0257	0·0242	- 0·0015	0·94
Oats .		0·0260	0·0198	- 0·0062	0·76	
Leguminosæ .	1858 {	Peas .	0·0227	0·0211	- 0·0016	0·93
		Clover .	0·0712	0·0665	- 0·0047	0·95
Other Plants .	1858	Beans .	0·0711	0·0655	- 0·0056	0·92
	1858	Buckwheat	0·0308	0·0292	- 0·0016	0·95

These results seem to exclude the possibility of any fixation of nitrogen by living plants, and as they had been obtained with plants of three different natural orders, and both without and with manure to induce an initial vigorous growth, for many years the whole trend of scientific opinion was against the possibility of the fixation of nitrogen by living plants.

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There remained, however, a number of facts difficult to account for: although laboratory experiments similar to those just described, but resulting in a gain of nitrogen, could be dismissed as vitiated by the many possible sources of error, yet the statistics of the nitrogen collected by various crops could not be explained in any such fashion. It has already been mentioned that Boussingault made out a balance-sheet of nitrogen supplied in manure and removed in crop during different rotations; he found that while in a rotation of wheat and fallow alone the wheat contained rather less nitrogen than was applied as manure, yet other rotations in which clover was included, and particularly a five years' continuous cropping with lucerne, gave a large surplus of nitrogen removed over that supplied. Similar evidence was accumulated at Rothamsted and was made more cogent by the analysis of the soils, which showed not only no decrease but an actual gain of nitrogen during the period when the leguminous crop was producing such large quantities of nitrogenous matter above ground. Thus when the various crops were grown continuously with mineral manures\* but without any supply of combined nitrogen, the following average amounts of nitrogen per acre were taken away:—

TABLE II.—*Average Removal of Nitrogen per acre by Crops grown continuously with Mineral Manures only.*

	Duration of Experiment.	Nitrogen removed per acre per annum.
Wheat . . .	24 years . . . . .	Lb. 22.1
Barley . . .	24 years . . . . .	22.4
Root Crops . . .	30 years . . . . .	16.4
Beans . . .	24 years, of which 2 fallow . . .	45.5
Clover . . .	22 years, 6 crops only . . .	39.8

In a comparison of the alternate wheat and fallow plots with the adjacent plots continually under leguminous plants,

\* The term mineral manures will be used throughout for mixtures of the constituents found in the ash of plants, *i.e.*, phosphates, sulphates and chlorides of sodium, potassium, calcium and magnesium, but always excluding nitrogen in any form.

## FIELD EXPERIMENTS INDICATING FIXATION 9

the following comparative figures were obtained after both had been under similar treatment for many years.

TABLE III.—*Nitrogen in Crop and Soil. Leguminous Plants compared with Wheat and Fallow. Hoos Field.*

	Unmanured	Mineral Manures only, 80 years.		
	Wheat and Fallow alternately.	Trifolium repens.	Mellilotus leucantha.	Medicago sativa.
Average Annual Removal of Nitrogen, 8 years (1878-85) . . . . .	Lb. 12	Lb. 33	Lb. 71	Lb. 110
Nitrogen per cent. in Surface Soil in 1885 . . . . .	0·1021	0·1269	0·1151	0·1219
Nitrogen as Nitric Acid in Soil and Subsoil to the depth of 9 feet, lb. per acre, 1885 . . . . .	42	101	79	17

In another experiment in *Little Hoos Field*, after five years' cropping by cereals without any nitrogenous manure, in 1872 a portion of the field in barley was sown with clover; in 1873 this portion carried a clover crop which was cut three times, the other portion which had not been sown with clover was again cropped with barley. Determinations of the nitrogen removed in 1873 showed 151 lb. in the clover crop and 37 lb. per acre in the barley crop respectively. In the following year (1874) barley was again sown over the whole area, but the barley crop which followed clover took away nearly twice as much nitrogen as that which followed barley, although this had contained less than the corresponding clover. Yet an analysis of the soil immediately after the 1873 crop had been removed showed more nitrogen in the land where clover had been growing than where the barley had been growing, as shown in Table IV. (p. 10), where all the results are summarised.

In yet another experiment, land which had previously grown beans and then been fallow for five years was sown with barley and clover in 1883, the clover being allowed to stand in 1884 and 1885. At starting, the soil was analysed; the surface 9 inches contained on an average 2657 lb. per acre of nitrogen, while of nitrogen as nitric acid the soil only con-

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tained 25·7 lb. per acre down to a depth of 6 feet. As a result of the three years' cropping with barley and clover, and then with clover only, an average amount of 319·5 lb. of

TABLE IV.—*Nitrogen accumulated by Clover Crop.*  
*Little Hoos Field.*

Year, etc.	Lb. of Nitrogen per acre in Crop removed.	
	1873 A.	1874 B.
1873 . . . . .	Barley, 37·3	Clover, 151·3
1874 . . . . .	Barley, 39·1	Barley, 69·1
Nitrogen per cent. in Soil at end of 1873 .	0·1416	0·1566

nitrogen was removed, yet the soil contained, on analysis at the end of the experiment, 2832 lb. of nitrogen per acre in the top 9 inches, or a gain of 175 lb. per acre in the three years; making a total, with the crop removed, of nearly 500 lb. of nitrogen per acre to be accounted for.

Experiments like these, coupled with the long experience of practical farmers\* of the beneficial effects of the growth of clover and other leguminous plants on the succeeding crops in a rotation, led many men to think that there still might be fixation of nitrogen by leguminous plants, in spite of the apparent exclusion of any such hypothesis by Pugh's experiments at Rothamsted. Voelcker, in England, when discussing the power of a clover crop to accumulate nitrogen, expressed the opinion that the atmosphere furnishes nitrogenous food to that plant; in France it was maintained by Ville; Berthelot also brought evidence to show that the soil itself, by the aid of microscopic vegetation, assimilated some free nitrogen.

\* Vergil, Georgics I., 73 :—

“Aut ibi flava seres, mutato sidere, farra  
Unde prius laetum siliqua quassante legumen  
Aut tenuis foetus viciae, tristisque lupini  
Sustuleris fragiles calamos, sylvamque sonantem.”

“Or, under a changed star, you will then sow the golden wheat, whence earlier you took away the bean, luxuriant with quivering pod, or the growth of the slender vetch, and the fragile stalks and rustling grove of the bitter lupin.”

Lawes and Gilbert themselves were disposed to look to the subsoil as the source of this excessive amount of nitrogen, and were conducting experiments to ascertain whether the widely ranging roots of the leguminous plants, in virtue of their highly acid sap, did not possess some special power of attacking the dormant nitrogenous compounds in the subsoil, when the clearing up of the whole subject came with the publication, in 1886, of the researches of Hellriegel and Wilfarth. These investigators found that when plants were grown in sand and were fed with nutrient solutions, the Gramineæ, the Cruciferæ, the Chenopodiaceæ, the Polygonæ, grew almost proportionally to the amount of combined nitrogen supplied; and, if this were absent, nitrogen starvation set in as soon as the nitrogen of the seed was exhausted. With the Leguminosæ, however, a plant was observed sometimes to recover from the stage of nitrogen starvation and begin a luxurious growth which lasted until maturity, though no combined nitrogen was supplied. In such cases the root of the plant was always found to be set with the little nodules characteristic of the roots of leguminous plants when growing under natural conditions. Further experiments were made in which the plants were grown in sterile sand, but as soon as the stage of nitrogen hunger was reached, a small portion of a watery extract of ordinary cultivated soil was added; whereupon the plants receiving the extract recovered from their nitrogen starvation and grew to maturity, assimilating considerable quantities of nitrogen. The renewed growth and the assimilation of nitrogen were always found to be attendant upon the production of nodules on the roots. The nodules were found to be full of bacteria, to which the name of *Bacillus radicicola* has been given; they could only be produced by previous infection, either by an extract of the crushed nodules or of a cultivated soil, in some cases (lupins, serradella) only by soil which had previously carried the same crop.

Gilbert had been present at the meeting of the Naturforscher Versammlung at Halle when Hellriegel and Wilfarth read their

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paper, and on his return to England experiments were immediately begun at Rothamsted to check their results.

A series of small pits were built up of slate slabs out of doors, and these were filled with either soil or washed sand and then sown with various leguminous plants, which were afterwards inoculated or not as desired. The growth was cut away for the determination of dry matter produced and the nitrogen collected; afterwards the roots were washed out from the soil or sand for the examination of the development of the nodules.

A more rigorous set of experiments were carried out in glazed stoneware pots in the glasshouse, and some of the results obtained are set out in Table V. (p. 13).

The table consists of a balance-sheet for the nitrogen only, in which the nitrogen supplied, either in the seed, in the sand or soil used, in the extract employed for inoculation, or in a few cases in the manure, is compared with that recovered in the soil or the plant. The first horizontal line for each plant shows the results obtained when there was no inoculation and the plant grew with simply the store of nitrogen present in the seed and what it could obtain from the soil; the second and third lines show the results of inoculation, both seed and soil being otherwise similar; the fourth line shows the result when the seeds were sown in ordinary soil.

It is needless to elaborate the results thus obtained; they confirmed, as has repeatedly been done since, the conclusions of Hellriegel and Wilfarth, and showed that the leguminous plants possess the power of "fixing" nitrogen under ordinary conditions of field culture by the agency of the bacteria living in the nodules on their roots.

The very rigour with which the earlier laboratory experiments, like those at Rothamsted on peas and beans in 1857-8, had been carried out, had prevented any fixation of nitrogen by excluding all possibility of inoculation.

The interpretation of the increased stock of nitrogen obtained with leguminous crops, which, as instanced above, had hitherto been so difficult of explanation, at once became

apparent, and the long controversy as to the sources of nitrogen in vegetation was thus closed by a vindication of both schools of opinion.

TABLE V.—*Nitrogen Balance-sheet, Leguminous Plants.* (See p. 12.)

Plant.	Pot No.	Duration of Experiment.	Nitrogen.						Gain or Loss of Nitrogen.	Nitrogen of Infected Plants to Uninfected = 1.
			At Beginning.		At End.					
			In Soil, Soil-Extract, and Seeds.	Total.	In Sand or Soil.	In Produce.	Total.			
Annuals.										
Peas	1	15	0·0265	0·0265	0·0090	0·0125	0·0215	-0·0050	...	
		2	15	0·0273	0·0273	0·0108	0·1475	0·1583	+0·1310	11·8
		3	15	0·0270	0·0270	0·0162	0·1825	0·1987	+0·1717	14·6
		4	15	6·9422	6·9422	6·8817	0·2075	7·0892	+0·1470	...
Vetches	9	15	0·0137	0·0137	0·0184	0·0065	0·0249	+0·0112	...	
		10	15	0·0141	0·0141	0·0260	0·1651	0·1911	+0·1770	25·4
		11	15	0·0139	0·0139	0·0230	0·1868	0·2098	+0·1959	28·7
		12	15	7·5966	7·5966	7·3052	0·2087	7·5139	-0·0827	...
Yellow Lupins	17	21	0·0375	0·0375	0·0551	0·0153	0·0704	+0·0329	...	
		18	21	0·0378	0·0378	0·0523	0·4980	0·5503	+0·5125	32·5
		19	21	0·0380	0·0380	0·0594	0·4914	0·5508	+0·5128	32·1
		20	21	6·0408	6·0408	6·7883	0·2146	7·0029	+0·9621	...
Plants of Longer Life.										
Red Clover	5	77	0·0082	0·0082	0·0273	0·2094	0·2367†	+0·2285	...	
		6	77	0·0089	0·0089	0·0312	0·2885	0·3197	+0·3108	...
		7	77	0·0083	0·2381*	0·0323	0·2986	0·3309†	+0·0930	...
		8	77	6·4274	6·4274	6·3198	1·7288	8·0486	+1·6212	...
Lucerne	21	68	0·0231	0·0231	0·0200	0·0030	0·0230	-0·0001	...	
		22	75	0·0247	0·0247	0·0514	0·3589	0·4103	+0·3856	119·6
		23	76	0·0236	0·3278*	0·0371	0·4307	0·4917†	+0·1639	143·5
		24	76	17·4983	17·4983	16·8141	1·2345	18·0486	+0·5503	...
White Clover	33	131	0·0110	0·0110	0·0148	0·0016	0·0164	+0·0054	...	
		34	131	0·0119	0·0119	0·0575	0·7098	0·7673	+0·7554	443·6
		35	131	0·0120	0·0120	0·0482	0·5465	0·5947	+0·5827	341·6
		36	131	...	...	5·3423	3·4726	8·8149	...	...
		37	131	0·0081	0·6746*	0·0459	0·4430	0·6754†	+0·0008	...

\* Including Calcium Nitrate, added as follows :—Pot 7, 0·2298 gram.; Pot 23, 0·3042 gram.; and Pot 37, 0·3665 gram.  
 † Including also the following amounts of Nitrate recovered :—Pot 7, none; Pot 23, 0·0239 gram.; and Pot 37, 0·1865 gram.  
 ‡ Accidentally inoculated.

Lawes and Gilbert were perfectly correct in maintaining that the ordinary green plant has no power of fixing nitrogen, but the whole class of leguminous plants form an exception

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when grown under ordinary field conditions, for then they become collectors of atmospheric nitrogen in virtue of the nodule bacteria with which they are associated.

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## CHAPTER II

### METEOROLOGICAL OBSERVATIONS

THE rainfall has been measured at Rothamsted since February 1853 in a 5-inch funnel gauge and in a rectangular gauge (7 feet 3·12 inches by 6 feet), having an area of one-thousandth acre.

In addition to these gauges, an 8-inch Board of Trade gauge has been employed since January 1881.

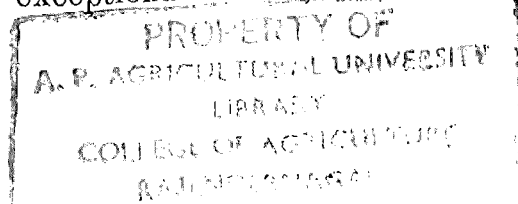
The ground on which the gauges are situated is 420 feet above the sea-level; it adjoins the Barn Field (continuous root crops), and is at a slightly lower level than the Broadbalk and Hoos fields.

The amount of water percolating through bare soil has been measured since 1870 by means of three drain-gauges, each having an area of one-thousandth acre. These were constructed by undermining the soil at the desired depths—20, 40, and 60 inches respectively—and inserting perforated iron plates to support the soil. When this was completed, trenches were cut round the blocks of soil, and these were then isolated by means of brick and cement walls. The external soil was then returned. The percolating water falls on to zinc funnels, from which it passes to the measuring cylinders.

Barometric and temperature records have been kept since 1873, and since July 1891 daily observations of the bright sunshine have been made by means of a Campbell-Stokes recorder.

The average yearly rainfall as measured at Rothamsted during the last sixty years, 1853-1912, is 28·34 inches. This is higher than the average in Hertfordshire (26·29).

As regards years of exceptional rainfall, either low or high,



the records show five years in which the rainfall was less than 21 inches—the lowest was 18.56 in 1864—and three years in which it was more than 35 inches—the highest recorded being 38.69 inches in 1903. More prolonged periods of wet occurred in 1875 and 1876, and in 1879 and 1880, when 69.34 and 70.0 inches fell in two consecutive years. The nine-year period, 1875 to 1883 inclusive, was an exceptionally wet one, each

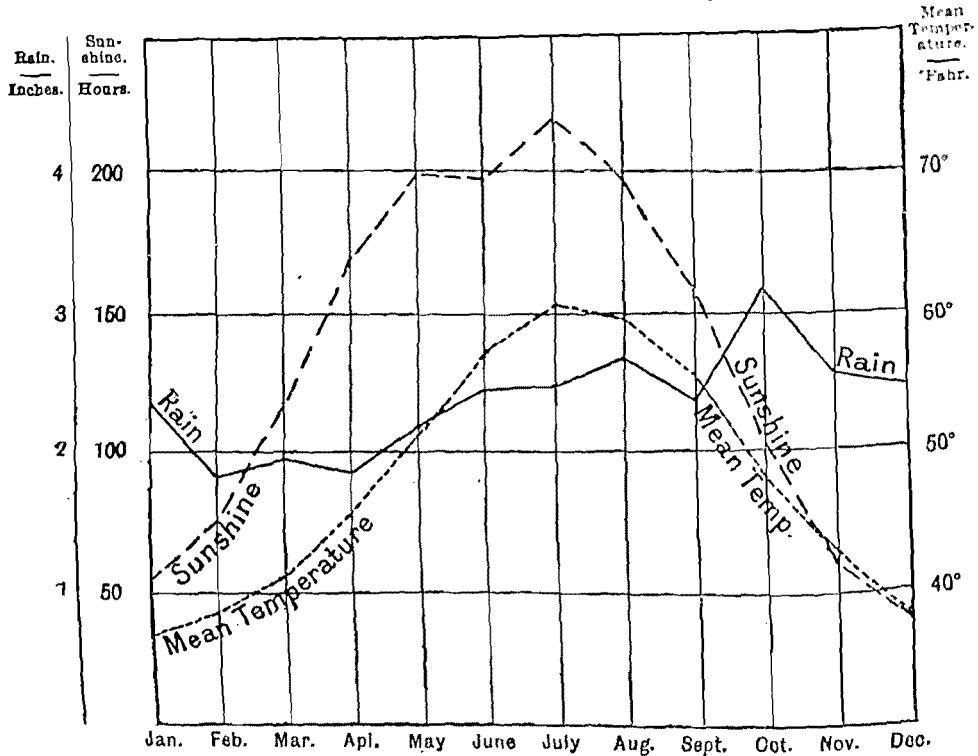


FIG. 1.—Rainfall: Average of 60 years (1853-1912).  
Sunshine: Average of 20 years (1892, 1893, and 1895-1912).  
Mean Temperature: Average of 35 years (1878-1912).

individual year giving a fall of more than 30 inches, and averaging 33.54 inches over the nine years. Exceptional periods of drought extending over two years are less frequent, and the lowest averages of two consecutive years are 21.7 in 1863 and 1864, 22.1 in 1901 and 1902, and 23.2 in 1870 and 1871. The longest consecutive period of years showing under average rainfall was the five years 1867-1871, when the falls ranged from 21.3 to 26.9 inches, and averaged over the five years 24.84 inches.

In Fig. 1 curves are set out showing the average rainfall,

# RAINFALL AND SUNSHINE RECORDS 17

mean temperature, and duration of sunshine from month to month.

The greatest average rainfall (see Table VI.) is in October, 3.18 inches, followed by 2.58 in November, while in December and January the amounts decline to 2.47 and 2.34 inches respectively. From February to August inclusive there is a gradual rise from 1.81 to 2.69 inches, but it declines to 2.37 inches in September.

TABLE VI.—*Meteorological Summary.*

	Rainfall.			Bright Sunshine.				Temperature.		
	Average, 60 years (1853-1912).			Average, 20 years (1892, 1893, and 1895-1912).				Average, 35 years (1878-1912).		
	Total Fall.	Rainy Days.		Total.	Per cent.	Days with 0.1 hour, or more.		Means.		Min. and Max. combined.
		Actual.	Per cent.			Actual.	Per cent.	Mini- mum.	Maxi- mum.	
Inches.	No.		Hours.		No.		°F.	°F.	°F.	
January . . .	2.34	16	52	55.2	21	17	55	31.7	42.0	36.9
February . . .	1.81	14	48	71.1	26	19	68	32.6	44.1	33.4
March . . .	1.92	14	45	115.9	31	26	84	33.7	48.3	41.0
April . . .	1.84	13	43	170.9	41	27	91	37.0	54.2	45.6
May . . .	2.19	13	42	199.6	42	29	93	42.5	60.6	51.6
June . . .	2.45	12	41	197.8	41	27	91	48.4	66.2	57.3
July . . .	2.50	13	43	217.9	45	30	96	51.8	69.8	60.8
August . . .	2.69	14	45	198.6	44	30	95	51.3	68.5	59.9
September . . .	2.37	13	44	157.3	42	27	92	47.4	63.9	55.7
October . . .	3.18	18	57	104.1	32	25	80	41.5	55.3	48.4
November . . .	2.58	16	55	61.1	23	19	62	36.5	48.2	42.4
December . . .	2.47	17	54	42.5	18	16	51	38.0	43.5	38.3
Whole year	28.34	173	47	1592.0	35	292	80	40.6	55.4	48.0

The average number of rainy days (with 0.01 inch or more) does not vary very much; the greatest is, like the rainfall, in October, and the lowest in June. The total number of rainy days in an average year amounts to less than 50 per cent.

The maximum amount of sunshine occurs in July (217.9 hours, or 45 per cent.). There is a slight decrease in August followed by a very rapid decrease until November. The minimum (42.5 hours, or 18 per cent.) is reached in December, after which there is a continuous increase until the maximum in July. As regards percentages of possible sunshine, the highest (45 per cent.) occurs in July, which is closely followed by August with 44 per cent., and September and May with 42 per cent., and April and June with 41 per cent. Of the remaining

months, March and October (31 and 32 per cent.) have the highest, and January and December the lowest percentages (21 and 18) of possible sunshine. In the whole year we have an average amount of 1592 hours, or not much more than a third of the actual sunshine above the level of the clouds.

*The Amounts of Nitrogen as Ammonia and Nitrates, Chlorine, and Sulphuric Acid, in the Rain-water at Rothamsted.*

At the time of the commencement of the Rothamsted Experiments very little was known as to the amounts of combined nitrogen and other substances present in rain-water.

The presence of ammonia, both in the atmosphere and in rain-water, was well known, but, owing to the imperfections of the methods of analysis then available, somewhat exaggerated ideas prevailed as to the amount. Liebig considered that the atmosphere was able to furnish the average crop with sufficient ammonia for its development, hence followed his celebrated "mineral" theory that to add to the soil the ash constituents of a crop would be a sufficient manuring. As this opinion of Liebig's was strongly contested by the Rothamsted investigators it was necessary to make accurate measures of the combined nitrogen brought by the rain.

The earliest analyses of Rothamsted rain were made in 1853-4, and were restricted to determinations of the nitrogen present as ammonia. These were followed in 1855-6 by determinations of ammonia and nitric nitrogen made by Professor Way. No further analyses were made until 1877, when monthly determinations of ammonia were recommenced. These were continued with some interruptions until December 1885, and again resumed by the late Dr Miller in December 1887 and February 1888, since which time until December 1916 ammonia was regularly determined each month. Dr Miller also determined nitric acid uninterruptedly from September 1886 till December 1916, for the first few months by Schloesing's method, and subsequently by Williams' zinc-copper couple method.

In addition to the analyses of monthly samples of rain, a large number of single samples have been analysed at Rothamsted, as well as about eighty samples by the late Sir E. Frankland.\*

TABLE VII.—*Nitrogen and Chlorine in Rothamsted Rain. Monthly Averages, 15 years (1889-1903).*

	Rainfall (Large Gauge). Inches.	Nitrogen.							Chlorine.	
		Per million.		Per acre.			Per cent. of Total.		Per million.	Per acre.
		As Ammonia.	As Nitrates and Nitrites.	As Ammonia.	As Nitrates and Nitrites.	Total.	As Ammonia.	As Nitrates and Nitrites.		
									Lb.	Lb.
January . . . . .	1·951	0·401	0·168	0·177	0·074	0·251	70·5	29·5	4·17	1·84
February . . . . .	1·710	0·424	0·209	0·164	0·081	0·245	66·9	33·1	3·33	1·29
March . . . . .	2·036	0·410	0·204	0·189	0·094	0·283	66·8	33·2	3·47	1·60
April . . . . .	1·516	0·571	0·227	0·196	0·078	0·274	71·5	28·5	2·71	0·93
May . . . . .	2·028	0·516	0·200	0·237	0·092	0·329	72·0	28·0	2·05	0·94
June . . . . .	2·185	0·520	0·216	0·257	0·107	0·364	70·6	29·4	1·46	0·72
July . . . . .	2·631	0·464	0·175	0·276	0·104	0·380	72·6	27·4	1·09	0·65
August . . . . .	2·959	0·476	0·170	0·319	0·114	0·433	73·7	26·3	1·33	0·89
September . . . . .	2·098	0·535	0·213	0·254	0·101	0·355	71·5	28·5	1·92	0·91
October . . . . .	3·407	0·335	0·160	0·258	0·123	0·381	67·7	32·3	2·32	1·79
November . . . . .	2·505	0·411	0·189	0·233	0·107	0·340	68·5	31·5	3·00	1·70
December . . . . .	2·590	0·379	0·195	0·222	0·114	0·336	66·1	33·9	3·60	2·11
Jan. to April . . . . .	7·213	0·445	0·200	0·726	0·327	1·053	68·9	31·1	3·47	5·66
May to Aug. . . . .	9·803	0·491	0·188	1·089	0·417	1·506	72·3	27·7	1·44	3·20
Sept. to Dec. . . . .	10·600	0·403	0·186	0·967	0·445	1·412	68·5	31·5	2·71	6·51
Whole year . . . . .	27·616	0·445	0·190	2·782	1·189	3·971	70·1	29·9	2·46	15·37

It will be convenient, for the purpose of summarising the results relating to nitrogen, to confine attention to the fifteen years 1889-1903, as during that period regular determinations both of ammonia and nitrates are available.

In Table VII. will be found the average monthly rainfall for the period in question, the amount of nitrogen as ammonia and as nitrate (or nitrite), also the chlorine, all expressed both as parts per million and as lb. per acre. Other columns show the relative proportions of the two combinations of nitrogen.

Reference to the table will show that the average amount of nitrogen in the two forms is 3·97 lb. per acre per annum,

\* See the Sixth Report of the Rivers Pollution Commission, 1874.

and that most of the nitrogen is in the form of ammonia, the nitric nitrogen representing only three-tenths of the whole. The monthly variations show little regularity either in the total nitrogen or in the relation of ammonia to nitrates. It is, however, of interest to note that in the period April to September, during which the rainfall is less than half the total for the year, the rain contains more nitrogen than in the six months, October to March, and that the amount of nitric nitrogen is nearly the same in both periods, the excess in the warmer periods being mainly due to ammonia.

When we compare the yearly amounts of nitrogen in the rain, the variations are not found to be great, and seem to have little if any relation to the rainfall. The highest result corresponds with the highest rainfall (4.84 lb. in 1903); but the minimum result (3.30 lb.) was obtained in 1890, when the rainfall amounted to 24.78 inches. With one of the lowest rainfalls of the period, however (20.967 inches in 1902), we get nearly the maximum amount of nitrogen, viz., 4.673 lb.

It must be borne in mind that the nitrogen in the forms of ammonia and nitrates does not represent the whole amount supplied to the soil. Frankland's results showed that the rain contains besides the nitrogen in these forms a certain amount of organic nitrogen, equal to about one-third of the nitrogen as ammonia and nitrates. So that we may consider that the average annual rainfall at Rothamsted contains 3.97 plus 1.3 or about 5 lb. of total nitrogen per acre.

The amount of chlorine in the monthly samples of rain has been determined at Rothamsted since 1877. The average amount over the whole year is 2.46 per million. The minimum amount is in the July rain (1.09 per million), and the maximum (4.17 per million) in the January rain. The amount falls and rises in the intermediate months with considerable regularity, the only break occurring in the March rain, which contains more chlorine than the rain falling in February. The total chlorine is equivalent to 25.3 lb. of common salt per acre per annum. Of this amount, 17.0 lb.

is contributed by the rain falling from October to March, and the rest (8.3 lb.) by the spring and summer rains (April to September). This difference is all the more striking as the rainfall of the two six-monthly periods is almost the same.

The yearly amounts of chlorine per acre vary considerably, and the variations depend more on the distribution of the rainfall during the year than on the total fall.

TABLE VIII.—*Comparison of Maximum and Minimum Precipitation of Rain and Chlorine.*

	Rainfall.	Chlorine.
	Inches.	Lb. per acre.
Maximum Rainfall (1903) .	38.69	19.99
Minimum Rainfall (1898) .	20.49	16.33
Maximum Chlorine (1903) .	38.69	19.99
Minimum Chlorine (1890) .	24.78	10.21

No recent determinations of sulphuric acid in rain-water have been made at Rothamsted, but a summary of the results obtained in 1881-7 is given here to complete the record.

Reference to the Table (IX.) will show that the rain contains on the average 2.57 per million of sulphuric acid

TABLE IX.—*Sulphuric Acid and Chlorine in Rain-water collected at Rothamsted.*

1881-7.	Rainfall.	Per million.		Per acre.		SO <sub>3</sub> to 1 Cl.
		Cl.	SO <sub>3</sub> .	Cl.	SO <sub>3</sub> .	
	Inches.			Lb.	Lb.	
April-September . . .	13.90	1.31	2.77	4.11	8.71	2.12
October-March . . .	16.05	2.89	2.39	10.51	8.70	0.83
Whole year . . .	29.95	2.16	2.57	14.62	17.41	1.19

(as SO<sub>3</sub>), and that the total annual amount per acre is 17.41 lb. The most noteworthy result is the close agreement between the amounts furnished by the summer and winter rain, especially in view of the great variations in the chlorine.

In conclusion, it may be pointed out that the rain falling

at Rothamsted contributes to the soil enough chlorine and sulphuric acid to meet the requirements of most crops.

*Proportion of Rainfall percolating through Bare Soil.*

Alongside the large rain gauge, three percolation or drain gauges were constructed in 1870. Portions of the undisturbed soil, each one-thousandth of an acre in area, were isolated from the surrounding soil by digging trenches and building brick and cement walls round the blocks of soil thus exposed. The blocks were then undermined, and eventually carried upon bars and plates of iron perforated to enable the percolating water to find its way into the collecting funnel beneath. Thus in the end three blocks of undisturbed soil were obtained, each one-thousandth acre in area, 20, 40, and 60 inches in thickness respectively, entirely isolated from the surrounding soil, and the rain-water percolating through each block is collected separately and measured like the rainfall.

Table X. shows the average results obtained during the forty-two years 1871-1912.

TABLE X.—*Rainfall and Drainage at Rothamsted.*

	Rainfall ( $\frac{1}{1000}$ th Acre Gauge).	Percolation through Soil.			Difference Evaporated (or Retained by Soil).		
		20 in. deep.	40 in. deep.	60 in. deep.	20 in. deep.	40 in. deep.	60 in. deep.
Average for each Month, 42 years (1871 to 1912).							
	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
January . . . . .	2·09	1·71	1·99	1·91	0·38	0·10	0·18
February . . . . .	1·97	1·32	1·45	1·42	0·65	0·52	0·55
March . . . . .	2·03	0·99	1·16	1·09	1·04	0·87	0·94
April . . . . .	1·82	0·49	0·56	0·53	1·33	1·20	1·69
May . . . . .	2·11	0·43	0·55	0·49	1·66	1·56	1·62
June . . . . .	2·52	0·67	0·71	0·68	1·85	1·81	1·84
July . . . . .	2·46	0·63	0·68	0·60	1·83	1·80	1·86
August . . . . .	2·85	0·68	0·70	0·54	2·17	2·15	2·31
September . . . . .	2·17	0·78	0·73	0·68	1·39	1·44	1·49
October . . . . .	3·29	1·92	1·87	1·75	1·37	1·42	1·54
November . . . . .	2·83	2·13	2·18	2·07	0·70	0·65	0·76
December . . . . .	2·71	2·14	2·35	2·25	0·57	0·36	0·54
Mean Total per year . .	28·75	13·89	14·91	13·93	14·94	13·88	15·32
Results for Maximum and Minimum Rainfall.							
Maximum (1903) . . . .	38·69	23·48	23·60	24·23	15·21	15·09	14·46
Minimum (1893) . . . .	20·49	7·32	7·90	7·69	13·17	12·59	12·80

It will be seen that the three different thicknesses of soil yield practically the same results, it being difficult to account for the small but constant differences which occur. On the average, about half the annual rainfall percolates through the gauges, and about one-half is evaporated. It should be borne in mind, however, that the surface of the soil in these gauges is kept free from vegetation of all kinds, so that there is no drying effect due to the crop. Again, as communication between the subsoil and the soil of the gauges is cut off, all capillary movements of water, both downwards during rain and back again during periods of drought, are stopped at a certain point, thus affecting both percolation and evaporation by unknown amounts.

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## CHAPTER III

### THE COMPOSITION OF THE ROTHAMSTED SOIL

THE Rothamsted soil was described by Lawes in the first paper he contributed to the *Journal of the Royal Agricultural Society* in 1847, as follows:—"The soil upon which my experiments were tried consists of rather a heavy loam resting upon chalk, capable of producing good wheat when well manured; not sufficiently heavy for beans, but too heavy for good turnips or barley. The average produce of wheat in the neighbourhood is said to be less than 22 bushels per acre, wheat being grown once in five years. The rent varies from 20s. to 26s. per acre, tithe free."

The geological character of the Rothamsted soils has been thus described by Mr H. B. Woodward, F.R.S.: "The geology of the Rothamsted estate is comparatively simple. Chalk forms the foundation of the entire area, but it is exposed only on the slopes. The plateau ground is covered with a very mixed deposit of clay-with-flints, with remnants of the mottled clays, sands, and pebble-beds of the Reading series, and also of remnants of drift gravel. The low grounds are occupied by valley gravel."

"The experimental fields belonging to the Lawes Agricultural Trust are entirely on the mixed deposit of clay-with-flints, etc."

"The chalk, which is extensively 'piped,' appears here and there in irregular pinnacles near the surface. It is usually lined with stiff red or dark brown clay-with-flints, the joints in

the clay, and also the flints, being blackened by manganese oxide. Masses of this stiff clay-with-flints form the subsoil in places; elsewhere light sands or red loamy sands with or without black flint pebbles, or masses of pebbles alone, form the immediate subsoil; again, grey or mottled clay or loam with occasional pebbles or free from stones, or with a gravelly pocket here and there, extends for some distance, immediately beneath the soil. These accumulations occur in irregular juxtaposition owing to the piped surface of the chalk, and in places there is a kind of marl formed on the slopes by the weathered rubbly chalk mixed with earth."

"Covering these subsoils there is a soil of grey flinty or pebbly loam, 10 inches or more in thickness, and varying in character according to the number of stones in it; in some cases rough and unworn flints prevail, elsewhere there is an admixture of pebbles; and over some areas the soil consists of loam with comparatively few stones. In all cases, excepting on the chalk slopes and in the valley bottom, the soil is to be regarded as a heavy mixed soil, for the subsoil is in the main a heavy clay; and were it not for the fact that the chalk here and there approaches very near to the surface of the higher grounds, the land would be much wetter after rain than is the case. These underground pinnacles of chalk, and the pockets of sand and gravel, act as dumbwells for the surface drainage."

Notwithstanding the irregularity of the subsoil, the agricultural character of the soil is fairly uniform all over the estate; some fields work rather more heavily than others, and the proportion of stones lying on the surface varies somewhat, but these differences are comparatively unimportant. The soil passes into the subsoil without any sharp line of distinction, and the distribution of flints in the subsoil is very irregular, while the solid chalk is reached at depths varying between 8 and 12 feet.

The following Table (XI.) shows the mean results obtained for the weight per cubic foot and the weight per acre of stones

## COMPOSITION OF ROTHAMSTED SOIL

and fine earth for successive layers 9 inches thick, down to a depth of 3 feet, on each of the chief experimental fields:—

TABLE XI.

	Broadbalk Field.	Hoos Field.	Aspell Field.	Barn Field.	Average.
Average Weights of Fine Dry Soil per acre.					
	Lb.	Lb.	Lb.	Lb.	Lb.
First 9 inches . . . . .	2,559,000	2,593,000	2,348,000	2,321,000	2,455,000
Second 9 inches . . . . .	2,592,000	2,721,000	2,448,000	2,673,000	2,609,000
Third 9 inches . . . . .	2,815,000	2,891,000	2,533,000	2,651,000	2,722,000
Fourth 9 inches . . . . .	2,886,000	3,048,000	2,442,000	...	2,792,000
Average Weights of Stones per acre.					
First 9 inches . . . . .	498,000	481,000	837,000	769,000	646,000
Second 9 inches . . . . .	443,000	346,000	480,000	530,000	450,000
Third 9 inches . . . . .	213,000	238,000	363,000	415,000	307,000
Fourth 9 inches . . . . .	164,000	170,000	477,000	...	270,000
Weight per cubic foot of Fine Dry Soil and Stones.					
First 9 inches . . . . .	93.6	94.1	97.5	94.6	94.9
Second 9 inches . . . . .	92.9	93.9	89.6	98.0	93.6
Third 9 inches . . . . .	92.7	95.8	88.6	93.9	92.7
Fourth 9 inches . . . . .	93.4	98.5	89.4	...	93.7

The mechanical analyses set out in Table XII. show that the Rothamsted soil is fairly uniform in the different fields, and

TABLE XII.—*Mechanical Analysis of Rothamsted Soils.*

	First 9 inches.			Second 9 inches.	Third 9 inches.
	Broad-balk.	Hoos Field.	Barn Field.	Broad-balk.	Broad-balk.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Fine Gravel, 3 to 1 mm. . . . .	1.9	2.0	3.1	1.7	0.5
Coarse Sand, 1 to 0.2 mm. . . . .	6.2	6.8	5.9	4.3	2.5
Fine Sand, 0.2 to 0.04 mm. . . . .	21.4	19.5	19.7	15.8	13.2
Coarse Silt, 0.04 to 0.01 mm. . . . .	32.5	28.9	26.0	24.0	18.0
Fine Silt, 0.01 to 0.002 mm. . . . .	13.8	16.5	13.1	16.7	13.8
Clay, less than 0.002 mm. . . . .	17.6	18.8	25.6	28.7	40.0
Carbonate of Lime, Loss on Solution, etc. . . . .	4.2	...	3.7	...	...
Hygroscopic Moisture . . . . .	2.2	2.5	2.8	3.8	5.8

consists essentially of a heavy loam containing little coarse sand

or grit, but a considerable amount of fine sand and silt and a large body of clay. In consequence, the soil has to be worked with care, becoming very sticky and drying to impracticable clods if moved when wet. It "runs together" if heavy rain falls after a tilth has been established, and then dries with a hard, unkindly surface, these difficulties being much exaggerated on the plots which have been farmed for a long time without any supply of organic matter in the manures.

The chemical analysis of the Rothamsted soils differs very much from plot to plot according to the long-continued manurial treatment which has been given to each plot. But everything points to the fact that the soil was of an ordinary type when the experiments began, certainly no richer in dormant plant food than the majority of fairly heavy soils in this country.

The following table gives the results of analyses (made by Dr B. Dyer as regards the mineral constituents) of samples drawn from the Broadbalk wheat soils in 1893:—

TABLE XIII.

Soil dried at 100° C.	First 9 inches.		Second 9 inches.		Third 9 inches.	
	Plot 3. Un- manured.	Plot 2. Farmyard Manure.	Plot 3. Un- manured.	Plot 2. Farmyard Manure.	Plot 3. Un- manured.	Plot 2. Farmyard Manure.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Loss on Ignition . . . . .	4.20	6.76	4.61	...	5.11	...
Containing Carbon . . . . .	0.888	2.230	0.565	0.748	0.483	0.492
Containing Nitrogen . . . . .	0.099	0.221	0.073	0.077	0.065	0.066
Soda * . . . . .	0.058	0.138	0.090	0.132	0.106	0.111
Potash * . . . . .	0.274	0.430	0.446	0.524	0.618	0.661
Potash, soluble in 1 per cent. Citric Acid . . . . .	0.0032	0.0384	0.0060	0.0276	0.0072	0.0128
Magnesia * . . . . .	0.360	0.320	0.420	0.340	0.400	0.420
Lime * . . . . .	2.486	2.665	0.460	0.616	0.538	0.504
Alumina * . . . . .	4.486	4.805	7.407	6.829	11.623	10.477
Oxide of Iron * . . . . .	3.400	3.600	5.200	4.800	7.200	6.400
Phosphoric Acid * . . . . .	0.114	0.215	0.113	0.111	0.097	0.083
Phosphoric Acid, soluble in 1 per cent. Citric Acid . . . . .	0.0078	0.0560	0.0045	0.0094	0.0025	0.0034
Sulphuric Acid † . . . . .	0.048	0.055	0.041	0.041	0.038	0.031
Carbonic Acid † . . . . .	1.300	1.400	0.050	0.200	0.100	0.050
Undissolved Matter * . . . . .	83.700	80.800	81.480	82.520	73.220	76.120

\* Determined in the solution obtained by treating the ignited soil with strong Hydrochloric Acid.  
 † Determined in the unignited soil.

The most notable feature in the Rothamsted soil is the amount of calcium carbonate in the surface layer; analyses of

the earliest samples available (1856) show more than 5 per cent. in the surface soil of Broadbalk field. This amount is always being reduced by the action of the rain washing it away as calcium bicarbonate; it is still more rapidly reduced by the action of many of the manures applied, particularly by the ammonium salts, so that at the present time there is only about 3 per cent. present on any of the plots. In other fields less is to be found, practically none at all in the soil of some parts of Agdell and of the Park. The subsoil below the depth of 9 inches also contains little or no calcium carbonate, and this fact together with the varying proportion in the surface soil indicate that the original soil was almost devoid of calcium carbonate, and that the quantity still found in the surface soil has all been applied artificially. We read, indeed, that the chief form of manuring known to Hertfordshire farmers in the eighteenth century consisted in digging pits through the clay soil until the chalk was reached, extracting chalk and spreading it over the land, and all of the Rothamsted fields show a depression or "dell" from which the chalk had thus been formerly obtained. Arthur Young, the elder, in his *General View of the Agriculture of Herts*, drawn up for the consideration of the Board of Agriculture, and published in 1804, writes of "the prevailing practice of sinking pits for the purpose of chalking the surrounding land," and mentions the application of 60 loads of chalk every ten years as customary. The chalk now present in the arable soil is visible in small grains varying in size from that of a pea downwards, additional evidence of its extraneous origin. But the amounts so added to the soil are enormous: if we assume that the wastage in the past had been at all comparable to that going on during the last half-century on the unmanured plot, then Broadbalk field must have begun the nineteenth century with something like 100 tons of chalk per acre in its surface soil.

The proportion of organic matter, carbon and nitrogen, present in the various soils is very variable and entirely dependent on the character of the manuring and cultivation.

As will be seen later, continuous cropping without manure soon reduces such materials in the soil to a low ebb, below which they do not fall appreciably in succeeding years; the crop production becomes very nearly stationary and is accompanied by a very small reduction in the original stock of carbon and nitrogen, even if there are not compensating influences at work maintaining the store at a constant low level. Similarly, when very large amounts of organic matter are added every year as when plots are continuously dunged, after a time there is but little increase in the proportions of carbon and nitrogen present in the soil, because the bacterial agencies which generate carbon and nitrogen compounds of a gaseous nature are so stimulated by the abundant food-supply as to keep pace with the annual additions.

Of the other important constituents of plant food the soil carries an abundant stock of potash; a complete mineral analysis, in which the Broadbalk soil was completely broken up by hydrofluoric acid, yielded as much as 2.26 per cent. of potash, quite four times the amount that can be extracted by long digestion with hydrochloric acid. Though this vast stock of potash is in the main dormant, it slowly becomes available for crops through the weathering agencies which are brought into play by cultivation.

In phosphoric acid the soil is by no means so rich; the unmanured plots contain now rather less than 0.1 per cent., the highest limit reached on some of the very heavily manured plots being about 0.25 per cent.; under ordinary farming conditions, however, the soil shows no particular need of phosphoric acid, as do many clay soils.

Magnesia is fairly abundant in the Rothamsted soils; in the subsoil, indeed, it is present in almost the same proportions as the lime, it is only in the artificially chalked surface soil that the ratio of lime to magnesia is a high one.

Soda is present in small quantities, partly combined with chlorine as common salt derived from rain, and partly in the double silicates of the clay.

In general, it may be said that the Rothamsted soil presents no striking peculiarities, either chemical or physical.

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## CHAPTER IV

### EXPERIMENTS UPON WHEAT

- I. The Continuous Growth of Wheat, Broadbalk Field :
  - A. Maintenance of the yield under Continuous Wheat growing on the same land.
  - B. Effect of Nitrogenous Manures.
  - C. Effect of the Mineral Constituents.
  - D. Retention of Manures by the Soil.
  - E. Character of the Crop as affected by Manuring and Season.
- II. Wheat after Fallow and in Rotation.
- III. Trials of Varieties of Wheat.  
Practical Conclusions and References.

#### I.—THE CONTINUOUS GROWTH OF WHEAT, BROADBALK FIELD.

THE experiments on the continuous growth of wheat were begun in the Broadbalk field in 1843, but for the first eight years the manuring was of a varied description, so that only three of the plots have received the same treatment during the whole period of sixty years. The plots as seen to-day began in 1852, since which time the few changes in manuring have been matters of detail and not of principle; thus the results represent a continuous trial of wheat grown with the same manures upon the same land year after year for more than half a century.

The Broadbalk field has an area of about 11 acres, and slopes somewhat to the east; the plots are each half an acre in area, and consist of strips 351 yards long by about 7 yards wide, running down the slope for the whole length of the field, and separated by paths which are not cropped. Previous to 1843 the land had been cropped on a five-course system: manure was last applied to the turnips in 1839, and two white

straw crops were taken immediately prior to the first experimental crop of wheat sown in the autumn of 1843, so that the land was in low condition from an agricultural point of view at the beginning of the trials. This is also shown by the fact that the first experimental crop in 1844 amounted to only 15 bushels per acre on the unmanured plot, although the wheat crop was generally much above the average in that year.

The soil of the Broadbalk field consists of a stiff greyish loam containing an abundance of flints; the subsoil is of a similar character, rather stiffer and redder in colour—"the clay-with-flints" of the geologist. The chalk lies below at a variable depth, rarely less than 8 or 10 feet, thus providing good natural drainage. In addition, each plot has a tile drain running down the centre of the plot at a depth of 2 to 2½ feet, the mouths of all the drains being led into a brick trench, where the water draining from each plot can be separately collected for analysis.

The field cannot be described as more than fair average wheat land, nor do the analyses show any special reserve of fertility beyond that natural to moderately strong land which has been under arable cultivation for a very long time.

The usual practice is to scuffle the land immediately after harvest and remove the weeds; the land is then ploughed 5 or 6 inches deep; the mineral and other autumn-sown manures are sown and harrowed in, after which the seed is drilled. The following varieties of seed have been used: Old Red Lammas, five years, 1843-4 to 1847-8; Red Cluster, four years, 1848-9 to 1851-2; Red Rostock, twenty-nine years, 1852-3 to 1880-1; Club or Square Head (Red), eighteen years, 1881-2 to 1898-9; and Square Head's Master (Red), in 1899-1900 and since.

The chief difficulty experienced in growing wheat continuously is that of keeping the land clean; not only does the crop occupy the ground for the greater part of the year, and so leave little opportunity for cleaning operations, but the weeds whose habit of growth is favoured by the crop tend to accumulate from year to year. Thus in spite of repeated hand-

hoeings, some weeds, like the "Black Bent" grass, *Alopecurus agrestis*, are kept under with the greatest difficulty.

The general scheme of the experiments in the Broadbalk field has been to test the manurial requirements of wheat by growing it continuously with various combinations of manures repeated year after year on the same plots. At the outset of the experiments it should be remembered that little was then known as to the manurial requirements of any crop. Liebig had just stirred the agricultural world by the general statement that if a plant were supplied with the mineral constituents left as ash when the plant is burnt, it will require no further assistance in the shape of manure, but will draw its carbon and nitrogen from the atmosphere. The first experiments were designed to verify the truth of this statement, and were extended to test the effect of each of the constituents found in the plant. The effect of mineral manures alone is compared with that of nitrogenous manure in various forms, or of a combination of the two. The constituents of the mineral manure—phosphoric acid, potash, soda, and magnesia—are variously combined with nitrogenous manures, so as to ascertain the part each of them plays in the nutrition of the crop. Thus Plots 6, 7, 8, 9, 15, 16, 17, and 18 receive varying amounts and combinations of nitrogen, together with the same mineral manure containing all the elements present in the ash of the wheat plant. Again, all the Plots 10, 11, 12, 13, and 14 receive the same amount of nitrogen, but differ in the arrangement of the accompanying mineral manure. Some of the plots also test the question of the season at which the manures are applied, and whether any of the residues are carried forward to another year. The long duration of the experiment serves to eliminate many of the sources of error in field experiments, such as initial variations in the condition of the soil of various plots due to previous manuring, irregular attacks of insect and other pests, and variations due to seasons which may favour some manures and not others. Also by gradually exhausting the soil of particular constituents, the continuity brings to light

the function of any element of manurial plant food in a way that is not possible in the first few years of an experiment, because of the large reserves of all plant foods contained in ordinary soil.

Table XIV. shows the nature and quantities of the manures applied each year to the plots. The mineral manures (by minerals is understood at Rothamsted the phosphoric acid, potash, magnesia, soda, and other constituents left as ash when the plant is burnt, but not any manure containing nitrogen) are sown before the seed in the autumn, the rape cake and the farmyard manure, and a portion of the ammonium-salts are also supplied in the autumn before seeding, but the nitrate of soda and the greater part of the ammonium-salts are put on as top-dressings in the spring.

TABLE XIV.—*Experiments on Wheat, Broadbalk Field. Manuring of the Plots per acre per annum, 1852 and since.*

Plot.	Abbreviated Description of Manuring.	Nitrogenous Manures.				Mineral Manures.			
		Farmyard Manure.	Rape Cake.	Nitrate of Soda.	Ammonium-salts.	Super-phosphate.	Sulphate of Potash.	Sulphate of Soda.	Sulphate of Magnesia.
		Tons.	Lb.	Lb.	Lb.	Cwt.	Lb.	Lb.	Lb.
2	Farmyard Manure . . . . .	14	...	...	...	...	...	...	...
3	Unmanured . . . . .	...	...	...	...	...	...	...	...
5	Minerals . . . . .	...	...	...	...	3·5	200	100	100
6	Single Ammonium-salts and Minerals . . . . .	...	...	...	200	3·5	200	100	100
7	Double do. do. . . . .	...	...	...	400	3·5	200	100	100
8	Treble do. do. . . . .	...	...	...	600	3·5	200	100	100
9	Single Nitrate and Minerals . . . . .	...	...	275	...	3·5	200	100	100
10	Double Ammonium-salts alone . . . . .	...	...	...	400	...	...	...	...
11	Do. and Superphosphate . . . . .	...	...	...	400	3·5	...	...	...
12	Do. do. and Sulph. Soda . . . . .	...	...	...	400	3·5	...	366·5	...
13	Do. do. and Sulph. Potash . . . . .	...	...	...	400	3·5	200	...	...
14	Do. do. and Sulph. Mag. . . . .	...	...	...	400	3·5	...	...	280
15	Double Amm.-salts in autumn, and Minerals . . . . .	...	...	...	400	3·5	200	100	100
16	Double Nitrate and Minerals . . . . .	...	...	550	...	3·5	200	100	100
17	Minerals alone, or Double Amm.-salts . . . . .	...	...	...	...	3·5	200	100	100
18	{ alone, in alternate years . . . . .	...	...	...	400	...	...	...	...
19	Rape Cake alone . . . . .	...	1889	...	...	...	...	...	...

*Notes on the Manures.*

The ammonium-salts consists of a mixture of equal parts of sulphate and muriate of ammonia; 200 lb. supply 43 lb. of nitrogen, equal to the amount contained in 275 lb. nitrate of soda, or 1889 lb. of rape cake. The super-

phosphate contains 37 per cent. phosphate made soluble, or 66 lb. of soluble phosphoric acid.

On Plots 9, 15, 16, and 19 certain changes in the manuring have been made during the progress of the experiments, which are set out in detail in the "Memoranda" for 1901.

Table XV. shows the average production of grain and straw for the whole period of sixty-one years, for the last ten years, and for the single year 1911.

TABLE XV.—*Experiments on Wheat, Broadbalk Field. Produce of Grain and Straw per acre. Average over 61 years (1852-1912); and over 10 years (1903-1912); also Produce in 1911.*

Plot.	Abbreviated Description of Manuring.	Dressed Grain.			Straw.		
		Average, 61 years (1852-1912).	Average last 10 years (1903-1912).	Season 1911.	Average, 61 years (1852-1912).	Average last 10 years (1903-1912).	Season 1911.
2	Farmyard Manure . . . . .	Bush 35.2	Bush 32.8	Bush 35.2	Cwt. 34.8	Cwt. 38.2	Cwt. 36.9
3	Unmanured . . . . .	12.6	10.0	12.5	10.3	9.3	9.8
5	Minerals . . . . .	14.5	12.5	14.8	12.1	11.9	12.8
6	Single Ammonium-salts and Minerals . . . . .	23.2	19.0	17.2	21.4	20.7	17.9
7	Double do. do. . . . .	32.1	27.9	25.6	32.9	32.3	27.6
8	Treble do. do. . . . .	36.6	33.8	36.4	41.1	42.1	35.7
9	Single Nitrate and Minerals . . . . .	...	26.0	29.9	...	28.7	29.0
10	Double Ammonium-salts alone . . . . .	20.0	16.3	22.8	18.4	16.7	17.2
11	Do. and Superphosphate . . . . .	22.9	17.1	20.1	22.3	20.2	15.2
12	Do. do. and Sulph. Soda . . . . .	29.1	24.6	27.0	28.0	26.2	20.6
13	Do. do. and Sulph. Potash . . . . .	31.0	28.7	29.7	31.5	33.1	27.4
14	Do. do. and Sulph. Mag. . . . .	28.8	22.0	24.1	28.0	24.1	18.9
15	Double Amm.-salts in autumn, and Minerals . . . . .	29.9	26.4	24.1	29.7	29.0	22.3
16	Double Nitrate and Minerals . . . . .	...	30.2	40.4	...	39.1	42.4
17	} Minerals alone, or Double Ammonium-salts } alone. in alternate years . . . . .	* 14.9	12.9	13.8	13.0	12.4	11.7
18		† 29.9	27.6	27.3	29.5	29.7	24.6
19	Rape Cake alone . . . . .	25.4	22.8	23.6	25.7	24.8	24.7

\* Produce by Minerals.

† Produce by Ammonium-salts.

The grain is expressed in measured bushels per acre, the weight of the bushel depending on the plot and season. The straw, which includes chaff, etc., is given in cwt. per acre.

Table XVI. shows the average production of certain of the plots for the six successive ten-year periods from 1852 to 1911. Although ten-year periods are not long enough entirely to remove the effect of season, yet the table enables one to judge whether the fertility of the plots has increased or diminished under the treatment they receive.

## EXPERIMENTS UPON WHEAT

TABLE XVI.—*Experiments on Wheat, Broadbalk Field. Average Produce of Grain and Straw per acre the first 8 years (1844-1851), and over the successive 10-year periods (1852-1911) inclusive.*

Plot.	Abbreviated Description of Manures.	Averages over						
		8 years (1844-1851).	10 years (1852-1861).	10 years (1862-1871).	10 years (1872-1881).	10 years (1882-1891).	10 years (1892-1901).	10 years (1902-1911).
Dressed Grain.								
		Bush.	Bush.	Bush.	Bush.	Bush.	Bush.	Bush.
2	Farmyard Manure . . . . .	28·0	34·2	37·5	28·7	33·2	39·2	35·1
3	Unmanured . . . . .	17·2	15·9	14·5	10·4	12·6	12·3	10·9
5	Minerals . . . . .	...	18·1	15·5	12·1	13·8	14·8	13·5
6	Single Ammonium-salts and Minerals . . . . .	...	27·2	25·7	19·1	24·5	23·1	21·4
7	Double do. do. . . . .	...	34·7	35·9	26·9	35·0	31·8	30·9
8	Treble do. do. . . . .	...	36·1	40·5	31·2	38·4	38·5	37·2
10	Double Ammonium-salts alone . . . . .	25·1	23·2	25·1	17·3	19·4	18·4	18·4
11	Do. and Superphosphate . . . . .	...	23·4	27·9	21·7	22·7	19·5	19·2
12	Do. do. and Sulph. Soda . . . . .	...	33·4	34·3	25·1	30·1	26·7	27·4
13	Do. do. and Sulph. Potash . . . . .	...	32·9	34·8	26·8	32·5	29·6	32·1
14	Do. do. and Sulph. Mag. . . . .	...	33·5	34·4	26·4	31·1	25·0	25·0
Straw.								
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
2	Farmyard Manure . . . . .	26·6	33·9	34·0	28·0	34·8	38·7	40·9
3	Unmanured . . . . .	15·5	15·2	11·6	8·5	8·5	9·1	9·6
5	Minerals . . . . .	...	17·1	12·8	9·7	9·9	11·5	12·4
6	Single Ammonium-salts and Minerals . . . . .	...	26·3	22·8	17·7	20·5	20·0	22·4
7	Double do. do. . . . .	...	36·4	34·3	28·7	34·1	31·1	35·4
8	Treble do. do. . . . .	...	40·5	43·2	36·6	42·5	41·7	45·5
10	Double Ammonium-salts alone . . . . .	23·7	24·5	21·9	15·2	15·8	16·2	18·0
11	Do. and Superphosphate . . . . .	...	28·2	24·5	21·3	20·8	18·8	21·7
12	Do. do. and Sulph. Soda . . . . .	...	34·2	30·5	25·0	27·3	24·0	28·6
13	Do. do. and Sulph. Potash . . . . .	...	34·4	33·4	27·6	31·9	28·6	35·8
14	Do. do. and Sulph. Mag. . . . .	...	35·0	30·7	26·3	28·6	23·4	26·3

A. *Maintenance of the yield under Continuous Wheat growing on the same land.*

The curves in Fig. 2 show the fluctuations in the yield of total produce for the first eight-year and six ten-year periods from the beginning of the experiment on certain of the plots—Plot 3, which is unmanured; Plot 2, which receives farmyard manure every year; Plots 6 and 7, which receive a complete artificial manure containing varying quantities of nitrogen; and Plot 10, which receives nitrogen only.

Considering the unmanured plot first, it will be seen that while there is evidence of a small decline in production for the

first eighteen years, yet the crop has been practically constant during the last thirty years. The fluctuations during this period

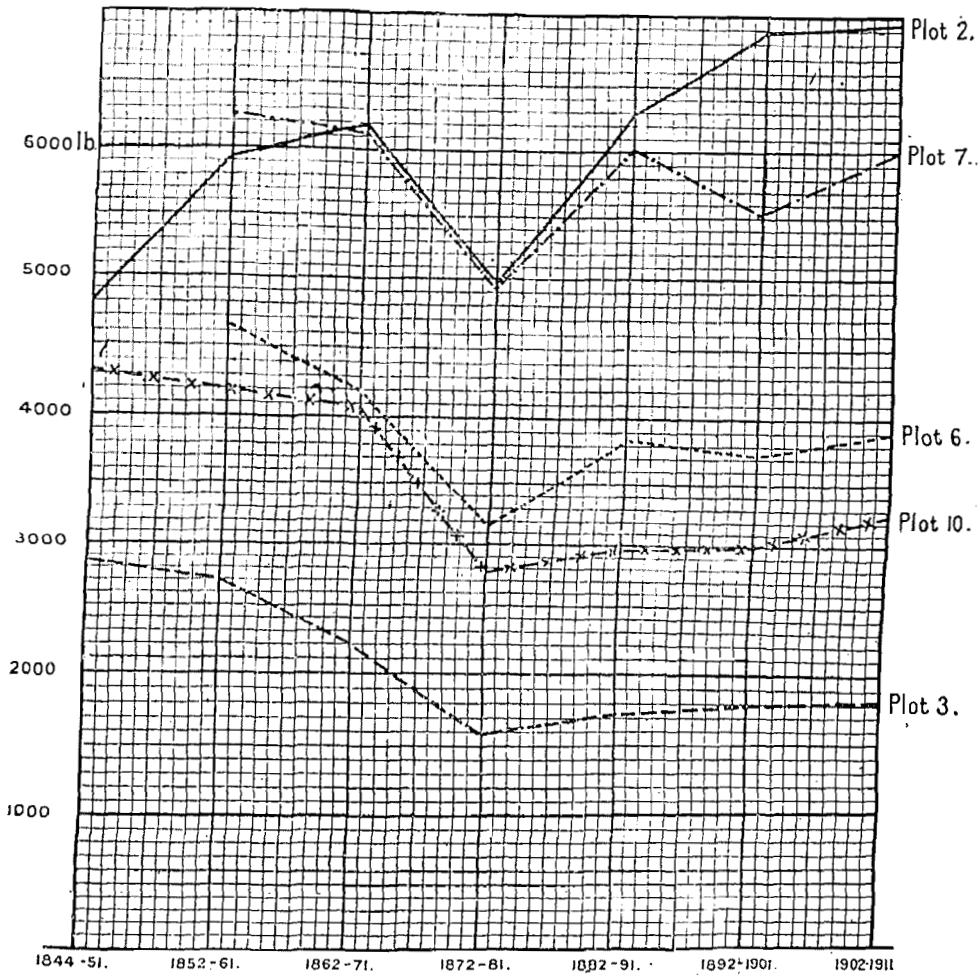


FIG. 2.—Broadbalk Wheat. Total Produce.

are in the main due to season, and correspond very closely with those of the completely manured Plots 6 and 7. For example, there was a considerable drop during the decade 1872-81, a period of notoriously bad seasons; then followed a considerable recovery in the next decade, which has been maintained for the last twenty years. But all the evidence seems to point to the fact that this plot, which has been without manure of any description since 1839, has reached a stationary condition, and that the average crop of twelve and a half bushels for the last fifty years will in future diminish very slowly, if at

all. It has been already pointed out that the Rothamsted soil is by no means exceptionally rich, how then can this continued production of crop without manure be accounted for? It is estimated that the average crop on this plot has removed about 17 lb. of nitrogen, 9 lb. of phosphoric acid, and 14 lb. of potash per acre per annum. In the drainage water there is also a further loss of nitrogen, which has been estimated at 10 lb. per acre per annum; some nitrogen is also removed in weeds. *Per contra*, the rain brings about 5 lb. of nitrogen each year, and the seed supplies perhaps 2 lb., thus leaving a nett annual loss of nitrogen of at least 20 lb. per acre. The analyses of the soil taken in 1865, 1881, and 1893, show that there is a steady diminution in the amount of combined nitrogen present in the soil; but since in 1893 the proportion present was 0·099, or rather more than 2500 lb. per acre in the top 9 inches of soil, there is still an enormous reserve untouched. There may also be hitherto unrecognised gains of nitrogen from the atmosphere. For example, the Black Medick is a common weed on this plot, and like other leguminous plants fixes some nitrogen from the atmosphere, part of which will be left behind in the soil when the roots decay. Soil bacteria are also known which are capable of fixing nitrogen independently of the higher plants; but until the analyses of the soil have been repeated after another long interval it is not possible to say whether such recuperative agencies have any practical effect, or whether the crop is still being grown out of the original resources of the soil. As regards potash and phosphoric acid, there can be no external sources of recovery, but the reserves are very great, amounting in 1893 to about 3000 lb. of phosphoric acid and as much as 50,000 lb. of potash per acre in the top 9 inches of soil, though of course the greater part of the latter would only become available for the plant very slowly.

On Plot 2 there has been a yearly dressing of 14 tons of farmyard manure, and though the composition of the dung is so far variable that it is impossible to say exactly what

## INCREASED FERTILITY OF DUNGED PLOT 39

quantity of plant food has been supplied, the annual application is estimated to contain about 200 lb. of nitrogen, 78 lb. of phosphoric acid, and 235 lb. of potash; whereas the average crop has only removed about 52 lb. of nitrogen, 27 lb. of phosphoric acid, and 53 lb. of potash per acre. There should be an accumulation of fertility on this plot, and an examination of the curve shows that after a rapid rise during the first eight years of the experiments, when the land was recovering from a state of comparative exhaustion, the yield of grain has been slowly increasing, despite the depression during the decade 1872-81. The increase was particularly manifest during the eighties and nineties, on the whole a period of dry seasons, when the moisture retained by the accumulation of humus from the dung also had its effect. The increased fertility of this plot would doubtless have been more manifest were it not for the tendency of the crop to be laid in the heavier yielding seasons. The analyses show that enormous reserves of plant food have been accumulated in the soil of this plot, the amount of nitrogen in the surface soil being more than double that of the unmanured plot, the phosphoric acid being also almost doubled, and the potash showing a very considerable increase. While some of these reserves are in a readily available form, there is evidence from the other experiments at Rothamsted that even in fifty years it would be impossible to crop them entirely out, if a course of growing corn without further manuring were now entered on.

Regarding now Plots 6 and 7, receiving artificial manures which supply nitrogen, potash, and phosphoric acid, but no organic matter to form humus, we see that Plot 7 for forty years yielded a crop very little inferior to that grown on the dunged plot, and shows no evidence of a decline in fertility. The manure on this plot supplies 86 lb. of nitrogen per acre, whereas the average crop has taken away not more than 50 lb. The phosphoric acid and potash supplied are also in excess of the requirements of the crop. On Plot 6 only 43 lb. of nitrogen per acre are supplied, little more than the

amount removed in the crop. If we consider the other sources of loss of nitrogen to the soil, such as the removal of weeds, drainage, etc., it becomes clear that the 43 lb. of nitrogen in the manure are not sufficient to repair the annual withdrawals of nitrogen. Consequently we should expect some diminution of fertility on this plot, and analyses of the soil seem to show that it is slowly losing nitrogen. The curve expressing the crop on Plot 6 is very similar to that of the unmanured plot, indicating a considerable fall in fertility during the first twenty years, and a comparatively constant position for the last twenty years. Thus this plot like the unmanured plot seems to have reached a position of comparative stability, when the annual withdrawal of nitrogen by crop and drainage, etc., is almost balanced by the additions from all sources, so that the fertility of the land is declining very slowly, if at all. Though no material to form humus has been supplied to Plots 6 and 7, and analysis shows that the soil is gradually being deprived of its original stock, yet the wheat crop so far seems to be unaffected by the loss of this important constituent of the soil.

Plot 10 has received an annual dressing of nitrogen only, in the shape of 400 lb. of ammonium-salts since the earliest date of the experiments. It will be evident from the curve showing the crop production that, despite this long-continued use of a manure supplying but one element of plant nutrition, the crop has been wonderfully maintained. Whereas the average production over the whole period is increased by the supply of minerals to the extent of 1.9 bushels, the nitrogen alone has produced an average increase of 7.4 bushels, the unmanured plot being taken as the standard in either case. The curve, however, shows that the production on this Plot 10 has declined, but for the last thirty years it has remained fairly steady, rising slightly from the low position in the years 1872-81. The crop on this plot presents a very unhealthy appearance, is very slow to mature, and is extremely liable to rust.

We thus see that it is possible to grow a cereal crop like

wheat year after year on the same land for at least sixty years without any decline in the productiveness of the soil, provided an appropriate manure be supplied to replace the nitrogen, phosphoric acid, and potash removed by the crops. There is no evidence in fact that the wheat gives a smaller yield when following a long succession of previous wheat crops than when grown in rotation, although the vigour of the plant does not appear to be so great. The real difficulty, however, in continuous corn-growing is to keep the land clean; certain weeds are favoured by the wheat and tend to accumulate, so that the land can only be maintained clean by an excessive expenditure in repeated hand-hoeing. Notwithstanding all the labour that is put on the plots, the "Black Bent" grass, *Alopecurus agrestis*, has from time to time become so troublesome that special measures have had to be taken to eradicate it and to restore the plots to a reasonable degree of cleanliness.

How little the wheat plant is able to survive when in competition with weeds, may be seen from a portion of the Broadbalk field where the wheat crop in 1882 was allowed to stand and shed its seed, the soil not being cultivated in any way. In the following season a fair wheat plant came up and gave about half a crop, but after it seeded the weeds increased their hold upon the ground until in the fourth season only two or three stunted wheat plants could be found, which have never reappeared since. The fundamental importance of cultivation and the suppression of weeds is further to be seen in the returns from the continuously unmanured plot. This piece of land at the beginning of the experiments was not only in poor agricultural condition but had been under arable cultivation for at least two or three centuries, and was therefore far removed from the condition of virgin soil with its accumulation of fertility, and yet by cultivation alone it has been able to grow for sixty years a crop averaging 13 bushels to the acre. This is almost the average crop produced in the United States, and is very similar to the general average production of the great wheat-growing areas of the world. Nor is there, as far as can

be judged from the records of the last forty years, any reason to expect that this crop cannot be maintained in the future, provided that the cultivation and cleaning of the land be continued.

### B. *Effect of Nitrogenous Manures.*

It will be remembered that one of the main objects in starting the Rothamsted Experiments was to ascertain the value of nitrogenous manures, and test the truth of Liebig's opinions that the crop could obtain a sufficiency of nitrogen from the atmosphere provided the ash constituents were supplied. Plots 5, 6, 7, and 8 all receive the same dressings of mineral manures, *i.e.*, phosphoric acid, potash, magnesia, and soda, in greater quantities than are removed in the crops. Plot 5 receives no nitrogen, Plots 6, 7, and 8 receive increasing quantities of ammonium-salts, supplying 43 lb. of nitrogen per acre on Plot 6, double that quantity on Plot 7, and treble the quantity on Plot 8. [An average crop of 30 bushels of grain, and 28 cwt. of straw, will remove about 50 lb. of nitrogen per acre.]

The diagram Fig. 3 shows the crops on these plots over the period from 1852 to 1902. Table XV. gives the figures to 1912.\*

Plot 5, which receives the minerals but no nitrogen, grows very little more than the continuously unmanured plot; its average over the whole period is only 14.9 bushels, as against 13.1 without manure of any description. The other three plots yield crops which increase with each addition of nitrogen; the grain increases from 24 bushels with 43 lb. of nitrogen, to 33 bushels with 86 lb. of nitrogen, and to 37 bushels with 129 lb. of nitrogen; the straw is even more affected by a free supply of nitrogen, rising from 21½ cwt. to 33 and 41 cwt. as the nitrogen is doubled and trebled. It is thus seen that the wheat crop is very specially dependent upon the supply of nitrogen in the manure. With nitrogen alone (*e.g.*, ammonium-salts alone on Plot 10, nitrate of soda alone on part of Plot 9, and rape cake alone on Plot 19), even over a long period of years, the crop

\* For the sake of clearness the figures in the diagram (1852-1902) are quoted. The differences between these figures and those in Table XV. are

# EFFECT OF NITROGENOUS MANURES 43

is considerable, and much superior to that grown by minerals without nitrogen. Being a deep-rooted plant and possessing a comparatively long period of growth, wheat is well able to

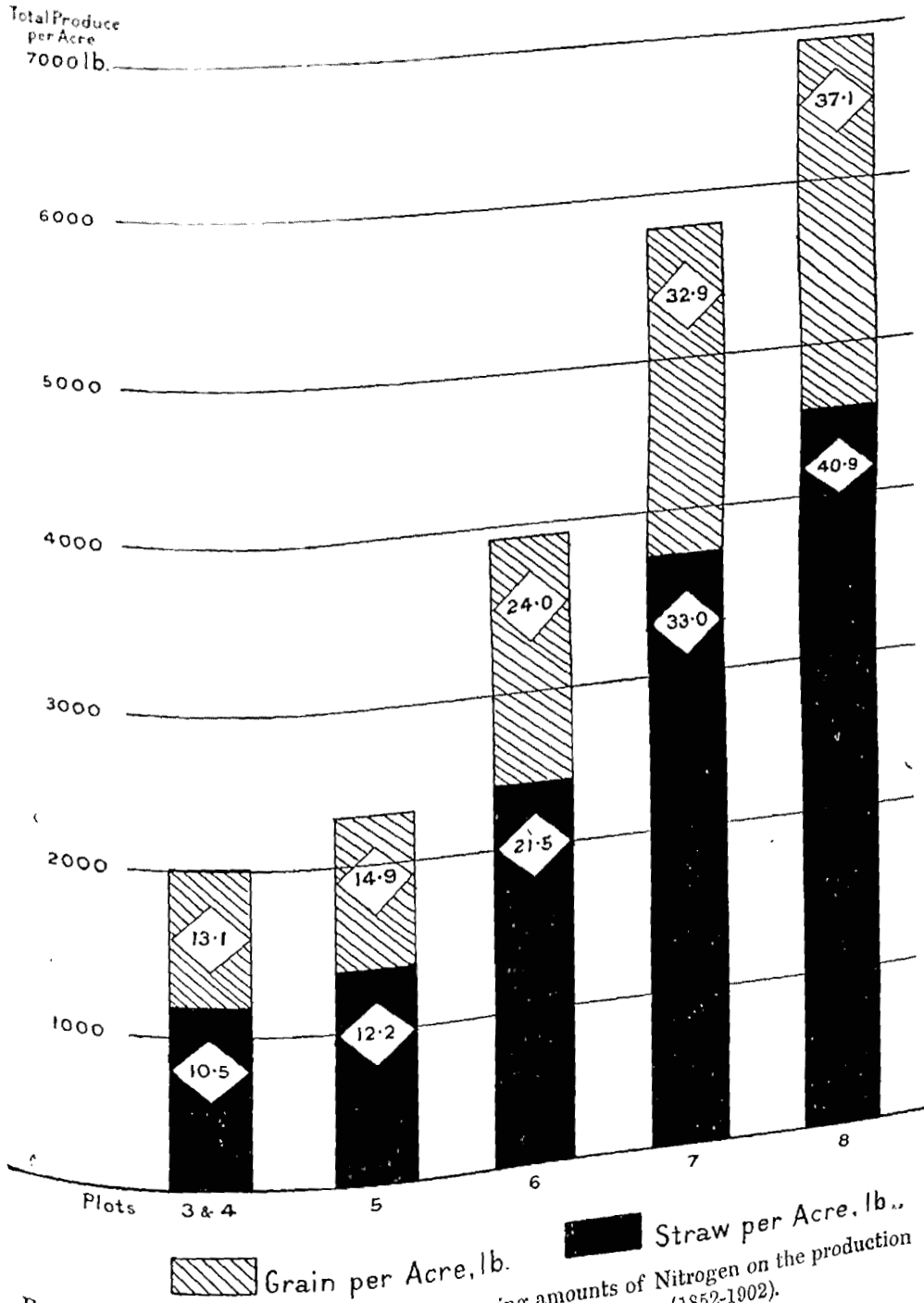


Fig. 3.—Broadbalk Wheat. Effect of increasing amounts of Nitrogen on the production of Wheat (Grain and Straw). Average, 51 years (1852-1902). The figures in the labels indicate bushels of grain and cwt. of straw.

search the soil for mineral plant food; hence when grown under ordinary farm conditions in rotation, it is rarely necessary to supply it with any but nitrogenous manures. As it is also grown during the cooler season of the year and with very little cultivation of the ground, the natural nitrifying processes are slow, hence the special need for an external supply of nitrogen in the shape of manure.

Plots 9 and 16 receive nitrate of soda and mineral manures, so that Plot 9 has the same manuring as Plot 6, and Plot 16 as Plot 7, except that the ammonium-salts on Plots 6 and 7 are replaced by equivalent amounts of nitrate of soda. The manuring of Plots 9 and 16 has however been changed during the progress of the experiments, so that they are only comparable with 6 and 7 since 1885. Taking the averages from 1893 to 1902 as set out in the diagram Fig. 4, it will be seen that nitrate of soda is a more effective source of nitrogen than the ammonium-salts; the single application yields 16 per cent. more grain and 26 per cent. more straw than the corresponding amount of ammonium-salts: the double application, however, yields practically the same amount of grain and only about 1 cwt. more straw. This superiority of nitrate of soda for wheat is no doubt partly due to the fact that it remains soluble, thus diffusing deep into the soil and encouraging a greater range of roots, whereas the ammonium-salts are retained near the surface. The injurious effects of continuous applications of ammonium-salts, which are due to the removal of the carbonate of lime from the soil and its resultant acidity, now so strikingly shown on the corresponding permanent wheat and barley plots on the Royal Agricultural Society's farm at Woburn, are not apparent at Rothamsted, where the soil started with a good supply of chalk. Analyses made in 1904 show that the soil of Plot 7 still contains more than  $2\frac{1}{2}$  per cent. of carbonate of lime.

It should be noticed that the increase of crop for each application of nitrogen is not proportional to the extra nitrogen supplied, but that each successive addition gives a smaller

return in the crop. Thus Plot 6 with 43 lb. of nitrogen gives 8.1 bushels more than Plot 5 with no nitrogen, another 43 lb. of nitrogen on Plot 7 produce a further increase of 8.9 bushels,

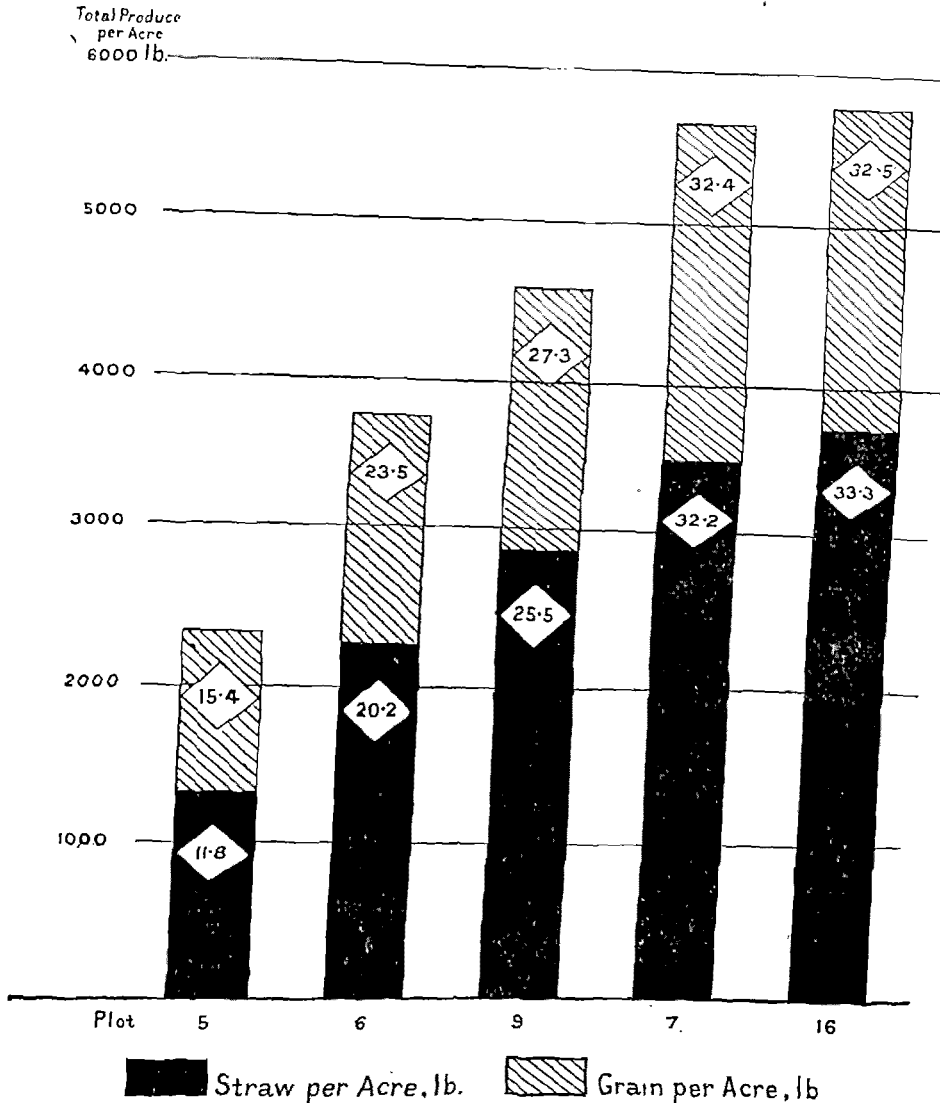


FIG. 4.—Comparison of Nitrate of Soda and Ammonium-salts on Wheat. 10 years (1893-1902). All Plots receive Minerals alike.

whereas the next addition of 43 lb. of nitrogen only produces an increase of 4.2 bushels.

During the first 13 years of the experiment one of the plots received a still further addition of nitrogen, making 172 lb. in all. The Table (XVII.) shows the yield of grain and straw of

the plots receiving successive increments of nitrogen during this period. It will be seen that the last 43 lb. of nitrogen had practically no effect upon the amount of grain produced and but little upon the straw.

TABLE XVII.—*Experiments on Wheat, Broadbalk Field.*  
*Averages over 13 years (1852-1864).*

Plot.	Manures per acre	Dressed Grain.		Straw.	
		Pro-duce per acre.	Increase for each additional 43 lb. N. in Manure.	Pro-duce per acre.	Increase for each additional 43 lb. N. in Manure.
5	Minerals alone . . . . .	Bush. 18·3	Bush. . . . .	Cwt. 16·6	Cwt. . . . .
6	Do. and 43 lb. N. as Ammonium-salts	28·6	10·3	27·1	10·5
7	Do. and 86 lb. do. do.	37·1	8·5	38·1	11·0
8	Do. and 129 lb. do. do.	39·0	1·9	42·7	4·6
16	Do. and 172 lb. do. do.	39·5	0·5	46·6	3·9

These results illustrate very clearly what is known as the "law of diminishing returns," *i.e.*, that each increment in the cost of production, whether labour or manure, gives rise to a smaller proportionate return, until a point is reached when the value of the increased yield is more than balanced by the outlay required to bring it about. This point, when the extra crop ceases to pay for the manure or labour expended on it, is sooner reached with low than with high prices for the crop. Hence high farming (intensive cultivation and liberal expenditure on manure) is only justified in times of high prices and is no remedy for low ones.

The diagram Fig. 5 shows a comparison between the returns from these plots, (1) with corn at 24s. a quarter and straw at 20s. a ton, and (2) when corn is 32s. and straw at 30s.

The straight line indicates the cost of production taking an arbitrary base of 80s. per acre for the cultivation, and adding 30s. for each 200 lb. of ammonium-salts. It will be seen that with the lower prices the crop ceases to be profitable before the third addition of manure is made; the second addition is the

most profitable, the extra 30s. for manure has produced an increased return of 36s. in the crop. At the higher scale of prices the crop remains profitable throughout, though the third addition of manure only returns 14s. for an expenditure

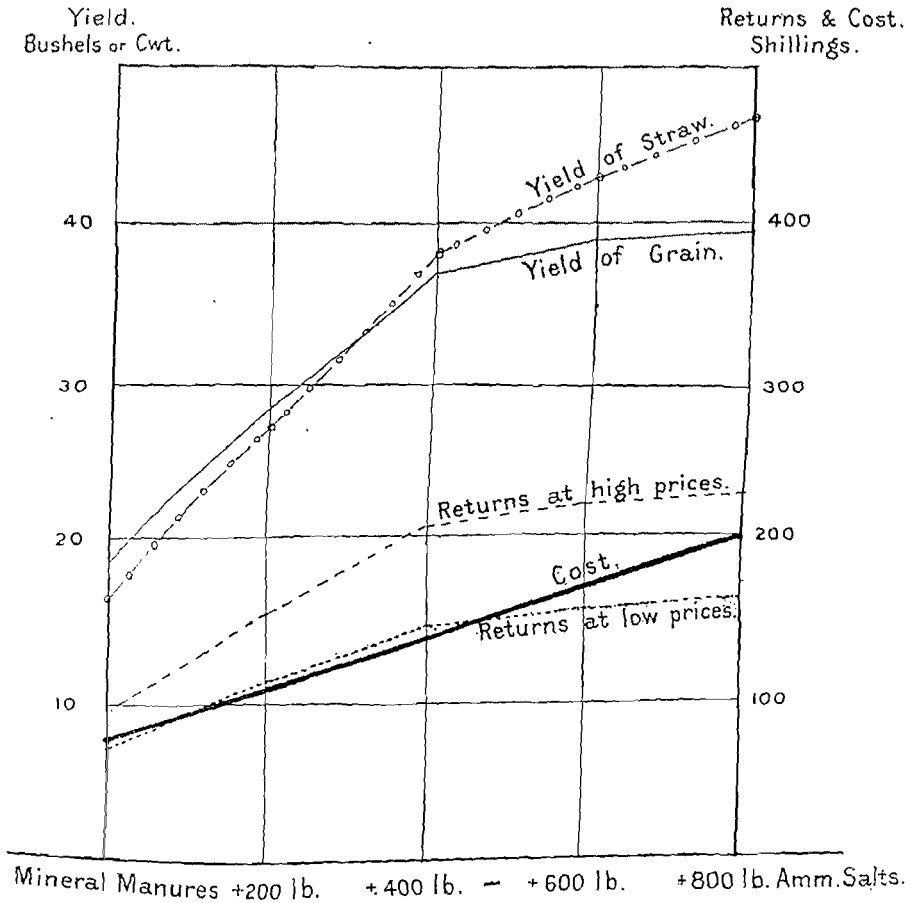


FIG. 5.—Relation between Cost of Production and Returns with varying quantities of Manure.

of 30s., and the fourth application only produces an increase of crop worth 8s.

C. *Effect of the Mineral Constituents.*

The series of Plots 7, 10, 11, 12, 13, and 14 all receive the same amount of nitrogen—86 lb., in form of 400 lb. of ammonium-salts per acre—but differ in regard to their mineral manuring. Plot 10 receives nothing beyond the

nitrogen, Plot 11 has superphosphate also, while 12, 13, and 14 receive a further addition of sulphate of soda, sulphate of potash, or sulphate of magnesia respectively, all three of which are combined to form a complete mineral manure on Plot 7. It should be remembered that soda, magnesia, and potash are always found in the ash of plants, and at the time the experiments were started little was known about the part they played in the nutrition of the plant. And

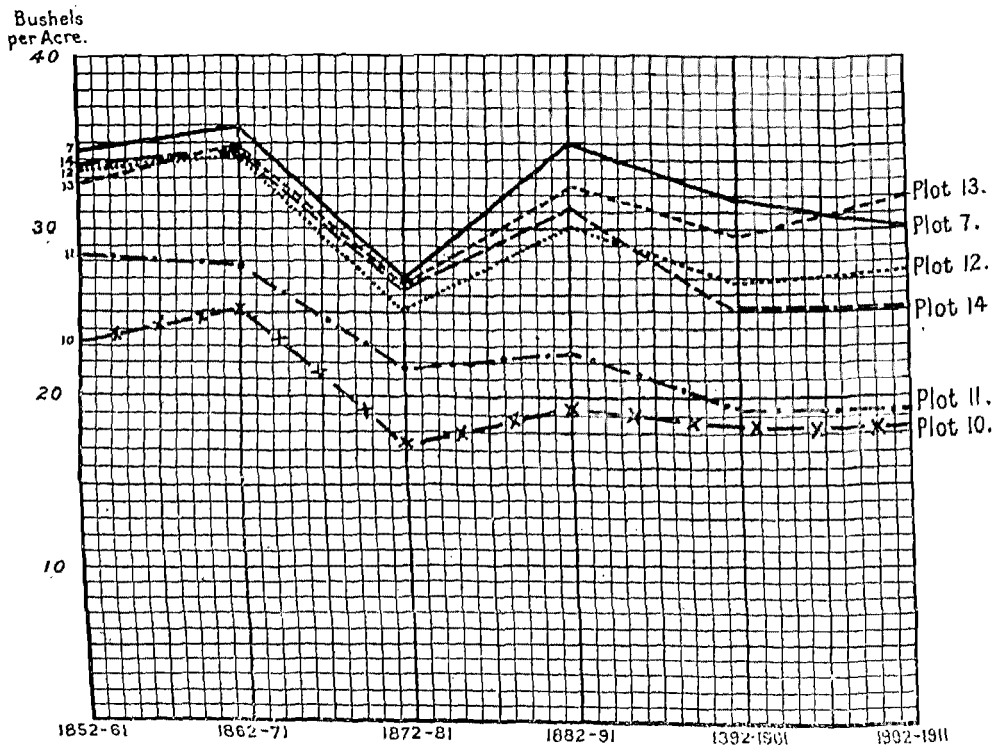


FIG. 6 — Production of Wheat with varying Mineral Manures. All Plots receive equally 86 lb. N. as Ammonium-salts. Averages over 10-year periods (1852-1911).

although we know to-day that for practical purposes potash alone of the three need be supplied in a manure, we are still uncertain what is the function of the other two, which being present in every plant can hardly be without some action. Fig. 6 shows the crops upon these plots in successive ten-yearly periods. It will be seen that Plot 11, receiving superphosphate, has always given a better crop than Plot 10, without it. This superiority was more marked in the early years of the experiment, when the reserves of potash, etc., were

abundant in the soil, and when in consequence the nitrogen and phosphoric acid together had practically the effect of a complete manure. Latterly, as the potash has become exhausted by the continual cropping, the yield with nitrogen and phosphoric acid has been but little superior to that produced by nitrogen alone. Similarly, in the earlier years of the experiment the crop on Plots 12 and 14, where soda and magnesia are added to the superphosphate and ammonium-salts, was but little inferior to that of Plot 13, which receives potash. The results in later years show, however, that neither magnesia nor soda can replace potash, their good effect in the first few years being due to the fact that the addition of any soluble salts to the soil brings into action some of the dormant potash. At first this is sufficient to grow as large a crop as where a potash manure is directly supplied, but in course of time the available potash becomes reduced, and there is a manifest decline on the plots receiving magnesia or soda only, till finally the steady state is attained, the soda giving permanently a higher yield than the magnesia. Plot 7, which differs only from Plot 13 in receiving magnesia and soda in addition to the potash, phosphoric acid, and nitrogen applied to 13, gave until recently a somewhat higher crop. This is not due to any specific effect of magnesia and soda, because Plot 13 does not show any progressive decline as compared with Plot 7, although its soil must be becoming exhausted of these constituents by their constant removal in the crops. Doubtless the effect of the sulphates of magnesia and soda on Plot 7 is due to their action as soluble salts, maintaining in a more soluble condition the other manurial constituents necessary to the crop.

#### *D. Retention of Manures by the Soil.*

It has already been stated that, as a rule, 100 lb. of the ammonium-salts are applied in the autumn when the seed is sown, the rest being reserved for a top-dressing in the spring. On one of the plots, however, Plot 15, the whole 400 lb. of ammonium-salts is applied in the autumn,

otherwise the manuring is identical with that of Plot 7. The crop, however, on Plot 15 is on the average below that of Plot 7, showing that some loss takes place when the ammonium-salts are applied before the plant is able to utilise them. Although the ammonium-salts are soluble in water

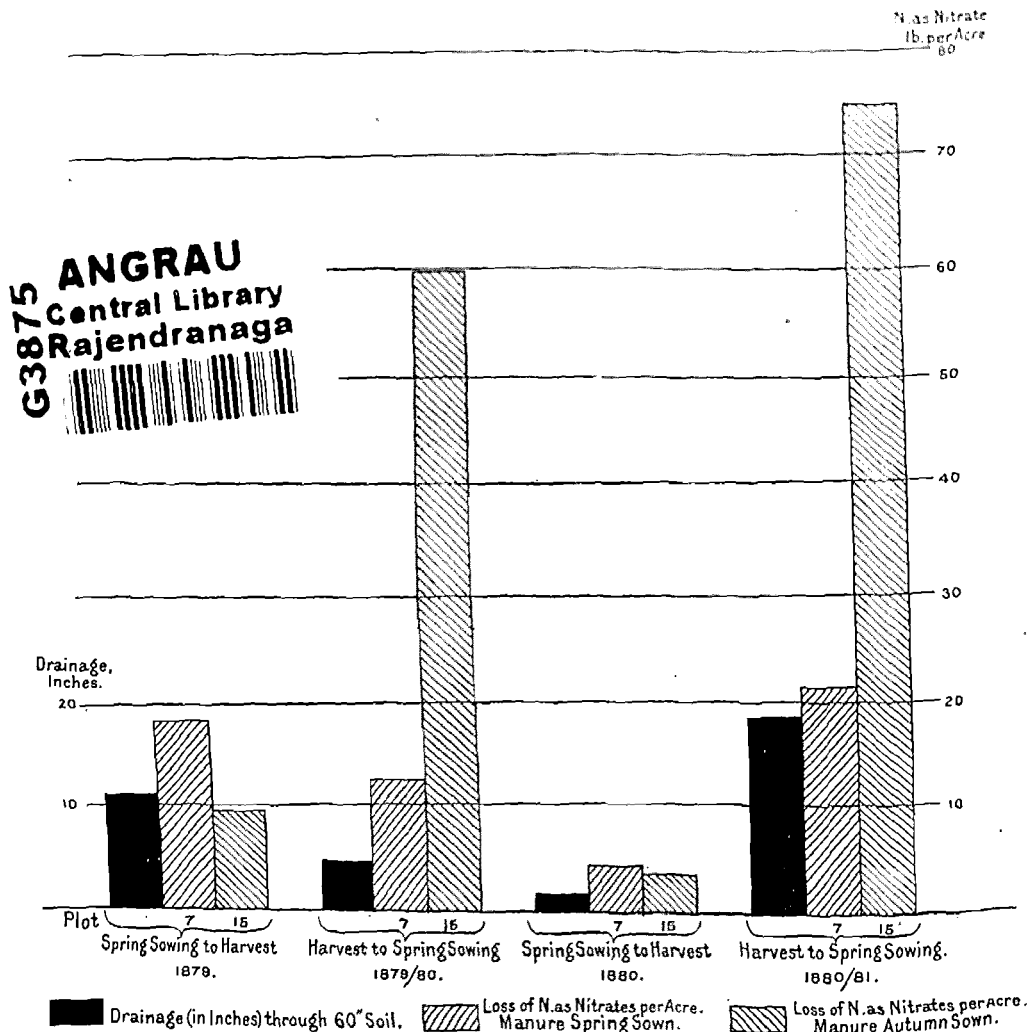


FIG. 7.—Loss of Nitrogen as Nitrates in the Drainage Water, lb. per acre. Comparison of Plot 7 manured with Ammonium-salts in the spring, and Plot 15 in the autumn.

they are caught by the soil and held very near to the surface, so that the loss does not arise by the washing out of the ammonium-salts themselves. They are, however, rapidly converted into nitrates when the land is warm and moist, especially after it has been recently stirred by the autumn cultivations. The nitrates thus produced are not retained by

the soil, and wash out very readily if heavy rain falls during the early winter. This is seen in the analyses of the drainage water collected beneath Plot 15. It is generally very rich in nitrates in the autumn as compared with Plot 7; whereas in the spring, when the ammonium-salts are applied, a corresponding loss does not happen with Plot 7, because the crop then occupies the land and is able to take up the nitrates as fast as they are formed.

The diagram Fig. 7 shows the estimated loss of nitrates in lb. per acre on these two plots during the summer and winter respectively, between the spring sowing of manures in 1879 and the corresponding date in 1881.

Table XVIII. shows that the drop in yield due to the autumn application is very small in dry winters but becomes considerably more serious in wet winters.

TABLE XVIII.—*Comparison of Spring and Autumn Dressings of Ammonium-salts in Wet and Dry Seasons respectively.*

	Rainfall of preceding Autumn and Winter (October-March).	Total Produce, lbs. per acre.				Grain, bushels per acre.			
		Ammonium-salts applied.		Difference in favour of Spring Dressing.		Ammonium-salts applied.		Difference in favour of Spring Dressing.	
		In previous Autumn, Plot 15.	In Spring, Plot 7.	Per acre.	Per cent.	In previous Autumn, Plot 15.	In Spring, Plot 7.	Per acre.	Per cent.
Mean of 11 yrs. of low winter rainfall *	11.73	5631	5829	+196	+ 3.4	31.8	32.5	+0.7	+ 2.2
Mean of 11 yrs. of high winter rainfall †	16.73	4932	6004	+1072	+21.7	27.5	32.5	+5.0	+18.1
Mean for whole period of 60 years (1852 to 1911)	13.9	5305	5843	+538	+10.1	30.5	32.7	+2.2	+ 7.2

\* The years of low winter rainfall were 1889, 1890, 1891, 1893, 1898, 1901, 1902, 1903, 1905, 1906, 1909.  
 † The years of high winter rainfall were 1892, 1894, 1895, 1896, 1897, 1899, 1900, 1907, 1908, 1910, 1911.

Plots 17 and 18 further illustrate the fate of ammonium-salts. These plots receive the dressing of Plot 7—400 lb. ammonium-salts and complete minerals—but the ammonium-salts and the minerals are applied in alternate years to the two

plots. Thus in 1910 Plot 17 received ammonium-salts but no minerals, and Plot 18 the minerals without the ammonium-salts, and the treatment was reversed in 1909 and again in 1911. It will be seen from the diagram, Fig. 8, that the plot which in any year is receiving minerals without nitrogen derives little or no benefit from the ammonia it had the year before. The crop shows every sign of nitrogen starvation, and amounts on the average to only 15·3 bushels of grain, as compared with 14·9 bushels on Plot 5 which has received minerals without any nitrogen every year since 1852. On the Rothamsted soil, then, we may conclude that the effect of sulphate of ammonia applied to a cereal crop is confined to the season of its application. In the seasons when the ammonium-salts are applied the crop is but little short of that on Plot 7, where minerals are used every year with the same amount of ammonium-salts, thus showing that the previous mineral manuring is carried forward and has an effect in seasons beyond the year of its application.

Much of our knowledge of the process of nitrification, by which not only ammonium-salts but other compounds of nitrogen, such as are contained in dung, are converted into nitrates, was worked out in the Rothamsted Laboratory by Mr Warington. From the continued analyses that have been made of the water flowing from the drains beneath the Broadbalk wheat plots, we learn that not only may readily nitrifying manures suffer great losses through nitrates forming and being washed out when a crop does not occupy the ground, but that the same causes lead to continuous loss of nitrogen from all cultivated land. This loss is at its highest when heavy rain falls after the land has been broken up after harvest; then the conditions occur which are most favourable to nitrification, *i.e.*, warmth, moisture, aëration, and stirring of the soil. Thus analyses of the soil show that, despite the fact that much larger amounts of nitrogen are applied to Plots 7 to 18 than are removed in the crop, the soil is not getting any richer in nitrogen; and even on Plots 2 and 10, where the same amount of

nitrogen are used, the accumulation of nitrogen is far less than the difference between the nitrogen applied and that removed would indicate.

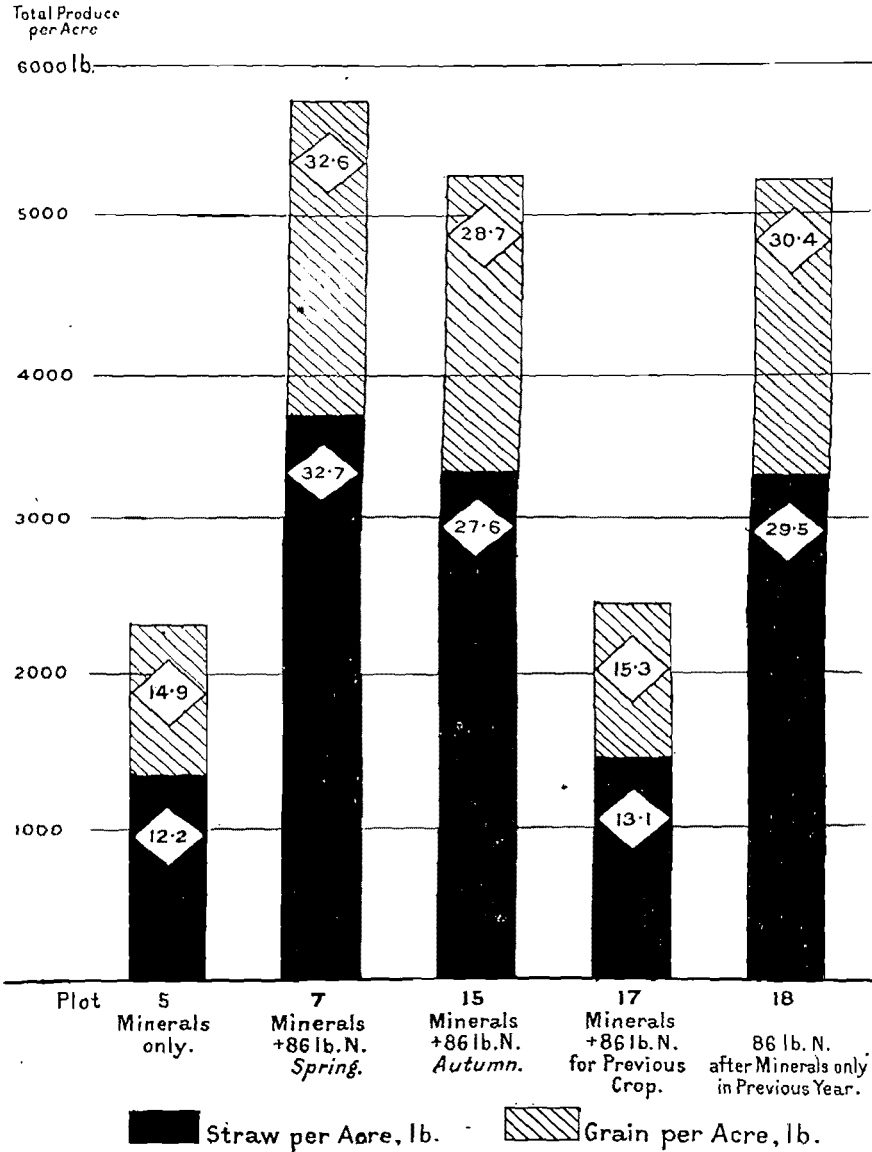


FIG. 8.—Comparative Effects on Wheat of Ammonium-salts applied at different times. Averages for 51 years (1852-1902). Plots 7 and 15, 25 years only (1878-1902).

Periodical determinations of nitrogen in soil and crop enable us to draw up an estimate of the nitrogen per acre supplied in the manure and recovered in the crop over a fifty-

year period, 1844-1893, together with the nitrogen contained in the soil at the close of that period for the unmanured Plot 3, and Plot 2 receiving farmyard manure. The top 9 inches of soil only are considered, because the analyses do not indicate that any appreciable amount of organic matter has found its way into the subsoil.

The results show that of about 10,000 lb. of nitrogen supplied as dung during the whole period, only about 2600 lb. have been recovered in the crop, or about 26 per cent., and that although the nitrogen present in the soil at the end of the period has been doubled, the excess over the manured plot is only 2580 lb. per acre; so that there is still 5670 lb. which has been supplied in the manure, but is unaccounted for either in the crop removed or in the accumulation in the soil:—

Plot.	Manuring.	Nitrogen in Soil, 9 inches deep, 1893.		Approximate Supply of Nitrogen in Manure in 50 Years.	Approximate Removal of Nitrogen in Crops, 50 years (1844-1893).	Surplus of Nitrogen over Plot 3, unaccounted for in Crop or Soil.
		Per cent.	Pounds per acre.			
3	Unmanured . . .	0.0992	2,570	Lb. ...	Lb. 850	Lb. ...
2	Farmyard Manure .	0.2207	5,150	10,000	2,600	5,670

Some of this has no doubt been washed away as nitrate into the drains and the subsoil water, some has been removed in the weeds, but much must have been lost by the conversion, through bacterial action, of nitrogenous compounds in the manure into free nitrogen gas.

Phosphoric acid and potash, however, behave very differently from nitrogen; but little of these substances are ever found in the drainage waters, and Dr Dyer's analyses show that the greater part of the excess of phosphoric acid supplied over that removed in the crop is still to be found in the top 9 inches of soil, where it remains in a condition readily available for the plant. The potash is not quite so completely retained as the phosphoric acid, and descends further below the surface. There is still, however, no practical loss to be feared when potash is

applied to the land before there is any crop immediately able to utilise it.

G 3875

E. Character of the Crop as affected by Manuring and Season.

Table XIX. gives certain particulars regarding the quality of crops grown during the fourteen years 1889-1902, in which Mr R. Hewlins of St Ives has made valuations of the grain from each of the plots. These valuations and figures respecting quality are to a certain extent disturbed by factors

TABLE XIX.—Wheat, Broadbalk Field. Averages over 14 years (1889-1902).

Plot.	Abbreviated Description of Manures.	Weight per Bushel of Dressed Grain.	Grain to 100 Straw.	Valuation of the Grain (Standard each year as 100).	Official Grain to 100 of Dressed.	Number of Grains in 100 grains.†	Weight of 100 Grains.†
		Lb.					Gms.
2	Farmyard Manure . . . . .	61.3	56.7	102.3	3.8	2536	3.94
4	Unmanured . . . . .	60.7	77.2	100.3	4.3	2708	3.69
5	Minerals . . . . .	60.8	74.4	100.5	4.7	2586	3.86
6	Minerals and Single Ammonium-salts . . . . .	61.1	66.3	101.4	4.0	2520	3.97
7	Do. and Double do. . . . .	61.1	57.2	101.1	3.7	2578	3.88
8	Do. and Treble do. . . . .	60.8	51.5	100.8	4.2	2636	3.79
9a*	Minerals and Single Nitrate . . . . .	60.8	59.5	100.9	3.5	2612	3.83
16	Double Nitrate and Minerals . . . . .	60.5	53.1	100.8	4.4	2772	3.61
10	Double Ammonium-salts only . . . . .	59.6	66.6	98.7	6.1	2966	3.37
11	Do. and Superphos. . . . .	58.6	59.5	97.1	7.4	3238	3.09
12	Do. do. and Sulph. Soda . . . . .	59.9	61.9	99.2	4.8	2926	3.42
13	Do. do. and Sulph. Potash. . . . .	61.0	57.3	101.0	3.6	2592	3.86
14	Do. do. and Sulph. Mag. . . . .	59.9	60.2	100.1	4.6	2978	3.36

\* 9a and b, 1894 and since.

† Average for 7 years (1893, '94, '96, '97, '98, 1900, and 1902).

arising only at second-hand out of the manuring. For example, Plots 8 and 2 are very liable to be lodged and to show a much higher proportion of sprouted corn in a wet harvest like that of 1902. These effects may easily overpower the differences directly due to the manuring and visible in normal seasons. The farmyard manure plot, No. 2, has given on the average the best grain, showing the highest weight per bushel and the highest price in the valuation, but there are several years in which the corn from this plot occupied a very low place in the series. Plot 10, again,

Plot No: G 3875  
Date: 21.6.81

receiving ammonium-salts only, shows almost the lowest weight per bushel and the lowest price. In some years, however, the highest valuation has been put on the corn from this plot. It is important to notice that the continuously unmanured plot, with its small yield, yet produces grains of corn which are almost up to the average in size, weight per bushel, and value from a commercial point of view. The plant, when starved, diminishes the number but not the quality of the seed; even the proportion of "tail" corn is not above the average on this plot. The proportion of corn to straw is the highest on this plot, as though starvation resulted in concentrating the highest possible proportion of material on the reproductive parts of the plant.

The plot receiving minerals only differs very little from the unmanured plot, but with each successive addition of nitrogen on Plots 6, 7, and 8, the weight per bushel, the size of the grain, and the value somewhat diminish; at the same time the proportion of straw to corn is much increased. The effect of a given quantity of nitrogen in the directions thus indicated seems to be intensified when it is applied as nitrate instead of ammonia.

Turning to the Plots 7, 10, 11, 12, 13, and 14, which receive the same amount of nitrogen but vary in their mineral manures, we get the highest weight per bushel, the largest grains, and the greatest value on Plots 7 and 13, where potash is supplied; on these plots also the proportion of straw is at a maximum, facts which depend upon the function of potash in the formation of carbohydrates—starch in the grain, and woody-fibre in the straw. The soda and magnesia applied to Plots 12 and 14 have rendered some of the potash of the soil available, and the quality of the grain is better than on Plots 10 and 11. Plot 11, receiving nitrogen and phosphoric acid, produces distinctly worse grain than Plot 10, showing by far the smallest grains, the lowest weight per bushel and value, and the highest proportion of "tail" corn; again demonstrating how the continued use of phosphoric acid and ammonia has depleted

TABLE XX.—*Wheat, Broadballe Field, Rothamsted. Comparison of the yield in a wet year (1879), and in a dry year (1893), with the average over 61 years (1852-1912).*

Plot.	Abbreviated Description of Manures.	Dressed Grain.			Straw.			Weight per Bushel of Dressed Grain.			Grain to 100 Straw.		
		1879.	1893.	Average, 61 years (1852-1912).	1879.	1893.	Average, 61 years (1852-1912).	1879.	1893.	Average, 61 years (1852-1912).	1879.	1893.	Average, 61 years (1852-1912).
2	Farmyard Manure . . . . .	Bush. 16.0	Bush. 34.2	Bush. 35.2	Cwt. 20.0	Cwt. 20.1	Cwt. 34.8	Lb. 56.8	Lb. 63.4	Lb. 60.7	47.5	99.5	53.2
3	Unmanured . . . . .	4.5	10.7	12.6	6.7	5.6	10.3	51.8	62.5	59.3	42.8	110.3	69.1
5	Minerals . . . . .	5.6	14.2	14.5	7.6	7.0	12.1	53.5	62.3	59.5	44.9	116.0	68.1
6	Single Ammonium-salts and Minerals . . . . .	10.5	19.4	23.2	14.2	10.2	21.4	56.5	63.1	60.3	43.5	110.4	61.5
7	Double do. do. . . . .	16.2	20.2	32.1	26.9	11.7	32.9	56.7	62.5	60.4	34.9	100.4	55.8
8	Treble do. do. . . . .	20.5	21.7	36.6	37.3	13.9	41.1	56.5	62.4	60.3	32.4	90.6	51.2
9a†	Nitrate‡ and Minerals . . . . .	21.9	17.9	...	38.8	10.6	...	56.5	61.7	59.9	33.6	96.2	52.5
9b	Nitrate‡ alone . . . . .	4.6	10.0	22.7*	9.5	6.5	23.4*	49.8	60.1	56.7*	32.3	87.1	54.4*
10	Double Ammonium-salts alone . . . . .	4.3	8.4	20.0	8.5	5.6	18.4	50.8	59.1	58.4	33.6	84.4	60.8
11	Do. and Superphos. . . . .	11.1	7.7	22.9	18.0	6.2	20.1	54.6	56.4	58.3	36.2	67.3	57.1
12	Do. do. and Sulph. Soda . . . . .	14.0	11.4	29.1	22.0	7.6	28.0	55.9	59.2	59.9	37.8	85.5	59.5
13	Do. do. and Sulph. Potash. . . . .	16.0	16.4	31.0	27.2	9.7	31.5	57.8	62.6	60.5	35.2	98.0	56.4
14	Do. do. and Sulph. Mag. . . . .	16.1	12.8	28.8	25.9	8.1	28.0	57.2	60.3	59.9	37.9	90.8	58.7

\* Average of 40 years (1852-1891).  
 † 550 lb. per annum to 1884 inclusive; 276 lb. only since.

‡ 9a to 1893 inclusive; whole plot (a and b), 1894 to 1902.

the potash in the soil of this plot. The plot receiving farm-yard manure gives corn of about the same size and weight per bushel, and also the same proportion of corn to straw, as Plot 7, which receives a medium amount of ammonium-salts.

Turning now to the influence of season on the wheat crop, Table XX. shows the yield of both grain and straw, the weight per bushel, and the proportion of grain to straw, in 1879, a typical wet year, and in 1893, an exceptionally dry one; the corresponding averages for the whole sixty-one years being put alongside for comparison. Table XXI. shows the monthly rainfall for the same periods, during the harvest-year from 1st September to the following August 31st.

TABLE XXI.—*Rainfall at Rothamsted (Large Gauge). Comparison of a wet and a dry harvest-year with the average over 60 years (1852-3 to 1911-12).*

	1878-9.	1892-3.	Average, 60 years (1852-3 to 1911-2).
	Inches.	Inches.	Inches.
September . . .	1·46	2·46	2·37
October . . . .	2·99	3·99	3·18
November . . . .	4·55	2·06	2·58
December . . . .	1·60	1·63	2·47
January . . . . .	2·85	2·05	2·34
February . . . . .	3·80	3·62	1·81
March . . . . .	1·18	0·42	1·92
April . . . . .	2·79	0·25	1·84
May . . . . .	3·48	1·22	2·19
June . . . . .	5·55	1·00	2·45
July . . . . .	4·24	3·00	2·50
August . . . . .	6·56	2·38	2·69
Total . . . . .	41·05	24·08	28·34

It will be seen that for the crop of 1879 there was a total rainfall of 41 inches, of which 23·8 inches fell in the last six months, as against 8·3 inches out of a total of 24·1 inches for the corresponding periods of the harvest-year of 1892-3. While the amount of grain produced is not so very different in the two years, the wet year grew a far bigger crop of straw, so that the grain weighed little more than one-third of the straw, whereas in the dry year grain and straw weighed about the same. The weight per bushel of the grain is very much

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higher in the dry than in the wet year, averaging 61.2 lb. against 55.0 lb. In the dry year the manures had comparatively little effect, the crops on all the plots being brought nearer to a uniform level; in the wet year, on the contrary, the differences due to manuring were much accentuated. The plot receiving farmyard manure occupies about its usual position in the wet year; but whereas it usually gives about the same proportion of grain to straw as the medium nitrogen plots, in 1879 it was rather better than they were in this respect. In the dry year this plot gives by far the heaviest yield of grain, almost up to its usual average; the straw also is much less reduced than on the plots receiving artificial manures, due no doubt to the water-retaining powers of the dung. It is interesting to find that Plot 9, receiving nitrate and minerals, gave the best crop both of grain and straw in the very wet year 1879, whereas in the dry year, 1893, the crop on this plot fell below the crop of Plot 6, which received the same amount of nitrogen as ammonium-salts, though on the average of years the nitrate answers better. This is contrary to the generally received opinion that nitrate of soda is the more effective in dry, and ammonium-salts in wet seasons.

The very low crops on Plots 9*b* and 10, which receive nitrogen only, show that in a wet season the plant has very little power of obtaining minerals from the reserves in the soil; and the great jump in crop produced by adding superphosphate to the ammonia on Plot 11 shows that the phosphoric acid is then more difficult to obtain. In a wet season when the maturity of the plant is retarded, the ripening effect of phosphoric acid will be exceptionally beneficial. In the dry season the lowest returns come from Plots 10 and 11 (without potash), and the potash on Plots 7 and 13 has an exceptionally marked effect, showing that under conditions of drought the plant specially responds to an abundance of potash in the manure. Probably the explanation is that a free supply of potash prolongs the growth of the plant, and that in the absence of potash the ripening action of the

phosphoric acid comes into play prematurely and stops development at a very early date, since it is acting in the same direction as the heat and dryness of the season.

The indication of the 1879 and 1903 returns, that the superiority of nitrate of soda over ammonium-salts is more marked in a wet than in a dry season, is confirmed by a further examination of the records over a series of years. Taking the thirty years 1873-1902 and dividing them into two groups according as the rainfall is above or below the average, and then comparing the yields of the two plots, which receive equal amounts of nitrogen, but one as nitrate of soda and the other as ammonium-salts, we find that in the dry seasons the yield from ammonium-salts is 86·6 per cent. of the yield from nitrate of soda. In the group of wet seasons, however, the yield from ammonium-salts is only 78·8 per cent. of that given by nitrate of soda, as shown in Table XXII. Thus the wet seasons are on the whole more favourable to nitrate of soda than to ammonium-salts. Presumably in the very wet and cold seasons the conditions are unfavourable to the nitrification of the ammonium-salts, and the immediately available nitrate of soda is more effective.

TABLE XXII.—*Broadbalk Wheat. Comparison of the yield of Dressed Grain with Nitrogen as Ammonium-salts or Nitrate of Soda; in seasons when the Rainfall was below or above the average, 30 years (1873-1902.)*

	Rainfall.	Dressed Grain per acre.		Ratio of yield by Am. salts to that of Nit. Soda = 100.
		Plot 6a. Nitrate Soda.	Plots 6 and 7. Ammonium-salts.	
14 Seasons <i>below</i> average Rainfall	Inches. 24·23	Bushels. 30·6	Bushels. 26·5	86·6
16 Seasons <i>above</i> average Rainfall	33·13	32·1	25·3	78·8

One of the most critical periods in determining the yield of wheat appears to be the winter months; if the wheat be sown in October or early November it spends the next three or four

months almost wholly in developing its system of roots: Should the weather be wet and the soil in a saturated condition the root-system will be restricted, both because of the deficient aëration and because the roots need not extend far in order to obtain the water necessary for its growth. From the indifferent development of roots which thus results, the plant seems never able to recover, so that a wet winter is almost invariably followed by a poor wheat crop at harvest. This fact is illustrated by Table XXIII., in which a comparison is made between the average wheat crop on three of the plots (6, 7, and 8) following the ten wettest and the ten driest winters respectively during the period 1852-1902, as measured by the rainfall in the four months November to February inclusive.

TABLE XXIII.—*Broadbalk Wheat. Comparison of 10 Wettest and 10 Driest Winters (1852-1902).*

		10 Wettest Winters.	10 Driest Winters.
Rainfall, November to February inclusive	. Inches	13.01	5.79
Average Crop per acre, Plots 6, 7, and 8	. Bushels	26.2	34.9
Comparison of Winters with more or less than the average percolation (1870-1 to 1903-4).			
		19 Seasons <i>above</i> average Percolation.	16 Seasons <i>below</i> average Percolation.
Percolation (60-inch gauge), Nov. to Feb.	. Inches	9.43	5.02
Average Crop per acre, Plots 2, 6, and 7.	. Bushels	26.8	31.5

The ten dry winters with an average rainfall of 5.79 inches were followed by an average wheat crop of 34.9 bushels per acre on the plots selected for comparison. The ten wet winters with a corresponding rainfall of 13 inches were followed by an average wheat crop on the same plots of only 26.2 bushels.

Making the comparison in another way and dividing the thirty-four seasons 1870-1904 into two groups according to whether the percolation during the winter months, November

to February, was above or below the average, we obtain a similar result. In fifteen seasons with a low winter percolation averaging 5·02 inches, there was an average crop on the selected plots of 31·5 bushels per acre; in the other nineteen seasons of high percolation, 9·43 inches, the average crop on the same plot was only 26·8 bushels. Although of course the weather later in the season has a great effect in determining the wheat crop, it is yet evident that the most critical period of its growth lies in the first four months, when the foundation of roots is being laid.

On the whole, it will be seen that the great differences of manuring to which the Rothamsted plots have been subject for so long a period have a much greater effect on the gross amount of crop than on the quality of the grain. Space does not admit of a discussion of the detailed analyses of the crops, but they show similar results in regard to the comparative stability of the nature of the grain. Fluctuations in the amount of the crop due to season or manuring are reflected to a much smaller degree in the composition of the grain; the composition of the straw, however, shows wider variations, induced by the differences in the manure applied.

## II.—WHEAT AFTER FALLOW, AND IN ROTATION.

Since the year 1856 two half-acre plots in the Hoos field have been cropped in alternate years with wheat without manure; every year one of the plots is in wheat while the other is being fallowed, so that the wheat crop always succeeds a year's bare fallow.

The accompanying Table (XXIV.) shows the average produce, grain and straw, on the cropped plot following fallow, compared with the crops on the plot in Broadbalk, which is continuously cropped without manure. It will be seen that the produce of wheat after fallow is considerably higher than when it is grown continuously, 16·0 against 12·2 bushels per acre; but if reckoned as produce over the whole area, half in crop and half fallow, the whole acre grows much less both of grain and

straw than where the crop is grown year after year on the same land. A given area of land would therefore be more productive when cropped every year than if the crop were alternated with fallow. The superior yield of the portion in crop after a fallowing may to some degree be attributed to the greater

TABLE XXIV.—*Wheat without Manure.—Grown continuously (Broadbalk Field), and in alternation with Fallow (Hoos Field). Average Produce per acre, 57 years (1856-1912).*

Wheat every Year. (Broadbalk Field, Plot 8.)		Wheat after Fallow. (Hoos Field, Plot 0.)	
Dressed Grain.	Straw.	Dressed Grain.	Straw.
Bushels.	Cwt.	Bushels.	Cwt.
12·2	9·8	16·0	13·7

freedom from weeds, but in the main it is due to the production of nitrates in the soil during the summer when it is fallow, a process which is much stimulated by the stirring and aëration the soil receives. The success of a fallowing depends upon these nitrates remaining for the succeeding crop, since they are not retained by the soil they may be entirely washed out by heavy autumnal rains.

That the autumnal rainfall is the great factor in determining whether a bare fallow shall be profitable or not to the following crop, may be well seen by comparing the crops yielded by these plots with the rainfall and percolation which took place during the autumn previous to each crop.

The percolation through 60 inches of bare soil for the four months September to December inclusive, as measured by the drain gauge, amounted on the average to 6·45 inches for the seasons 1870-1901. If, then, we divide the years into two groups according as the autumnal percolation is above or below the average, and allot to each year the crops on the continuous wheat and wheat after fallow plots for the harvest following the given percolation, we shall obtain the average results shown in Table XXV. and illustrated in the diagram Fig. 9.

EXPERIMENTS UPON WHEAT

TABLE XXV.—*Effect of Wet or Dry Autumns on the increase of the Wheat Crop due to Fallowing (1870-1902).*

	16 Seasons <i>less</i> than average Rainfall.	16 Seasons <i>more</i> than average Rainfall.
Rainfall (Sept. to Dec. inclusive) . . . . . In.	8.88	13.66
Percolation through 60 in. of Soil (Sept. to Dec. inclusive) In.	4.93	8.92
Total Produce (Wheat after Wheat) . . . . . Lb.	1810	1627
Total Produce (Wheat after Fallow) . . . . . Lb.	2743	1757
Increase due to Fallowing . . . . . Lb.	933	130
Percentage increase due to Fallowing . . . . .	51.5	7.9

Taking the seasons of small rainfall, averaging 8.88 inches for the four months September to December inclusive, the

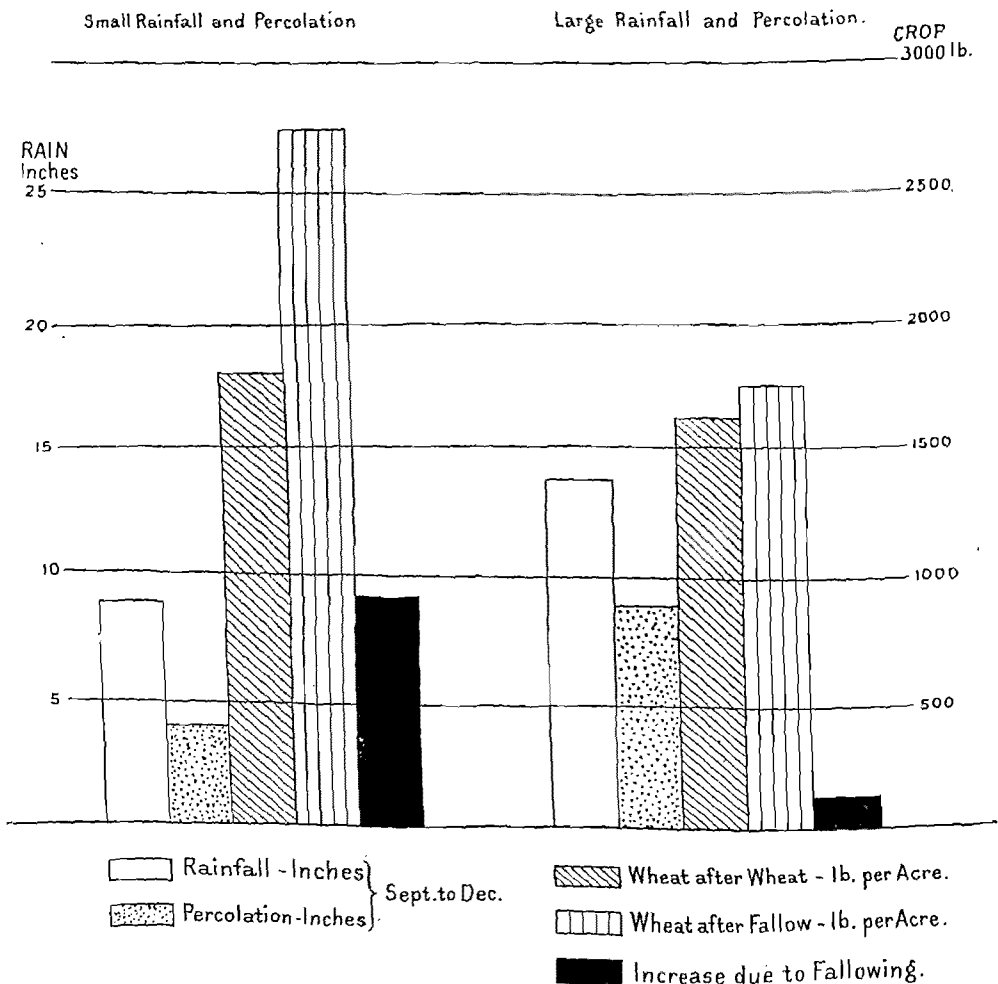


FIG. 9.—*Effect of Wet or Dry Autumns on continuous Wheat, and Wheat alternated with Fallow.*

percolation was only 4 inches, and the total produce on the wheat after fallow plot was 2743 lb. as against 1810 lb. on the continuous wheat plot, or a gain of 933 lb. due to fallowing.

For the wet autumns, however, with an average rainfall of 13.66 inches and a percolation of 8.92 inches, the wheat after fallow yielded 1757 lb. against 1627 lb. on the continuous wheat plot, or a gain of 130 lb. only due to fallowing.

It will be seen that the bare fallow increased the wheat crop coming after it by nearly 52 per cent. when a comparatively dry autumn succeeded the fallow, but the increase was less than 8 per cent. when there was much rain and percolation after the summer fallow.

It is interesting to compare these two plots, both without manure, with the continuously unmanured plot in the Agdell field, which comes into wheat once every four years in the course of the rotation (see p. 190). The plot in question has received no manure since 1852; it is cropped on a four-course rotation, beginning with turnips which are completely removed

TABLE XXVI.—*Wheat grown without Manure at Rothamsted.* (1) *Grown continuously*; (2) *In alternation with Fallow*; (3) *In Four-course rotation.* Average for the 15 years (1855, '59, '63, '67, '71, '75, '79, '83, '87, '91, '95, '99, 1903, 1907, and 1911).

Dressed Grain per acre.		
Continuous Wheat. (Broadbalk, Plot 3.)	Wheat after Fallow. (Hoos Field, Plot 0.)	Rotation Wheat. (Agdell Field, Plots 21-22.*)
Bushels. 11.8	Bushels. 17.2	Bushels. 26.9

\* Now called Plot 5.

from the land, after the turnips barley is taken, then comes a season of bare fallow before the wheat. It will thus be seen that three crops are removed in the course of the four years, but so very small is the turnip crop that practically the land is cropped only every other year. For the fifteen years during which comparison is possible, the average crop of wheat grown thus in rotation on continuously unmanured land has been 26.9

bushels per acre, as against 17·2 bushels for wheat after fallow and 11·8 bushels for continuous wheat.

It is difficult to explain this superiority of the wheat grown in rotation over the wheat after fallow. There are no more residues in the land in the one case than in the other, the land is equally clean and has similarly received a summer fallowing before the wheat crop. In the case of the rotation plot, however, the particular stratum of soil usually occupied by the wheat roots is only drawn upon once in four years, the intermediate crop being the much shallower-rooted barley.

### III.—TRIALS OF VARIETIES OF WHEAT.

In the eleven years 1871-1881, trials were made of about twenty varieties of wheat under the ordinary conditions of

TABLE XXVIIA.—*Varieties of Wheat grown at Rothamsted. Produce of Grain per acre (bushels). Results arranged in order of highest average yield.*

	1871.	1872.	1873.	1874.	1875.	1876.	1877.	1878.	1879.	1880.	1881.	Mean.
Rivet (Red) . . . . .	...	...	48·1	67·0	48·4	42·5	49·6	66·1	16·0	22·4	52·2	45·8
White Chaff (Red) . . . . .	...	...	40·6	55·1	40·2	49·5	48·4	59·0	22·8	28·1	51·5	44·2
Club Wheat (Red) . . . . .	36·0	45·8	47·5	59·6	46·6	47·6	49·5	61·0	23·5	16·4	43·4	43·4
Golden Drop (Red), Hallett's . . . . .	39·5	49·8	44·2	51·8	38·1	48·4	49·5	52·8	21·0	18·9	50·8	42·3
Bole's Prolific (Red) . . . . .	33·6	42·8	45·2	48·1	43·8	41·4	44·8	52·8	31·0	24·5	46·5	41·3
Hardcastle (White) . . . . .	...	46·5	42·0	49·6	33·9	44·0	42·1	54·0	21·5	24·4	45·6	40·4
Red Rostock . . . . .	37·0	...	46·3	53·8	37·4	40·0	46·4	57·0	8·5	28·4	45·8	40·1
Red Langham . . . . .	30·8	43·8	34·1	53·1	34·9	42·5	42·9	50·8	25·8	28·6	48·5	39·6
Bristol Red . . . . .	29·4	44·4	39·5	53·4	31·6	42·4	44·1	52·1	21·6	30·6	46·2	39·6
Red Wonder . . . . .	31·2	43·8	37·1	55·1	33·2	44·2	41·6	52·1	22·0	28·2	45·9	39·5
Red Chaff (White) . . . . .	32·8	37·0	35·3	48·8	34·3	43·8	41·0	...	...	...	...	39·0
Browick (Red) . . . . .	35·3	40·5	38·5	51·1	38·5	39·1	40·9	49·5	24·0	19·6	47·3	38·6
Casey's White . . . . .	29·9	42·1	37·5	52·1	39·0	45·5	43·0	47·8	15·4	24·1	42·9	38·1
Red Nursery . . . . .	34·1	45·3	27·1	41·1	39·0	37·5	40·6	47·8	30·9	27·5	46·0	37·9
Woolly Ear (White) . . . . .	31·2	42·8	37·0	51·3	36·1	46·6	37·5	48·3	20·0	21·0	44·1	37·8
Burwell (Old Red Lammas) . . . . .	31·1	41·3	35·1	47·3	38·5	38·4	39·0	46·3	27·0	27·0	44·8	37·8
Golden Rough Chaff (Red) . . . . .	33·0	39·3	38·5	52·1	38·8	38·4	36·4	46·8	14·4	31·3	41·6	37·3
Chubb Wheat (Red) . . . . .	28·4	40·0	35·8	50·5	38·3	40·3	41·5	55·1	20·8	14·9	...	36·6
Original Red (Hal- lett's) . . . . .	30·0	35·3	36·4	43·6	26·0	40·1	44·4	...	...	...	...	36·5
Victoria White (Hal- lett's) . . . . .	33·8	45·3	38·3	44·3	33·8	41·1	42·6	43·9	14·9	15·8	44·0	36·2
White Chiddam . . . . .	26·9	38·8	31·8	42·0	32·4	37·5	37·6	49·8	11·9	27·4	47·1	34·8
Hunter's White (Hal- lett's) . . . . .	26·9	39·8	38·6	45·4	26·4	43·5	40·0	42·3	17·4	22·8	...	34·3
Mean . . . . .	32·2	42·3	38·8	50·7	36·8	42·5	42·9	51·8	20·5	24·1	46·5	39·1

farming, the wheats being grown in a different field each year. Table XXVIIA. shows the results obtained in bushels per acre each year, and Table XXVIIB. the same results reduced each year to the common ratio of the average

TABLE XXVII B.—Varieties of Wheat grown at Rothamsted, 1871-1881. Mean Produce of all the varieties each year taken as 100.

Variety.	1871.	1872.	1873.	1874.	1875.	1876.	1877.	1878.	1879.	1880.	1881.	Mean.
Rivet (Red) . . .	...	...	125	132	131	100	116	128	78	93	112	113
White Chaff (Red) . . .	...	...	105	109	109	117	113	114	111	117	117	112
Club Wheat (Red) . . .	112	108	122	119	127	112	115	118	115	68	93	110
Golden Drop (Red), Hallett's . . .	123	119	114	102	104	114	116	102	102	78	109	108
Bole's Prolific (Red) . . .	104	101	116	95	119	97	104	102	151	102	100	108
Red Langham . . .	95	104	88	105	95	100	100	98	126	119	104	103
Red Wonder . . .	97	104	95	109	90	104	97	101	107	117	99	102
Bristol Red . . .	91	105	102	105	86	100	103	101	106	127	99	102
Harcastle (White) . . .	...	110	108	98	92	104	98	104	105	101	98	102
Red Rostock . . .	115	...	119	106	102	94	108	110	41	118	98	101
Red Nursery . . .	106	107	70	81	106	88	95	92	151	114	99	101
Browick (Red) . . .	109	96	99	101	105	92	95	96	117	81	102	99
Burwell (Old Red Lanmas) . . .	97	98	90	93	105	90	91	89	132	112	96	99
Woolly Ear (White) . . .	97	101	95	101	98	111	87	93	98	87	95	97
Casey's White . . .	93	100	96	104	106	107	100	92	75	100	92	97
Red Chaff (White) . . .	102	88	91	96	93	103	96	...	...	...	...	96
Golden Rough Chaff (Red) . . .	102	93	99	100	106	90	85	90	70	130	90	96
Chubb Wheat (Red) . . .	88	95	92	100	104	95	97	107	101	62	...	94
Victoria White (Hal- lett's) . . .	105	107	98	87	92	97	99	85	73	65	95	91
Hunter's White (Hal- lett's) . . .	83	94	99	89	72	103	93	82	85	95	...	90
Original Red (Hal- lett's) . . .	93	83	94	86	71	94	104	...	...	...	...	89
White Chiddam . . .	83	92	82	83	88	88	88	96	58	114	101	88
	100	100	100	100	100	100	100	100	100	100	100	100

crop taken as 100. The final order represents the mean of these last figures, and shows the average relative position occupied by each variety when seasonal fluctuations are eliminated and each year is allowed the same weight in making up the average. It is evident from the fluctuating position any wheat occupies from year to year that variety tests require a good many repetitions before great trust can be placed in their results. In the present case five wheats stand out as considerably heavier croppers than the others on the strong Rothamsted land—Rivet, White Chaff (Red), Club,

Golden Drop, and Bole's Prolific. Of these, Rivet is perhaps the oldest English wheat remaining in cultivation, known everywhere for its heavy yields on strong land, its coarse straw, the inferior quality of its grain, and its bearded character. White Chaff (Red) appears to be the wheat now grown as Square Head's Master, Teverson, etc., just as Club wheat is the original form of the wheat now generally known as Square Head. These two wheats are perhaps the most generally grown of any at the present time. Golden Drop is an old wheat of fair quality, still very generally grown. Bole's Prolific is no longer grown as such, but may represent the wheat now known as Pilgrim's Prolific and Red Giant, not uncommon in the South Midlands.

#### PRACTICAL CONCLUSIONS

1. The results obtained on the rotation field show that wheat, with its deeply-rooting habit and its long period of growth, is in less need of direct manuring than most crops of the farm. If the land is in good heart it can usually be grown with the residues in the soil, especially if it follows a clover crop.

2. Whenever manure is needed it should be mainly nitrogenous, and nitrate of soda generally answers better for wheat than sulphate of ammonia. After a wet autumn and winter a top-dressing of nitrate of soda, 1 to  $1\frac{1}{2}$  cwt. per acre, will be found particularly valuable.

3. When wheat is grown two or three times in succession, about 1 cwt. per acre of some slow-acting nitrogenous manure and 2 cwt. of superphosphate, should be ploughed before seeding, and a top-dressing of 1 to 2 cwt. per acre of nitrate of soda should be applied in February. Only on the lightest sandy and gravelly soils will any return be obtained for the use of kainit and other potash salts with wheat.

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## CHAPTER V

### EXPERIMENTS UPON BARLEY

- I. The Continuous Growth of Barley upon the same Land, Hoos Field :
  - A. Maintenance of Yield under the Continuous Growth of Barley on the same Land.
  - B. Effect of Nitrogenous Manures.
  - C. Effect of Mineral Manures.
  - D. Character of the Crop as affected by Manuring.
- II. Barley grown in Rotation—Agdell Field.  
Practical Conclusions and References.

#### I.—THE CONTINUOUS GROWTH OF BARLEY UPON THE SAME LAND, HOOS FIELD.

THE experiments on the continuous growth of barley were begun in the Hoos field in 1852. The arrangement of the plots and the manures applied to each plot have practically been unchanged since, so that the plots to-day show the effects of more than sixty years' continuous growth of barley under the same treatment year after year.

The Hoos field adjoins the Broadbalk wheat field, and the soil is very similar.

The following varieties of seed have been sown :—Chevalier, twenty-nine years, 1852-1880 ; Archer's Stiff Straw, ten years, 1881-1890 ; Carter's Paris Prize, seven years, 1891-1897 ; and Archer's Stiff Straw, 1898 and since.

The manures are sown in the spring, and ploughed in about a week or a fortnight before seeding. The plots do not run the whole length of this field, as in Broadbalk. Instead, there are four longitudinal strips receiving different combinations of the mineral manures ; these are all crossed by four breadths receiving different nitrogenous manures. The mineral manuring on the strips is as follows :—(1) none ; (2) phosphoric acid only,

no potash or alkali salts; (3) potash, magnesia, and soda, no phosphoric acid; and (4) complete mineral manure, supplying both phosphoric acid and the alkaline salts. Each of these is combined with the four different cross-dressings of nitrogenous manures—Series O no nitrogen, Series A ammonium-salts, Series AA nitrate of soda, and Series C rape cake. There are other plots, one of which has received farmyard manure each year, and a second which received farmyard manure for the first twenty years but has since been unmanured.

Table XXVIII. shows the nature and quantity of the

TABLE XXVIII.—*Experiments on Barley, Hoos Field. Manuring of the Plots per acre per annum, 1852 and since.*

Plot.	Abbreviated Description of Manures.	Nitrogenous Manures.				Mineral Manures.			
		Farmyard Manure.	Rape Cake.	Ammonium-salts.	Nitrate of Soda.	Super-phosphate.	Sulphate of Potash.	Sulphate of Soda.	Sulphate of Magnesia.
		Tons.	Lb.	Lb.	Lb.	Cwt.	Lb.	Lb.	Lb.
1 O	No Minerals, and no Nitrogen . . .	...	...	...	...	...	...	...	...
2 O	Superphosphate only, do. . . .	...	...	...	...	3·5	...	...	...
3 O	Alkali Salts only, do. . . .	...	...	...	...	...	200	100	100
4 O	Complete Minerals, do. . . .	...	...	...	...	3·5	200	100	100
1 A	Ammonium-salts alone . . . .	...	...	200	...	...	...	...	...
2 A	Superphosphate and Ammonium-salts	...	...	200	...	3·5	...	...	...
3 A	Alkali Salts and do. . . .	...	...	200	...	...	200	100	100
4 A	Complete Minerals and do. . . .	...	...	200	...	3·5	200	100	100
1 AA	Nitrate of Soda alone . . . .	...	...	...	275	...	...	...	...
2 AA	Superphosphate and Nitrate of Soda .	...	...	...	275	3·5	...	...	...
3 AA	Alkali Salts and do. . . .	...	...	...	275	...	200	100	100
4 AA	Complete Minerals and do. . . .	...	...	...	275	3·5	200	100	100
1 C	Rape Cake alone . . . .	...	1000	...	...	...	...	...	...
2 C	Superphosphate and Rape Cake . . .	...	1000	...	...	3·5	...	...	...
3 C	Alkali Salts and do. . . .	...	1000	...	...	...	200	100	100
4 C	Complete Minerals and do. . . .	...	1000	...	...	3·5	200	100	100
7-1	Unmanured (after dung 20 yrs., 1852-71)	...	...	...	...	...	...	...	...
7-2	Farmyard Manure . . . .	14	...	...	...	...	...	...	...

manures applied each year to the plots. Table XXIX. shows the average production of grain and straw for the whole period, for the last ten years, and for the single year 1911. Table XXX. shows the average production during each of the successive ten-year periods from 1852.

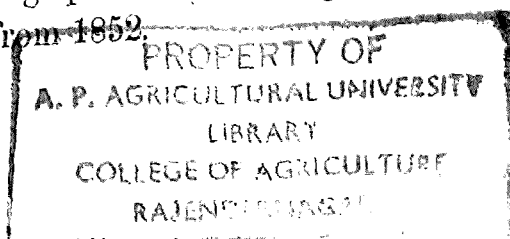


TABLE XXIX.—*Experiments on Barley, Hoos Field. Produce of Grain and Straw per acre. Averages over 60 years (1852-1911), and over 10 years (1902-1911). Also Produce in 1911.*

Plot.	Abbreviated Description of Manures.	Dressed Grain.			Straw.		
		Average, 60 years (1852-1911).	Average, 10 years (1902-1911).	Season 1911.	Average, 60 years (1852-1911).	Average, 10 years (1902-1911).	Season 1911.
		Bush.	Bush.	Bush.	Cwt.	Cwt.	Cwt.
1 O	No Minerals and no Nitrogen . . . . .	12.7	9.3	4.9	8.4	6.2	5.5
2 O	Superphosphate only, do. . . . .	19.7	17.6	11.9	10.0	9.2	9.1
3 O	Alkali Salts only, do. . . . .	15.2	10.1	4.3	8.8	8.2	5.3
4 O	Complete Minerals, do. . . . .	19.7	15.9	5.9	11.1	12.4	7.8
1 A	Ammonium-salts alone . . . . .	25.5	19.7	13.8	14.7	13.0	12.5
2 A	Superphosphate and Ammonium-salts . . . . .	38.2	29.7	10.3	22.0	19.3	11.6
3 A	Alkali Salts and do. . . . .	28.0	20.3	11.8	18.9	15.6	14.1
4 A	Complete Minerals and do. . . . .	41.5	38.4	28.5	25.0	25.3	22.9
1 AA	Nitrate of Soda alone . . . . .	29.3	23.0	16.2	17.8	16.1	17.8
2 AA	Superphosphate and Nitrate of Soda . . . . .	43.1	38.6	26.1	26.3	26.5	24.7
3 AA	Alkali Salts and do. . . . .	30.0	21.4	12.5	19.3	16.1	14.5
4 AA	Complete Minerals and do. . . . .	42.7	37.8	28.9	27.3	26.3	23.7
1 AAS	As Plot 1 AA and Silicate of Soda . . . . .	32.8*	28.0	19.7	19.7*	18.5	18.4
2 AAS	As Plot 2 AA do. do. . . . .	42.3*	37.2	26.0	26.0*	25.9	24.6
3 AAS	As Plot 3 AA do. do. . . . .	35.2*	29.0	17.6	21.7*	20.3	18.1
4 AAS	As Plot 4 AA do. do. . . . .	43.6*	40.4	27.5	27.7*	27.1	24.8
1 C	Rape Cake alone . . . . .	33.3	33.4	27.4	22.1	20.7	20.7
2 C	Superphosphate and Rape Cake . . . . .	40.5	35.4	28.2	23.6	22.0	20.8
3 C	Alkali Salts and do. . . . .	36.9	33.1	21.6	22.3	21.9	18.6
4 C	Complete Minerals and do. . . . .	40.5	38.2	25.7	24.5	24.4	20.1
7-1	Unmanured (after dung 20 years, 1852-71)	24.8†	18.3	9.5	14.8†	12.9	10.5
7-2	Farmyard Manure . . . . .	47.1	44.3	23.0	29.6	31.7	24.0

\* Average 48 years (1864-1911).

† Average, 41 years (1872-1911).

### A. Maintenance of Yield under the Continuous Growth of Barley on the same Land.

One of the plots, 1 O, has been without manure since the beginning of the experiments. Under the continuous barley-growing the decline in production has been much more marked than on the wheat plot similarly treated, the average crop having been only 9.3 bushels for the ten years 1902-1911, against an average of more than 12 bushels for the whole period. The continual fall of crop from decade to decade would seem to show a progressive exhaustion of the soil, without reaching the comparatively stable condition of the continuously unmanured

# YIELD IN SUCCESSIVE DECADES

TABLE XXX.—*Experiments on Barley, Hoos Field. Average Produce per acre of Dressed Grain and Straw over successive 10-year periods, from 1852-1911 inclusive.*

Plot.	Abbreviated Description of Manures.	Averages over					
		10 years (1852-1861).	10 years (1862-1871).	10 years (1872-1881).	10 years (1882-1891).	10 years (1892-1901).	10 years (1902-1911).
<b>Dressed Grain.</b>							
1 O	No Minerals and no Nitrogen . . . . .	Bush. 22·4	Bush. 17·5	Bush. 13·7	Bush. 12·7	Bush. 10·0	Bush. 9·3
2 O	Superphosphate only, do. . . . .	27·9	23·2	17·9	17·7	13·5	17·6
3 O	Alkali Salts only, do. . . . .	24·7	20·1	14·5	12·4	9·1	10·1
4 O	Complete Minerals, do. . . . .	30·5	24·4	17·7	16·9	12·8	15·9
1 A	Ammonium-salts alone . . . . .	33·6	31·2	26·2	25·0	16·6	19·7
2 A	Superphosphate and Ammonium-salts . . . . .	45·6	48·4	40·5	36·7	28·0	29·7
3 A	Alkali Salts, do. . . . .	35·0	35·0	30·1	25·5	22·1	20·3
4 A	Complete Minerals, do. . . . .	46·1	46·4	41·0	40·7	36·3	38·4
1 AA	Nitrate of Soda alone . . . . .	39·7	34·2	28·2	28·5	21·9	23·0
2 AA	Superphosphate and Nitrate of Soda . . . . .	48·9	49·6	42·0	42·7	36·5	38·4
3 AA	Alkali Salts, do. . . . .	38·6	36·1	29·9	29·1	24·8	21·4
4 AA	Complete Minerals, do. . . . .	49·9	49·5	42·2	40·4	36·0	37·8
1 C	Rape Cake alone . . . . .	47·0	43·6	39·0	35·4	31·3	33·4
2 C	Superphosphate and Rape Cake . . . . .	47·8	45·7	41·5	38·4	33·7	35·4
3 C	Alkali Salts, do. . . . .	44·0	43·2	37·4	33·8	29·7	33·1
4 C	Complete Minerals, do. . . . .	47·4	47·2	41·9	36·0	32·4	38·2
7-1	Unmanured (after dung 20 yrs., 1852-71)	} 45·0	} 51·5	34·2	26·4	20·3	18·3
7-2	Farmyard Manure . . . . .			50·2	47·6	44·3	44·3
<b>Straw.</b>							
1 O	No Minerals and no Nitrogen. . . . .	Cwt. 13·4	Cwt. 10·2	Cwt. 6·9	Cwt. 6·8	Cwt. 6·6	Cwt. 6·2
2 O	Superphosphate only, do. . . . .	14·9	11·8	8·4	8·1	7·8	9·2
3 O	Alkali Salts only, do. . . . .	13·9	10·7	7·1	6·8	6·3	8·2
4 O	Complete Minerals, do. . . . .	16·1	12·6	8·5	8·4	8·0	12·4
1 A	Ammonium-salts alone . . . . .	19·8	17·4	13·6	13·4	11·0	13·0
2 A	Superphosphate and Ammonium-salts . . . . .	27·9	27·5	20·5	19·7	17·0	19·3
3 A	Alkali Salts, do. . . . .	21·9	19·7	15·6	14·6	13·9	15·6
4 A	Complete Minerals, do. . . . .	28·9	28·0	23·5	23·4	21·1	25·3
1 AA	Nitrate of Soda alone . . . . .	24·0	20·1	15·4	16·5	14·8	16·1
2 AA	Superphosphate and Nitrate of Soda . . . . .	31·9	29·2	22·8	23·9	23·3	26·5
3 AA	Alkali Salts, do. . . . .	25·8	22·1	17·5	17·6	16·4	16·1
4 AA	Complete Minerals, do. . . . .	34·6	30·1	24·4	24·5	23·5	26·3
1 C	Rape Cake alone . . . . .	29·4	24·3	21·1	18·9	18·6	20·7
2 C	Superphosphate and Rape Cake . . . . .	30·8	26·0	22·3	20·7	19·8	22·0
3 C	Alkali Salts, do. . . . .	28·9	25·3	20·8	18·9	18·4	21·9
4 C	Complete Minerals, do. . . . .	31·3	27·8	23·1	20·5	19·9	24·4
7-1	Unmanured (after dung 20 yrs., 1852-71)	} 26·6	} 29·9	18·5	14·5	13·3	12·9
7-2	Farmyard Manure . . . . .			30·1	29·3	29·9	31·7

wheat plot. The more limited root-range of the plant would bring about a complete exhaustion of the available soil much sooner with barley than with wheat, but there is evidence that the decline in the yield of these barley plots is to some extent

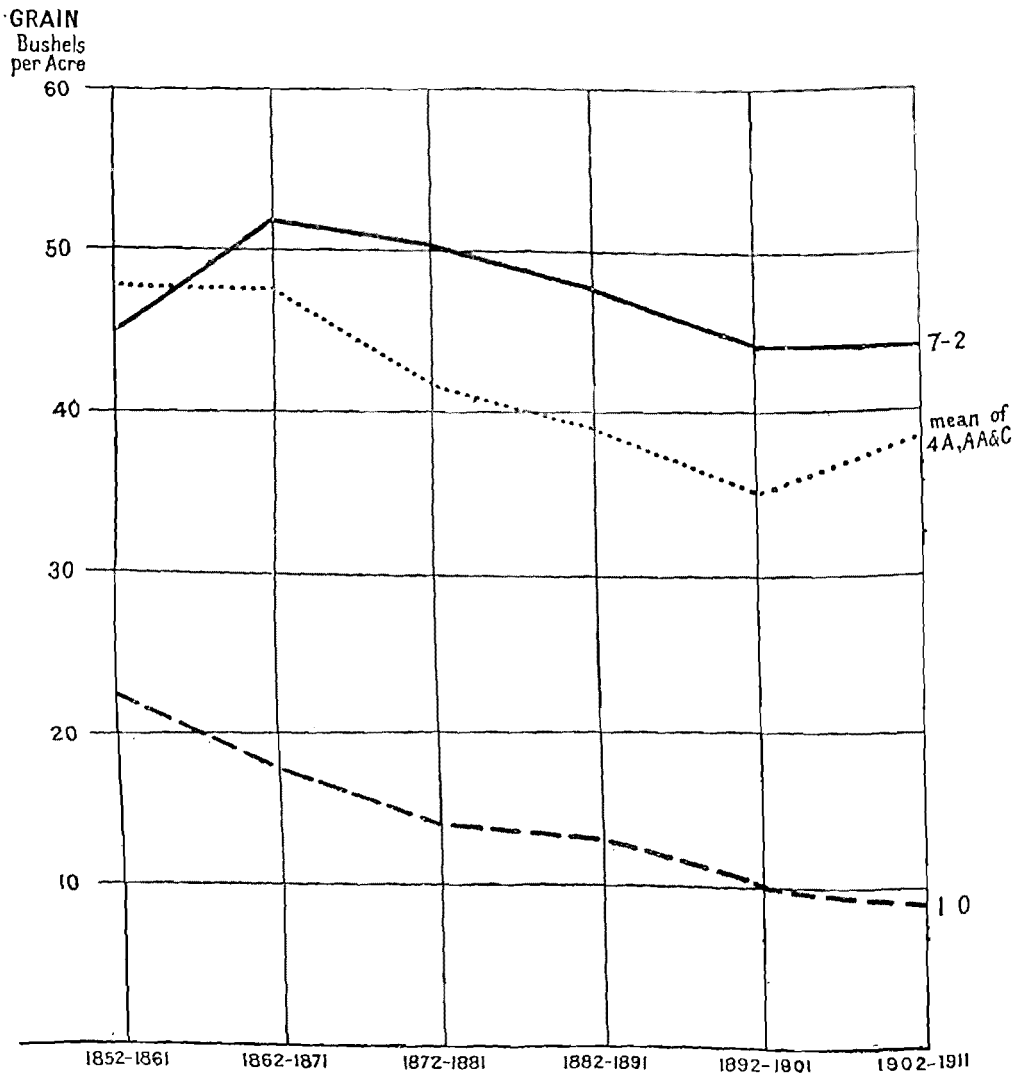


FIG. 10.—Yield of Barley during successive 10-year periods (1852-1911). Plot 7-2.—Farmyard Manure. Plots 4 A, AA, and C.—Each receive Complete Minerals, + N. as Amm.-salts, Nitrate Soda, or Rape Cake. Plot 1 O.—Unmanured.

due to a run of less favourable seasons. Both the continuously dunged plot, which must be gaining fertility, and the plots which receive heavy complete dressings of artificial manures showed a similar decline in the average production from 1862 to 1902, though for the last ten years the yield on the latter

## COMPARISON WHEN GROWN IN ROTATION 75

plots has gone up, as may be seen from diagram Fig. 10, which shows the average yield of grain on the unmanured plot, on the dunged plot, and the mean of the three plots completely manured with artificial manures. The decline in the production of the dunged plot is the least marked, although considerable.

Again, the Agdell field, which comes into barley every four years, has shown a decline in its yield of barley during the last fifty years, which is very similar to that of the continuous barley plots when the yields of each field are compared for the same years. Table XXXI. shows the total produce from the unmanured and two of the completely

TABLE XXXI.—*Barley, grown continuously, Hoos Field, and in four-course rotation, Agdell Field. Comparison of the Total Produce (Grain and Straw) per acre in the years 1853, '57, '61, '65, '69, '73, '77, '81, '85, '89, '93, '97, 1901, '05, '09, and '13.*

	Continuous Barley, Hoos Field.			Rotation Barley, Agdell Plot.	
	Un- manured.	Farm- yard Manure.	Complete Minerals and Nitrate Soda.	Un- manured.	Complete Mineral and Nit. Manure.
	Plot 1 O.	Plot 7-2.	Plot 4 AA.	* Plots 21 and 22.	† Plots 3 and 4.
Mean of:—	Lb.	Lb.	Lb.	Lb.	Lb.
First 5 years (1853, '57, '61, '65, '69) . . .	2521	5738	6694	3922	6055
5 years (1869, '73, '77, '81, '85) . . .	1626	6028	5681	2730	5718
5 years (1885, '89, '93, '97, 1901) . . .	1001	5122	4066	2100	4579
Last 4 years (1901, '05, '09, '13) . . .	1452	5836	5845	2010	6106
Mean of 16 years . . .	1731	5779	5564	2788	5153

\* Now Plot 5.

† Now Plot 2.

manured plots in the Hoos field for the years when barley was grown in the Agdell rotation field, for which field the crops on the unmanured and the most highly manured plot are also given. It will be seen that the barley crop grown in rotation on the plot that is highly manured (a complete manure is put on for the preceding Swede crop, which is returned to the land) showed until 1901 the same decline in yield as the crop on completely manured plots growing barley continuously,

the average production over the whole period and in successive twenty-year periods being very similar. This seems to show that the decline in production on the manured plots in the later periods in the Hoos field is due to season, and not to the fact that barley has been grown continuously on the same land. The unmanured plot, however, under continuous barley showed a much greater progressive decline than the corresponding unmanured plot growing barley in rotation, where the land is practically fallowed in alternate seasons. Although rather different results have been obtained during the last four years given in the table, the figures on the whole point to the probability that unmanured land will become unable to grow barley continuously at a much earlier date than will be the case with wheat, so comparatively restricted is the range of the barley roots.

#### B. *Effect of Nitrogenous Manures.*

The effect of nitrogenous manures upon the barley crop is best seen by comparing the yields of the various Plots 4, all of which receive the same mineral manures; the diagram \* Fig. 11 shows this comparison in a graphic form. Plot 4 O, receiving no nitrogen, has only given an average crop of 20.4 bushels per acre, and this has been more than doubled by the application of 43 lb. of nitrogen per acre to the other three plots. But little difference is seen in the return for this amount of nitrogen, whether it be applied as ammonium-salts, nitrate of soda, or rape cake. Over the whole period the nitrate of soda gives the highest return by about 3 per cent., but during the last three decades, the plot receiving ammonium-salts has been slightly the best of the three. In the straw, again, the differences are very small, though the superiority of nitrate of soda is rather more pronounced with the straw than with the grain. The fact that ammonium-salts answer better with barley than with wheat is due to their retention by the soil close to the surface; the comparatively shallow-rooted habit of barley and its growth

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\* Figures up to 1911 are given in Table XXIX.: they are very similar.

## WITH VARIOUS NITROGENOUS MANURES 77

during the warmer portion of the year when nitrification is active, renders such a surface accumulation of nitrogen as readily available to the plant as the nitrate of soda itself.

On the completely manured plots the rape cake, 4 C, is

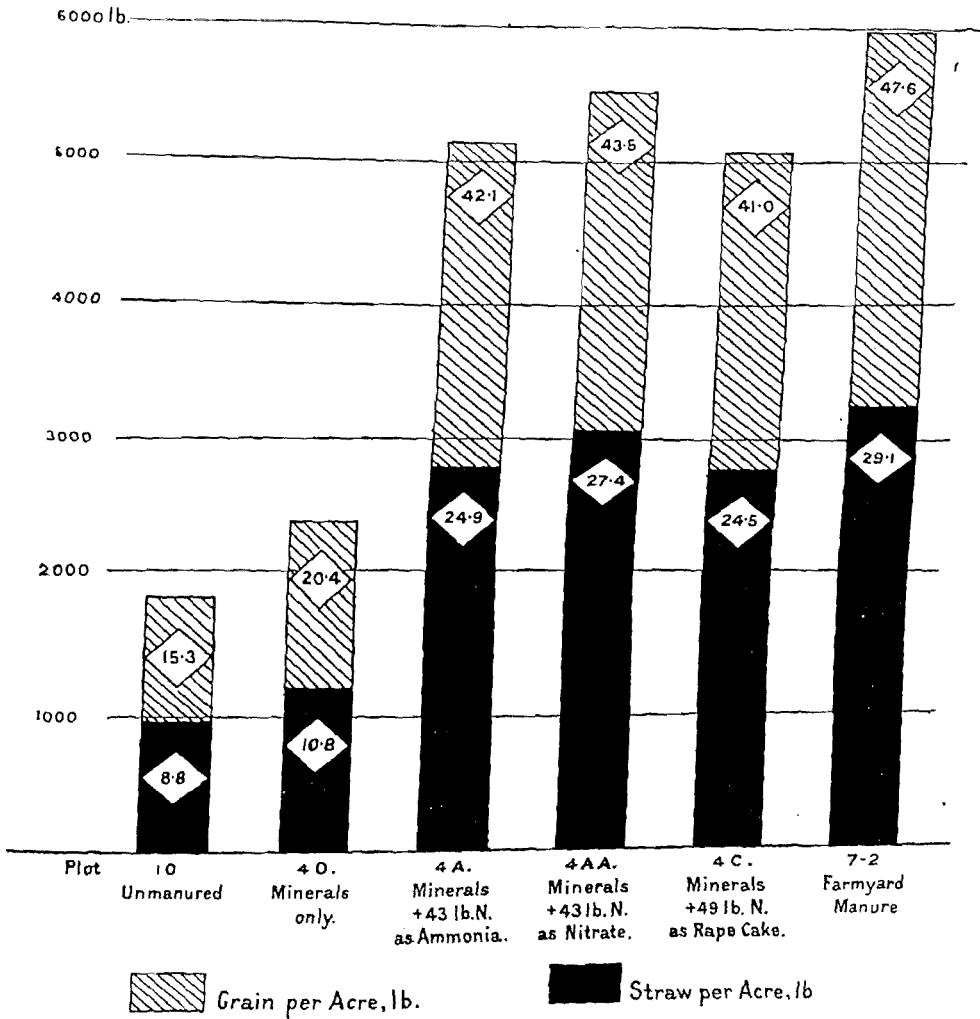


FIG. 11.—Yield of Barley (Grain and Straw) with different sources of Nitrogen. Averages for 51 years, 1852-1902. The figures in the labels indicate bushels of grain and cwt. of straw.

not quite so effective as the more active forms of nitrogen, giving over the whole period an average yield of 41 against 43.5 and 42.1 bushels of grain. This small deficiency has not diminished in the later years, which seems to indicate that the nitrogen compounds of rape cake are almost wholly utilisable by the crop to which they are applied. At any rate,

no large amount of residue slowly becoming available is left in the soil, as in the case of farmyard manure.

The plot receiving farmyard manure, 7-2, gives a higher crop than any other, but the amount of nitrogen supplied in this case is very high, being estimated at nearly five times as much as on any of the other plots.

One of the permanent barley plots (Plot 7) received 14 tons of farmyard manure per acre each year for twenty years in succession, viz., from 1852 to 1871. It was then divided into two plots, one of which, 7-1, has received no manure of any kind since; the other, 7-2, continued to get its annual dressing of 14 tons of dung. After the discontinuance of the dung, the barley crop on that half of the plot naturally began to fall off, but only slowly, and even now, after forty-seven years' cropping without manure, the effect of the residues left by the previous twenty years' application of dung is still to be seen in a yield that is double the crop obtained from the continuously unmanured plot. Table XXXII. shows the total produce

TABLE XXXII.—*Total Produce per acre of Barley Plots, showing Residual Effects of Dung.*

	Dung every year, 1852 and since.	Dung for 20 years, 1852-71. Unmanured since.	Unmanured continuously.	Relation to Produce of Plot 7-2, reckoned as 100.		
	Plot 7-2.	Plot 7-1.	Plot 1 O.	Plot 7-2.	Plot 7-1.	Plot 1 O.
	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
Mean, 1852-1871	5933		2454	100		41
1872	5202	4870	1282	100	94	25
1873	6561	5165	1570	100	79	24
1874	7943	5675	1922	100	71	24
1875	5825	3955	1448	100	68	25
1876	6166	4010	1561	100	65	25
Mean, 1877-1881	6167	3305	1528	100	54	25
„ 1882-1886	6546	3494	1529	100	53	23
„ 1887-1891	5334	2664	1379	100	50	26
„ 1892-1896	6477	3101	1508	100	48	23
„ 1897-1901	5349	2251	1141	100	42	21
„ 1902-1906	6223	2485	1301	100	38	20
„ 1907-1911	6144	2582	1251	100	40	20

# RESIDUAL EFFECT OF FARMYARD MANURE 79

obtained from the three plots in question for the first forty years that elapsed since the dung on Plot 7-1 was discontinued,

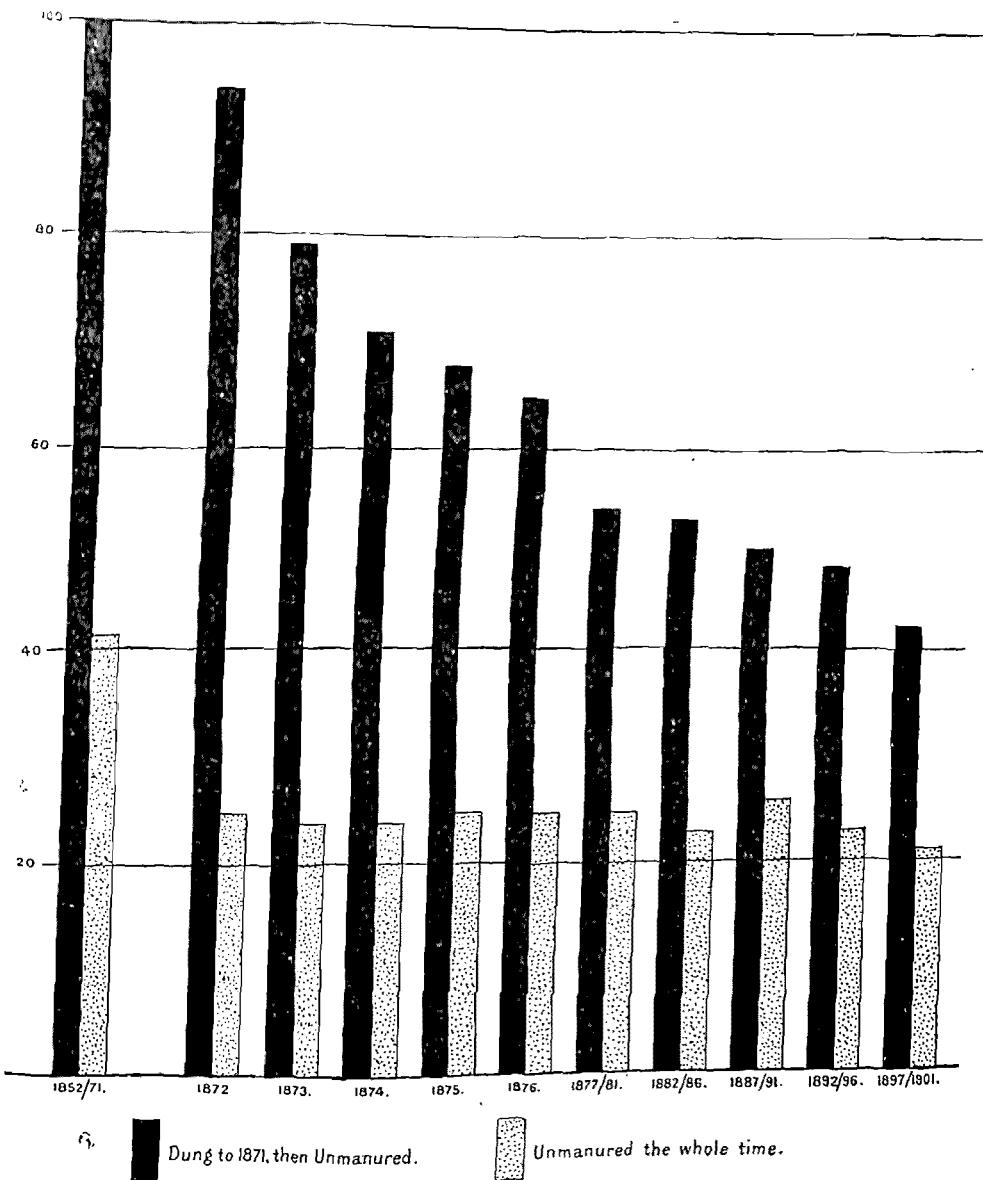


FIG. 12.—Barley. Total Produce, showing residual effect of Dung and no Manure in relation to the Dung Plot=100.

the first five years are given singly, after that five years are grouped into one period and the mean result given. In order to eliminate the effect of seasons, the crop results have all been reduced to the common standard of the crop on the

continuously dunged plot, 7-2, which has varied very little during the period.

Diagram 12 expresses these results in a graphic form for thirty years, and shows that, though the crop grown with the residues of dung is continually falling, it will only reach the level of that on the continuously unmanured plot after a long time.

### C. *Effect of Mineral Manures.*

The Rothamsted barley field affords a more thorough series of comparisons of the effect of the various mineral manures than does the wheat field, for in conjunction with each of the nitrogenous manures we get plots receiving no minerals (1), phosphoric acid alone (2), potash and the other alkaline salts, but no phosphoric acid (3); and the complete mineral manure, containing both phosphoric acid and the alkaline salts (4). In the absence of nitrogen the mineral manures have but little effect, though they produce a much greater increase of crop over that of the unmanured plot with barley than with wheat. Ammonium-salts and nitrate of soda used alone are not so effective as with wheat, but the rape cake used without minerals gives almost as big a crop as when supplemented with a complete mineral manure. Of course rape cake is not a purely nitrogenous manure, but itself supplies about 24 lb. of phosphoric acid and 17 lb. of potash per acre per annum.

The diagram \* Fig. 13 shows in a graphic form the effects of the various mineral manures, the nitrogen supply being the same in all cases.

The great importance of phosphoric acid to the barley crop is seen on comparing Plots 3 and 4, which only differ from one another in the omission of phosphoric acid on Plots 3. It will be seen that Plots 3 give but little more crop than Plots 1, which receive nitrogen alone—only 31.6 bushels per acre against 31.0, taking the average of the three series, A, AA, and C—but that a very marked increase to 41.6 bushels per acre is

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\* Figures to 1911 are given in Table XXIX. : they are very similar to those in the diagram.

found on Plots 4 for the addition of phosphoric acid. The straw shows just as marked an increase of crop brought about

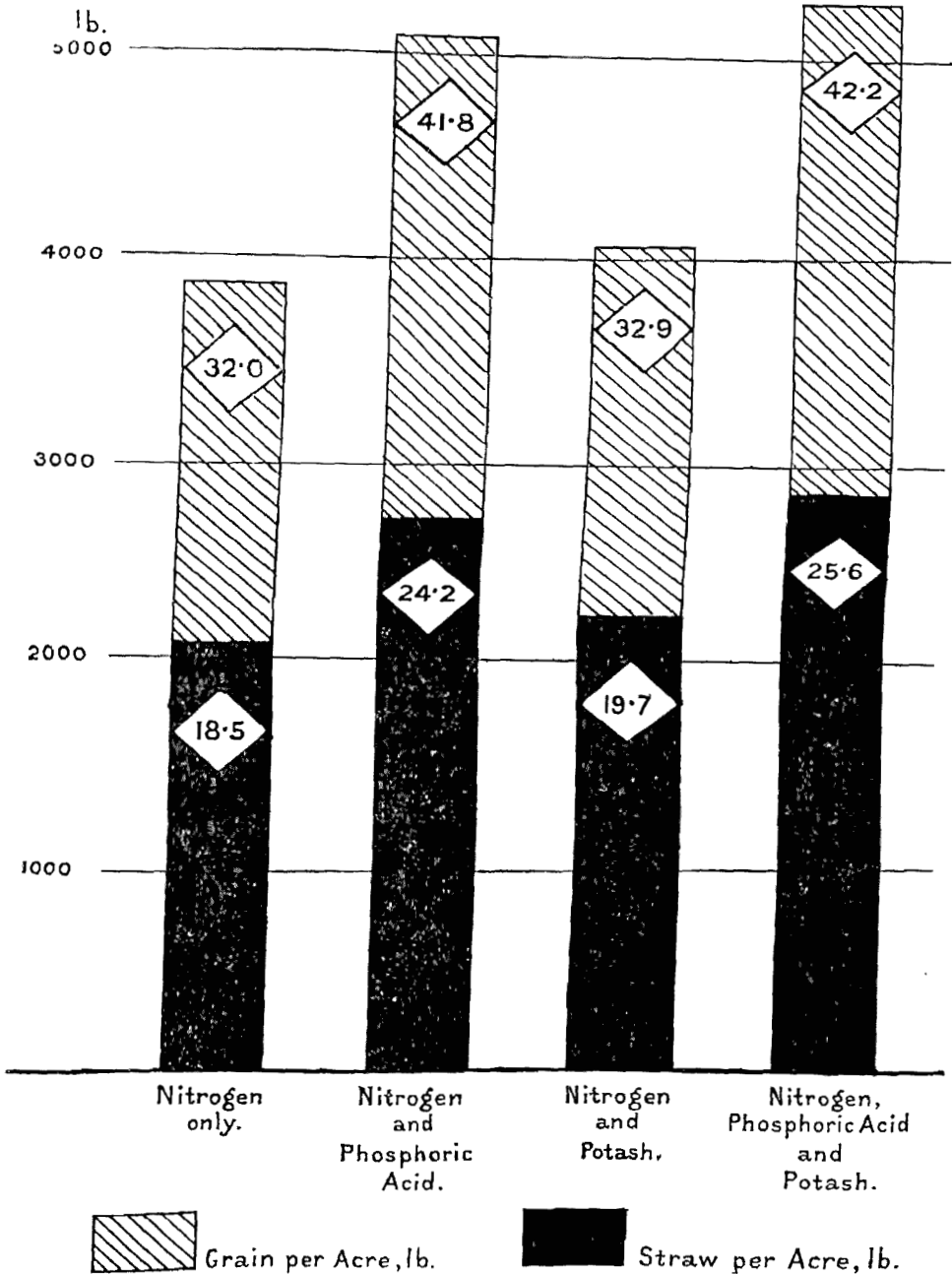


FIG. 13.—Effect of Mineral Manures on the yield of Barley (Grain and Straw). Mean of Series A, AA, and C. 51 years (1852-1902).

by phosphoric acid as does the grain, rising from 19.5 cwt. to 25.6 cwt. per acre. In the field the most striking effect is

seen in the hastened maturity brought about by the phosphoric acid. Not only are Plots 2 and 4, which receive phosphoric acid, in the ear long before Plots 3 and (to a less extent) Plots 1, but they will have begun to yellow for harvest when Plots 3 still show only upright green ears.

Comparing Plots 2 and 4, we see that a manure supplying phosphoric acid and nitrogen is almost as effective as a complete manure containing also potash and the other alkaline salts. There is a great increase of crop caused by the superphosphate and nitrogen on Plots 2, over the nitrogen alone on Plots 1, and very little further increase for the further addition of potash and other alkaline salts on Plots 4. Where the nitrogenous manure is nitrate of soda or rape cake, the omission of the

TABLE XXXIII.—*Ratio of yield of Barley (Grain) without Potash to yield with Potash, for successive 10-year periods, Ammonium-salts and Nitrate of Soda being the respective sources of Nitrogen.*

	1852-61.	1862-71.	1872-81.	1882-91.	1892-1901.	1902-11.
Ratio of 2 A to 4 A, Ammonium-salts.	98·9	104·3	98·8	90·2	77·1	77·3
Ratio of 2 AA to 4 AA, Nitrate of Soda	98·0	100·2	99·5	105·7	101·4	101·6

potash on Plots 2 compared with Plots 4, receiving a complete manure, shows no effect, whether we make the comparison over the whole period or for successive ten-year periods. With ammonium-salts, however, as the source of nitrogen the omission of potash does eventually diminish the crop; for the first thirty years the crops on Plots 4 A and 2 A, with and without potash, were equal, but in the fourth decade, as the soil became depleted by the continual removal of potash, the crop on Plot 2 began to fall off, and the diminution is much increased in the following decades. That there is no similar falling-off in the yield of the corresponding plot receiving nitrate of soda, is partly due to the greater root-range induced by the soluble nitrate, and partly to the effect of the soda base of this salt in rendering available to the plant the potash reserves of the soil.

Table XXXIII. shows very clearly how the omission of potash begins to tell upon Plot 2 A, manured with ammonium-salts and superphosphate, after the first thirty years, whereas on the corresponding Plot 4 AA, receiving nitrate of soda and superphosphate, the omission of potash has made no difference to the yield up to the end of the sixty-year period. The figures show the ratio the yield of Plot 2 (without potash) bore to that of Plot 4 (with potash), during each decade.

Thus the yield on Plot 2 A (ammonium-salts and superphosphate), which for the first thirty years was practically equal to that on Plot 4 A (ammonium-salts, superphosphate and potash), showed a decrease of 10 per cent. in the fourth decade and 23 per cent. both in the fifth and also in the sixth; whereas the corresponding yield on Plot 2 AA (nitrate of soda and superphosphate) is as good as that of 4 AA (nitrate of soda, superphosphate and potash) up to the end of the sixth decade.

Potash plays a less important part than phosphoric acid in the manuring of barley. Very little increase of crop has resulted from its use on the Rothamsted soil, and the only indication of the supply in the soil giving out has been seen in the last twenty years on the plot receiving superphosphate and ammonium-salts. Of course the Rothamsted soil starts with a very large original store of potash.

Speaking generally, we find that barley is much more dependent on a supply of mineral manures than is wheat, a free supply of phosphoric acid in particular being essential to its proper development.

#### *D. Character of the Crop as affected by Manuring.*

Table XXXIV. shows some of the characteristics of the barley crop during the fourteen years 1889-1902 compared with the average market valuations put upon the samples by Mr Few, of Cambridge, who examined them from year to year. The current market price prevailing at the time [of the valuation is taken as 100, and the value put on each sample is calculated on that basis. The first thing that becomes

## EXPERIMENTS UPON BARLEY

apparent on inspecting the table is that it is impossible to grow high-class barley by simply starving the plant. In each of the series it will be seen that the barley showing the highest average value, the best weight per bushel, the largest grains, and the smallest proportion of tail corn, is that grown on Plots 4, where a complete manure containing both nitrogen and minerals is supplied. It does not, however, follow that any

TABLE XXXIV.—*Experiments on Barley, Hoos Field. Particulars of Quality. Averages over 14 years (1889-1902).*

Plot.	Abbreviated Description of Manures.	Weight per Bushel of Dressed Grain.	Grain to 100 Straw.	Valuation of the Grain. (Standard each year as 100.)	Offal Grain to 100 of Dressed.	Weight of 100 Grains.*	N. per cent. in Grain (Dry) (Dry at average, 1.52-11).
		Lb.				Grams.	
1 O	No Minerals, and no Nitrogen . . . . .	52.4	86.3	97.3	7.9	3.67	...
2 O	Superphosphate only . . . . .	53.4	96.5	101.1	6.9	3.93	...
3 O	Alkali Salts only . . . . .	53.0	79.2	96.6	7.8	3.91	...
4 O	Complete Minerals . . . . .	53.5	86.8	99.4	5.9	3.91	1.45
1 A	Ammonium-salts alone . . . . .	52.3	84.5	91.1	8.5	4.03	...
2 A	Superphosphate, and Ammonium-salts	52.2	88.1	92.6	8.1	3.86	...
3 A	Alkali Salts, and do. . . . .	53.3	81.2	93.8	5.5	4.14	...
4 A	Complete Minerals, and do. . . . .	53.8	84.6	104.3	2.6	4.21	1.44
1 AA	Nitrate of Soda alone . . . . .	52.6	82.2	91.3	8.9	4.05	...
2 AA	Superphosphate, and Nitrate of Soda .	53.6	84.6	100.0	7.5	4.04	...
3 AA	Alkali Salts, and do. . . . .	53.4	80.9	93.6	6.1	4.12	...
4 AA	Complete Minerals, and do. . . . .	53.9	79.1	100.3	4.6	4.10	1.53
1 C	Rape Cake alone . . . . .	53.7	89.4	102.0	4.9	...	...
2 C	Superphosphate, and Rape Cake . . .	54.1	87.1	103.2	3.3	...	...
3 C	Alkali Salts, and do. . . . .	53.8	83.4	101.5	4.3	...	...
4 C	Complete Minerals, and do. . . . .	54.2	83.2	103.2	4.0	...	1.52
7-1	Unmanured after Dung . . . . .	54.2	84.0	100.5	5.9	...	...
7-2	Farmyard Manure . . . . .	54.6	75.9	96.4	4.3	4.47	1.51

\* Based on average samples of 24 years (1872-1895). See "Manurial Conditions affecting the Malting Quality of English Barley," by Munro & Beaven, J. R. Ag. Soc., 1897.

kind of manure will improve the quality of the barley. The grain from the plot receiving farmyard manure every year, despite the high weight per bushel, and the bold berry indicated by the high weight of 100 grains, has yet a value considerably below the average. Again, the use of nitrogen alone on Plot 1 A or 1 AA gives the lowest weight per bushel and the lowest valuation of the whole series. It has already been seen that

the yield of the barley crop is very dependent on the supply of minerals, especially of phosphoric acid, and the table now under consideration shows that the same effect extends to the quality of the crop. The use of superphosphate on Plots 2 as compared with Plots 1 gives a better proportion of grain to straw, a higher weight per bushel, and a greatly increased value; similarly, the omission of superphosphate on Plots 3 as compared with Plots 4 results in a deterioration of all the qualities making for value in the barley. Comparing the barley from Plots 3 and Plots 1, in the absence of superphosphate the potash salts on Plots 3 do not effect much improvement, though their presence on Plots 4 as compared with Plots 2 results in an improved quality. The presence of potash in the manure increases the straw more than the grain. In all the series it will be seen that Plots 3 and 4, receiving potash, give a lower proportion of grain to straw than do Plots 1 and 2, without potash.

If we compare the series together, the rape cake gives better barleys than either ammonium-salts or nitrate of soda, but the sample which on the average is the best is that grown with the full minerals and ammonium-salts.

Table XXXV. gives a comparison of the crop of grain and straw, the weight per bushel of the grain, and the proportion of grain to straw, in 1893, a typically dry and hot year, and in 1894, a wet but free-growing year.

The amount of grain produced is not dissimilar in the two years, but 1894 grew very much more straw, the average proportion of grain to straw being only about 70 as against 90 in the dry season. The weight per bushel of the grain is also higher, averaging 55.7 lb. in the dry year 1893 as against 52.5 lb. in the wet year 1894. In the dry year the plot receiving farmyard manure had a very great advantage, and grew 25 per cent. more than the other completely manured plots; whereas in the wet season when it gave about its average crop, several others gave almost as much, and it was actually excelled by the plot receiving nitrate of soda and

## EXPERIMENTS UPON BARLEY

TABLE XXXV.—Comparative Effects of Wet and Dry Season on Barley, Hoos Field.

Plot.	Abbreviated Description of Manures.	Dressed Grain.		Straw.		Weight per Bushel of Dressed Grain.		Grain to 100 Straw.		N. per cent. in Dry Matter of Grain.	
		1893.	1894.	1893.	1894.	1893.	1894.	1893.	1894.	1893.	1894.
1 O	No Minerals, and no Nitrogen	Bush.	Bush.	Cwt.	Cwt.	Lb.	Lb.	Per cent.	Per cent.	Per cent.	Per cent.
2 O	Superphosphate only, no Nitrogen	8.3	10.0	6.0	7.8	55.6	51.1	71.9	70.3	1.899	1.409
3 O	Alkali Salts only, do.	11.7	16.7	6.9	10.1	56.1	52.1	89.1	85.6	1.890	1.380
4 O	Complete Minerals, do.	7.8	9.5	5.9	6.9	55.5	51.6	70.0	73.4	1.995	1.411
1 A	Ammonium-salts alone	9.9	13.1	7.0	8.4	56.1	52.1	74.3	79.2	2.011	1.467
2 A	Superphosphate, and Ammonium-salts	11.6	10.4	7.3	9.5	55.1	50.4	85.3	67.5	2.188	1.646
3 A	Alkali Salts, do.	18.1	34.9	9.8	24.0	54.0	51.9	101.0	77.0	2.129	1.600
4 A	Complete Minerals, do.	16.8	17.8	10.3	12.3	55.8	51.5	85.9	73.8	2.171	1.614
1 AA	Nitrate of Soda alone	30.8	41.4	16.0	26.8	56.3	51.1	102.2	77.7	2.081	1.440
2 AA	Superphosphate, and Nitrate of Soda	14.5	14.8	9.5	12.3	55.1	50.3	81.3	63.5	2.243	1.741
3 AA	Alkali Salts, do.	31.3	40.9	17.1	30.5	55.8	53.1	99.8	71.1	1.984	1.476
4 AA	Complete Minerals, do.	17.9	19.0	11.6	14.4	56.3	51.0	81.9	68.4	2.198	1.688
1 C	Rape Cake alone	29.6	45.0	15.8	33.4	55.1	51.2	100.4	69.2	2.132	1.561
2 C	Superphosphate, and Rape Cake	28.2	35.9	15.5	23.2	55.1	53.9	96.5	78.5	2.046	1.549
3 C	Alkali Salts, do.	30.8	36.8	16.0	26.6	55.4	53.4	100.8	79.5	1.963	1.543
4 C	Complete Minerals, do.	28.4	32.0	16.9	23.0	55.1	51.1	87.8	72.0	2.108	1.587
7-1	Unmanured, after Dung	31.6	37.4	17.6	28.1	56.5	51.2	95.2	68.3	2.025	1.601
7-2	Farmyard Manure	20.2	23.8	13.5	15.4	56.0	53.4	78.5	78.2	2.109	1.665
		43.4	44.6	21.8	41.3	57.3	52.4	95.7	57.4	2.229	2.009

minerals. As was noticed in the case of the wheat crop, nitrate of soda answered better than ammonium-salts in the wet year, giving on Plot 4 AA 45 bushels of grain and 33·4 cwt. of straw against 41·4 bushels of grain and 26·8 cwt. of straw on Plot 4 A ; whereas in the dry year the ammonium-salts had a slight advantage. Taking, however, averages over the whole period, it is found that the seasons in which the ammonium-salts give a better crop than the nitrate of soda are wetter throughout than those in which the nitrate of soda is the more effective source of nitrogen. A wet March seems to be the most hurtful to the nitrate of soda plot. The comparative effects of the mineral manures in a wet and dry season are also similar to those noticed in the case of the wheat. In the wet season the crop is very dependent upon supplies of minerals in the manure, and especially on an abundance of phosphoric acid. In 1894 the addition of phosphoric acid raised the yield from 10·4 bushels per acre on Plot 1 A to 34·9 bushels per acre on Plot 2 A, and from 17·8 bushels per acre on Plot 3 A to 41·4 bushels per acre on Plot 4 A. In a dry season it is potash that chiefly tells ; for example, in 1893 the addition of potash on Plot 4 A to the superphosphate and ammonium-salts on Plot 2 A produced a specially marked increase of crop, from 18·1 to 30·8 bushels per acre.

Doubtless in the wet season the ripening effect of the phosphoric acid is specially valuable, while in a dry season the potash, by inducing a longer period of growth, is more effective in increasing the crop. The ripening action of the phosphoric acid may also be seen in the way it increases the weight per bushel of the grain in a wet season, whereas in a dry season it has little or no effect.

In the dry season the weight per bushel is much higher than in the wet, and the grain is about equal in weight to the straw, whereas in the wet season the weight of grain only amounts to about 70 per cent. of the straw.

Taking the results as a whole, it is seen that season has a much greater effect in bringing about changes in the composi-

tion of the barley grain than have variations in the manuring, but that the best barley will be grown with a fair but not large amount of nitrogenous manure combined with a free supply of phosphoric acid in some way or other.

It does not appear possible to establish any such critical periods for the rainfall in relation to the growth of barley as could be done for wheat.

The Table (XXXVI.) shows fifty-three barley crops from 1852 to 1901, taking the average of the completely manured plots divided into five groups according to their yield of grain,

TABLE XXXVI.

Produce per Acre. Average of Plots 7-2, 4 A, 4 AA, and 4 O.		Rainfall.					Total. March, April, May.	Total. June, July.
Grain.	Straw.	March.	April.	May.	June.	July.		
Bushels.	Cwt.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
50.2	29.2	1.442	1.649	1.919	2.302	2.967	5.010	5.269
43.4	25.5	1.909	1.803	2.122	2.769	2.801	5.834	5.570
38.6	21.6	1.938	1.609	1.996	2.506	3.074	5.543	5.580
34.8	22.5	2.092	1.940	2.048	2.386	2.666	6.080	5.052
27.7	18.1	1.590	2.086	2.807	2.103	1.840	6.483	3.943

together with the mean rainfall for each of the five months during which growth is proceeding. No very definite relationship is observable, though a general tendency will be seen to get the heaviest average yield when the earlier months of growth (March to May) are dry, also the lightest average yield when the later months of growth (June and July) are the driest.

## II.—BARLEY GROWN IN ROTATION, AGDELL FIELD.

It has already been stated that the production of barley in the rotation field shows much the same decline on the manured plots as it does on the completely manured plots in the Hoos field, and the fall has continued instead of being reversed as in the case of the continuous barley plots.

For selected plots on the rotation field, Table XXXVII. gives the production of grain and straw and certain particulars

## QUALITY OF BARLEY GROWN IN ROTATION 89

as to quality, taking an average of the five courses from 1885 to 1901. The first plot has been wholly unmanured, and all the crops in the rotation are removed from the land; the average production is, however, higher than on the unmanured plots growing barley continuously, because of the fallowing the land receives. When minerals only are applied to the root-crop on Plot 2 (roots are grown immediately before the barley), there results a comparatively large production of roots; since these are removed and since no nitrogen has been supplied,

TABLE XXXVII.—*Agdell Rotation Barley. Average of 5 years*  
(1885, '89, '93, '97, and 1901).

Manuring for Roots before Barley.	Treat- ment of Roots.	Third Course in Rotation.	Produce per acre.		Weight Per Bush.	Grain to 100 of Straw.	Weight of 1000 Grains.	Nitrogen per cent. in Dry Grain.	Estimated Value per Quarter.	
			Grain.	Straw.					s.	d.
1. Unmanured	Carted	Fallow	Bush.	Cwt.	Lb.					
2. Minerals .	Carted	Fallow	15·6	10·8	53·8	76·6	42·4	1·562	27	10
3. Do. . .	Carted	Fallow	13·6	9·3	54·0	77·3	39·7	1·484	28	7
4. Do. . .	Fed	Clover	19·9	12·8	54·4	80·0	43·0	1·559	29	0
5. Complete .	Fed	Clover	28·9	17·5	55·3	85·9	44·3	1·576	29	11
			34·1	23·4	55·3	74·9	46·2	1·693	29	6

These plots have been differently numbered since 1904. The present numbers are:  
Plot 5 (unmanured—fallow); Plot 3 (minerals—fallow); Plot 4 (minerals—clover).  
All roots are now carted.

they take away a certain quantity of nitrogen, and therefore exhaust the soil on this plot of its nitrogen to a much greater extent than on Plot 1, which grows a very small root-crop; hence a smaller barley crop follows the roots on Plot 2. The minerals in fact do not increase the production of the barley to an extent which will compensate for the loss of nitrogen in the increased root-crop previously brought about by the minerals.

On Plot 3, however, clover (or beans) is grown as the third crop in the rotation, and by collecting nitrogen from the atmosphere leaves behind a residue in the soil which is still available for the barley crop coming three years later. On Plot 4 there is a still greater supply of nitrogen, for not only is a leguminous crop grown, but also the root-crop preceding the clover is returned to the land. On Plot 5 the barley finds the maximum amount of nitrogen; here clover is grown, and the

root-crop receives a nitrogenous dressing of rape cake and ammonium-salts; all this nitrogen is returned to the soil in the root-crop which precedes the barley. It will be seen that on these five plots the growth of barley is proportional to the amount of nitrogen which may be supposed to be available; all except Plot 1 receive heavy mineral dressings containing both phosphoric acid and potash, yet in the absence of nitrogen these minerals on Plot 2 are not able to raise the crop above, nor even up to the level of the wholly unmanured Plot 1.

The weight per bushel increases with each addition of nitrogen; up to a certain point the proportion of grain to straw, and the weight of 1000 grains also increases, but on Plot 5, with the highest nitrogen, these characters begin to show a decline. The percentage of nitrogen in the barleys increases with the supply in the soil, but only becomes at all above the average with the highest sample from Plot 5. The valuation rises with the supply of nitrogen in the soil up to a certain point, but shows a slight decline for the last sample from Plot 5.

Summarising these results, we see that a good weight per bushel and a large berry cannot be obtained without a sufficient supply of nitrogen in the soil, but when a certain point has been reached further excess of nitrogen in the soil results in coarseness and an excessive proportion of nitrogen in the grain, deteriorating the quality. A fair supply of phosphates is also necessary to ensure early and complete maturation. In the Agdell field, Plot 4 represents the best soil conditions to obtain high quality in the barley; on Plot 5 this optimum point has been passed, and the land has become too rich in nitrogen compounds.

The barley grown in rotation is on the whole much superior to that grown continuously, mainly because its supply of nitrogen is derived from the nitrification of nitrogenous residues in the soil, *i.e.*, from what a farmer would call "condition," and not from nitrogenous manure directly applied.

## PRACTICAL CONCLUSIONS

1. The barley crop is far more dependent than wheat upon a supply of manure, and will require manuring when it is grown as a second white-straw crop, except on land in very good condition. After roots which have been wholly or partially fed on the land, or after a clover ley, there is already sufficient, and often too much, nitrogenous matter in the land.

2. The artificial manure used in the first case should contain a fair amount of nitrogen, as without it both the yield will be low and the berry small. Sulphate of ammonia is a better barley manure than nitrate of soda, giving equal yield and generally superior quality. The quantity used should not be more than  $1\frac{1}{2}$  cwt. per acre. Rape cake up to 5 cwt. per acre is also a good source of nitrogen for the barley crop.

3. Barley is particularly dependent on a free supply of phosphoric acid, 3 cwt. of superphosphate per acre may be profitably used on most soils, especially where the climate is wet. Even with barley after roots superphosphate is valuable, hastening the ripening and making the sample more uniform.

4. An artificial supply of potash is rarely likely to be wanted, except on dry sands and gravels and in dry seasons.

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## CHAPTER VI

### EXPERIMENTS UPON OATS

Experiments upon Oats grown continuously upon the same Land,  
Geescroft Field.

EXPERIMENTS upon oats on very similar lines to the trials with wheat and barley were begun in 1869 in the Geescroft field, but on a smaller scale, as only six plots, each one-eighth acre, were set out. These experiments were, however, abandoned after ten years: the Geescroft field, although it shows on physical analysis a lighter texture than either Broadbalk or Hoos fields, yet always lies comparatively wet, and appears to suffer more than any other field from the continued use of nitrate of soda, probably because the chalking to which the other fields have been subjected has not been carried out in this field. As the experiments ran into the cycle of wet seasons from 1873 onwards, it became almost impossible to work the land, and the experiment was abandoned after 1878.

The average results set out in Table XXXVIII. are for the first five years only of the experiment.

Putting aside the deterioration of the texture of the land, which may be taken as an accident independent of the nature of the crop, there is no evidence that oats cannot be grown continuously on the same land—the tenth crop on the unmanured plot, for example, was larger than any other since the first. The manurial requirements of the oats are also very similar to those of the other cereal crops, resembling barley perhaps more than wheat. The crop shows some response to minerals only, but the chief increase of crop comes with

applications of nitrogen. Even allowing for the deterioration of soil texture which so much affected the nitrate of soda plots, ammonium-salts appear to be the better source of nitrogen.

TABLE XXXVIII.—*Oats, Geescroft Field. Average Produce per acre, 5 years (1869-1873). Description of Oats—Black Tartarian.*

Plot.	Manures per acre.						Produce per acre.		
	Mineral.				Nitrogenous.		Grain.		Straw.
	Sulphate of Potash.	Sulphate of Soda.	Sulphate of Magnesia.	Superphosphate of Lime.	Ammonium-salts.*	Nitrate of Soda.	Quantity.	Weight per Bushel.	
Lb.	Lb.	Lb.	Cwt.	Lb.	Lb.	Bush.	Lb.	Cwt.	
1	...	...	...	...	...	...	19.9	33.8	10.4
2	200	100	100	3.5	...	...	24.5	35.0	13.4
3	...	...	...	...	400	...	47.0	35.9	23.5
4	200	100	100	3.5	400	...	59.0	37.0	41.1
5	...	...	...	...	...	550	47.1	35.5	27.5
6.	200	100	100	3.5	...	550	57.5	35.8	35.0

\* Equal parts of Sulphate and Muriate Ammonia of Commerce.

For the manuring of oats in practice the recommendations set out for barley may be followed, except that the quantities there given may be somewhat increased for oats.

## CHAPTER VII

### EXPERIMENTS UPON ROOT-CROPS GROWN CONTINUOUSLY ON THE SAME LAND

- I. Experiments upon Mangolds, Barn Field, 1876-1911 :
  - A. Effect of Nitrogenous Manures.
  - B. Effect of Mineral Manures.
  - C. Comparison of Nitrate of Soda and Ammonium-salts as sources of Nitrogen.
  - D. Effect of Nitrogenous and Mineral Manures when used in Conjunction with Dung.
  - E. Proportion of Root to Leaf.
  - F. Proportion of the Nitrogen recovered in Crop to that supplied in Manure.
  - G. The Composition of the Mangold Crop as affected by Manuring.

Practical Conclusions.
- II. Experiments upon Turnips, Barn Field, 1843-70.

Practical Conclusions.
- III. Experiments on the Continuous Growth of Potatoes on the same Land, Hoos Field, 1876-1901.

Practical Conclusions.
- IV. Experiments on the Growth of Sugar-Beet, Barn Field :
  - A. First Series, 1871-75.
  - B. Second Series, 1898-1901.

Practical Conclusions.

References.

As the original design of the Rothamsted Experiments embraced all the crops of the farm, so essential a feature of English farming as the root-crops naturally occupied a prominent place; indeed we find that the second paper of experimental results issued from Rothamsted in 1847 dealt with turnip culture. In 1843, accordingly, the Barn field was set aside for experiments on turnips, the trials being on Norfolk white turnips for six seasons, 1843-1848, followed by

Swedes for four seasons, 1849-1852. Barley was then grown for three years to equalise the soil conditions, and the plots were rearranged on substantially the plan they occupy to-day. Swede turnips were grown for fifteen seasons, 1856-1870, but it was found impossible to continue the growth of Swedes upon the same land year after year with any success. This was mainly due to the incidental circumstance that on growing the same description of crop, with the same comparatively limited and superficial root-range, for so many years in succession, the surface soil became less easily worked, and the tilth, so important for turnips, was frequently unsatisfactory; whilst for want of variety and depth of root-range of the crop, a somewhat impervious pan was formed below. After the Swedes sugar-beet followed for five years with the same manures, except that in the last two the nitrogenous manures were omitted, and in 1876 mangolds took the place of sugar-beet and have continued ever since. No difficulty has been experienced in growing mangolds continuously on the same land, as may be seen from the fact that the twenty-fifth crop in 1900 was the largest of the series. This success must be attributed partly to the extended root-range of the mangold, partly also to its freedom from insect and fungoid attacks, which tend to accumulate on land carrying one crop continuously. The only difficulty is experienced on the plots receiving saline manures only, especially where large dressings of nitrate of soda are repeated every year. Owing to the constant removal of organic matter and the injurious action of the saline manures upon the texture of the soil the land gets into a bad mechanical condition, very sticky when wet, and drying with a hard crust, so much so that there is occasionally a complete loss of plant from this cause alone.

In the Hoos field experiments upon potatoes were begun in 1876, and continued for twenty-six years; they were then discontinued, because the crop on the plots receiving no organic manures had fallen to a very low ebb in consequence of the deterioration of the texture of the soil. But on the plots

receiving farmyard manure, and even on those receiving only a complete artificial manure, the crop was maintained in favourable seasons. No falling-off was observed which could be attributed to the land having become "sick" through the continuous growth of the same crop, or through the accumulation of disease in the soil.

The essential feature of the root-crops is the large amount of digestible carbohydrate they contain; in the case of Swedes this consists of glucose, which forms 6 to 7 per cent. of the whole weight of the Swedes, the total dry matter being about 11 per cent. of the whole. In the mangold there is about 8.5 per cent. of cane sugar, the total dry matter being about 12.5 per cent. In potatoes the carbohydrate is starch, of which the tubers contain about 20 per cent., out of a total dry matter content of 25 per cent.

#### I.—EXPERIMENTS UPON MANGOLDS, BARN FIELD, 1876-1911.

The area under experiment amounts to about 8 acres, most of the plots being about one-seventh acre in extent; the whole produce from each plot is weighed, but the roots only are carted away, the leaves after weighing being spread and ploughed in.

The field is divided longitudinally into seven strips running the whole length of the field; each of these strips receives one manure throughout its length; farmyard manure alone on Strip 1, and in combination with superphosphate and sulphate of potash on Strip 2, nothing on Strip 3, superphosphate alone on Strip 5, superphosphate and sulphate of potash on Strip 6; and complete minerals, including further sulphate of magnesia and common salt, on Strip 4. The strips are then subdivided into plots by cross-dressings of nitrogenous manures; nothing on the O Series, nitrate of soda on Series N, ammonium-salts on Series A, rape cake on Series C, and a combination of ammonium-salts and rape cake on Series AC. Thus, as shown in Table XXXIX.,

there are plots showing every combination between the various mineral and nitrogenous dressings employed.

The mineral manures, the dung and the rape cake, are

TABLE XXXIX.—*Experiments on Mangolds, Barn Field, beginning 1876. Quantities of Manures per acre per annum.*

Strip.	Strip Manures.						Nitrogenous Manures running across all the Strips.					
	Farmyard Manure.	Superphosphate.	Sulphate of Potash.	Sulphate of Magnesia.	Chloride of Soda. (Salt.)	Ammonium-salts.*	Series O.	N.	A.	AC.		C.
							None.	Nitrate of Soda.	Ammonium-salts.*	Rape Cake.	Ammonium-salts.*	Rape Cake.
Tons.	Cwt.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	
1	14	...	...	...	...	...	...	550	400	2000	400	2000
2	14	3·5	500†	...	...	...	...	550	400	2000	400	2000
4	...	3·5	500	200	200	...	...	550	400	2000	400	2000
5	...	3·5	...	...	...	...	...	550	400	2000	400	2000
6	...	3·5	500	...	...	...	...	550	400	2000	400	2000
7	...	3·5	500	...	...	36·5	...	550	400	2000	400	2000
8	...	...	...	...	...	...	...	550	400	2000	400	2000

\* Equal parts Sulphate and Muriate Ammonia of Commerce.  
 † The addition of Potash to Plot 2 began in 1895.

ploughed in just before seeding, the ammonium-salts and nitrate of soda are sown as top-dressings.

The seed was dibbled in the earlier years of the experiment ; it is now drilled, 26 inches between the rows, and the plants are singled out to 10 inches apart.

The following tables give, (XL.) the average weight of roots grown on each plot during the thirty-four years, 1876-1912 ;\* (XLI.) the weight of roots and leaves grown in the best season, 1900.

A first inspection of the results shows the enormous value of farmyard manure in growing mangolds, especially when they are grown continuously on the same land. In favourable seasons it is possible to obtain good crops by the aid of manures containing no organic matter, as seen in 1900 ; but in ordinary years the bad texture of the soil and its tendency to lose water on account of the lack of humus affect both the germination of the seed and the growth of the plant in its early stages. It will be convenient, therefore, to consider separately

\* 1885, 1901, and 1908 omitted.

EXPERIMENTS UPON ROOT-CROPS

the plots receiving dung and those which are manured exclusively with "artificials."

TABLE XL.—*Barn Field Mangolds. Average produce of Roots per acre over 34 years (1876 to 1912).\**

Strip.	Strip Manures.	Cross-Dressings.				
		O.	N.	A.	AC.	C.
		None.	Nitrate of Soda.	Ammonium-salts.	Rape Cake and Ammonium-salts.	Rape Cake.
		Tons.	Tons.	Tons.	Tons.	Tons.
1	Dung only . . . . .	18.15	26.24	22.48	24.84	24.69
2	Dung, Super., Potash † . . . . .	18.87	26.63	24.37	27.24	26.49
4	Complete Minerals . . . . .	5.05	17.71	14.75	26.73	22.11
5	Superphosphate only . . . . .	4.92	15.05	7.04	9.68	10.78
6	Super. and Potash . . . . .	4.32	15.42	14.08	23.42	19.28
7 †	Super., Potash, and 7.8 lb. N. as Am.-salts . . . . .	5.93	15.63	14.60	22.30	19.19
8	None . . . . .	3.69	9.94	5.61	9.29	9.71

\* 1885, 1901, and 1908 omitted. † The addition of Potash to Plot 2 only began in 1895. ‡ Average up to 1902 only; manuring was then altered.

TABLE XLI.—*Barn Field Mangolds. Produce of Roots and Leaves per acre. Season 1900. (Good season.)*

Strip.	Strip Manures.	Cross-Dressings.				
		O.	N.	A.	AC.	C.
		None.	Nitrate of Soda.	Ammonium-salts.	Rape Cake and Ammonium-salts.	Rape Cake.
		Tons.	Tons.	Tons.	Tons.	Tons.
1	Dung only . . . . .	R. 25.25	41.30	26.10	27.65	30.35
		L. 2.15	4.35	3.65	3.55	3.10
2	Dung, Super., Potash * . . . . .	R. 23.05	41.85	35.70	38.40	35.55
		L. 2.60	5.00	5.60	6.00	3.55
4	Complete Minerals . . . . .	R. 8.75	33.10	28.95	43.20	34.55
		L. 1.10	4.95	3.25	6.30	3.80
5	Superphosphate only . . . . .	R. 9.15	28.35	12.00	14.95	14.90
		L. 1.30	3.85	2.95	2.15	2.60
6	Super. and Potash . . . . .	R. 7.05	29.65	28.20	37.55	29.40
		L. 0.95	3.60	3.60	5.65	2.95
7	Super., Potash, and 7.8 lb. N. as Amm.-salts . . . . .	R. 10.80	28.70	28.70	36.95	29.20
		L. 1.35	4.85	5.10	7.20	4.20
8	None . . . . .	R. 7.75	22.55	12.85	15.05	15.40
		L. 1.15	4.85	3.65	3.35	3.40

\* The addition of Potash to Plot 2 only began in 1895.

A. *Effect of Nitrogenous Manures.* The mangold, being a plant with a large leaf development, was at one time to a certain extent regarded as one of the restorative crops, capable, with its large area of leaf, of drawing upon the atmospheric nitrogen and thus rendering itself independent of nitrogenous manures. Though it was obvious that nitrogenous manures had a powerful effect even upon leafy crops, it was urged that the benefit consisted in starting the crops, which, as soon as they had attained their proper development of leaf, would continue to feed themselves by drawing upon the nitrogen of the atmosphere. It was with the view of testing the truth of this opinion that the manuring on Plots 7 was arranged. They receive superphosphate and sulphate of potash as mineral manures, together with a small quantity of nitrogen,  $36\frac{1}{2}$  lb. per acre of ammonium-salts containing 7.8 lb. of nitrogen per acre, *i.e.*, about one-eleventh of the amount applied to the plots in Series A.

On the hypothesis indicated above, the small quantity of nitrogen would act as a starter, and establish the plant, which should then be able to maintain itself upon atmospheric nitrogen.

The results, however, yielded by Plots 7 as compared with Plots 6 showed this opinion to be mistaken; the small addition of 7.8 lb. of nitrogen per acre produced an increase of crop of 1.4 ton per acre only, whereas a further 86 lb. of nitrogen raised the crop by 8.7 tons per acre. This experiment was discontinued 1902.

Thus the opinion may be dismissed that the mangold plant when once started can become independent of the nitrogen in the soil and manure.

We may next pass on to a consideration of the effects of the varying forms and amounts of nitrogen when used without any mineral manuring, *i.e.*, on Plots 8, where no standard manures are applied. The entirely unmanured plot (8 O) has produced an average crop of 3.69 tons of roots only, which is increased by the application of 86 lb. nitrogen in the ammonium-salts to 5.61 tons, and by 98 lb. of nitrogen in the

form of rape cake to 9.71 tons. A further addition of 86 lb. of nitrogen (as ammonium-salts) to the 98 lb. of nitrogen in rape cake (Plot 8 AC) produces no more increase of crop, which remains practically stationary at 9.29 tons. However, with 86 lb. of nitrogen in the shape of nitrate of soda the result is somewhat higher than in any other case, for the crop amounts to 9.9 tons, a result which will be more intelligible later. In all these cases, however, the crop is a very indifferent one for the large amounts of nitrogen employed, and the aspect of the plots clearly shows that the plant has received far more nitrogen than it can effectively utilise in the absence of the other mineral constituents which go to make up a complete plant food.

We may now turn to Plots 4, where superphosphate, sulphates of potash and magnesia, and common salt are used in conjunction with nitrogenous manures, thus constituting a complete manure which supplies all the elements of plant nutrition.

The diagram Fig. 14 shows on the left hand the average results obtained with the varying amounts and compounds of nitrogen on the Plots 4 in question, where there is an abundant supply of mineral manure. The right-hand half of the diagram shows the effect of the same nitrogenous manures when used in conjunction with dung instead of complete minerals, for an account of which see page 108.

Without nitrogen\* (Plot 4 O) a very small crop is grown, 5.05 tons per acre, which is increased to 14.75 tons per acre by the addition of 86 lb. nitrogen in ammonium-salts, or to 17.71 tons per acre by the same amount of nitrogen applied in the shape of nitrate of soda. The application of 98 lb. of nitrogen per acre in rape cake increases the crop to 22.11 tons per acre, and when both rape cake and ammonium-salts are used together, making an application of 184 lb. of nitrogen per acre, the crop is raised to 26.73 tons per acre. Thus when all the other elements of a plant food are present, the crop increases with each addition of nitrogen. The increase

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\* Figures are from Table XL.



neither nitrate of soda nor ammonium-salts leave any effective residue.

In seasons of exceptional growth, with a big crop like that of 1900, it might be expected that as the plant was utilising much more thoroughly the supply of nitrogen, then the smaller amounts on some of the plots, plentiful enough for an ordinary year, might prove to be insufficient. There is no indication, however, of this being the case, as may be seen by a consideration of Table XLI. ; the increase of crop on Plots 4, receiving no dung but a complete mineral manure, continues with each application of nitrogen, but not more so than in normal seasons. On the dunged plots, indeed, it is not those receiving most nitrogen (Plots 1 and 2 AC) which give the highest crop, but those cross-dressed with nitrate of soda, as though the availability of the nitrogen and the presence of a large supply of alkaline salts had been the determining factors in producing the maximum crop. The whole results go to show that, dependent on nitrogen as the mangold crop is, the first application is the most effective, each succeeding addition of nitrogen producing a smaller return in the shape of an increase of crop.

The injurious effects of the very large amounts of nitrogen added to some of the plots is very manifest wherever there is more nitrogen than the plant can properly deal with. The leaves have a dark green appearance, are much curled and crinkled, and show an increased tendency to variegation, the chlorophyll collecting into dark green or almost black blotches on the lighter background of the leaf. The leaf-stalks are often much more coloured, and become a bright orange yellow.

On these plots the leaves do not ripen off and obtain the general yellow flaccid appearance presented on the more healthy plots when the crop is ready to lift ; instead, the outer leaves begin to die and shrivel up quite early in October ; in some places they show numbers of dead spots and burnt-looking patches round the edges of the leaf.

The destruction appears to be due to a leaf-spot fungus,

*Uromyces betæ*, and to a *Torula*, which is abundantly developed on the mangolds on the plots receiving an excess of nitrogen but is not present elsewhere in the field.

Thus, towards the end of October the plots receiving the excess of nitrogen present a very unhealthy appearance; a large proportion of the plants seem scorched and withered as regards the outer leaves, and only show a cluster of small dark green active leaves at the heart.

The above appearances are not confined to the plots receiving very large amounts of nitrogen; it is rather a question of the relative excess of nitrogen as compared with the quantity of available alkalies, especially of potash. Thus the plants on Plot 1 AC are particularly bad, as they receive the maximum amount of active nitrogen in addition to the dung, whereas the plants on Plot 2 AC, which receive the same nitrogen but also sulphate of potash, are comparatively healthy. The plants receiving nitrate of soda as a source of nitrogen show less damage than those receiving an equivalent amount of nitrogen in the shape of ammonium-salts. Superphosphate, in the absence of alkaline salts, seems to increase rather than diminish the injurious effects.

*B. Effect of Mineral Manures.* The effect of the different mineral constituents of a manure upon the mangold crop can be seen by an examination of the results yielded by Plots 4, 5, and 6. Plots 5 receive superphosphate only at the rate of 392 lb. per acre, Plots 6 receive 500 lb. per acre of sulphate of potash in addition to the superphosphate, while on Plots 4 the other alkalies which are taken up by the plant are added in the shape of 200 lb. of sulphate of magnesia and 200 lb. of common salt per acre. In the cross-dressings of nitrogenous manures it should be noticed that all the plots in Series N receive soda through the use of nitrate of soda, whereas the other nitrogenous dressings, being either ammonium-salts or rape cake, provide no appreciable amount of alkaline salts.

Table XL. gives the results to 1912, and the following diagram (15) shows these results set out in a graphic form, for

Plots 8, 5, 6, and 4; the first column in each group represents the mean crop for twenty-seven years on Plot 8, receiving no mineral manures; the second column represents the crop of Plot 5, receiving superphosphate only; the third, that of

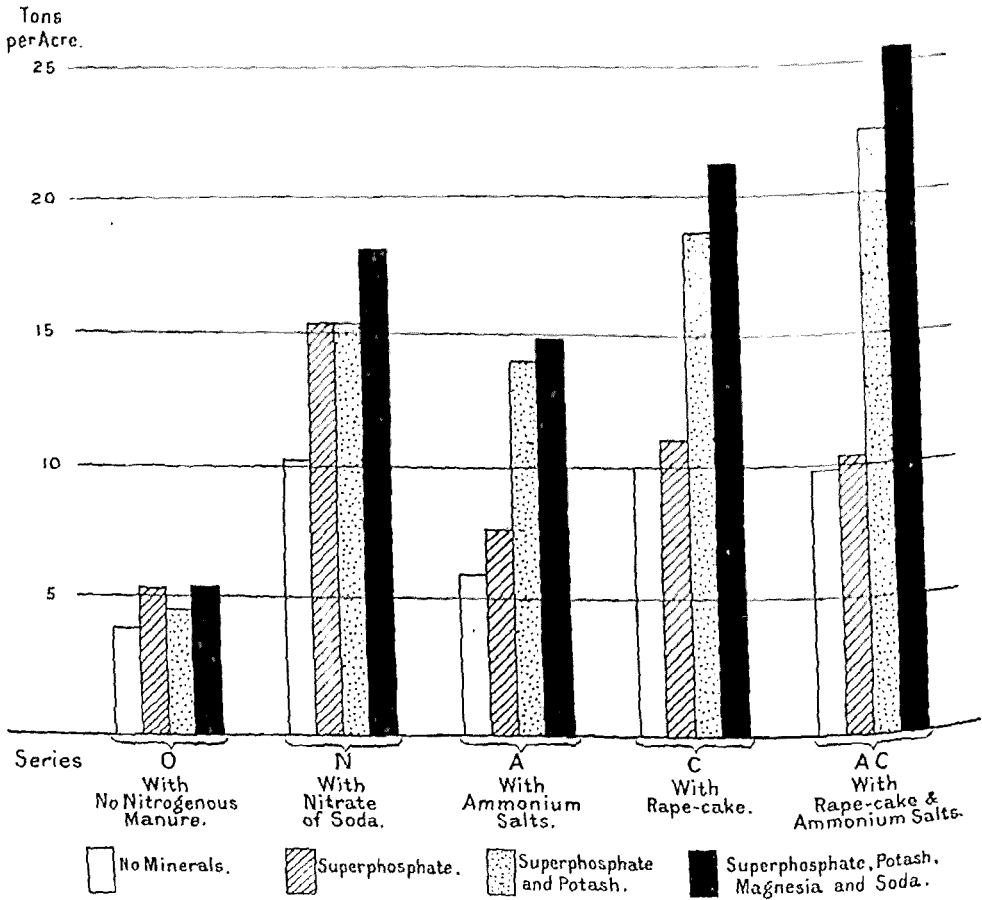


FIG. 15.—Mangolds. Effect of various Mineral Manures. Average Produce of Roots per acre, 1876-1902.\*

Plot 6, with potash in addition to the superphosphate; and the last column represents the crop of Plot 4, which receives superphosphate and all the alkalis — potash, magnesia, and soda. The four plots in each series are grouped together. To the first group (O) no nitrogenous manure is applied; in the second (N), nitrate of soda; in the third (A), ammonium-salts; in the fourth (C), rape cake; and in the fifth (AC), rape cake and ammonium-salts, are respectively the sources of nitrogen.

A first inspection of the diagram shows that superphosphate

\* The averages are practically identical with those of Table XL., 1876-1912.

produces but little increase of crop except when used with nitrate of soda; the average increase of crop due to superphosphate on Series A, AC, and C, where ammonia or rape cake is the source of nitrogen, is only one ton per acre, whereas the average increase it causes where nitrate of soda is used amounts to 5.1 tons per acre. This latter result demonstrates that phosphoric acid is necessary for the proper development of the mangold plant, but that in the absence of alkaline salts on the ammonia and rape cake plots it cannot exercise any sensible influence.

The great increase of crop comes as a rule when potash is added to the superphosphate: the crop on the plots receiving ammonium-salts rises from 7.04 to 14.08 tons per acre; with rape cake the rise is from 10.78 to 19.28 tons per acre; with rape cake and ammonium-salts the increase is from 9.68 to 23.42 tons per acre. Only with nitrate of soda as the source of nitrogen is there no increase for the addition of potash, the crop being practically equal on the two plots 6 and 5, with and without potash. The necessity of potash for the mangold crop is still more strikingly seen in the seasons of large crop: where no potash is supplied in the manure the plant has to get as much as it can from the reserves of potash contained in the soil, and, as it is difficult to accelerate this process, the crop on these plots cannot make nearly such good use of favourable conditions for growth as the crops which have a large amount of potash at command. For example, in 1900 the addition of potash to superphosphate and ammonium-salts raised the crop from 12.0 to 28.2 tons per acre, and on the plots receiving rape cake and ammonium-salts the rise was from 14.9 to 37.5 tons per acre.

A further inspection of the diagram shows that the addition of magnesium sulphate and salt to the plots receiving potash and superphosphate, as represented by the last columns in the figure, brings about a further small but perceptible increase of crop, and the increase is proportionately more for the larger crops. The most probable cause is that the 400 lb. of soluble

salts, the magnesium sulphate and sodium chloride added to Plots 4 but not to Plots 6, though providing no direct plant food, yet so assist to render soluble the reserves in the soil and to economise the supply of potash, that the crop receives an indirect benefit equivalent to an addition of the more indispensable elements of nutrition.

The great effect of potash, and to a less degree of the other alkaline salts, upon the mangold crop is very striking, and is to be correlated with the fact that the mangold is essentially a sugar-producing plant, and that large supplies of potash seem to be essential to the processes in the plant which result in the formation of sugar and similar carbohydrates.

Doubtless the long period over which the experiments have been continued has intensified the effect, because the soil of Plot 5, which has received no potash for at least forty-seven years, must by this time have been very thoroughly exhausted of available potash. The poor returns of Plots 5, receiving no potash, have been progressive, getting worse each year as the initial stock of potash in the soil has become more and more exhausted. For this reason, the farmer taking his mangold crop in rotation need not expect to find an addition of potash produce such a very large proportionate increase as is here manifest.

The effect of potash and of the other saline manures is plainly visible in the appearance of the plants themselves. On the plots receiving potash the plant begins to ripen early, the leaves turn yellow and become flaccid, so that in October these plots may be seen outlined from the rest by their lighter tint at any distance from which the field can be viewed. The ripening effect and the lighter colour are even more apparent where the complete mineral manure, containing also magnesium sulphate and salt, has been applied, than where potash has been used alone. On the contrary, the plots receiving no potash show all the signs previously described as indicating an excess of nitrogen—the premature death of the outer leaves, and the dark green, curled, and unhealthy appearance of the

remaining tufts of small leaves, which show no signs of completing their growth however prolonged the season may be.

C. *Comparison of Nitrate of Soda and Ammonium-salts as sources of Nitrogen.* It has already been pointed out that the plots of Series N cross-dressed with nitrate of soda, give better crops than the corresponding plots of Series A, which receive the same amount of nitrogen in the form of ammonium sulphate and chloride. This is particularly the case on Plots 5 and 8, where no potash is added, for the soda of the nitrate of soda seems to supply the alkali needed by the plant, or at any rate enables it to utilise the reserves contained in the soil. The superiority of nitrate of soda is, however, also very evident on the other plots receiving potash or the complete alkaline salts. Taking the mean of Plots 1, 2, 4, 6, and 7, and comparing Series N and A, the crop obtained with 86 lb. of nitrogen in the form of nitrate of soda exceeds the crop of the corresponding plots in the ratio of 100 to 89. On the Rothamsted soil nitrate of soda always gives rather a higher return than ammonium-salts, but not quite to the same extent with other crops as with mangolds; the superiority of nitrate of soda is, however, not so marked as to suggest any specific affinity of mangolds for nitrate of soda, lovers of saline matter and of nitrates though they are.

The cause of the superiority of the nitrate of soda is probably to be found in the different character of the growth it induces; being freely soluble in water and not retained in any way by the soil, it sinks more readily, with the result that the plant develops a longer and deeper root-system to follow the nutriment. Ammonium-salts, on the contrary, are immediately absorbed by soil of the Rothamsted type, and are retained very close to the surface; the plant in consequence develops a root-system correspondingly near the surface, and does not search the subsoil so thoroughly for either food or water.

The appearance of the mangold crop when it is ready to lift also confirms the opinion expressed above, that the superiority of the nitrate of soda is partly due to the increased root-range

it induces. If we compare the plots receiving potash, viz., 4, 6, and 7, those which are cross-dressed with ammonium-salts are dead ripe and the leaves all yellowing off, when the corresponding nitrate of soda plots are still green and growing vigorously. The droughts and heat of the summer and the autumnal fall of temperature all have a greater effect on the more shallow-rooted mangolds grown with ammonium-salts, and bring their growth to an earlier conclusion; the prolonged growth with the nitrate of soda helps also to explain the greater weight of produce on these plots. If, however, we compare the appearances presented by the mangolds grown with nitrate of soda and with ammonium-salts on Plots 5 and 8, where the manure contains no potash, the nitrate of soda plants are far healthier and more mature. In this case the nitrate of soda seems to be also able to do some of the work of the potash, both by enabling the plant with its extended root-range to draw more freely upon reserves of potash in the soil and subsoil, and also by the soda acting itself as a potash substitute, or perhaps more correctly, as a potash economiser. Here, with no potash supplied, the superiority of the plots receiving nitrate of soda over the corresponding plots with ammonium-salts has been a progressive one, increasing from year to year; while the relative effect of nitrate of soda and ammonium-salts when potash is also supplied in the manure is constant, or only varies with the character of the seasons.

D. *Effect of Nitrogenous and Mineral Manures when used in Conjunction with Dung.* It has already been indicated that the crops on plots receiving dung are on the average much better than those grown with artificial manures only. To a large extent this is due to the improvement in the texture and water-retaining capacity of the soil, which has been effected by the repeated application of farmyard manure. The seed always germinates better on these plots and grows away at an earlier date, so that in some years of great heat and drought, like 1895 and 1901, a crop is obtained on the dunged plots when the plant fails almost entirely on the plots receiving no organic

manure. Even when the plant does not entirely fail it has been often noticed that, if a spell of hot weather comes in the early part of the season, the plant on the dunged plots will be growing vigorously when that on the other plots is still struggling for existence. Later on, when all the plant is established, the differences are not so marked, and in favourable seasons the crop on the plots manured with artificials rivals the crop grown with dung, if due allowance be made for the larger amount of nitrogen actually supplied to the dunged plots.

The right-hand portion of the diagram Fig. 14, page 101, shows the effect of the successive additions of other nitrogenous manures to dung.

Considering first the crops on Plot 1, in each series (see Table XL., page 98), we find that notwithstanding the large amount of nitrogen which the dung supplies, and its accumulation in the soil, yet dressings of quickly-acting nitrogenous manures will still bring about an increase of crop. The amount of nitrogen annually supplied to Plot 1 O is much greater than is removed by the crop, hence there must be a considerable accumulation of nitrogen from year to year in the soil of this plot. Nevertheless, these reserves cannot become active quickly enough for the needs of so rapidly growing a plant as the mangold, hence the increase which is seen when a further addition of active nitrogen in the shape of ammonium-salts or of nitrate of soda is made.

When more than 86 lb. per acre of nitrogen is added, as on Plot 1 C, which receives 98 lb. of nitrogen as rape cake, or as on Plot 1 AC, which receives 184 lb. of nitrogen as rape cake and ammonium-salts, no further increase of crop is seen, the average remains stationary at 24 tons per acre. The crop has, in fact, attained its maximum, and is limited, not by the amount of nitrogen and other plant food available, but by its restricted period of growth, or by a scarcity of water, sunlight, and other factors of development.

Turning to a comparison of Plots 1 and 2, some interesting results are to be seen; both receive a similar dressing of

14 tons per acre of farmyard manure every year, but for the first nineteen years of the experiment, from 1876 to 1894, Plot 2 received in addition 3½ cwt. per acre of superphosphate.

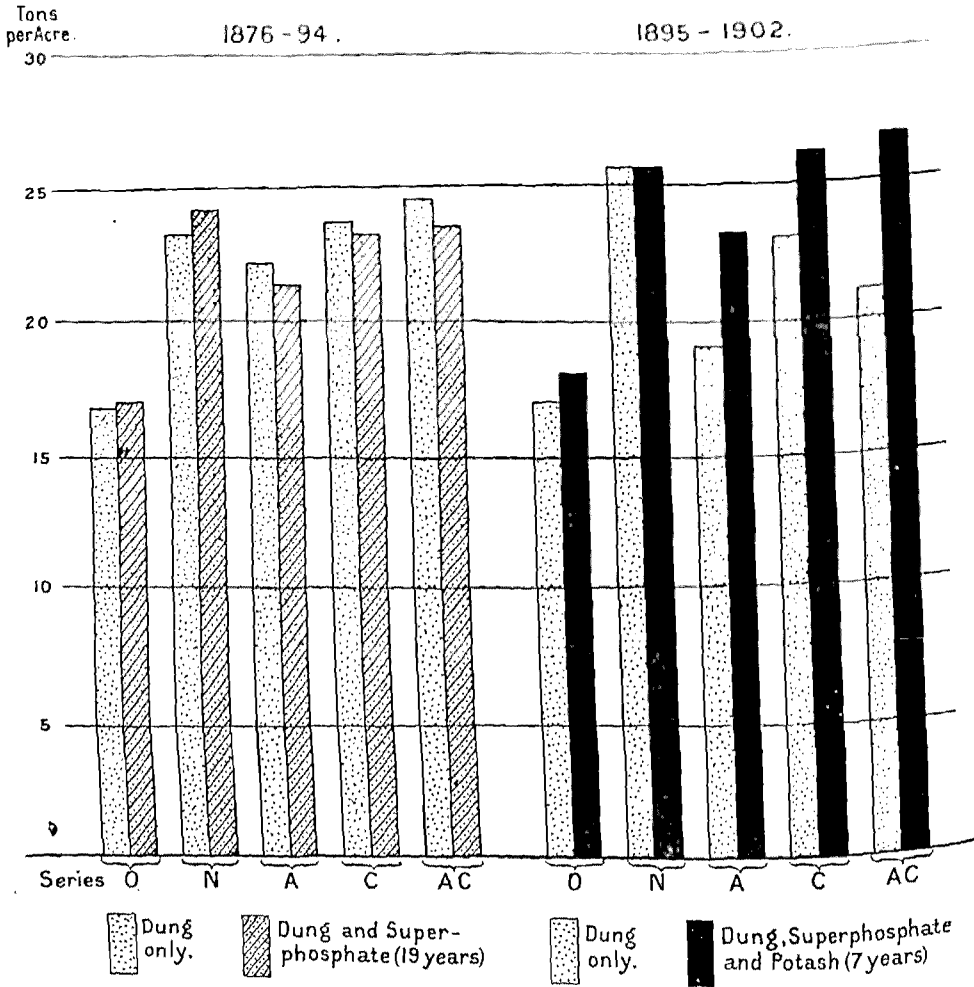


FIG. 16.—Mangolds. Effect of addition of Mineral Manure to Dung, with various Nitrogenous Cross-dressings. Average Produce of Roots per acre.

From this first period we can ascertain the effect of superphosphate as a supplement to dung. In the second period, which begins in 1895, sulphate of potash has been added to the superphosphate on Plots 2, so as to institute a comparison between the effect of dung alone and of dung in conjunction with potash and phosphates. The results are set out graphically in the accompanying diagram Fig. 16. The left-hand half of this diagram shows the first period, when dung is compared with dung and phosphates. The right-hand

half of the diagram refers to the second period, 1895-1902, when potash was being used on Plot 2.

The dotted columns in the diagram represent the crops on Plots 1, where no mineral manures are used with the dung; the cross hatched columns represent Plots 2, to which in the first period superphosphate was added; the black columns the same Plots 2 in the second period, when potash was also being employed. Each of the pairs of columns represents a different nitrogenous cross-dressing.

From the left-hand half it is evident that superphosphate when used with dung has produced no effect upon the crop during the nineteen years of the first period. With no other nitrogenous manures, or when nitrate of soda is used as a cross-dressing, there is a small increase from the use of superphosphate, but it seems to cause even a falling-off when added to ammonium-salts or rape cake and dung.

Turning now to the effect of sulphate of potash when added to dung, as represented by the right-hand diagram in Fig. 16, we find that the potash produces a very marked effect. During this last period the crops on Plots 2, receiving potash and phosphates, have been much superior to those on Plots 1, receiving dung alone; although in the earlier period, when phosphates but no potash were used on 2, the two series of plots were practically equal. The increase caused by potash is naturally most seen in Series O, A, C, and AC; in Series N, which is cross-dressed with nitrate of soda, much less benefit is seen for the addition of potash.

Considering the large amount of potash contained in dung, and the enormous residue which must have accumulated by the yearly application of 14 tons per acre for the last forty-seven years, the result is very striking, as showing the dependence of the mangold crop on an abundant supply of potash. The application of farmyard manure is generally considered to supply sufficient potash to remove the need for any further specific manuring with potash salts even to so potash-loving a crop as mangolds, but these experiments show that even when dung

has been applied continuously for a long time, the application of potash will still result in an increase of crop. The appearance of the crop is even more indicative of the value of the potash dressing; where it has been applied the crop is altogether healthier and ripper, especially where the excessive dressings of nitrogen have been used.

*E. Proportion of Root to Leaf.* At the time the crop is lifted the leaves are weighed, then they are spread upon the land to be ploughed in again.

The amount of leaf grown is almost wholly dependent upon the supply of nitrogen, and variations in the mineral manures have but little effect. When the growth is normal, the weight of leaf is about 20 per cent. of that of the root, and the more the alkaline salts, potash, soda, and magnesia are added in the manure, the more thorough is the maturation of the crop and the lower does the proportion of leaf become. The highest proportion of leaf to root is shown on those plots which receive a comparative over-supply of nitrogen, but no alkaline salts, potash, soda, or magnesia, to restore the balance of the constituents of the manure.

In good seasons when the crop of roots is large, the amount of leaf shows little corresponding increase, hardly more than would be accounted for by the comparative absence of blanks and missed plant which characterises a good season.

It is evident that when once the plant has developed a sufficiency of leaf, the difference between a good and a bad season depends upon the rapidity with which the leaves can do their work of carbon assimilation from the atmosphere, for all the products of that action are at once passed on to the root and stored there, in the case of the mangold chiefly in the form of sugar. A good season with a heavy yield of roots does not involve any greater luxuriance of leaf than usual, just as, in a similar manner, plots which grow a small crop of roots because of the absence of alkaline salts may yet possess a normal development of leaf.

*F. Proportion of the Nitrogen recovered in Crop to that*

supplied in Manure. In view of the large amounts of nitrogen applied in the manures, it is important to consider what proportion of each of the different nitrogenous compounds is recovered in the crop.

If the soil has suffered no loss of nitrogen, then the whole of the nitrogen removed in the crop must have been derived

TABLE XLII.—*Mangolds. Relation between the Nitrogen recovered in Crop and that supplied in Manure.*

Series.	Cross-Dressings.	Average Produce per acre of Roots.	Nitrogen.			
			Per cent. in Fresh Roots.	Per acre per annum in Roots.	Supplied in Manure per acre per annum.	Recovered in Roots for 100 in Manure.
Plots 4.—Superphosphate, Sulphates of Potash and Magnesia, and Common Salt.						
		Tons.	Per cent.	Lb.	Lb.	Per cent.
N	Nitrate of Soda, 550 lb. = 86 lb. N.	17·95*	0·164*	67·2	86	78·1
A	Ammonium-salts, 400 lb. = 86 lb. N.	15·12*	0·145*	49·3	86	57·3
AC	Rape Cake, 2000 lb. = 98 lb. N. and Ammonium-salts, 400 lb. = 86 lb. N.	24·91†	0·184†	103·0	184	56·0
C	Rape Cake, 2000 lb. = 98 lb. N.	20·95†	0·148†	69·4	98	70·9
Plots 1.—Farmyard Dung, 14 tons.						
O	None	17·44	0·162‡	63·3	200	31·6
N	Nitrate of Soda, 550 lb. = 86 lb. N.	24·74	0·209‡	115·8	286	40·5
A	Ammonium-salts, 400 lb. = 86 lb. N.	21·73	0·217‡	105·6	286	36·9
AC	Rape Cake, 2000 lb. = 98 lb. N. and Ammonium-salts, 400 lb. = 86 lb. N.	24·05	0·241‡	129·8	384	33·8
C	Rape Cake, 2000 lb. = 98 lb. N.	23·96	0·207‡	111·1	298	37·3

\* Average for 21 years, omitting 1876-7, 1885, 1895, 1901-2.  
 † Average for 22 years, omitting 1876-7, 1885, 1901-2.  
 ‡ Percentage calculated from 9 years, 1878-82, 1897-1900.

from the manure, and on that assumption the percentages given in the table above are calculated. In calculating the amount of nitrogen recovered each year no account has been taken of the leaves, because they are returned to the soil and their nitrogen is not removed from the land; if both leaf and root were taken into account the recovery of nitrogen for any single year would be very much greater; indeed in some seasons when a big crop is grown more nitrogen is removed in

the roots alone than was supplied in the form of manure. Table XLII. shows the nitrogen supplied and removed from Plots 4, where there was a full supply of mineral manures, and from Plots 1, where dung was used with nitrogenous manures.

The results show that both the nitrate of soda and the rape cake are very effective manures, about three-quarters of the nitrogen they supply each year being recovered in the roots removed from the land; the ammonium-salts, and ammonium-salts mixed with rape cake are less effective, the recovery being between 50 and 60 per cent. of that applied. On the plots receiving dung, the proportion of nitrogen recovered at once becomes very much less, sinking to about one-third of that supplied in the manure. It is known that there is a very large accumulation of nitrogen in the soil of these continuously dunged plots, though not sufficient to make up all the difference between the nitrogen supplied and that removed in the crop. Of the nitrogen unaccounted for, some has been washed as nitrate into the subsoil, and some liberated as nitrogen gas by the agency of bacterial changes.

Thus, when dung and nitrate are used, 115·8 lb. of nitrogen is recovered in the crop as compared with 63·3 lb. recovered from the dung when used alone; if we deduct the 63·3 lb., as due to the dung, from the 115·8 lb. we obtain 52·5 lb., which may be taken as the return from the nitrogen of the nitrate of soda when it is used in conjunction with dung. This amounts to 61 per cent. of the 86 lb. of nitrogen supplied, a proportion which compares favourably with the proportion recovered from nitrate of soda when used with a mineral manure only, if we take into consideration the fact that a much bigger crop is being grown with the two manures in conjunction than with either singly; and, as we have seen before, it is the smaller applications of manure which give the best proportionate returns.

These results, showing the large proportion of the nitrogen of nitrate of soda and other nitrogenous manures that is recovered, even when they are used in large amounts with

dung year after year on the same land, lend no colour to the opinion that in ordinary farming there is likely to be serious loss of nitrogen by "denitrification"\* when nitrogenous manures and dung are used together. The soil is probably always suffering losses of nitrogen in the gaseous state through various bacterial changes, and these losses will increase the higher the condition of the land becomes and the more nitrogenous bodies of an easily decomposable nature are present. But there is no evidence in the Rothamsted mangold experiments to support the view that specific and excessive loss will set in when dung and nitrate of soda, or other active nitrogenous manure, are used together.

G. *The Composition of the Mangold Crop as affected by Manuring.* In many of the years during which the mangolds have been grown, determinations have been made of the amount of sugar contained in the roots from the different plots, sugar being the chief constituent of the dry matter of the mangold and the main element in its value as food. Table XLIII. gives a summary of the results obtained in 1900 and 1902, years when crops were obtained above the average both in regularity and magnitude. In the various columns are set out the average weight of the roots, the proportions of dry matter and of sugar, both the glucose or reducing sugar and the more important cane sugar, also the dry matter and sugar in pounds per acre on each plot. Other columns give the quotient of purity, by which is meant the percentage of cane sugar in the dry matter, and the glucose coefficient or the relation per cent. of the glucose to the cane sugar.

It will be at once seen that the variations in the composition of the roots are small compared with the variations in the yield from plot to plot; the average weight of root varies from 0.71 to 3.95 lb., but the proportion of dry matter only fluctuates between 15.3 per cent. and 10.9 per cent. In the main the root grows as a whole from a very early stage, increasing in size but maintaining a fairly uniform composition.

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\* See p. 219.

If one or other element necessary to the nutrition of the plant be lacking, the root ceases to swell instead of altering its composition to meet the deficiency.

TABLE XLIII.—*Composition of Mangold Roots. Mean of two Seasons (1900 and 1902).*

Series and Plot.	Nitrogen per acre in Manure.	Average Weight of Roots.	Dry Matter.	Sugar.				Per acre.		
				Reducing.	Cane.	Quotient of Purity.	Glucose Co-efficient.	Dry Matter.	Total Sugar.	
	Lb.	Lb.	Per cent.	Per cent.	Per cent.			Lb.	Lb.	
O	1	200	2.44	13.37	0.34	8.64	64.6	3.9	6644	4292
	2	200	2.81	13.93	0.29	8.32	63.9	3.5	7217	4620
	4	...	0.74	14.89	0.23	9.78	65.7	2.4	2433	1579
	5	...	0.76	15.25	0.21	10.85	71.1	1.9	2801	1996
	6	...	0.71	15.30	0.23	11.02	72.0	2.1	2074	1505
	N	1	286	3.65	11.87	0.38	7.42	62.5	5.1	9833
2		286	3.95	11.65	0.42	6.47	55.5	6.5	9684	5370
4		86	3.16	11.77	0.23	7.64	64.9	3.0	7699	4972
5		86	2.47	11.87	0.42	7.10	59.8	5.9	6629	3973
6		86	2.69	12.47	0.26	7.76	62.2	3.4	7305	4519
A		1	286	2.89	11.40	0.25	6.87	60.3	3.6	6368
	2	286	3.22	11.90	0.25	7.09	59.6	3.5	8622	5112
	4	86	2.29	12.75	0.27	8.10	63.5	3.3	6487	4088
	5	86	1.10	12.69	0.17	7.79	61.4	2.2	2950	1791
	6	86	2.41	13.43	0.25	8.81	65.6	2.8	6877	4488
	AC	1	384	2.74	10.94	0.23	5.70	52.1	4.0	6294
2		384	3.59	11.83	0.24	6.30	53.3	3.8	9619	5101
4		184	3.72	11.60	0.25	6.74	58.1	3.7	9542	5449
5		184	1.30	11.86	0.18	6.85	57.8	2.6	3218	1835
6		184	3.07	11.70	0.26	7.08	60.5	3.7	8739	5257
C		1	298	2.86	11.87	0.33	7.29	61.4	4.5	7382
	2	298	3.29	13.04	0.28	7.92	60.7	3.5	9579	5801
	4	98	3.25	12.05	0.32	7.76	64.4	4.1	7997	5127
	5	98	1.25	12.84	0.25	7.95	61.9	3.1	3561	2193
	6	98	2.69	12.94	0.44	8.28	63.8	5.3	7700	4904

There are, however, certain differences in composition which, if not large, are regular, and brought about by the differences in manuring. Dealing with a series of roots which receive an ample supply of mineral constituents, as on Plots 2, 4, or 6, the size of the root and the proportion of water rise with each addition of available nitrogen. The smallest and richest roots are those grown without nitrogenous manure, the largest and most watery are those where nitrate of soda is used in conjunction with dung. The roots grown with ammonium-salts

or with rape cake as the source of nitrogen are less watery than those grown with nitrate of soda, rape cake producing the richest roots for their size. As regards its effect both on the magnitude and composition of the crop, 200 lb. of nitrogen in dung are less effective than 86 lb. in nitrate of soda or 98 lb. in rape cake, and have about the same value as 86 lb. of nitrogen in ammonium-salts.

It has already been noticed that the use of ammonium-salts promotes an earlier maturity than does nitrate of soda; this is seen in the generally higher "quotient of purity" of the "A" as compared with the "N" series. The glucose coefficient is correspondingly lower in the "A" series. Excess of nitrogen has the same effect as the substitution of nitrate of soda in lowering the quotient of purity and raising the glucose coefficient. For instance, Plot 2 N gives a quotient of purity of 55.5 as compared with 64.9 and 62.2 on Plots 4 N and 6 N, which receive the same mineral manures but not the extra nitrogen of the dung on Plot 2 N; similarly, the glucose coefficient is 6.5 on Plot 2 N and only 3.0 and 3.4 on 4 N and 6 N. Again, all the plots on the AC series, receiving both rape cake and ammonium-salts, show worse results as regards purity than the corresponding plots on either the A or the C series, which receive only one portion of the nitrogenous manure on series AC.

The dependence of sugar-formation upon potash is well seen by comparing the weights of sugar per acre produced on Plots 4 or 6, receiving potash, with the corresponding weights from Plot 5, without potash; or by comparing Plots 2, where dung, nitrogenous manures, phosphates, and potash are applied, with Plots 1, which receive dung and nitrogenous manures only. To this latter statement the nitrate Plots 1 and 2 afford an exception. As a rule, however, the percentage of sugar in the root is little if at all increased by the use of potash; the effect comes from the increased crop, and is apparent in the amount of sugar grown per acre. The quotient of purity is, however, better on Plots 4 and 6, with potash, than on Plots 5, without

potash; but this effect of potash in inducing the ripening of the mangold is not visible in the dunged plots.

Although the analyses which have been made of the nitrogenous constituents of mangolds are not yet wholly satisfactory, certain results are apparent.

As regards the total nitrogen, the proportion present in the root reflects the supply of nitrogen in the manure, and as the roots get larger and more watery with the use of nitrate of soda or any excess of nitrogenous manure, so also does the proportion of nitrogen rise in the substance of the root. As to the forms in which the nitrogen is combined: the proportion of nitrogen in the protein condition, whether soluble or insoluble, is at its highest in the plants which are nitrogen starved, and falls to its lowest point where nitrate of soda or any excess of other nitrogenous manures are used.

The amides are also at their highest on the plots which show immaturity because of the use of large quantities of nitrogen, and especially of nitrate of soda; on the contrary, the use of potash at once diminishes the proportion of amides. The proportion of nitrates present is less affected by the manuring, but it is highest when an excessive amount of nitrogenous manure is used, or when nitrate of soda supplies the nitrogen in the manure, and is usually diminished by the use of a free supply of potash.

Speaking generally, then, it will be seen that though the composition of mangolds is not greatly influenced by manuring, yet certain factors go together. Highly nitrogenous manure, especially when the nitrogen is in the form of nitrate of soda, produce large and watery roots, whose immaturity is reflected in the low quotient of purity, the high glucose coefficient, the high content of nitrogenous matters, of which again a large proportion is in the form of amides and nitrates. If the nitrogen is in excess and the mineral manures are deficient these differences are intensified, whereas an abundant supply of potash tends to produce a more normal root.

## PRACTICAL CONCLUSIONS

Looking at the results of the experiments at Rothamsted on the continuous growth of mangolds with various manures for over forty years, from the point of view of the practical farmer the following general conclusions can be drawn :—

1. Mangolds can be grown continuously on the same land without injuring the tilth of the land or the health of the crop.
2. A liberal dressing of farmyard manure forms the best basis of the manure for mangolds.
3. The crop will further respond to considerable additions of active nitrogenous manures to the dung, particularly of nitrate of soda.
4. A free supply of potash salts is essential to the proper development of the mangold, hence a specific potash manuring is desirable even when dung is used in large quantities, and on a strong soil initially rich in potash. When nitrogenous manures are used in addition to dung, the potash salts should be increased *pro rata*, in order to maintain the health and feeding value of the crop and to bring it to maturity.
5. Superphosphate or other phosphatic manure is less necessary with dung, especially when the crop is grown in rotation.
6. Since soluble alkaline salts are beneficial to the mangold crop, either as direct foods or as economisers of potash, a dressing of salt should always be included among the manures for the mangold crop.

## II.—EXPERIMENTS UPON TURNIPS, BARN FIELD, 1843-70.

The experiments upon turnips may be divided into four series, the two earlier dealing with Norfolk white turnips, the two later with Swedes. The chief difference between these two crops lies in the greater proportion of leaf and the more watery nature of the white turnip.

It will not be necessary to give the results obtained in the first trial 1843-5, but the three later experiments were set out

on practically the same lines as have been maintained for the mangold crop to-day, and are summarised in Table XLIV.

These results show the great dependence of the turnip crop upon the supply of a phosphatic manure like superphosphate, whereas there seems but little need of any external supply of alkaline salts when turnips are growing on a soil like that of Rothamsted. The crop was increased by each addition of nitrogen, but the increase was not large, and affected the leaf more than the root. Until the soil had become depleted of its available nitrogenous compounds by repeatedly growing the crop without any application of nitrogen, superphosphate alone without any nitrogenous manure gave rise to a comparatively good crop. The value of superphosphate as a manure for Swedes and turnips of all kinds was found to lie in the extended root-development it induced, especially when the plant was young. It was from these early experiments that agriculturists first learnt how essential were phosphatic manures to the growth of turnips, and the fact that the manure for turnips should consist of superphosphate in the main with but little nitrogenous manure, soon passed into the common stock of farming knowledge and is universally acted upon to-day. At the same time the success of superphosphate manuring for Swede and turnip crops led to an enormous development of the manufacture of superphosphate from mineral phosphates, which was then beginning under the patents taken out by Lawes.

In the earlier years but little return was obtained for potash manures, but as the plots continued to be cropped with nitrogen and phosphoric acid but without potash, the soil became gradually depleted of available potash and the potash manures began to show large effects.

As has already been mentioned, it was soon found necessary to discontinue the attempt to grow Swedes year after year on the same land. The soil at Rothamsted is not very well suited to the crop, being heavy and awkward to work, and in consequence of the use of saline manures and the restricted

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TABLE XLIV.—*Turnips grown in Barn Field, Rothamsted. Produce of Roots per acre per annum.*

Strip.	Strip Manures.	Cross-Dressings.				
		O.	N.	A.	AC.	C.
		None.	Nitrate of Soda.*	Ammonium-salts.	Amm. salts and Rape Cake.	Rape Cake.
<b>Norfolk White Turnips, 4 seasons (1845-48).</b>						
	Nitrogen per acre in Cross-Dressings . . . . .	Lb. . . . .	Lb. . . . .	Lb. 45	Lb. 135	Lb. 90
3	Gypsum, 1845; afterwards Unmanured (av. 1846-47-48) Superphos. each year; Pot., Sod., and Mag., 1847-48 Superphosphate . . . . . Superphos. each year; and Potash in 1847-48 . . . . .	Cwt. 24	Cwt. . . . .	Cwt. 27	Cwt. 110	Cwt. 131
4		161	. . . . .	195	205	222
5		176	. . . . .	198	201	218
6		160	. . . . .	196	207	217
7						
<b>Swedes, 4 seasons (1849-52).†</b>						
	Nitrogen per acre in Cross-Dressings . . . . .	Lb. . . . .	Lb. . . . .	Lb. 43	Lb. 141	Lb. 98
3	No Standard Manure, 1846 and since Superphos., Sulphates Pot. and Mag., and Soda-ash Superphosphate . . . . . Superphosphate and Sulphate Potash . . . . .	Cwt. 46	Cwt. . . . .	Cwt. 77	Cwt. 140	Cwt. 154
4		157	. . . . .	189	261	247
5		149	. . . . .	174	224	210
6		136	. . . . .	174	248	234
7						
<b>Swedes, 5 years (1856-60).‡</b>						
	Nitrogen per acre in Cross-Dressings . . . . .	Lb. . . . .	Lb. 43	Lb. 43	Lb. 51	Lb. 8
1	14 tons Farmyard Dung . . . . . Do. and Superphosphate . . . . . No Standard Manure, 1846 and since Complete Mineral Manure . . . . . Superphosphate . . . . . Superphosphate and Sulphate Potash . . . . . Superphos., Sulph. Pot., and 36½ lb. Amm.-salts . . . . . No Standard Manure, 1853 and since . . . . .	Cwt. 145	Cwt. 156	Cwt. 190	Cwt. 181	Cwt. 127
2		155	152	191	171	119
3		17	24	21	30	24
4		106	124	130	134	95
5		96	123	103	119	86
6		82	103	129	128	91
7		100	116	143	152	111
8		39	48	34	46	59
<b>Swedes, 10 years (1861-70).</b>						
	Nitrogen per acre in Cross-Dressings . . . . .	Lb. . . . .	Lb. 86	Lb. 86	Lb. 184	Lb. 98
1	14 tons Farmyard Dung . . . . . Do. and Superphosphate . . . . . No Standard Manure, 1846 and since Superphos. only; previously Complete Minerals Superphosphate . . . . . Do.; previously Sulph. Potash also Do.; previously Sulph. Pot., and 36½ lb. Amm.-salts also No Standard Manure, 1853 and since . . . . .	Cwt. 143	Cwt. 177	Cwt. 194	Cwt. 210	Cwt. 202
2		143	183	190	210	198
3		11	21	13	89	95
4		52	115	100	158	134
5		49	103	81	138	124
6		45	105	88	150	126
7		49	104	95	156	130
8		22	35	23	104	93

\* In the 5 years (1856-60) the Nitrogen was applied as Nitric Acid mixed with sawdust.  
 † No Cross-Dressings applied in 1861 or 1852.  
 ‡ Average produce of 8 years only (1856-55), as the crops of 1859 and 1860 failed.

root-range of the plant, a satisfactory tilth on some of the plots became so difficult to establish that a good plant rarely resulted.

### PRACTICAL CONCLUSIONS

1. The experiments show that Swedes and white turnips cannot be grown repeatedly on the same land, or even at short intervals.

2. The manuring for Swedes must be liberal, as the yield is much more quickly affected by poverty or exhaustion in the soil than is the case with the other crops of the farm.

3. Although under favourable conditions Swedes can be grown with artificial manures only, yet they are so dependent on a good tilth and on the retention of moisture in the surface soil that the manuring should begin with an application of farmyard manure, unless the land is already in high condition.

4. Since Swedes grow at a warm time of the year and receive much cultivation of the soil, nitrification is active and the crop does not require a large amount of nitrogenous manure. In the absence of dung, about 2 cwt. per acre of some nitrogenous manure like fish guano or rape dust, together with 1 cwt. per acre of sulphate of ammonia, will be sufficient. When dung is used, the latter only is necessary. For the shallow-rooting Swede crop sulphate of ammonia appears to be a better manure than nitrate of soda.

5. The phosphatic manuring is most important, and should consist of 3 to 5 cwt. of superphosphate or an equivalent of basic slag in the case of strong soils. Only on the lighter soils will potash be required; about 3 cwt. of kainit per acre in the winter may then be used.

### III.—EXPERIMENTS ON THE CONTINUOUS GROWTH OF POTATOES ON THE SAME LAND, HOOS FIELD, 1876-1901.

These experiments were commenced in 1876, and went on for twenty-six seasons until 1901. The varieties grown were —“Rock,” four years; “Champion,” eleven years; “Sutton’s

Abundance," five years; "Bruce," one year; and "White Beauty of Hebron," 1897-1901. The question was not as to the comparative merits of different varieties, but different sorts were selected on the supposition that in growing the crop year after year a change was desirable, especially with a view to the avoidance or lessening of disease. The special object was to ascertain the manurial requirements of the crop and the comparative character and composition of the produce. Table XLV. gives the details of the manuring and the average produce for the whole period of twenty-six years.

TABLE XLV.—Potatoes, average yield per acre over 26 years (1876-1901).

Plot.	Manures per acre per annum.							Average Produce per acre.				Per cent. Diseased in Total.
	Farmyard Dung.	Ammonium-salts.	Nitrate of Soda.	Sulphate of Potash.	Sulphate of Soda.	Sulphate of Magnesia.	Super-phosphate.	Good.	Small.	Diseased.	Total.	
	Tons.	Lb.	Lb.	Lb.	Lb.	Lb.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Per cent.
1	...	...	...	...	...	...	...	22.7	3.8	0.9	27.4	3.3
2	(14)*	...	...	...	...	...	...	47.5	4.7	2.6	54.8	4.7
3	14	...	...	...	...	...	†	82.6	4.7	7.8	95.1	8.2
4	14	...	+	...	...	...	†	87.4	4.6	10.2	102.2	10.0
5	...	400	...	...	...	...	...	27.9	4.7	1.4	34.0	4.1
6	...	...	550	...	...	...	...	36.2	4.3	2.0	42.5	4.7
7	...	400	...	300	100	100	3.5	93.5	5.1	7.1	105.7	6.7
8	...	...	550	300	100	100	3.5	96.4	4.8	7.5	108.7	6.9
9	...	...	...	...	...	...	3.5	48.3	4.2	1.9	54.4	3.5
10	...	...	...	300	100	100	3.5	52.3	3.9	2.0	58.2	3.4

\* Applied in the first 6 years only (1876-81).  
 † 3.5 cwt. Superphosphate also in the first 7 years (1876-82).  
 ‡ 550 lb. Nitrate of Soda also in the first 6 years (1876-81).

The crop was grown continuously without manure, with various artificial manures, and also with farmyard manure, both alone and with some artificial manures. There were ten differently manured plots, and under each of the ten conditions the crop more or less declined over the later compared with the earlier years. The average produce per acre of total tubers over the twenty-six years was—without manure, only 27.4 cwt.; with ammonium-salts alone, 34.0 cwt.; with nitrate of soda alone, 42.5 cwt.; with superphosphate alone, 54.4 cwt.;

with mixed mineral manure, including potash, 58·2 cwt. Thus, purely nitrogenous manures yielded less than purely mineral manures, indicating that the potato finds a difficulty in obtaining ash constituents rather than nitrogen from an impoverished soil.

By superphosphate of lime alone the produce was raised from an average of 27·4 to 54·4 cwt. ; and by a mixed mineral manure containing besides superphosphate of lime, salts of potash, soda, and magnesia, to 58·2 cwt. ; that is to very little more than by the superphosphate alone. It is clear that as regards the small crops in question the land is still able to supply sufficient available potash when it has become comparatively exhausted of the phosphoric acid which can reach the crop.

In reference to this increase of produce of potatoes by mineral manures alone, it may be observed that the result is quite consistent with that obtained with other root-crops having comparatively shallow root-development ; and in such cases the source of the nitrogen is chiefly the store of it in the surface soil. The beneficial effects of mineral manures, and especially of phosphates, are indeed observed generally with all crops which are spring sown and have but a short period of growth, so that they possess a comparatively superficial root system, and are therefore forced to rely much on the stores of food in the surface soil only.

It is remarkable that there is much less increase of produce of potatoes by nitrogenous manures alone than by mineral manures alone. Thus by ammonium-salts alone there is an average produce of 34 cwt., or only between 6 and 7 cwt. more than without manure ; and with nitrate of soda alone there is an average of only 42·5 cwt. per acre.

With the mixed mineral manure and ammonium-salts together, the average produce of total tubers was 105·7 cwt., and with the mixed mineral manure and nitrate of soda, 108·7 cwt. per acre. The better result from the nitrate of soda is doubtless due to its nitrogen being more immediately available

and more rapidly distributed within the soil, thus inducing a more extended development of feeding root. The average produce by the mineral and nitrogenous manures together, over twenty-six years of continuous growth, was very nearly that of the estimated average produce of Great Britain under ordinary cultivation, and much more than that of Ireland.

The plots receiving farmyard manure, containing about 200 lb. of nitrogen, gave less produce than the mixture of mineral manure and ammonium-salts or nitrate of soda, supplying only 86 lb. of nitrogen. In fact, only a small proportion of the nitrogen of farmyard manure is rapidly available, that due to undigested matter being more slowly available, and that in the litter remaining for a long time inactive. Farmyard manure is, however, often applied in very large quantities for potatoes, the process being to a great extent one of forcing, after which remains a great amount of unexhausted manure-residue within the soil.

The characteristic effect of nitrogenous manures, provided there be a sufficient available supply of ash-constituents, and especially of potash, is to increase the amount of the non-nitrogenous substance—starch, in the tubers. Thus, the produce of starch per acre was about 650 lb. without manure, about 1350 lb. with purely mineral manure, and with nitrogenous and mineral manures together about 2500 lb., or rather more than 1 ton. In other words, the increased produce of starch by the use of mineral and nitrogenous manures together was more than  $\frac{3}{4}$  ton per acre.

Since we know that a free supply of potash is essential to the production of any carbohydrate like starch, it might have been expected that a bigger crop and an increased production of starch would be obtained from Plot 10, receiving a complete mineral manure containing potash, than from Plot 9 which receives superphosphate only. There is, however, practically no difference in the yield from the two plots; in the absence of nitrogen and the exhaustion of the soil of its available supplies of this constituent, the small crops grown could always obtain

a sufficient quantity of potash from the soil, as may be seen from the fact that while the unmanured crop withdrew about 21 lb. of potash per acre per annum from the soil, the addition of superphosphate on Plot 9 raised this to 51 lb., and the further addition of potash salts and other alkaline salts to Plot 10 only increased the amount annually withdrawn to 54 lb. Clearly the soil, which is known to have been originally well stocked with potash and also to contain considerable residues from potash manurings previous to this experiment, could from its own resources supply ample potash for the requirements of a crop averaging no more than 2 to 3 tons per acre. Where, however, big crops of potatoes are grown with the aid of dung and artificial manures, it is well known that an abundant supply of potash salts is essential both to the yield and the quality of the potatoes.

It is well known that season has much to do with the development of potato disease; and there was on the average much more disease in the wetter seasons. As regards the influence of manure, the proportion of diseased tubers was the least where there was no supply of nitrogen; that is, where there was the least luxuriance, the most restricted growth, and where the ripening was early developed. On the other hand, with liberal supply of nitrogen and luxuriant growth there was the greatest proportion of diseased tubers; these being the conditions resulting in a juice relatively rich in nitrogenous and mineral matters.

#### PRACTICAL CONCLUSIONS

1. The best basis for the growth of potatoes is a supply of well-rotted farmyard manure, 12 to 15 tons per acre. In the absence of farmyard manure it should be replaced by some manure containing organic nitrogen, *e.g.*, by 5 cwt. per acre of a good Peruvian guano, or by a meat or fish manure, or by 10 cwt. per acre of shoddy.

2. A free supply of ash-constituents is essential to the successful growth of the potato; 3 cwt. of superphosphate

and 1 to 1½ cwt. of sulphate of potash per acre should be sown in the drills before the seed is planted. If kainit is used as a source of potash, it should be sown broadcast some time before the land is got ready for planting.

3. A little active nitrogen is generally also needed, 1 cwt. of nitrate of soda as a top-dressing when the haulm is growing or 1 cwt. sulphate of ammonia with the other manures at planting time will be sufficient.

#### IV.—EXPERIMENTS ON THE GROWTH OF SUGAR-BEET.

##### A. *First Series*, 1871-1875.

The experiments made at Rothamsted with sugar-beet were commenced in 1871 and continued for five years in succession to 1875 inclusive. They were conducted on the land which had been devoted to the continuous growth of root-crops (Norfolk Whites and Swedes) from 1843 to 1870; excepting that in the three years 1853-55 barley had been grown without manure to equalise the condition of the plots as far as possible before re-arranging them and the manuring.

During the first three of the five years of sugar-beet the arrangement of the plots and of the manures was substantially the same as during the preceding ten years with Swedish turnips and the subsequent years with mangolds. But during the last two years of the five, neither farmyard nor any other nitrogenous manure was applied; the object being to determine the effects of the unexhausted residue of the nitrogenous application during the preceding three years. The description of sugar-beet grown was Vilmorin's "Green-top White Silesian." In 1871 the seed was dibbled on ridges in rows 26 inches apart, and 10 inches from plant to plant in the rows; in 1872 and subsequently it was dibbled on the flat, in rows 22 inches apart, and 11 inches apart in the rows; the plants being moulded up afterwards. The roots were all carted off and weighed; the leaves were weighed, spread on the respective plots, and ploughed in.

## EXPERIMENTS UPON ROOT-CROPS

Table XLVI. shows, for selected plots, the manuring, the average produce of root and of leaf, the average percentages of nitrogen and of mineral matter in the dry matter of the roots, and the average percentages and amounts per acre of sugar in the roots, over the three years 1871-73 during which the farmyard manure and the nitrogenous cross-dressings were annually applied.

TABLE XLVI.—*Sugar-Beet. Average produce of Roots, and Sugar per cent. and per acre in the Roots, 3 years (1871-73).*

Plot.	Standard Manures.	O. Standard Manures only.	Standard Manures and Cross-Dressings each year as under.			
			N. Nitrate of Soda, 550 lb. = 86 lb. N.	A. Ammonium-salts, 400 lb. = 86 lb. N.	AC. Ammonium-salts, 400 lb. = 86 lb. N., and Rape Cake, 2000 lb. = 98 lb. N.	C. Rape Cake, N. 3000 lb. = 98 lb. N.
Produce of Roots per acre.						
		Tons.	Tons.	Tons.	Tons.	Tons.
1	Farmyard Manure (14 tons) . . .	16·3	23·8	22·3	25·1	24·9
5	Superphosphate alone . . .	5·9	19·5	13·4	17·7	16·2
4 & 6	Superphos. and Sulphate of Potash . .	5·9	18·8	14·9	22·1	17·8
Sugar per cent. in the Roots.						
		Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1	Farmyard Manure (14 tons) . . .	11·84	10·42	10·84	9·99	10·81
5	Superphosphate alone . . .	13·08	10·66	11·88	9·89	12·17
4 & 6	Superphos. and Sulphate of Potash . .	12·97	11·04	12·16	10·66	12·07
Sugar per acre in the Roots.						
		Lb.	Lb.	Lb.	Lb.	Lb.
1	Farmyard Manure (14 tons) . . .	4309	5508	5413	5630	5976
5	Superphosphate alone . . .	1731	4661	3563	3886	4407
4 & 6	Superphos. and Sulphate of Potash . .	1704	4635	4063	5279	4788

It will be seen that the nitrogenous cross-dressings, which were the same as those before and subsequently adopted for feeding roots, were very heavy; indeed, much heavier than is recognised as suitable in the case of beet grown for the production of sugar. The result was that when these were used

in addition to farmyard manure, the produce of roots per acre was large, in some cases about twice as much as that obtained in the growth of sugar-beet for the manufacture of sugar in Germany or France at the present time.

The figures in the table for Plot 1 show, however, that when farmyard manure was used the amount of sugar in the roots never reached 12 per cent.; but it was the highest, 11.84 per cent. on Plot 1 O, with the farmyard manure alone, and the smallest crop; it was lowest, 9.99 per cent. on Plot 1 AC, with the farmyard manure and the heaviest nitrogenous cross-dressing, and the heaviest crop. The roots of the other series, with intermediate amounts of crop, had also intermediate percentages of sugar—namely, 10.42, 10.84, and 10.81. Further, the crop grown with the farmyard manure alone, which had the highest percentage of sugar in the roots, had the smallest amount and proportion of leaf, and the smallest percentages of both nitrogen and mineral matter in the dry matter of the roots; whilst the crop yielding the highest produce, but the lowest percentage of sugar in the roots, had the highest proportion and amount of leaf (9 tons 12 cwt. per acre), and the highest percentages of nitrogen and of mineral matter in the roots, conditions indicating immaturity.

The results next recorded in the table (Plots 4, 5, and 6) show the amounts of roots and of sugar obtained with artificial mineral manures, both when used alone and with the nitrogenous cross-dressings.

The figures further show that there was a greater produce in the case of three out of the four cross-dressings where potash was used as well as superphosphate; but that the omission of potash was without effect where nitrate was used as the source of nitrogen.

The result with potash is fully established in other experiments; namely, that a liberal supply of it tends to maturation, a condition favourable for the production of sugar.

The percentage of sugar in the roots is, with one exception,

considerably higher where the mineral manures were used than where farmyard manure was employed, whether alone or with the cross-dressings. With the mineral manures used alone, and less than 6 tons of roots produced, there was in one case rather over, and in the other very nearly, 13 per cent. of sugar in the roots; and in several other cases there was nearly, or over, 12 per cent.

The lowest percentage of sugar comes where the very excessive cross-dressing of 184 lb. of nitrogen was employed; the nitrate of soda produces almost as bad a result, and in both cases the sugar is lowest where potash is omitted and only superphosphate is supplied with the nitrogenous manure. The best results, as to proportion of sugar, come where rape cake or ammonium-salts are used as sources of nitrogen and where potash is also supplied. The amount of nitrogen and of mineral matter in the roots was found to vary in the opposite sense, being at the highest where the sugar was lowest, and *vice versa*.

It is quite evident from these results, that the amount of crop grown depends very largely upon the amount of nitrogen available within the soil; but that with crops forced beyond a certain moderate limit of produce, the proportion of leaf is unduly large, the percentages of nitrogen and of mineral matter in the root are relatively high, and the percentage of sugar is objectionably low; all these conditions indicating too much luxuriance and defective maturity at the time of taking up the crop.

#### B. *Second Series, 1898-1901.*

The conditions under which the sugar-beet was grown in the first series were so different from those which prevail when the crop is grown for sugar-making that a second series was begun in 1898, when much smaller amounts of nitrogen were employed and the plants were grown more closely together.

The land was a portion of the mangold field which had previously been receiving dung. It was subsoiled and well

worked before the trials began, so that it was in good farming condition. The seed (Vilmorin's White Green-top Brabant) was sown in rows 17 inches apart, with 8 inches apart in the rows.

The following Table (XLVII.) shows the average results for the four years 1898-1901.

TABLE XLVII.—*Sugar-Beet, Second Series. Average produce per acre, and Sugar per cent. and per acre in the Roots, 4 years (1898-1901).*

	Plot 9-1. Basic Slag, 400 lb., and Sulphate Potash, 500 lb.	Plot 9-2. As 9-1, and 2 cwt. Sulphate Ammonia.	Plot 9-3. As 9-1, and 272 lb. Nitrate Soda.
Roots per acre (as carted) . . . . . Tons	12·8	14·6	14·0
Leaf do. . . . . Tons	4·5	5·9	6·5
"Cleaned and Trimmed" Roots per acre . . . Tons	11·7	13·3	12·7
Sugar per cent. in "Cleaned and Trimmed" Roots per cent.	14·11	13·53	13·63
Sugar per acre . . . . . Lb.	3693	4099	3938

The results go to show that the land was initially in very good condition, for very little increase of root is produced by the use of the nitrogenous manures. Even in the fourth year of the experiment the plot receiving no nitrogen still grew nearly 13 tons of roots; the nitrate produced no increase, and the sulphate of ammonia an increase of 1 ton only. As a nitrogenous manure, sulphate of ammonia was more effective than nitrate of soda; this is never the case with mangolds, but the sugar-beet, growing smaller and more closely planted roots than the mangolds, does not search the ground so deeply, and derives more benefit from a manure like sulphate of ammonia, which is held up near the surface. The proportions of sugar obtained were not in any case high, and considering that no very large crops were grown, the amount of sugar produced and the low quotient of purity were disappointing. Probably the land is too heavy and its situation too high and exposed for a good result to be expected, save in rather exceptional seasons.

## PRACTICAL CONCLUSIONS

1. As the value of sugar-beet depends so much on its purity, it should be grown rather on land in high condition from previous manuring than enriched by the direct application of manures. If farmyard manure has not been used for the previous crop a fair dressing should be given for sugar-beet, but it should be ploughed in during the autumn before sowing.

2. Just before sowing the seed, 3 cwt. of superphosphate, 1 cwt. sulphate of potash, and 1 cwt. of sulphate of ammonia per acre, should be applied and harrowed in. Nitrate of soda is not so desirable a manure for sugar-beet as it is for mangolds.

3. The high quality of the crop will much depend on the thorough and deep cultivation of the soil before sowing, and on planting very closely as compared with mangolds.

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## CHAPTER VIII

### EXPERIMENTS UPON THE CONTINUOUS GROWTH OF LEGUMINOUS CROPS

- I. The Continuous Growth of Beans on the same land, Geescroft Field.
  - II. The Continuous Growth of Red Clover on ordinary Arable Land, Hoos Field.
  - III. The Continuous Growth of Clover on Rich Garden Soil.
- References.

#### I.—THE CONTINUOUS GROWTH OF BEANS ON THE SAME LAND, GEESCROFT FIELD.

FROM the outset of the Rothamsted Experiments repeated attempts have been made to grow leguminous crops year after year on the same land. The particular importance of these attempts comes from the special position occupied by the leguminous plants. It is well known that ordinary farming experience considers that the land requires a "rest" before the growth of any of these crops is repeated. Satisfactory crops of clover are rarely obtained except at intervals of four years, and on many soils even six or seven years must elapse before the growth of clover can be renewed with any prospect of success. Not only does land become "clover sick," but the farmer considers it will equally become bean or pea "sick"; even lucerne, though it stands without failure for five or six years or more, rarely succeeds when re-sown immediately after the removal of a previous crop of the same kind. The leguminous crops of course contain far greater amounts of nitrogen than any others, but it is now known that the greater part of this is obtained from the atmosphere, so that the

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ground, instead of being impoverished, is actually enriched by the residues left behind after the growth of some of these crops.

In the Geescroft field, which is no longer under experiment, and where the land lies wetter than in any of the other Rothamsted fields, trials with beans began in 1847 and were continued with several years of failure until 1878, when they were finally abandoned. Table XLVIII. shows a summary of the crops obtained under the three conditions of no manure, mineral manures only, and a complete manure containing minerals and nitrogen; the nitrogen was applied at first as ammonium-salts, which, because of their ineffectiveness, were afterwards replaced by nitrate of soda.

It will be apparent from the table that the mineral manures containing potash were the most effective factor in promoting the growth of the beans, the addition of nitrogenous manure producing little or no increase in the crop. The crop shows a continual deterioration, but this is more apparent in the failures of the plant than in the diminution of the crop whenever a plant could be obtained; the crops of 1874 and 1875, for example, being only exceeded a few times during the whole course of the experiments, though it should be observed that these crops followed three years during which the land lay completely fallow.

The difficulty of obtaining a plant which characterised the later years of the experiment cannot, however, be wholly attributed to what might be termed bean "sickness," for the tilth of the land had deteriorated considerably through the repeated growth of a shallow-rooted crop. The use of nitrate of soda and other saline manures had also a bad effect on the texture of this soil, and from the combination of these causes it acquired a close and unfavourable condition, with a comparatively impervious pan in the subsoil below.

The whole evidence points, however, to the land becoming gradually unsuited to the growth of beans, independently of the deterioration of the tilth of the soil.

After the experiments with beans ceased in 1878 the land was left fallow until 1883, when barley was grown and clover

TABLE XLVIII.—Beans grown year after year on the same land, Geescroft Field, Rothamsted. Results, without Manure, with Mineral Manure, and with Mineral and Nitrogenous Manure. Produce per acre, each year, in lbs.

Years.	Total Corn.			Total Straw.			Total Produce (Corn and Straw).		
	Unmanured.	Mixed Mineral Manure (including Potash).	Mixed Mineral Manure and Nitrogen.*	Unmanured.	Mixed Mineral Manure (including Potash).	Mixed Mineral Manure and Nitrogen.*	Unmanured.	Mixed Mineral Manure (including Potash).	Mixed Mineral Manure and Nitrogen.*
	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
1847	1611	1697	1746	2125	1959	2185	3736	3656	3931
1848	1390	1831	2048	1269	1532	1730	2659	3363	3778
1849	2173	(2390)	2250	1641	†	1743	3314	†	3993
1850	1071	1432	1679	1070	1312	1441	2141	2744	3120
1851	2074	3315	3554	1920	3279	3568	3994	6594	7122
1852	697	855	1007	820	1286	1541	1517	2141	2548
1853	260	462	555	489	802	992	749	1264	1547
1854	365	1423	1266	394	1272	1133	759	2695	2399
1855	987	956	889	770	828	788	1757	1784	1677
1856	755	1627	1568	808	1914	1900	1563	3541	3468
1857	732	660	648	676	644	636	1408	1304	1284
1858	126	640	612	654	1392	1300	780	2032	1912
1859	142	352	401	196	416	498	338	768	899
1860	Fallow	...	...	...	...	...	...	...	...
1861†	(2156)	(2434)	(2509)	(3869)	(4596)	(4742)	(6025)	(7030)	(7251)
1862	513	1014	1479	930	2256	3064	1443	3270	4543
1863	Fallow	...	...	...	...	...	...	...	...
1864	133	1672	1837	960	2568	2468	1093	4240	4305
1865	261	514	1296	704	1080	2180	965	1594	3476
1866	142	316	914	317	628	1190	459	944	2104
1867	49	381	604	280	1252	1360	329	1633	1964
1868	48	384	478	533	930	1203	581	1314	1681
1869	106	926	1303	338	1394	1607	444	2320	2910
1870	458	450	615	516	483	533	974	933	1148
1871	Failed	...	...	...	...	...	...	...	...
1872	Fallow	...	...	...	...	...	...	...	...
1873	Fallow	...	...	...	...	...	...	...	...
1874	1259	1899	2087	944	1328	1568	2203	3227	3655
1875	1193	882	1114	1674	1988	2576	2367	2870	3690
1876	Fallow	...	...	...	...	...	...	...	...
1877	674	1974	1685	722	1809	1533	1396	3783	3218
1878	148	949	1108	301	1216	1496	449	2165	2604

\* 5 years (1847-1861), 46 lb. Nitrogen as Ammonium-salts; 11 years (1862, 1864-1870, 1876, 1878, and 1878), 86 lb. Nitrogen as Sodium Nitrate.  
 † Accidentally not weighed. ‡ Wheat.

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TABLE XLVIII.—Continued.

Years.	Total Corn.			Total Straw.			Total Produce (Corn and Straw).		
	Unmanured.	Mixed Manure (including Potash).	Mixed Mineral Manure and Nitrogen.*	Unmanured.	Mixed Mineral Manure (including Potash).	Mixed Mineral Manure and Nitrogen.*	Unmanured.	Mixed Mineral Manure (including Potash).	Mixed Mineral Manure and Nitrogen.*
Average per acre per annum, over each period of 8 years, and the total period of 32 years.									
8 years (1847-1854) .	Lb. 1205	Lb. 1573†	Lb. 1763	Lb. 1216	Lb. 1635†	Lb. 1792	Lb. 2421	Lb. 3208†	Lb. 3555
8 years (1855-1862) .	676	960	1013	988	1506	1616	1664	2466	2629
8 years (1863-1870) .	150	580	831	456	1042	1317	606	1622	2198
8 years (1871-1878) .	409	713	749	455	793	897	364	1506	1646
32 years (1847-1878) .	610	937‡	1102	779	1231‡	1405	1389	2168‡	2507
Average per acre per annum, over the years of crop only, each period.									
1st 8 years, 8 crops	1205	1573§	1763	1216	1635§	1792	2421	3208§	3555
2nd 8 years, 7 crops	773	1097	1153	1129	1721	1847	1902	2818	3005
3rd 8 years, 7 crops	171	663	1007	521	1191	1506	692	1354	2513
4th 8 years, 4 crops	819	1426	1499	910	1585	1793	1729	3011	3292
32 years, 26 crops	751	1162	1356	958	1526	1730	1709	2688	3086

\* 6 years (1847-1861), 40 lb. Nitrogen as Ammonium-salts; 11 years (1862, 1864-1870, 1875, 1876, and 1878) 86 lb. Nitrogen as Sodium Nitrate.  
 † 7 years, excluding 1840.  
 ‡ 81 years, excluding 1840.  
 § 7 crops, excluding 1840.  
 || 26 crops, excluding 1840.

sown in the barley. From the first the clover grew luxuriantly, and in 1884 and again in 1885 a large crop was obtained.

The following Table (XLIX.) shows the yield of dry matter and the quantity of nitrogen it contained, taking an average of the three plots which had been differently manured during the times the beans occupied the ground. Analyses of the soil had also been made before and after the clover was sown, and from these it is seen that the soil, which was somewhat impoverished in nitrogen after the continuous growth of beans, gained a considerable amount of nitrogen during the years of clover, notwithstanding the large quantities removed in the clover.

In this case the land showed no reluctance to grow clover,

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another leguminous crop, after it had become "sick" through the long-continued growth of beans; there is other evidence, however, that the growth of one leguminous crop renders the soil less fitted to carry another, even of a different species.

TABLE XLIX.

	1883.*	1884.	1885.
Crop per acre (Dry Matter) . . . Lb.	3457	7649	3325
Nitrogen in Crop per acre . . . Lb.	53.8	194.2	71.4
Nitrogen per cent. in Surface Soil . . .	0.1081	...	0.1152
Nitrogen per acre in Surface Soil . . . Lb.	2657	...	2832

\* Barley and Clover together.

After the removal of the clover crops in 1885 this portion of the field was fenced off to exclude cattle, and has been left uncultivated ever since. A luxuriant growth of grasses and other vegetation soon established itself, which may be profitably compared with the similar natural vegetation that has established itself after the wheat at the top of Broadbalk field (see p. 41). In the summer of 1903 a portion of the herbage was cut on both these portions of land which had been allowed to run wild after wheat and leguminous plants respectively; these were sampled as usual and a full botanical analysis made, the results of which are set out in Table L. Early in 1904 soil samples were also obtained from three places in each field, and determinations of carbon and nitrogen have been made to compare with those made at the beginning of the experiments, so as to ascertain the accumulation of fertility by the land left under "prairie" conditions for twenty years.

It will be observed that the leguminous plants had never been able to obtain a footing in the Geescroft field after clover and beans, although in the similar wilderness following wheat in the Broadbalk field, *Lathyrus* constituted a considerable proportion of the herbage. The conclusion seems inevitable that the preliminary long-continued growth of leguminous

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TABLE L.—*Botanical Composition of Self-sown Herbage from an uncultivated portion of land in Broadbalk and Geescroft Fields. Season 1903. Number of Species and Percentage by weight of each Species in the Herbage.*

	Broadbalk.	Geescroft.	
<b>Gramineous Herbage.</b>			
Number of Species.	11	10	
Botanical Names:—	Per cent.	Per cent.	Ordinary English Names:—
1. <i>Phleum pratense</i> . . . . .	4·89	0·08	1. Meadow Cat's Tail.
2. <i>Agrostis alba</i> . . . . .	11·02	0·20	2. Marsh Bent Grass.
3. <i>Deschampsia cespitosa</i> . . . . .	...	86·18	3. Tufted Hair-grass.
4. <i>Arrhenatherum avenaceum</i> . . . . .	3·50	2·34	4. False Oat.
5. <i>Dactylis glomerata</i> . . . . .	35·12	4·53	5. Cock's Foot.
6. <i>Lolium perenne</i> . . . . .	3·22	0·05	6. Perennial Rye Grass.
Other Species amounting to	1·89	1·87	
Total . . . . .	59·64	95·26	
<b>Leguminous Herbage.</b>			
Number of Species.	5	2	
1. <i>Trifolium repens</i> . . . . .	3·08	0·05	1. White or Dutch Clover.
2. <i>Trifolium pratense</i> . . . . .	0·55	...	2. Common Red Clover.
3. <i>Lathyrus pratensis</i> . . . . .	18·36	...	3. Meadow Vetchling.
4. <i>Vicia sepium</i> . . . . .	0·10	0·38	4. Bush Vetch.
5. <i>Medicago lupulina</i> . . . . .	2·92	...	5. Black Medick or Nonsuch.
Total . . . . .	25·31	0·43	
<b>Miscellaneous Herbage.</b>			
Number of Species.	24	14	
1. <i>Heraclium sphondylium</i> . . . . .	4·28	1·71	1. Cow Parsnip or Hogweed.
2. <i>Scabiosa arvensis</i> . . . . .	2·87	...	2. Field Scabious.
3. <i>Centaurea nigra</i> . . . . .	1·05	...	3. Black Knapweed.
4. <i>Carduus arvensis</i> . . . . .	0·81	0·30	4. Creeping Plume Thistle.
5. <i>Plantago lanceolata</i> . . . . .	2·46	0·26	5. Ribwort Plantain.
6. <i>Rumex obtusifolius</i> . . . . .	...	0·94	6. Broad-leaved Dock.
Other Species amounting to	3·58	1·10	
Total . . . . .	15·05	4·31	
<b>SUMMARY.</b>			
Total Number of Species.	40	26	
Total Gramineæ . . . . .	59·64	95·26	
„ Leguminosæ . . . . .	25·31	0·43	
„ Miscellanæ . . . . .	15·05	4·31	
Total . . . . .	100·00	100·00	

plants (beans and clover) had in some way unfitted the soil for carrying other leguminous plants, or at least had so reduced their vigour that they were unable to resist the competition of the grasses in a natural herbage. At the present time leguminous plants are making their appearance in some quantity, and are tending to spread.

TABLE LI.—*Accumulation of Carbon and Nitrogen in Soil of Arable Land allowed to run wild for over 20 years.*

	Per cent. in Fine Dry Soil.			
	Carbon.		Nitrogen.	
	1881-88.*	1904.	1881-83.	1904.
Broadbalk, 1st 9 inches .	1·143	1·233	0·1082	0·1450
Do. 2nd do. .	0·624	0·703	0·0701	0·0955
Do. 3rd do. .	0·461	0·551	0·0581	0·0839
Geescroft, 1st 9 inches .	1·111	1·494	0·1081	0·1310
Do. 2nd do. .	0·600	0·627	0·0739	0·0829
Do. 3rd do. .	0·447	0·435	0·0597	0·0652

\* Broadbalk, 1881; Geescroft, 1883.

*Note.*—In November 1885 (that is, after the land had grown Barley and Clover in 1883, and Clover in 1884 and 1885), samples were taken of the first 9 inches of soil from the same portion of the field as in 1883 (Plots 1-10), and gave a mean of 2152 per cent. of Nitrogen.

The most noteworthy fact is the enormous accumulation of nitrogen: during the twenty-year period the Broadbalk wilderness would appear to have gained nearly 98 lb., and Geescroft a little more than 44 lb. of nitrogen per acre per annum. The gain in carbon is less pronounced, although the amount accumulated is greater than that of nitrogen, yet the ratio of carbon to nitrogen in the increase is very much lower than the ratio in ordinary vegetable matter or in the original organic matter of the soil.

Owing, however, to changes in the consolidation of the ground it is difficult to secure an exact comparison of the same layer of soil at the two periods, *i.e.*, the surface nine inches after the land has been in grass for some time will contain a certain amount of recent turf, and less of the poor subsoil than

the original sample from arable land. For these reasons it is necessary to reduce the estimate made of the annual gain of nitrogen, but however large an allowance be made on this score, it is still difficult to account for the magnitude of the accumulation, especially for Geescroft, where, as the botanical analysis showed, there were no leguminous plants.

The other sources of nitrogen which may be invoked, such as the rain, dust, and absorption from the atmosphere, would equally affect the arable land, yet, as the various unmanured plots on the wheat, barley, and rotation fields show, there is no evidence of a corresponding gain of nitrogen on the arable land.

The only explanation that seems at all probable depends on the intervention of the bacterium *Azotobacter chroococcum* (Beyerinck), which possesses the power of fixing atmospheric nitrogen without any host plant, and which has been found in all the Rothamsted soils. On the arable soils this bacterium would not be able to effect much fixation because of the lack of recent organic matter, by the combustion of which the necessary energy for bringing the nitrogen into combination could be obtained. On the wild grass-land, however, there is every year an accumulation of vegetable matter which would supply the bacterium with its needed carbohydrate, and in consequence considerable fixation is possible. The greater gain on the Broadbalk land may be due to the presence of leguminous plants in the herbage, or to the comparative richness of the soil in calcium carbonate, since the *Azotobacter* has been found to be active only in soils containing calcium carbonate.

It would appear from the chemical analyses that the Geescroft field has never been subjected to the chalking operations previously described (p. 28), since the surface soil in 1904 contained only 0.16 per cent. of calcium carbonate, about the same quantity as was found in the soil of the adjoining uncultivated common land, whereas the soil of Broadbalk wilderness contained as much as 3.3 per cent.

Mechanical analysis shows the two soils are practically identical, the subsoil of Geescroft being somewhat the lighter of the two, and the situation of the two fields is equally good as regards surface drainage. The constant wetness and unworkability of Geescroft appears to be entirely due to the unflocculated character of the clay due to the absence of chalk, in other words, the cultivation of the other Rothamsted fields has been rendered possible by the improvement in the texture of the soil effected by the large quantities of chalk put on, probably in the eighteenth century. Even at the present time water will often stand on the surface of the Geescroft land, and the predominant growth of *Deschampsia caespitosa* is additional evidence of the persistent wetness of the soil, a wetness which cannot be accounted for by the situation, the nature of the subsoil, nor the constitution of the surface soil, but only by its bad condition induced by the absence of lime or chalk.

## II.—THE CONTINUOUS GROWTH OF RED CLOVER ON ORDINARY ARABLE LAND, HOOS FIELD.

In the Hoos field, experiments upon the growth of leguminous crops began in 1849 with red clover. The following table shows the results for a period of twenty-nine years, during which clover was sown fifteen times but only produced a crop in seven of the years. Even with the many intermissions, when the land grew wheat or barley or was left fallow, only the first crop of all was a satisfactory one; nor, as will be seen, had either mineral or nitrogenous manures any effect in keeping the land in a condition to grow clover successfully.

In 1878, the land on which these attempts to grow red clover had been continued since 1849 was divided into a number of small plots, and sown with various leguminous plants. Various systems of manuring were tried on each series of plots, which carried the following leguminous plants—lucerne, peas or beans alternately, Bokhara clover,

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TABLE LII.— *Red Clover sown frequently on the same land, in Hoos Field, Rothamsted. Total produce per acre per annum; Clover as Hay, other Crops Corn and Straw together.*

Year.	Description of Crop.	1.	2.
		Mineral Manure alone.	Mineral and Nitrogenous Manures.
1849	Clover	Lb.	Lb.
1850	Wheat	10,214	10,326
1851	Clover	(6,261)	(6,345)
1852	Clover	2,309	2,368
1853	Clover	5,895	4,914
1854	Fallow	No crop	No crop
1855	Clover	...	...
1856	Fallow	1,281	2,606
1857	Fallow	...	...
1858	Barley	...	...
1859	Clover	(6,598)	(7,578)
1860	Clover	2,752	3,087
1861	Fallow	No crop	No crop
1862	Barley	...	...
1863	Fallow	(5,745)	(6,730)
1864	Clover	...	...
1865	Clover	No crop	No crop
1866	S. 1 Clover, S. 2 Barley	2,467	4,500
1867	Fallow	No crop	(2,974)
1868	Clover	...	...
1869	Clover	No crop	No crop
1870	Barley	No crop	No crop
1871	Clover	(3,328)	(3,312)
1872	Fallow	No crop	4,085
1873	Fallow	...	...
1874	Clover	...	...
1875	Clover	No crop	Fallow
1876	Fallow	4,277	Fallow
1877	Barley	...	...
		(1,864)	(1,864)

### SUMMARY. Produce.

29 years (1849-1877)	{ Total		
Years of Crop only	{ Average	52,991	60,689
	{ Average	1,827	2,093
Years of Clover only (7)	{ Total	4,416	4,668
	{ Average	29,195	31,886
		4,171	4,555

### SUMMARY. Nitrogen (Estimated).

29 years (1849-1877)	{ Total		
Years of Crop only	{ Average	929.4	1043.1
	{ Average	32.0	36.0
Years of Clover only (7)	{ Total	77.5	80.2
	{ Average	700.7	765.3
		100.1	109.3

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sainfoin, white clover, red clover, and vetches; the same plot being always re-seeded when necessary with the same leguminous plant. The results are described in detail in the "Memoranda," and Table LIII. shows typical results in the earlier and later years of the experiment.

At first a fair growth of some of the plants was obtained on the land which had ceased to carry red clover, but in later years the growth of any but the powerfully-rooting lucerne and Bokhara clover became very poor, and repeated failures to

TABLE LIII.—*Hoos Field, Leguminous Experiments. Dry Matter in produce per acre per annum. Mean of Plots 4, 5, and 6.*

	Lucerne.	Peas or Beans.	Bokhara Clover.	Sainfoin.	White Clover.	Red Clover.	Tares.					
	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.					
1878	Not sown	Neither	1,854	...	No cutting	No cutting	1,400					
1879	No crop	Peas nor	4,498	No crop	2,275	1,722	1,742					
1880	843	Beans	1,240	No crop	5	270	1,666					
1881	809	grown	2,085	780	215	716	2,501					
1882	4,458	till 1884.	10,804	5,450	2,087	615	4,401					
1898	626	2,343	Not sufficient crop to cut	Not sufficient crop to cut	Not sufficient crop to cut	Not sufficient crop to cut	2,416*					
1899	4,799	2,940						7,143	2,090	No crop	No crop	681
1900	4,014	3,302						Fallow	1,611	313	705	697
1901	4,010	957						963	758	No crop	No crop	382
1902	1,390	729						7,431	No crop	No crop	No crop	810
1903	No crop	...	...	...	...	...	...					

\* Plot 4 only.

obtain a plant occurred on re-seeding. The land itself got very foul and in a poor mechanical condition; so that in 1898 the greater part of the land under experiment was sown with wheat without manure, only a portion of each plot being retained for continuous experiment.

Five successive crops of wheat were taken and harvested separately from each of the old plots, the combined result from the various plots which had previously carried the same leguminous plant being put together in the Table LIV. It will be seen that all the leguminous crops left a large residue containing nitrogen in the soil, so that the crop of wheat

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which followed was generally more than 40 bushels per acre with 2½ tons of straw. But this residue was rapidly exhausted; the succeeding crop was very poor, and fell to a point from which it has deteriorated but little since. The lucerne, however, left behind a much larger and more enduring residue; and though the crop on the plots following lucerne has been falling

TABLE LIV.—Wheat following Leguminous Crops, Hoos Field. Produce and Nitrogen per acre per annum, 1899-1903.

	Harvest.	Leguminous Plants previously grown.						
		Lucerne.	Peas (or Beans).	Bokhara Clover.	Sainfoin.	White Clover.	Red Clover.	Vetches.
Dressed Grain per acre, bushels.	1899	39.3	42.6	43.7	45.2	43.5	43.0	39.9
	1900	28.9	14.3	16.4	19.1	19.3	19.1	14.2
	1901	27.0	16.8	20.1	20.9	21.4	21.4	17.7
	1902	20.1	14.0	15.6	15.8	17.9	17.7	13.9
	1903	19.9	13.0	14.8	14.7	17.2	16.7	14.0
Total Straw per acre, lb.	1899	5499	5622	5592	5611	5404	5580	5051
	1900	2722	1312	1549	1788	1707	1787	1360
	1901	2312	1484	1748	1796	1822	1824	1591
	1902	2327	1495	1588	1627	2011	1934	1390
	1903	1837	1156	1317	1380	1602	1526	1261
Total Produce (Grain and Straw) per acre, lb.	1899	8108	8430	8508	8639	8308	8505	7766
	1900	4554	2202	2582	2986	2927	2992	2262
	1901	4054	2571	3038	3137	3201	3185	2729
	1902	3553	2379	2542	2600	3086	3023	2257
	1903	3035	1926	2205	2256	2635	2528	2102
Nitrogen in Total Produce per acre, lb.	1899	88.9	61.9	72.1	75.0	70.9	74.5	63.6
	1900	42.3	17.7	21.2	24.6	25.7	25.3	19.3
	1901	38.2	22.0	25.8	27.8	29.1	28.8	24.0
	1902	27.0	17.9	18.2	18.9	22.3	22.1	16.7
	1903	24.7	15.3	16.9	17.3	20.7	19.5	16.3

year by year, in 1903 it was still much greater than on the other plots. *Per contra*, after the first year, the crop on the plots following peas or beans has always been a little below that of the other plots. Of the other plots, the crops on those following white and red clover have been a little better than those following sainfoin, Bokhara clover, or vetches.

In 1904 the land was sown with oats and seeded afresh with leguminous plants in plots which run at right angles to the old plots.

## III.—THE CONTINUOUS GROWTH OF CLOVER ON RICH GARDEN SOIL.

In 1854, after it seemed clear that clover would not continue to grow on the arable land, it was sown in a garden only a few hundred yards distant from the experimental field, on soil which had been under ordinary kitchen-garden cultivation for probably two or three centuries. In view of the failures in the attempt to grow clover continuously on ordinary arable land, it is remarkable that, under these conditions, the crop has grown luxuriantly almost every year since—1917 being the sixty-fourth season of the continuous growth. At the commencement the percentage of nitrogen in the surface-soil of the garden was four or five times as high as in that of the arable soil of the field; and it would doubtless be richer in all other manurial constituents also. Indeed, after the growth of clover for twenty-five years in succession, even the second 9 inches of the garden clover soil was found to be still very much richer in nitrogen than the first 9 inches in the Hoos field. Table LV. gives the results for each of the sixty years of experiment with clover on the rich garden soil. The second column shows the number of cuttings each year, the third the amounts of produce per acre reckoned in the condition of dryness as hay, the fourth the amount of dry substance, and the last the estimated amounts of nitrogen per acre in the crops. At the bottom of the table are given the average annual results over two periods of twenty-five years each, over the period of fifty years 1854-1903, and over ten years 1904-13. It should be stated that as the garden clover plot is only a few yards square, calculations of produce per acre can only give approximations to the truth; but it is believed that they can be thoroughly relied upon so far as their general indications are concerned.

Confining our attention to the amounts of produce reckoned as hay, and to the estimated amounts of nitrogen in the produce, it is seen at a glance that, excepting a few occasional years of very high produce during the later periods, the amount of crop is very much greater in the first twenty-five years than in the

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second twenty-five years. In fact, as is seen at the foot of the table, there was an average annual produce equal to 7664 lb. of hay over the first half, but of only 3924 lb. over the latter half of the period of fifty years.

TABLE LV.—*Red Clover grown year after year on rich Garden Soil, Rothamsted. Hay, Dry Matter, and Nitrogen per acre, 1854-1913.*

Year.	Number of Cuttings.	As Hay.	Dry Matter.	Nitro- gen.*	Seed Sown.
		Lb.	Lb.	Lb.	
1854	2	5,191	4,326	(125)	1854, March.
1855	3	18,113	15,094	(435)	...
1856	2	11,027	9,190	265	...
1857	3	14,855	12,379	357	...
1858	2	7,608	6,340	183	...
1859	2	6,227	5,189	149	...
1860	1	8,679	7,233	208	1860, May.
1861	2	13,353	11,128		...
1862	2	10,042	8,368		...
1863	2	11,798	9,832	1,123	...
1864	2	5,500	4,583		...
1865	1	2,044	1,704		1865, April.
1866	2	10,456	8,713		...
1867	2	6,748	5,624		...
1868	1	991	826		1868, April.
1869	2	4,183	3,486		...
1870	1	1,741	1,451	679	...
1871	1	4,513	3,761		1871, April.
1872	2	10,142	8,452		...
1873	2	9,237	7,740		...
1874	3	5,899	4,916		1874, May and July.
1875	1	2,731	2,276	607	1875, July and September.
1876	2	3,517	2,931		1876, September.
1877	1	3,533	2,944		1877, May.
1878	3	13,416	11,180		...
1879	1	2,738	2,282		1879, May.
1880	2	5,742	4,785	856	1880, April.
1881	2	4,262	3,552		1881, April (mended).
1882	3	6,433	5,361		1882, April (mended).
1883	1	2,716	2,264		1883, May.
1884	3	9,990	8,325		...
1885	3	6,511	5,426	680	...
1886	1	2,702	2,252		1886, April.
1887	2	3,287	2,739		1887, April (mended).
1888	1	1,841	1,535	56	1888, April (mended, June).
1889	2	8,664	7,221	203	1889, April (mended).
1890	1	2,817	2,348	73	1890, April.
1891	2	6,696	5,580	163	1891, May (mended).
1892	1	3,568	2,973	100	1892, May 7 (May 27, mended).
1893	2	5,941	4,951	135	1893, April (mended).
1894	2	5,347	4,456	127	1894, April (mended).
1895	No crop	...	...	...	1895, April, May, and July.
1896	1	412	344	(10)	1896, July.
1897	2	6,381	5,318	169	1897, April.
1898	2	2,188	1,823	56	...
1899	2	3,095	2,579	74	...
1900	No crop	...	...	...	1900, August.
1901	2	3,464	2,887	84	...
1902	2	1,403	1,169	39	1902, April (mended).
1903	1	1,907	1,589	64	1903, May.

\* For the years 1854-1860, and also for 1896, the Nitrogen is estimated, but for all other years it is according to direct determinations either in mixed or individual year samples.

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TABLE LV.—*Continued.*

Year.	Number of Cuttings.	As Hay.	Dry Matter.	Nitro- gen.*	Seed Sown.
		Lb.	Lb.	Lb.	
1904	2	3960	3300	103	...
1905	2	5900	4917	145	1905, April (mended).
1906	2	3798	3165	84	1906, April (mended).
1907	2	3864	3220	100	1907, April (mended).
1908	No crop	...	...	...	...
1909	2	3361	2801	82	1909, April (mended).
1910	2	4122	3435	94	1910, April (mended).
1911	1	1390	1158	31	1911, April (mended).
1912	1	2028	1690	64	1912, April (mended).
1913	2	4910	4092	116	...
<b>SUMMARY. Averages.</b>					
25 years (1854-1878)		7,664	6,387	179	
25 years (1879-1903)		3,924	3,270	101	
50 years (1854-1903)		5,794	4,829	140	
10 years (1904-1913)		3,333	2,778	82	

\* See footnote, p. 146.

Now even this latter amount corresponds to what would be considered a fair, though not a large crop, when clover is grown in rotation once only in four or eight years or more; so that the produce in the earlier years on this rich garden soil was very unusually heavy. Indeed the average annual produce over the period of fifty years—namely, 5794 lb., or more than  $2\frac{1}{2}$  tons of hay.—would be a good yield for the crop grown only occasionally in the ordinary course of agriculture.

But it is when we look at the figures in the last column of the table, which show the estimated amounts of nitrogen in the crops, that the importance and significance of these results obtained on rich garden soil are fully recognised; and this is especially the case when they are compared with those obtained on ordinary arable land.

Thus the amount of nitrogen in fair crops of wheat, barley, or oats would be 40-50 lb. per acre, of beans about 100 lb., of meadow hay about 50 lb., and of clover grown in rotation, from 100 to 150 lb.; but on this rich garden soil the produce of clover has in one year contained more than 400 lb. of nitrogen, and the average over the first ten years was 247 lb. The

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average over the period of fifty years is 140 lb., or about as much as a fair but not large crop grown occasionally under the ordinary conditions of agriculture.

Analysis of the soil taken at intervals would seem to show a considerable falling-off in the amount of nitrogen and carbon contained in the surface soil, not sufficient however to account for all the nitrogen removed by the clover crop.

It will be apparent from a consideration of the crops reported for the later years of the experiment that great difficulty is beginning to be experienced in maintaining a plant of clover; re-seeding, which was only necessary five times in the first twenty years, had to be carried out eight times from 1904-13, during which time the crop wholly failed for one year.

During January 1897 the plots were inoculated with the watery extract of the rich kitchen-garden soil at Rothamsted. This did not however arrest the failure which was in progress at that time. Again, in March 1897 and in July 1899, all the plants were removed by hand, burnt, and their ashes returned, and the surface soil was carefully picked over by hand, to remove the *Sclerotia* of the fungus *Sclerotinia trifoliorum*, many of which were found. The soil was also dressed with carbon bisulphide as a fungicide, before fresh seed was sown. In 1903, which was a favourable year for the growth of clover, a fair plant was obtained by re-seeding, and in the spring of 1904 the best crop for many years was cut from this plot. Notwithstanding the repeated failures to grow clover continuously on ordinary arable soil and the increasing difficulty of maintaining a plant on the rich garden soil, which is the one place where any growth has been continuous, it is noteworthy that when clover grows in a mixed herbage on grass-land it increases in amount from year to year under suitable conditions of manuring. It has already been pointed out that on the grass plots in the park, where mineral manures including potash are applied every year, as on Plots 15, 6 and 7, the proportion of leguminous plants, including red clover, increases from year to year, without there being any sign of "clover sickness" setting in. Nor can this

result be due to manuring only, for on the small plots in the Hoos field all sorts of variations in the manuring were tried, without enabling the clover to stand. On the grass paths, however, separating these "clover sick" plots on Hoos field, paths which are not more than a yard broad, both red and white clover grow abundantly. Were "clover sickness" due merely to the infection of the plant by *Sclerotinia trifoliorum*, it is difficult to see how these plants could escape infection when the neighbouring clover plants in the arable land succumb. These and other facts would seem to show that the presence of the fungus *Sclerotinia trifoliorum* is not the determining cause of "clover sickness"; in many cases it is the direct cause of the death of the clover plants, but what is not yet understood is why plants on "clover sick" land alone succumb to the infection.

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## CHAPTER IX

### EXPERIMENTS UPON GRASS LAND MOWN FOR HAY EVERY YEAR

- I. The Unmanured Plots.
  - II. Use of Nitrogenous Manures alone.
  - III. Mineral Manures used alone.
  - IV. Complete Manures—Nitrogen and Minerals.
  - V. The Action of Organic Matter.
  - VI. Effects of Lime.
  - VII. Changes in Herbage following Changes in Manuring.
  - VIII. The Effect of Season.
- Practical Conclusions and References.

THE experiments upon grass at Rothamsted began in 1856, about 7 acres of the park close to the house being set aside for the purpose. The land has been in grass as long as any recorded history of it exists, for some centuries at least. It is not known that seed has ever been sown, and at the beginning of the experiments the herbage on all the plots was apparently uniform. The soil is the same stiff reddish loam as is found in the other fields, though owing to the length of time the land has been in grass stones are not abundant near the surface.

The plots, of which there are twenty in all, vary somewhat in size between one-half and one-eighth of an acre. Up to 1874 inclusive the grass was only cut once, the aftermath being fed off by sheep. Since that time there has been no grazing, and the plots are generally cut twice in the year. The grass is made into hay in the usual way and the whole produce of each plot is then weighed. On some occasions, however, with the second crop, continuous wet weather has rendered it necessary to weigh the produce in a wet condition and

calculate its equivalent in hay from the amount of dry matter in the material as weighed. On most of the plots the manuring has been continued without change from the beginning of the experiments; the cases in which a change has been made serve to show how rapidly the character of the herbage will respond to alterations in the manure.

Table LVI. shows the amount and nature of the manures

TABLE LVI.—*Manuring of the Permanent Grass Plots per acre per annum, 1856 and since.*

Plot.	Abbreviated Description of Manures.	Nitrogenous Manures.		Mineral Manures.				
		Ammonium-salts.	Nitrate of Soda.	Super-phosphate.	Sulphate of Potash.	Sulphate of Soda.	Sulphate of Magnesia.	Silicate of Soda.
		Lb.	Lb.	Cwt.	Lb.	Lb.	Lb.	Lb.
3 12	} Unmanured every year . . . . .	...	...	...	...	...	...	...
2 1		Unmanured; following Dung first 8 years . Ammonium-salts alone; with Dung also first 8 years . . . . .	200	...	...	...	...	...
4-1 8 7	Superphosphate of Lime . . . . . Mineral Manure without Potash . . . . . Complete Mineral Manure . . . . .	...	...	3·5 3·5 3·5	... ... 500	... 250 100	... 100 100	... ... ...
6 15	As Plot 7; Ammonium-salts alone first 13 years . . . . . As Plot 7; Nitrate Soda alone first 18 years	...	...	3·5 3·5	500 500	100 100	100 100	... ...
5 17	Ammonium-salts alone (to 1897) . . . . . Nitrate of Soda alone . . . . .	400 ...	... 275	... ...	... ...	... ...	... ...	... ...
4-2 10 9	Superphosphate and Ammonium-salts . Mineral Manure (without Potash) and Am- monium-salts . . . . . Complete Mineral Manure and Ammonium- salts . . . . .	400 400 400	... ... ...	3·5 3·5 3·5	... ... 500	... 250 100	... 100 100	... ... ...
13 11-1 11-2	As Plot 9, and Chaffed Wheat Straw also to 1897 . . . . . Complete Mineral Manure and Ammonium- salts . . . . . As Plot 11-1, and Silicate of Soda . . . . .	400 600 600	... ... ...	3·5 3·5 3·5	500 500 500	100 100 100	100 100 100	... ... 400
16 14	Complete Mineral Manure and Nitrate Soda Complete Mineral Manure and Nitrate Soda	... ...	275 550	3·5 3·5	500 500	100 100	100 100	... ...

applied each year to the plots, and Table LVII. the average produce over the whole period, over the last ten years, and for the single year 1912.

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TABLE LVII.—*Produce of Hay per acre. Average over the period of 57 years (1856-1912), the 10 years (1903-1912), and the individual year 1912. Rothamsted. Total of first and second crops (if any).*

Plot.	Abbreviated Description of Manures.	Averages over		Season 1912.
		57 years (1856-1912).	10 years (1903-1912).	
		Cwt.	Cwt.	Cwt.
3	Unmanured every year . . . . .	20·9	16·2	10·2
12		23·9	21·0	20·1
2	Unmanured; following Farmyard Dung for first 8 years	28·6†	20·2	15·4
5-1	(N. half) Unmanured; following Ammonium-salts alone for 42 years . . . . .	14·4‡	15·0	7·1
1	Ammonium-salts alone (=43 lb. N.); with Farmyard Dung for first 8 years	35·9‡	26·8	23·6
5	Ammonium-salts alone=86 lb. Nitrogen (to 1897)	(26·1)††	...	...
17	Nitrate of Soda alone=43 lb. Nitrogen . . . . .	33·7**	33·2	31·2
4-1	Superphosphate of Lime . . . . .	21·6¶	21·0	17·2
8	Mineral Manure without Potash . . . . .	28·0	27·4	22·5
7	Complete Mineral Manure . . . . .	40·9	50·9	46·4
5-2	(S. half) Complete Mineral Manure: following Ammonium-salts alone for 42 years . . . . .	23·2‡	21·9	16·8
6	Complete Mineral Manure as Plot 7; following Ammonium-salts alone first 13 years . . . . .	37·2§	45·3	37·8
15	Complete Mineral Manure as Plot 7; following Nitrate of Soda alone first 13 years . . . . .	36·8	45·8	37·0
4-2	Superphosphate and Ammonium-salts=86 lb. N. . . . .	33·5¶	34·5	25·1
10	Mineral Manure (without Potash),* and Ammonium-salts=86 lb. N. . . . .	47·7	40·5	32·5
9	Complete Mineral Manure and Ammonium-salts=86 lb. N. . . . .	54·3	54·7	36·0
11-1	Complete Mineral Manure and Ammonium-salts=129 lb. N. . . . .	66·5	71·2	67·2
11-2	As Plot 11-1, and Silicate of Soda . . . . .	73·3	79·3	72·6
16	Complete Mineral Manure and Nitrate Soda=43 lb. N. . . . .	46·3**	48·1	40·7
14	Complete Mineral Manure and Nitrate Soda=86 lb. N. . . . .	56·9**	57·7	52·9

\* Including Potash, first 8 years.  
 † After the change. Before the change 42·9.  
 ‡ " " " 49·5.  
 § " " " 30·6.  
 || " " " 35·4.

¶ 54 years only (1850-1912).  
 \*\* 55 years only (1858-1912).  
 †† 42 years (1856-07).  
 ‡‡ 15 years (1893-1912).

Table LVIII. shows the first crops only for six successive ten-year periods.

In dealing, however, with the produce of grass land, which is a mixed herbage consisting of many different species of grasses, leguminous plants, and other orders, it is not sufficient to consider only the gross weight of produce. The various species are differently stimulated by particular manures; even among the grasses themselves, such a difference of habit as a

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deep or shallow root system will determine to which manure the grass will respond. The aspect of any meadow represents the results of severe competition among the various species represented; the dominant species are those most suited to their environment, *i.e.*, to the amount and nature of the plant

TABLE LVIII.—Average produce of Hay per acre over the six successive 10-year periods from 1856 to 1915. First crops only.

Plot.	Abbreviated Description of Manuring.	Averages over					
		10 years (1856-1865).	10 years (1866-1875).	10 years (1876-1885).	10 years (1886-1895).	10 years (1896-1905).	10 years (1906-1915).
3 12	} Unmanured every year . . . . .	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
		22·6	20·0	17·5	16·8	13·2	10·9
		25·1	22·9	18·0	17·1	17·6	14·0
1	Ammonium-salts alone; with Dung also first 8 years. . . . .	48·4	37·8	30·1	23·8	19·3	18·9
4-1	Superphosphate of Lime alone. . . . .	24·4†	21·3	19·1	16·5	15·7	16·8
8	Mineral Manure without Potash* . . . . .	33·6	26·6	21·8	16·5	21·3‡	19·3
7	Complete Mineral Manure . . . . .	33·9	36·8	32·3	27·1	36·1	30·0
17	Nitrate of Soda alone = 43 lb. N. . . . .	34·3‡	33·5	30·1	27·0	28·9	25·7
4-2	Superphosphate and Ammonium-salts = 86 lb. N.	39·6†	30·5	30·4	29·0	26·8	22·5
10	Mineral Manure (without Potash),* and Ammonium-salts = 86 lb. N.	52·8	39·6	38·6	35·5	34·6	25·6
9	Complete Mineral Manure and Ammonium-salts = 86 lb. N.	53·6	48·4	50·5	39·3	44·1	36·8
11-1	Complete Mineral Manure and Ammonium-salts = 129 lb. N. . . . .	61·7	53·6	48·5	47·6	57·8	45·9
16	Complete Mineral Manure and Nitrate Soda = 43 lb. N. . . . .	48·1‡	47·6	41·5	37·4	40·4	39·9
14	Complete Mineral Manure and Nitrate Soda = 86 lb. N. . . . .	58·1‡	60·5	53·8	45·6	50·0	47·7

\* Including Potash, first 6 years.

† Seven years only (1869-65).

‡ Eight years only (1858-65).

food in the soil, the water supply, the texture of the soil, and other factors. If any of these factors be altered, as is done in the case of the Rothamsted plots by manuring in different fashions, the original equilibrium between the contending species is disturbed; some species are favoured, and increase at the expense of the others until a new equilibrium is attained, and the general character of the herbage from the botanical point of view is completely altered. It thus becomes important to ascertain the nature of the plants

comprising the herbage produced by a given manure, as well as to determine its amount; from time to time therefore at Rothamsted a carefully selected fraction of the herbage from each plot has been separated into its constituent species, the relative proportions of which are determined by weighing. As this complete separation involves a great amount of work, a partial separation only is made every year, in which case the herbage is separated into three groups—the grasses, the leguminous plants, and the miscellaneous species respectively.

Table LIX. shows the results of these partial separations as averages for the whole period of fifty-seven years, and for the single year 1902. Summaries of the six complete separations made in 1862, 1867, 1872, 1877, 1903, and 1914 are given in Table LXII. (see p. 173).

#### I. *The Unmanured Plots.*

Two of the plots have remained without manure during the whole of the experiment. They are situated near the extremities of the field, and show a slight but constant difference in crop. Taking the average of the whole period, these unmanured plots have produced rather more than a ton of hay per acre per annum. If we compare the successive ten-year returns, there is no sign of approaching exhaustion or great falling-off in crop from year to year. The impoverishment of these unmanured plots is more to be seen in the character of the herbage than in the gross weight of produce. Weeds of all descriptions occupy the land, and the relative proportion they bear to the grasses and clovers has increased from year to year. A fair proportion of clovers, both red and white, is found on these plots, but the weeds, which amount to 26 per cent. taking the average over the whole period, have of late years constituted nearly one-half of the herbage. The most prominent species among the grasses are the Sheep's Fescue, Bent Grass, and Quaking Grass; among leguminous plants the Bird's Foot Trefoil; and Burnet, Hawkbit, and Black Knapweed among the weeds.

TABLE LIX.—Percentages of Gramineous, Leguminous, and Miscellaneous Herbage. Average of determinations made at different times during 57 years (1856-1912, and 1902 separately).† Rothamsted. First crops.

Plot.	Manures.	Averages of determinations over 57 years (1856-1912).			Season 1902.		
		Gramineæ.	Leguminosæ.	Miscellaneæ.	Gramineæ.	Leguminosæ.	Miscellaneæ.
		Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
3	Unmanured every year	61·0	8·7	30·3	34·3	7·5	58·2
12		64·8	9·0	26·2	33·1	16·1	45·8
2	Unmanured; following Farmyard Dung for first 8 years. (N. half) Unmanured; following Ammonium-salts alone 42 years	75·5	4·3	20·2	24·4	5·7	69·9
5-1		...	...	...	76·9	0·6	22·5
1	Ammonium-salts alone (=43 lb. N.); with Farmyard Dung for first 8 years	87·7	0·7	11·6	77·6	1·4	21·0
5	Ammonium-salts alone=86lb. N. (to 1897)	(80·5)	(0·4)	(19·1)	...	...	...
17	Nitrate of Soda alone=43 lb. N.	63·8	1·5	29·7	43·8	3·4	52·9
4-1	Superphosphate of Lime	59·3	7·4	33·3	54·4	15·4	30·2
8	Mineral Manure without Potash *	61·0	9·2	29·8	28·8	22·1	49·1
7	Complete Mineral Manure	58·8	24·9	16·3	20·3	55·3	24·4
5-2	(S. half) Complete Mineral Manure; following Ammonium-salts alone for 42 years	...	...	...	68·7	0·8	30·5
6	Complete Mineral Manure as Plot 7; following Ammonium-salts alone first 13 yrs.	64·8	18·6	16·6	18·4	61·0	20·6
15	Complete Mineral Manure as Plot 7; following Nitrate of Soda alone first 18 years	59·5	22·6	17·9	26·2	63·1	10·7
4-2	Superphosphate and Ammonium-salts=86 lb. N.	89·1	0·1	10·8	91·5	(0·01)	8·5
10	Mineral Manure (without Potash*) and Ammonium-salts=86 lb. N.	90·7	0·1	9·2	97·6	(0·01)	2·4
9	Complete Mineral Manure and Ammonium-salts=86 lb. N.	89·9	0·3	9·8	91·2	1·3	7·5
11-1	Complete Mineral Manure and Ammonium-salts=129 lb. N.	96·5	0	3·5	99·2	0	0·8
11-2	As Plot 11-1, and Silicate of Soda	97·4	0	2·6	99·5	0	0·5
16	Complete Mineral Manure and Nitrate Soda=43 lb. N.	82·9	5·4	11·7	61·7	12·8	25·5
14	Complete Mineral Manure and Nitrate Soda=86 lb. N.	89·0	3·1	7·9	88·8	3·7	7·5

\* Including Potash, first 6 years.

† The hay from some plots is partially separated nearly every year, but that from others is only analysed at irregular intervals as occasion arises. Consequently the averages in the above table refer to a different number and selection of years for each individual plot, according to the analyses that have been made.

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Speaking generally, these plots now present the appearance, perhaps in a rather exaggerated degree, of much of the poor pasture and meadow land in this country, wherever milch cows and wet flocks are habitually grazed and the land occasionally hayed, without anything being restored in the shape of artificial food or manure. Fig. 17 shows a photograph of a piece of turf taken from this plot at the end of June 1903.

The great value of occasional dressings of farmyard manure to grass land may be seen in the returns from Plot 2, which for the first eight years of the experiment received farmyard manure at the rate of 14 tons per acre. The application was then discontinued, but the effect has persisted to the present day, *i.e.*, for fifty years.

Table LX. shows the produce on this as compared with

TABLE LX.—*Produce of Hay per acre, first and second crops, showing residual effect of Dung. Rothamsted.*

Plot.	Manures.	Mean 8 years (1856-1863).	Season 1864.	Season 1865.	Average of				
					10 years (1866-1875).	10 years (1876-1885).	10 years (1886-1895).	10 years (1896-1905).	10 years (1906-1915).
		Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
2	Farmyard Manure, 8 yrs. (1856-63); Unmanured since	4804	5392	2848	3726	3748	2791	1943	2040
3	Unmanured continuously	2665	2688	1296	2374	3025	2621	1686	1589
Relation to Produce of Plot 3 reckoned as 100.									
2	Farmyard Manure, 8 yrs. (1856-63); Unmanured since	180	201	220	157	124	106	115	122
3	Unmanured continuously	100	100	100	100	100	100	100	100

the unmanured plot for the preliminary period for which the dung was used, for the two years following its discontinuance, and for five ten-year periods 1866-1915. Although the yield on this plot remains at a higher level than where the land has been continuously unmanured, yet the plot now shows great impoverishment in the character of its herbage, having about

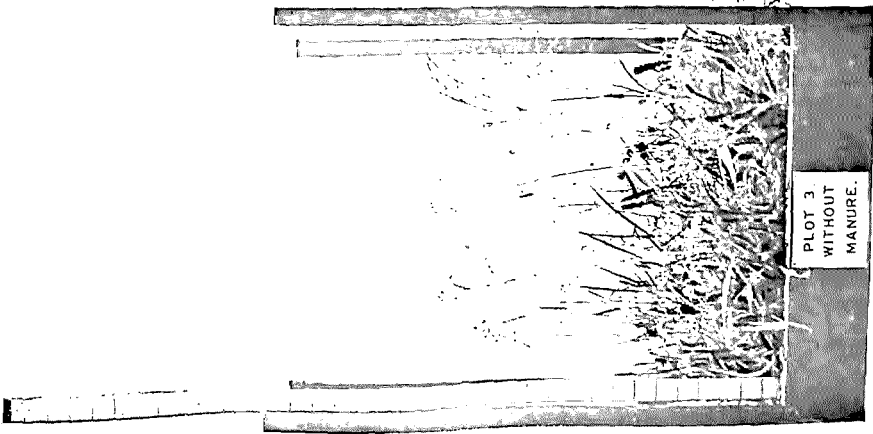


Fig. 17.

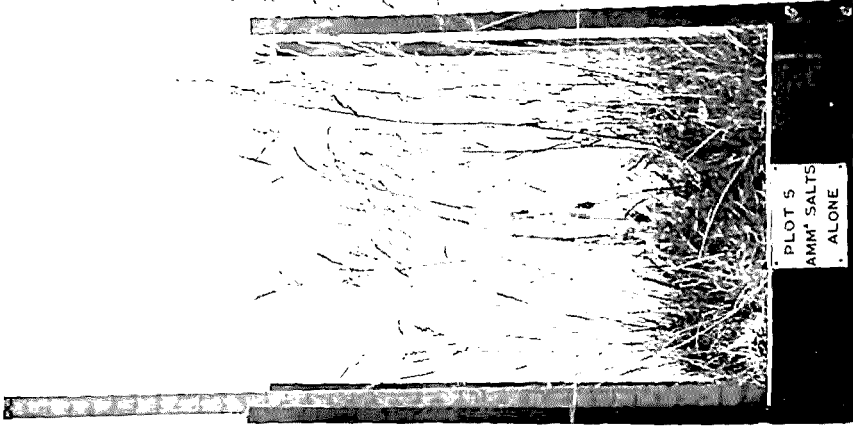


Fig. 18.



the same proportion of weeds and the same general aspect as the continuously unmanured plot.

## II. *Use of Nitrogenous Manures alone.*

Three of the plots—17, 5, and 1—show the effect of the long-continued use of nitrogenous without any mineral manures. Plot 5 has been receiving 86 lbs. of nitrogen as ammonium-salts, Plot 17 half the quantity of nitrogen in the shape of nitrate of soda, and Plot 1 the same half quantity of nitrogen as ammonium-salts, though on this plot dung was applied in each of the first eight years of the experiment. It is very evident when a nitrogenous manure is used alone for grass, nitrate of soda is far more effective than the ammonium-salts; *e.g.*, on Plot 17 it has given an average crop of 34 cwt. against 26 cwt. produced by double the quantity of nitrogen in ammonium-salts on Plot 5.

For this superiority of the nitrate of soda two reasons may be traced; being completely soluble it sinks deeply into the soil, and encourages grasses of a deeply-rooting habit, which not only obtain more food from the soil, but also are better able to withstand the droughts of spring and early summer. On Plot 17 (nitrate) deep-rooting grasses like Meadow Foxtail and Downy Oat Grass are prominent, but latterly Sheep's Fescue (14 per cent.) and Bent Grass (14 per cent.) are well represented. The plots receiving only ammonium-salts are almost wholly occupied by Sheep's Fescue and Common Bent, whose feeding roots are close to the surface, where the ammonium-salts are caught and retained by the humus in the soil.

The continued use of large applications of ammonium-salts has also had an injurious effect upon the reaction of the soil, since it behaves as an acid, and continually removes carbonate of lime. The creeping surface vegetation tends to accumulate, and decays into a substance resembling peat; at the same time the vegetation shrinks into tufts, between which are bare patches of black soil, showing an acid reaction to litmus

paper. So pronounced had this effect become on Plot 5, which received the larger amount of ammonium-salts, that the application has been discontinued since 1897, lest the turf should be entirely killed. Another sign of the sourness caused by the use of ammonium-salts without minerals is seen in the prevalence of Sorrel on this plot; it forms nearly 15 per cent. of the whole herbage, and it is interesting to note that the only portion of the plot from which the Sorrel is absent is a strip that was dressed with chalk in 1883 and 1887.

The aspect of the plots receiving only nitrogenous manure shows very characteristic differences; both possess a very dark green unhealthy colour, but, while the ammonium plot seems in the main to be clothed with Sheep's Fescue and other grasses, amounting to 77 per cent. of the whole, the nitrate of soda plot possesses a much more varied herbage, of which weeds form 30 per cent. Leguminous plants are practically absent from both plots, though a small proportion may be found where the nitrate of soda is used. The impoverishment due to the continual use of a manure like nitrate of soda supplying one element only of plant food is to be seen in the gradual decline of production on Plot 17, and in the present predominance of weeds there. Considering, however, the length of time that nitrate has been used on this plot, the crop has been wonderfully maintained; the deep root-range induced by the solubility of the nitrate enables the plant to feed widely in the soil, and the soda base assists in bringing the dormant potash into a form available for the plant. The photographs, Figs. 18 and 19, show the characteristic appearance of the turf from Plot 5, with ammonium-salts alone, and Plot 17, with nitrate of soda alone.

### III. *Mineral Manures used alone.*

On three of the plots no nitrogenous manures have been applied since the beginning of the experiments. On Plot 7 a complete mineral manure, supplying phosphoric acid, potash, magnesia, and soda, is used; Plot 8 has received the same



Fig. 19.

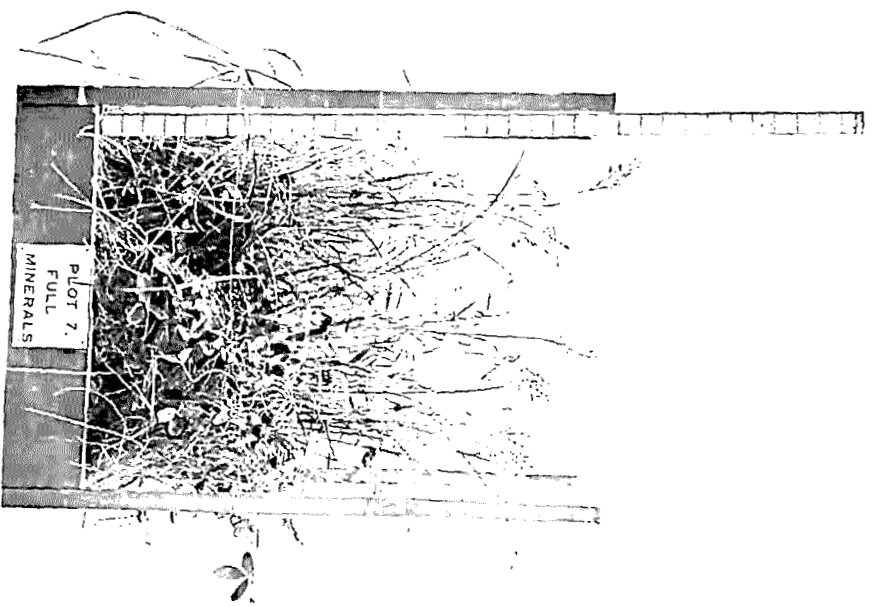


Fig. 20.

application, but without potash, since 1861, while Plot 4-1 receives superphosphate only. With the complete minerals a fair crop is grown, averaging over  $1\frac{1}{2}$  ton of hay for the first cut alone, and when the successive ten-year averages are considered there are no signs that the fertility of this plot is declining, since the production only shows such fluctuations as may be put down to seasons. The reason that the crop on this plot is maintained, although no nitrogen is supplied in the manure, lies in the free growth of leguminous plants. It will be seen that, taking the average over the whole period, the leguminous plants form 24 per cent. of the herbage, and the proportion has increased from year to year. These leguminous plants are not only themselves independent of nitrogen in soil or manure, but by fixing the atmospheric nitrogen and leaving it behind in the residues of their dead roots, they provide a supply for the grasses and other plants which cannot of themselves feed on the nitrogen of the air. The predominant leguminous plant is *Lathyrus pratensis*, but Red Clover is also abundant. A large number of species of grasses are represented on the plot, none of which are specially prominent. Amongst the weeds, Knapweed is fairly abundant, and there is also a rather large proportion of Yarrow. The general aspect of the vegetation is shown by the photograph of turf, Fig. 20.

The omission of potash on Plot 8 has caused a very striking difference both in the crop and in the character of the herbage. The average crop has been about one-quarter less over the whole period, and shows a progressive decline in fertility, until at the present time it is little more than half that of Plot 7. The poor results on this plot, as compared with Plot 7, must be put down to its poverty in leguminous herbage, the development of which seems to depend on a free supply of potash. Of late years the proportion of leguminous plants on this plot has amounted to about one-half of that found on Plot 7, the grasses are about the same, the difference being made up by an increased amount of weed. The

characteristic leguminous plant is the *Lathyrus pratensis*. The characteristic weeds of this plot are the Hawkbit, the Black Knapweed, Plantain, and Yarrow; see photograph, Fig. 22.

Plot 4-1, which each year has received superphosphate only, now presents a very impoverished appearance, and is giving very little more crop than the unmanured plots. Indeed, the aspect of this plot, where weeds, chiefly Hawkbit, Burnet, Plantain, Knapweed, and Yarrow, are unusually prominent, would seem to indicate that the land is more exhausted here than on the unmanured plot. It is not uncommon to find cases where the application to grass land of a purely phosphatic manure, like superphosphate or basic slag, is followed by a great increase of crop, the addition of the phosphoric acid to the dormant nitrogen and potash in the soil having supplied the missing element in a complete plant food. The result, however, of this plot shows how disastrous a continuation of such one-sided manuring may become; a nitrogenous manure alone is often thought exhausting, but probably a phosphatic manure used singly will even more quickly impoverish the soil. The photograph, Fig. 23, shows the impoverished and weedy aspect of this plot in 1903. The diagram, Fig. 21, shows the effect of the mineral manures, and particularly of potash, both with and without nitrogen, on the yield of grass.

#### IV. Complete Manures—Nitrogen and Minerals.

Four of the plots receive a complete artificial manure. On all of them the mineral manuring is the same, and supplies both phosphoric acid and potash; on Plot 9, ammonium-salts containing 86 lb. of nitrogen are added; and on Plot 11-1 the amount of ammonium-salts is increased by one-half, to 129 lb. of nitrogen. Plot 14 receives 86 lb. of nitrogen as nitrate of soda, and therefore compares with Plot 9. Plot 16 also receives nitrate of soda, but only half the amount on Plot 14. Considering Plots 9 and 11-1 first, it

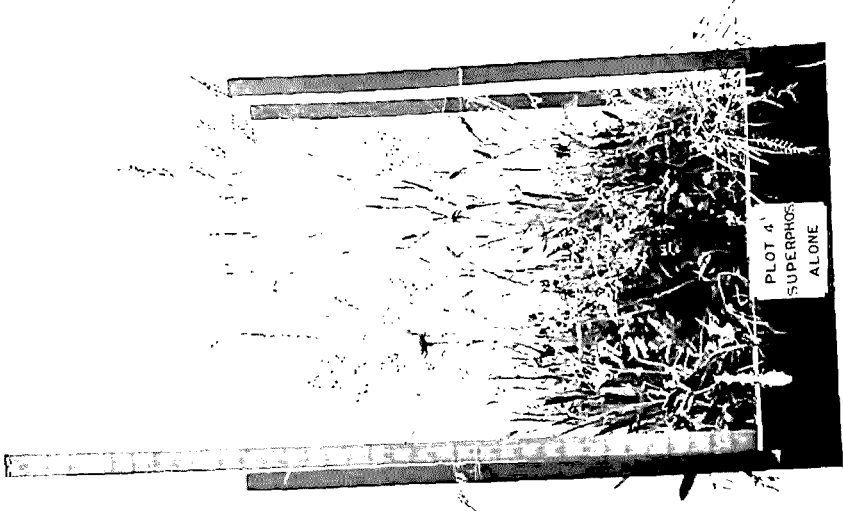


Fig. 23.

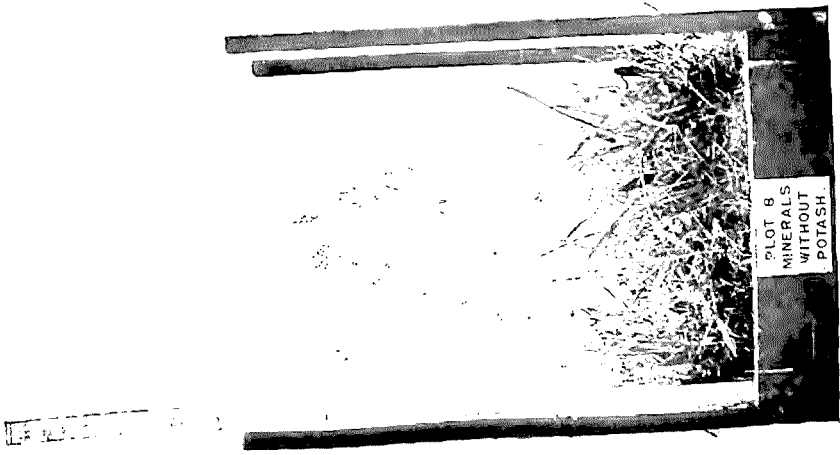


Fig. 22.

## EFFECT OF NITROGENOUS MANURES 161

will be seen that, large as is the amount of nitrogen applied to Plot 9, the increased quantity on Plot 11-1 has its effect in an increased crop. On Plot 9 the hay has averaged

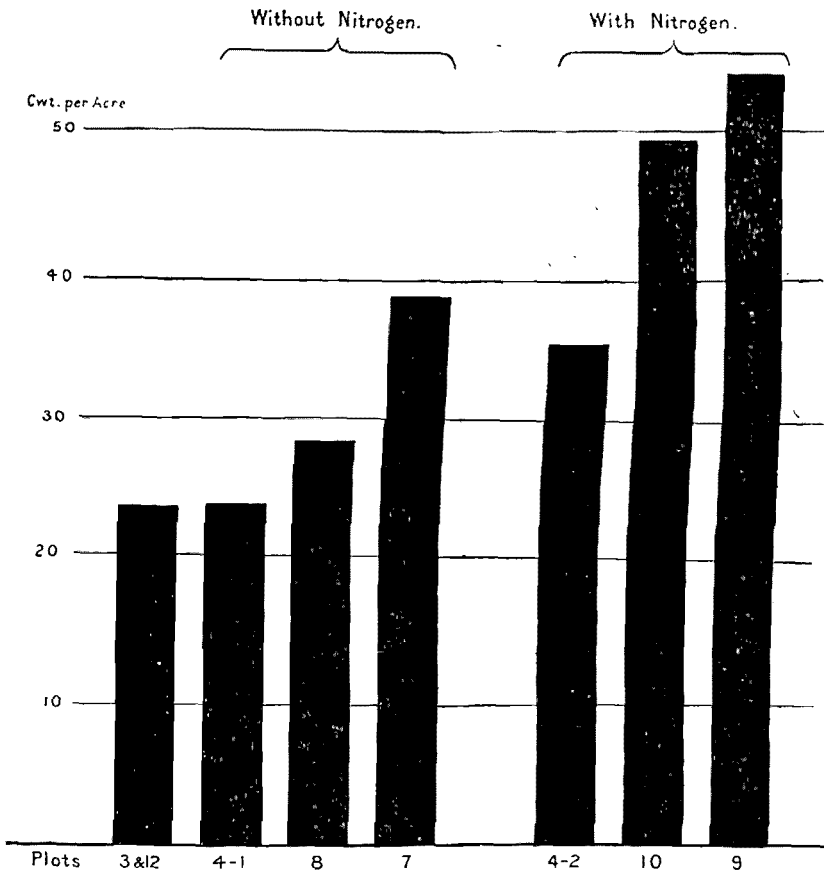


FIG. 21.—Effect of the various Ash constituents with and without Nitrogen on the produce of Hay per acre. Average over 47 years (1856-1902).

Plots 3 and 12. Unmanured.

Plot 4-1. Superphosphate.

Plot 8. Minerals without Potash.

Plot 7. Complete Mineral Manure.

Plot 4-2. Super. and Amm.-salts = 86 lb. N.

Plot 10. Minerals (without Potash) and Amm.-salts = 86 lb. N.

Plot 9. Complete Mineral Manure and Amm.-salts = 86 lb. N.

54 cwt. over the whole period, on Plot 11-1 the crop is increased to more than 66 cwt.\* Comparing these results with the 41 cwt. obtained from Plot 7 (minerals without nitrogen), it will be seen how great is the effect of nitrogen in the produc-

\* The figures are taken from Table LVII.; they differ very slightly from those in the above diagram, which gives the figures up to 1902.

tion of hay. The hay, however, is by no means so good in quality as that grown with mineral manures alone, because the large amounts of nitrogen have so stimulated the development of the grasses that leguminous plants have disappeared entirely, and even the weeds are crowded out. In 1903 the latter formed only a trifle more than 4 per cent. of the herbage on Plot 9, and were barely perceptible on Plot 11-1; as may be seen in the photographs, Figs. 24 and 25, representing turf from these plots. The dominant grasses on Plot 9 consist of False Oat Grass, Bent Grass, Sweet Vernal, and Sheep's Fescue; Meadow Foxtail, Cocksfoot, Yorkshire Fog, and Smooth-stalked Meadow Grass constituting practically the rest of the herbage. On Plot 11-1 there is every sign that an excess of nitrogen has been employed; the vegetation is very rank and soft, and tends to grow in tufts with bare patches between; the smaller grasses are almost wholly crowded out, and the coarse vegetation is generally laid and begins to rot at the bottom before the grass is ready to cut. Owing to the great competition of the strong-growing grasses the number of species on this plot has been reduced to a minimum; 91 per cent. of the herbage is made up of Yorkshire Fog, 7.6 per cent. is represented by False Oat Grass and Meadow Foxtail. In the earlier years of the experiment Yorkshire Fog was by no means so prominent. As late as 1872 it only formed 10 per cent. of the herbage, while more than 39 per cent. was composed of Cocksfoot, which has now practically disappeared. The replacement of Cocksfoot by Yorkshire Fog seems to have been coincident with the abandonment of the practice of grazing the aftermath; the custom of late years has been to cut it.

On Plot 11-2 the same manure is employed as on Plot 11-1, with the addition of 400 lb. of silicate of soda. The silicate of soda has resulted in a considerable increase of crop, which has averaged as much as 73 cwt. for the whole period; the grass on this part of the plot is also more healthy and uniform, and ripens earlier. The effect of the silicate of soda must probably be attributed to the soda base rather than to the silica; for with

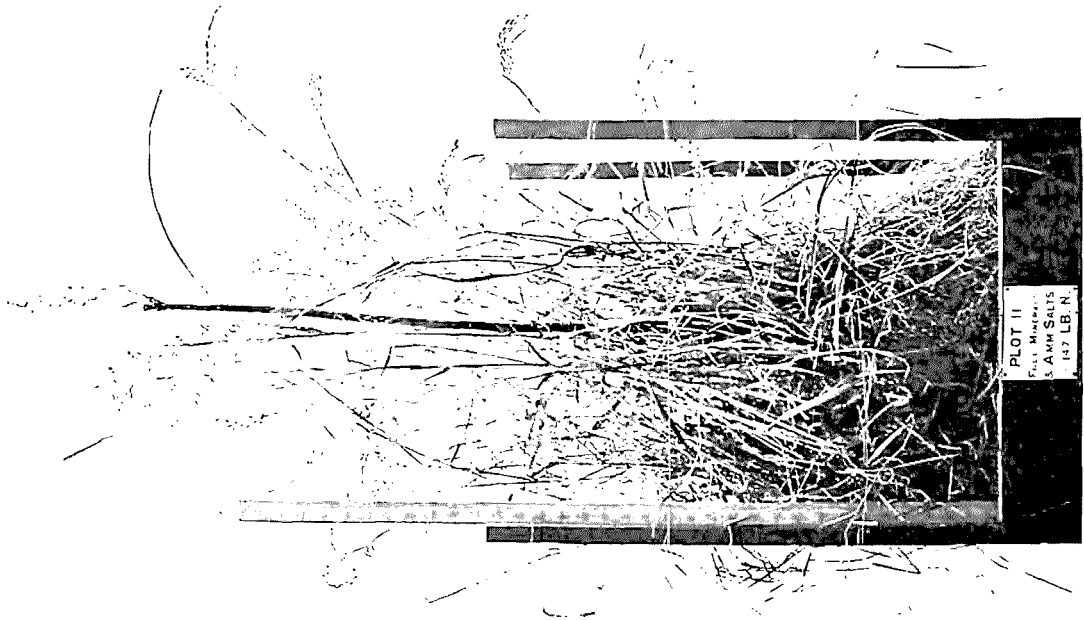


FIG. 25.

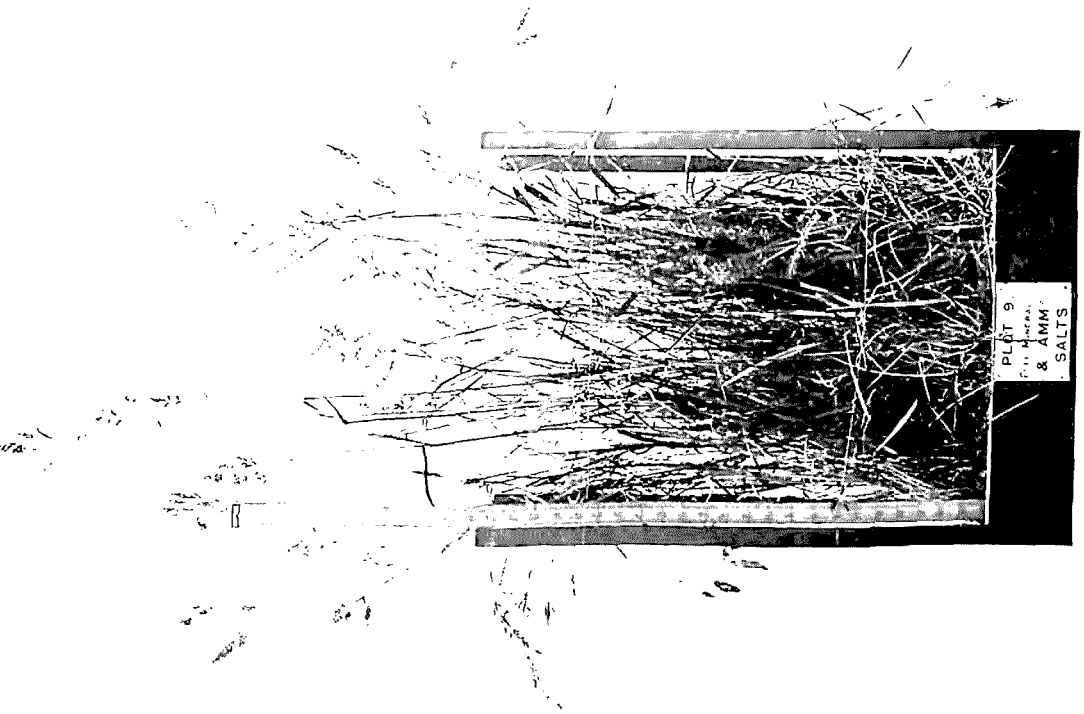


FIG. 24.

the great excess of nitrogen applied to this plot, any substance like soda, which supplements and economises the potash available, will be of service to the plant.

Turning now to Plot 14, which receives the same manure as Plot 9, but with its nitrogen in the form of nitrate of soda, we notice first that the nitrate of soda has been the more effective source of nitrogen, giving an average crop of 56 cwt. against 54 cwt. with ammonium-salts. The superiority of the nitrate of soda has been most pronounced in dry seasons, owing to the generally deeper-rooted habit of the grasses found on this plot.

During the great drought of 1870, holes were dug for the examination of the subsoil on this plot and on Plot 9. On the latter, where ammonium-salts formed the source of nitrogen, very few roots could be distinguished below 36 inches, and the subsoil below 27 inches seemed to have been but little changed by the development of roots and their decay. On Plot 14, with the nitrate of soda, wiry roots extended nearly to 4 feet, and the subsoil down to 4 feet 6 inches had suffered a marked change.

The vegetation on plots grown with nitrate of soda is more varied, nor are the leguminous plants so completely suppressed by the large amount of nitrogen. This plot, for example, showed in 1903 more than 3 per cent. of Meadow Vetchling and a trace of White Clover. The aspect of the nitrate and ammonia plots is strikingly different, as may be seen by comparing the two photographs taken in 1903, Figs. 26 and 24. With the nitrate of soda a great part of the herbage, 23 per cent., was composed of Soft Brome in 1903, but only 5 per cent. in 1914; this grass is hardly to be found on any of the other plots. Again, Beaked Parsley is very prominent, though it is hardly to be found on any of the other plots; it constituted 10 per cent. of the herbage in 1903, but 1 per cent. in 1914, so that just before hay time the whole plot showed white with its flowers. In addition to the Soft Brome, the grasses which predominate are Meadow Foxtail, False Oat, and Sheep's Fescue.

Plot 16, which receives the smaller quantity of nitrate of

soda, still grows a very large crop, averaging 46 cwt. over the whole period. The vegetation resembles that of Plot 14, but there is much less False Oat than on 14—3 per cent. instead of 40 per cent.—and it is more varied, there being about four times as much leguminous herbage, among which the Meadow Vetchling predominates. This plot probably marks the limit of the amount of nitrate of soda which it would be profitable to apply in ordinary farming, since the second 275 lb. per acre of nitrate of soda on Plot 14 has only produced an average increase of 11 cwt. of hay.

Reviewing the whole of the evidence, nitrate of soda is distinctly a better manure for hay on the Rothamsted soil than are ammonium-salts, producing more grass and that of a better quality.

On Plot 10 the potash is omitted from the mineral manure, though the other minerals and the nitrogen are the same as on Plot 9. The result of the omission of the potash is a considerable decline in yield, which has become more accentuated as the experiments have progressed and the original stock of potash in the soil has been reduced. The herbage consists even more wholly of grass than does that of Plot 9, and the development of flower and seed is distinctly later.

Plot 4-2 receives the same ammonium-salts, supplying 86 lb. of nitrogen, and superphosphate only, so that it compares with Plot 9, except for the entire absence of alkaline salts. The lack of potash shows itself in a great reduction of crop, the average over the whole period having been only 33 cwt. against 54 cwt. on Plot 9. It is thus much below Plot 10, also without potash, but which receives magnesia and soda. The herbage on this plot again consists almost wholly of grasses, which have a very dark green colour and are late to mature. The dwarf-growing and shallow-rooted grasses predominate; Sheep's Fescue constitutes more than one-half, and, with Sweet Vernal and Bent Grass, as much as 93 per cent. of the whole herbage.

The characteristic appearance of the herbage is well seen in the photograph, Fig. 27, of turf taken from this plot in 1903.

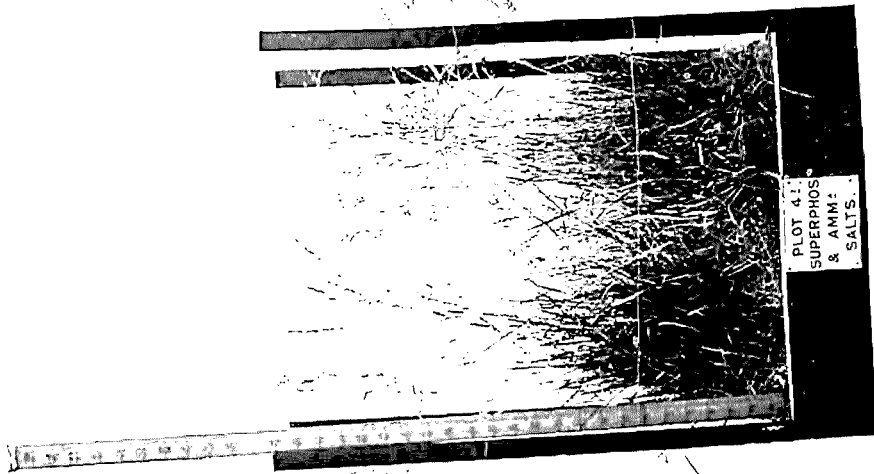


Fig. 27.

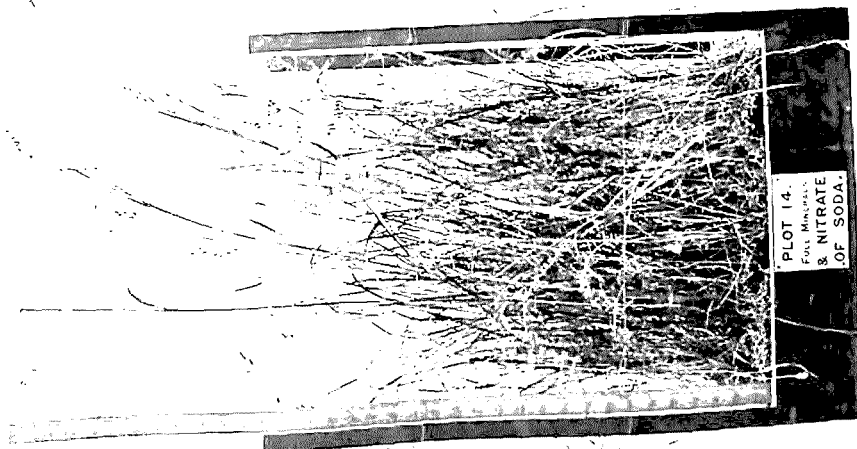


Fig. 26.

Another feature in these two Plots, 10 and 4-2, which receive nitrogen but no potash, is the weakness of the stems; short as the grass is, it is often laid before it is ready to cut. The grass is also found to be more susceptible to fungoid attacks on these plots than elsewhere.

The diagram Fig. 28 shows a comparison of the yields of the unmanured plot, the plot receiving mineral manures only, and the plots receiving mineral manures and varying amounts of nitrogen as nitrate of soda or ammonium-salts.

#### V. *The Action of Organic Matter.*

In the early years of the experiments farmyard manure was applied every year to two of the plots, but owing to the accumulation of unrotted material on the surface it was found necessary to discontinue the experiment in this form. On another of the plots, however, an attempt was made to ascertain the effect of the organic matter present in dung by adding to a complete artificial manure, such as is supplied to Plot 9, 2000 lb. of chaffed wheat straw every year. The wheat straw contains so little manurial matter, compared with the quantities artificially supplied, that it may be neglected; thus the straw should be regarded as simply providing organic matter. If we compare the crop on this Plot 13 with that of Plot 9, we see that the straw has had its effect, and that on the average a larger crop by about 7 cwt. per acre per annum has been produced.\* The effect of the wheat straw has been due partly to the shelter it provides in the early spring (for it is noticed that the grass starts more quickly on this plot than on the others), and partly also to the water-retaining power of the humus produced by its decay. Of late years the organic matter added accumulated to such an extent as to form a peaty layer that was beginning to injure the growth of the plant; in consequence the application of straw has been discontinued. The value of occasional applications of farmyard manure to grass land is thus seen to be a mechanical factor

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\* Up to 1902 the average yields were: Plot 9, 54.1 cwt.; Plot 13, 61.3 cwt.

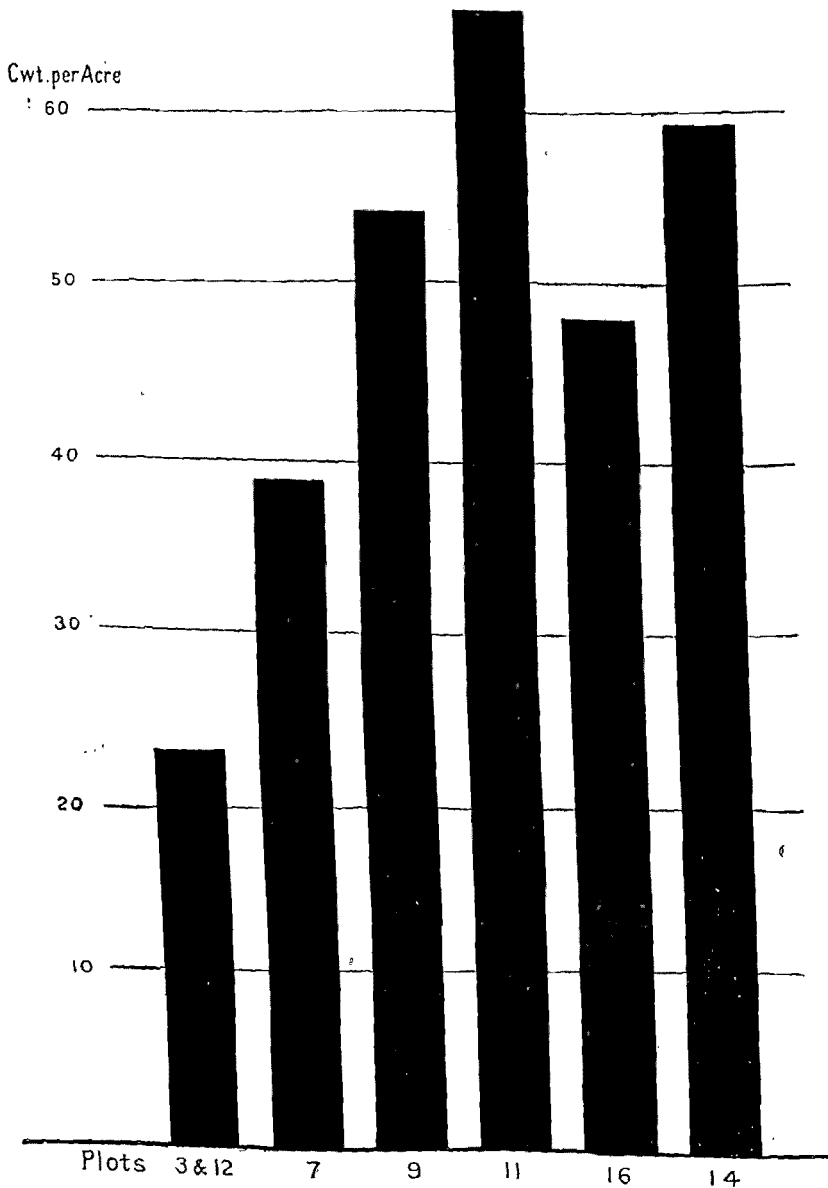


FIG. 28.—Effect of Nitrogenous Manures on the produce of Hay per acre. Average over 47 years (1856-1902).

Plots 3 and 12. Unmanured.

Plot 7. Complete Mineral Manure, no Nitrogen.

Plot 9. Do. and Amm.-salts = 86 lb. N.

Plot 11. Do. do. = 129 lb. N.

Plot 16. Do. and Nitrate of Soda = 43 lb. N.

Plot 14. Do. do. = 86 lb. N.

depending very much upon the shelter which the long manure affords to the young grass in the early spring, and to its water-retaining power when it has rotted down to humus in the soil.

### VI. *Effects of Lime.*

In November 1883, lime at the rate of 2000 lb. per acre was applied to one-half of each of the plots, and in 1885, 1886, and 1887 the limed and unlimed portions of certain of the plots, where the lime had obviously produced an effect, were weighed separately and subjected to partial botanical separation. The results of the liming may be seen in Table LXI., which gives the averages of the three seasons, both as regards crop and its botanical composition. It will be seen that on three of the plots—6, 7, and 15—the liming has had a

TABLE LXI.—*Effects of Lime on Grass Land. Mean of 3 years (1885-87), first crops. Produce and Botanical Composition of the Herbage, Rothamsted.*

Plot.	Manuring.	Hay per acre, cwt.		Botanical Composition per cent.					
				Gramineæ.		Leguminosæ.		Other Orders.	
		Un-limed.	Limed.	Un-limed.	Limed.	Un-limed.	Limed.	Un-limed.	Limed.
3*	Unmanured	18·6	18·9	76·0	69·0	7·1	16·0	16·9	15·0
6	Complete Minerals; following Ammonium-salts	23·8	28·7	72·8	67·7	11·7	20·1	15·5	12·2
7	Complete Mineral Manure	26·1	33·1	64·3	48·4	22·0	41·8	13·7	9·8
8	Mineral Manure without Potash	17·0	16·7	60·6	71·8	7·5	8·1	31·9	20·1
15	Complete Minerals; following Nitrate of Soda	12·4	25·6	67·4	53·8	3·2	35·3	29·4	10·9

\* Results for one year only (1885).

considerable effect in increasing the crop. On the unmanured plot and on Plot 8 the effect has been nil. Again, on examining the composition of the herbage it will be seen that on the same three plots which gave an increase of crop the lime has brought about a great increase in the proportion of leguminous plants. On Plot 6 it has risen from 11 to 20 per cent., on Plot 7 from 22 to 42 per cent., and on Plot 15 from 3 to 35 per cent.

The reason for these differences in the action of lime is to be found in the previous manuring of the plots. On Plots 6, 7, and 15, potash has been applied every year, so that there was a large accumulation of potash residues in the soil. On Plots 3 and 8, on the contrary, no potash had been used; and as Plot 8 had been receiving phosphoric acid, the store of available potash originally in the soil must have become considerably exhausted. As we have also seen from the effect of mineral manures with and without potash on the other plots, that the development of leguminous plants is largely dependent on the supply of potash, it is obvious that the effect of lime had been mainly due to bringing into action the residues of potash accumulated from the previous manuring; the lime only acts where there is such a residue of potash, and has chiefly stimulated the growth of leguminous plants, just as a direct application of potash would do.

The long-continued use of manures like ammonium-salts, which are in effect acids, has altered the reaction of the soil and made it sour on some of the plots. This is very palpable on Plot 5, which has received a very heavy dressing of ammonium-salts alone, and on which, as has before been mentioned, there is now a large amount of Sorrel, except on a small portion where chalk had been applied. A dressing of lime is, without doubt, necessary for grass land on most soils, in order to neutralise the acidity produced by decaying vegetation, and to enable the manures to exert their full effect. Thus although the liming at the rate of 2000 lb. per acre above mentioned was extended in 1887 to cover the whole of the experimental field, yet a further dressing of lime in January 1903 to the halves of the plots had an immediate effect upon the following crop. As the results of only one or two years are available as yet, they need not here be considered.

#### VII. *Changes in Herbage following Changes in Manuring.*

On two of the plots, which had received ammonium-salts and nitrate of soda respectively until the herbage consisted entirely

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of grasses, the nitrogenous manures were discontinued, and in their place a complete mineral manure containing potash was applied. The diagram Fig. 29 shows the effect of this change of treatment on the composition of the herbage; the columns show the average proportion of grasses, leguminous plants, and

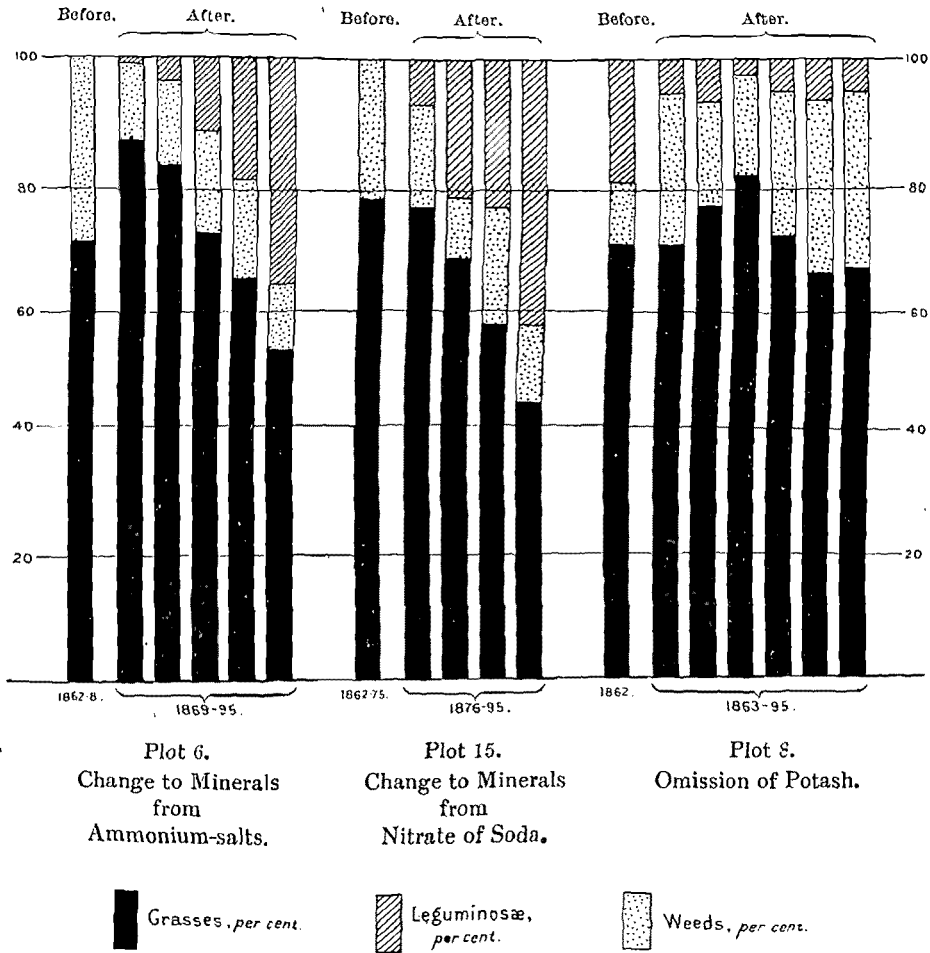


FIG. 29.—Progressive effect of Changes in the Manuring on the Composition of the Hay Crop. Five-year periods.

weeds before the change, and for successive five-year periods afterwards.

On Plot 6 ammonium-salts alone was applied up to 1868, at which time the grasses constituted 63 per cent. of the herbage, and the weeds 37 per cent.—the leguminous plants

being barely perceptible. In 1903 the leguminous plants had risen to over 40 per cent. of the herbage, but the weeds had not altered much. The change, as is seen in the diagram, did not take place at once, the leguminous plants requiring nearly twenty years to spread and establish themselves; after five years, for example, they constituted less than 5 per cent. of the herbage. The photograph, Fig. 30, shows how closely the herbage on this plot now resembles that on Plot 7, which has never had anything but minerals.

On Plot 15 nitrate of soda was used up to 1875, when the nitrate was dropped and a change was made to the same complete mineral manure as is used on Plots 6 and 7. At the time of the change the grasses constituted 80 per cent. of the herbage and the rest was weeds, the leguminous plants being again almost imperceptible. At the present time this plot is almost identical in aspect with the one previously described and with Plot 7 which has received only mineral manures from the beginning; it contained in 1903 about 50 per cent. of grass and 30 per cent. of leguminous plants. The photograph, Fig. 31, shows that *Lathyrus* is more prominent than the clovers. The change in the herbage on this plot took place rather more rapidly than on the plot which had received ammonium-salts beforehand, being practically complete in ten years.

Plot 8 had received mixed mineral manure containing potash up to 1861, by which time the herbage had become largely leguminous, as on the adjoining Plot 7. The potash was dropped in 1862, though the superphosphate, magnesia, and soda have been continued. The effect of the absence of potash was seen very quickly, the proportion of leguminous plants dropping from 20 to about 9 per cent. in the first five years. Owing to the continued manuring with phosphoric acid and the lack of potash, this plot has become seriously impoverished, and is now very little better than Plot 4-1 which has received superphosphate only since the beginning of the experiments, the weeds constituting about one-third of the

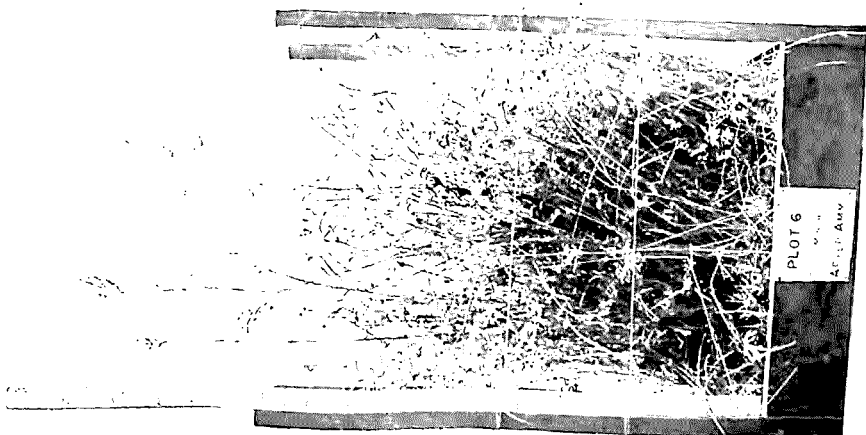


Fig. 30.

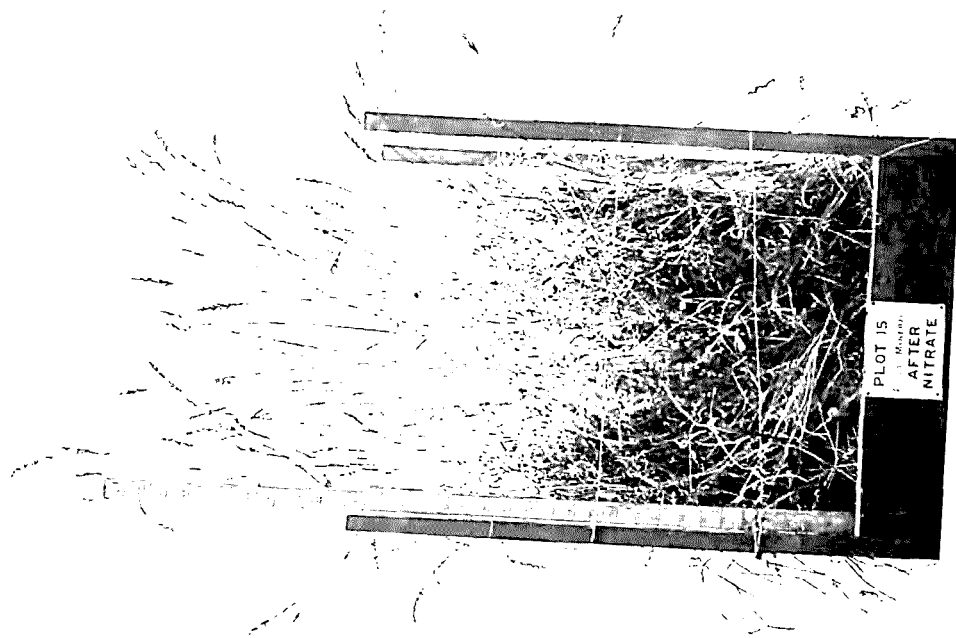


Fig. 31.

herbage. The photograph, Fig. 22, shows the present state of the turf.

It should be remembered that no new seed of any kind has been sown on the plots; the increase in the amount of clover and other leguminous plants is therefore due either to spreading from occasional stunted plants which were hardly perceptible in the herbage before, or to the blowing on of seeds which find after the change a congenial soil for their development. Immediately after the change the crop falls off, and only reaches a new constant level when the redistribution of the species occupying the ground has taken full effect. After the change in the manuring the herbage is not suited to the new conditions; at first the particular species favoured by the manure are not prominent, and it is only when they bulk largely in the herbage that the new manure can show its full effect. Hence it would seem desirable in manuring grass land to keep to the same kind of manure year after year, so as to produce herbage which will get the maximum effect out of the particular manure that is used. Again, if land is grazed one year and laid up for hay the next, the grasses which were at first favoured by the grazing will be discouraged during the growth of the hay crop: a better result will probably be attained by always grazing or always haying the same piece of land, so that there is present at the beginning of any season the special class of herbage which has been stimulated by the same conditions previously, and is therefore likely to give the best return.

The changes which manuring can produce in the composition of the herbage is perhaps best seen in Table LXII., where the complete separations of the herbage in the years 1862, 1867, 1872, 1877, 1903, and 1914 are summarised for the more abundant species. Figs. 32-40, again, show in a graphic form the distribution on certain selected plots of these more important species.

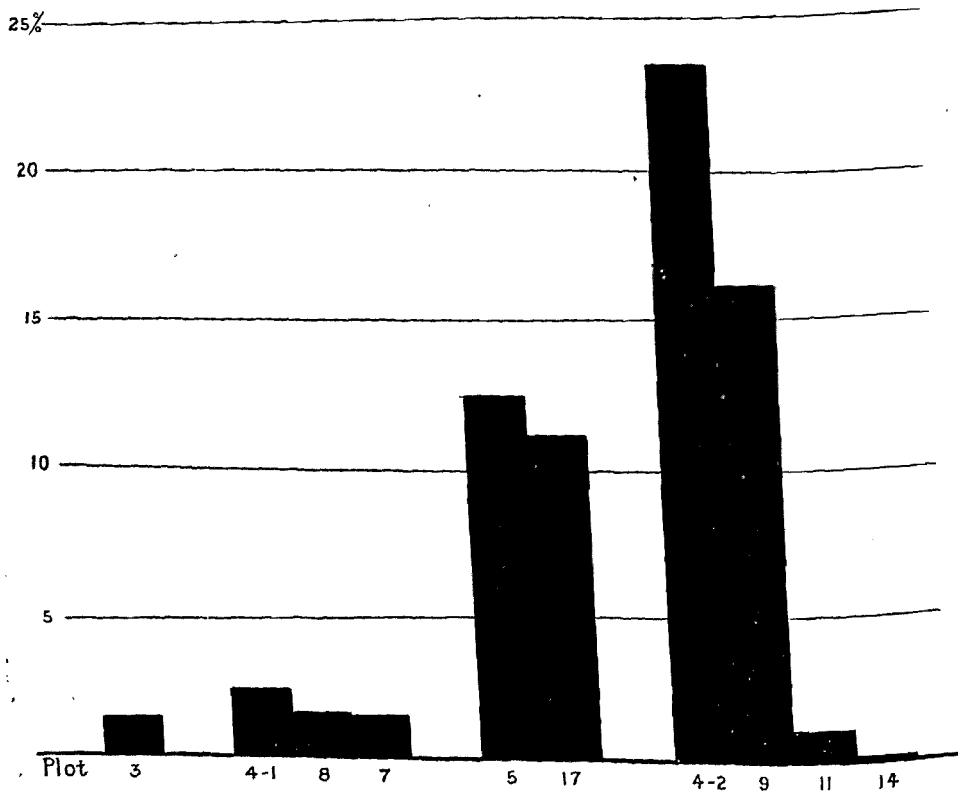


FIG. 32.—Percentage of *Anthoxanthum odoratum* in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	Minerals only.	Nitrogen only.	Nitrogen and Minerals.
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash
	8. No Potash.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. }
			14. Complete; Nit. Soda.

TABLE LXII.—*Rothamsted Park Hay. Percentage of each Species by weight in the Mixed Herbage from Twelve selected Plots (first crops). Six separations, 1862, '67, '72, '77, 1903, and 1914.*

(The maximum attained by each species in the particular year is printed in heavier type.)

GRAMINEÆ.												
Years	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
<i>Anthoxanthum odoratum</i> (Sweet-scented Vernal Grass).												
1862	4.28	3.66	3.72	3.06	3.92	1.82	<b>5.77</b>	2.06	2.24	1.24	0.09	0.35
1867	<b>8.68</b>	7.16	6.98	3.93	4.31	1.83	5.51	2.31	5.52	3.59	0.06	0.13
1872	5.20	4.74	<b>7.94</b>	2.72	6.22	4.49	3.04	4.50	1.47	2.25	0.78	0.02
1877	5.12	5.11	<b>7.55</b>	3.18	4.89	4.16	4.09	5.32	2.36	2.94	0.19	0.06
1903	1.34	2.40	1.50	1.36	1.90	1.67	12.29	11.06	<b>23.44</b>	16.19	0.98	0.13
1914	2.69	3.98	3.85	4.21	4.96	3.04	8.18	4.81	7.72	<b>38.53</b>	0.08	0.16
<i>Alopecurus pratensis</i> (Meadow Foxtail).												
1862	4.49	1.32	0.39	0.34	1.70	6.90	0.65	<b>23.94</b>	0.66	0.27	2.80	0.22
1867	5.82	1.84	0.88	0.88	0.02	5.95	0.47	<b>21.71</b>	14.75	0.07	13.11	3.54
1872	0.52	0.86	0.52	1.17	0.03	2.46	0.33	<b>16.25</b>	3.94	2.76	12.35	3.72
1877	0.30	1.40	0.87	0.48	0.09	7.17	0.23	12.72	1.58	0.96	9.91	<b>20.18</b>
1903	0.59	0.31	0.55	4.51	0.59	10.24	0.27	9.74	4.56	4.08	28.51	<b>28.72</b>
1914	0.28	0.06	0.41	1.69	1.89	13.69	0.11	14.29	2.49	1.65	1.15	<b>22.86</b>
<i>Agrostis vulgaris</i> (Common Bent).												
1862	11.36	7.21	10.01	7.14	21.43	7.65	<b>24.30</b>	11.01	19.38	12.81	13.17	0.42
1867	3.63	6.08	4.32	5.69	14.41	6.86	<b>20.97</b>	7.05	14.00	13.43	19.27	0.61
1872	16.14	13.88	9.32	11.72	23.37	7.66	<b>26.62</b>	10.60	20.59	15.46	13.56	0.24
1877	13.28	9.87	12.40	12.02	3.53	12.90	<b>29.46</b>	17.92	24.39	12.23	29.20	1.55
1903	0.19	0.03	0.72	3.34	2.51	2.99	<b>11.65</b>	1.76	2.04	3.81	1.42	0.14
1914	12.52	0.93	7.77	7.00	7.25	11.96	17.03	12.33	12.32	18.18	0.51	1.43
<i>Holcus lanatus</i> (Woolly Soft Grass, or Yorkshire Fog).												
1862	5.04	11.82	4.51	5.06	8.17	7.61	10.08	8.23	<b>16.21</b>	12.14	9.92	6.60
1867	7.97	9.16	10.25	<b>11.81</b>	3.07	<b>11.81</b>	5.15	8.13	10.53	9.84	2.86	6.63
1872	3.60	4.71	4.61	3.16	5.31	5.32	1.90	5.87	2.03	7.61	<b>10.33</b>	3.67
1877	12.55	19.35	18.22	13.16	14.89	14.95	3.01	10.91	6.03	10.37	20.29	12.75
1903	5.07	4.74	6.31	3.07	2.37	2.35	0.03	4.84	1.05	3.94	45.57	0.02
1914	2.75	3.64	7.90	3.42	3.37	5.56	0.22	7.39	0.04	4.01	90.90	...
<i>Arrhenatherum avenaceum</i> (False Oat Grass).												
1862	0.07	0.13	<b>4.52</b>	2.41	3.44	0.04	3.93	0.68	2.46	...	0.77	3.14
1867	0.21	0.18	3.16	0.06	<b>6.50</b>	...	2.78	0.23	0.41	2.50	4.55	...
1872	0.13	0.15	4.40	0.46	3.60	...	1.49	0.48	2.48	<b>11.40</b>	10.41	...
1877	0.05	0.05	3.17	1.29	2.77	...	0.23	0.01	1.02	13.23	<b>14.86</b>	0.32
1903	0.10	0.03	4.20	1.16	1.94	0.16	0.19	...	0.95	<b>43.30</b>	23.00	17.28
1914	0.11	0.44	3.02	1.21	1.15	0.52	0.39	0.28	0.25	3.49	6.57	40.47
<i>Avena pubescens</i> (Downy Oat Grass).												
1862	9.65	9.42	12.68	13.84	<b>14.54</b>	3.53	7.31	4.24	7.38	10.22	1.66	0.90
1867	3.07	<b>4.97</b>	3.44	3.90	0.90	0.70	0.63	1.15	3.94	1.41	0.01	0.92
1872	3.55	4.09	3.66	2.36	1.33	1.56	0.24	4.09	0.28	0.49	...	0.19
1877	2.69	4.02	1.67	2.25	1.67	3.13	0.12	4.27	0.03	0.07	...	0.47
1903	4.76	<b>9.77</b>	8.04	4.28	7.50	4.18	0.01	8.69	...	0.06	...	2.32
1914	3.32	<b>9.94</b>	5.16	2.58	6.47	1.99	0.50	3.33	0.04	...	...	3.57

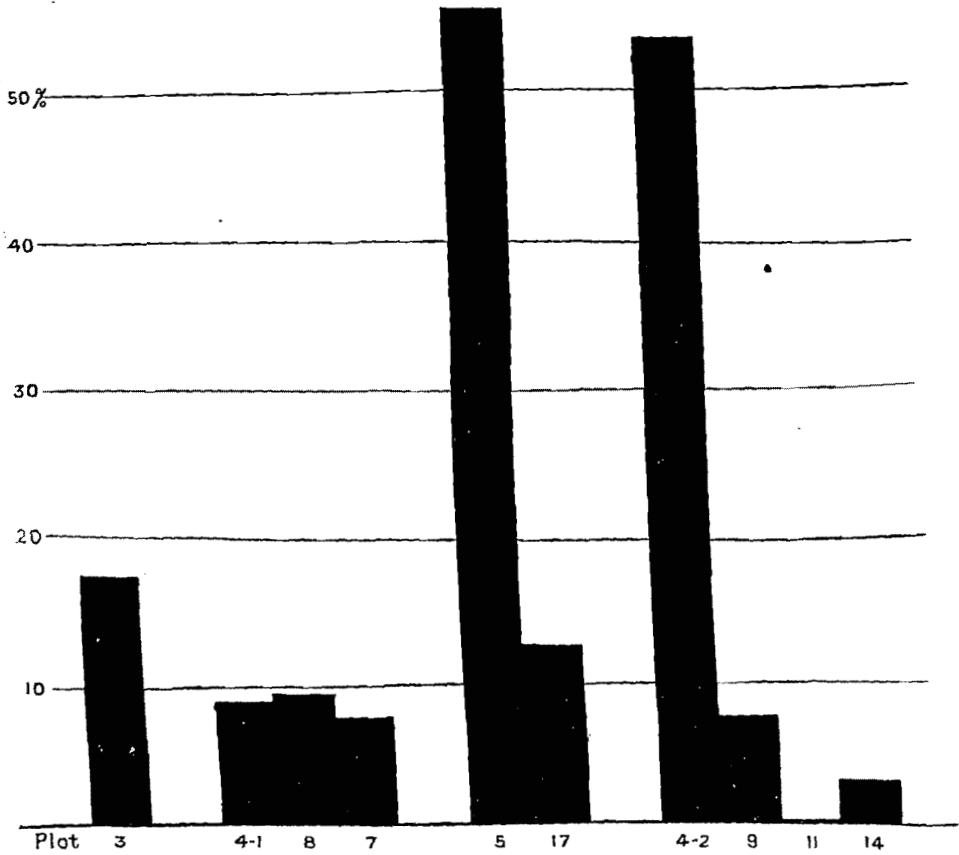


FIG. 33.—Percentage of *Festuca ovina* in the Herbage of the Grass Plots. First Crop, Season 1903.

<i>Unmanured.</i>	<i>Minerals only.</i>	<i>Nitrogen only.</i>	<i>Nitrogen and Minerals.</i>
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash
	8. No Potash.	17. Nitrate Soda.	9. Complete
	7. Complete.		11. Excess N.
			14. Complete; Nit. Soda.

TABLE LXII.—Continued.

GRAMINEÆ—Continued.												
Years	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
<i>Avena flavescens</i> (Yellow Oat Grass).												
1862	2.37	4.12	5.42	4.02	1.18	3.86	0.65	1.45	2.09	9.08	5.28	4.88
1867	1.86	4.28	3.52	4.84	0.24	4.26	0.46	3.18	0.41	3.78	0.46	7.12
1872	3.49	6.09	6.94	3.72	1.49	3.83	0.16	4.96	0.09	5.30	0.09	5.67
1877	1.08	2.47	2.45	3.65	0.48	2.98	0.01	1.98	0.03	0.67	0.01	2.93
1903	0.92	2.83	3.94	6.64	1.47	5.53	0.01	1.78	...	0.16	...	0.81
1914	0.56	2.18	2.06	1.84	0.81	1.68	...	1.19	...	0.05	...	1.86
<i>Poa pratensis</i> (Smooth-stalked Meadow Grass.)												
1862	0.29	0.56	1.72	1.13	2.28	0.14	1.07	0.02	0.67	10.68	9.43	1.45
1867	0.17	0.26	1.50	1.05	1.65	0.13	0.65	0.21	3.87	13.02	12.86	1.05
1872	0.09	0.45	2.11	2.27	2.42	0.37	0.61	0.09	5.11	22.67	10.40	2.57
1877	0.07	0.02	1.03	1.75	1.73	0.11	0.23	0.09	1.56	18.03	1.47	4.01
1903	0.33	0.83	0.98	2.34	3.74	2.52	0.90	0.20	7.67	11.68	0.17	9.20
1914	0.06	0.93	1.10	1.42	1.15	0.42	1.11	0.14	1.22	1.80	...	2.18
<i>Poa trivialis</i> (Rough-stalked Meadow Grass.)												
1862	1.54	5.16	5.48	3.81	1.53	6.53	0.89	5.21	8.14	8.72	13.25	22.48
1867	1.17	5.65	3.48	4.38	0.40	23.67	0.30	12.08	2.15	2.14	0.14	32.93
1872	0.50	3.79	1.62	2.30	0.98	7.95	0.59	2.74	2.10	0.64	0.09	24.76
1877	0.56	4.72	3.20	2.11	0.63	6.05	0.01	1.59	0.31	0.11	0.33	21.59
1903	0.01	0.64	0.10	1.00	0.19	1.20	...	0.96	0.24	0.01	...	0.95
1914	...	0.56	0.21	0.53	0.15	0.42	0.17	0.07	...	...	...	1.27
<i>Briza media</i> (Quaking Grass).												
1862	1.89	0.58	0.07	0.03	...	0.05	0.06	0.01	...	...	...	...
1867	0.63	0.32	0.08	0.06	...	0.02	...	0.07	...	...	...	...
1872	6.40	2.12	1.16	0.10	0.01	0.20	0.01	0.31	0.01	0.01	...	...
1877	7.25	2.16	0.57	0.14	...	0.30	0.02	0.72	...	...	...	...
1903	20.15	11.23	5.87	0.13	0.18	0.22	...	2.20	...	...	...	...
1914	4.10	2.24	1.51	...	...	...	...	1.05	...	...	...	...
<i>Dactylis glomerata</i> (Cocksfoot).												
1862	1.76	2.25	3.50	2.57	2.05	2.09	2.39	1.80	2.28	5.58	24.16	10.00
1867	1.74	0.99	1.48	4.67	1.71	0.21	1.39	0.57	0.38	4.64	39.31	7.23
1872	0.90	0.57	0.66	1.68	1.28	0.11	0.70	0.64	0.16	11.88	39.28	3.33
1877	0.70	1.41	0.98	3.67	4.09	0.36	3.25	0.58	1.83	14.07	17.11	12.48
1903	1.05	1.30	1.12	4.97	3.51	0.48	1.32	0.92	0.14	5.14	0.15	0.71
1914	3.65	4.60	3.99	10.17	7.33	2.41	9.18	5.72	1.01	5.04	0.20	6.10
<i>Festuca ovina</i> (Sheep's Fescue).												
1862	13.30	10.20	7.51	13.73	13.33	13.69	21.99	9.43	6.80	5.21	1.46	0.88
1867	15.20	16.75	17.74	11.38	25.93	12.08	30.57	11.18	26.09	18.42	0.50	1.58
1872	21.67	20.44	23.95	14.86	31.15	34.71	46.56	18.05	49.29	8.68	0.38	0.16
1877	21.89	16.02	19.76	26.59	38.02	20.77	53.31	12.04	55.20	21.80	4.15	0.48
1903	17.45	8.81	9.48	7.67	8.80	15.03	55.65	12.84	53.56	7.52	0.02	2.75
1914	23.62	21.20	24.74	31.44	27.37	13.64	45.57	14.21	72.88	15.28	0.12	5.87

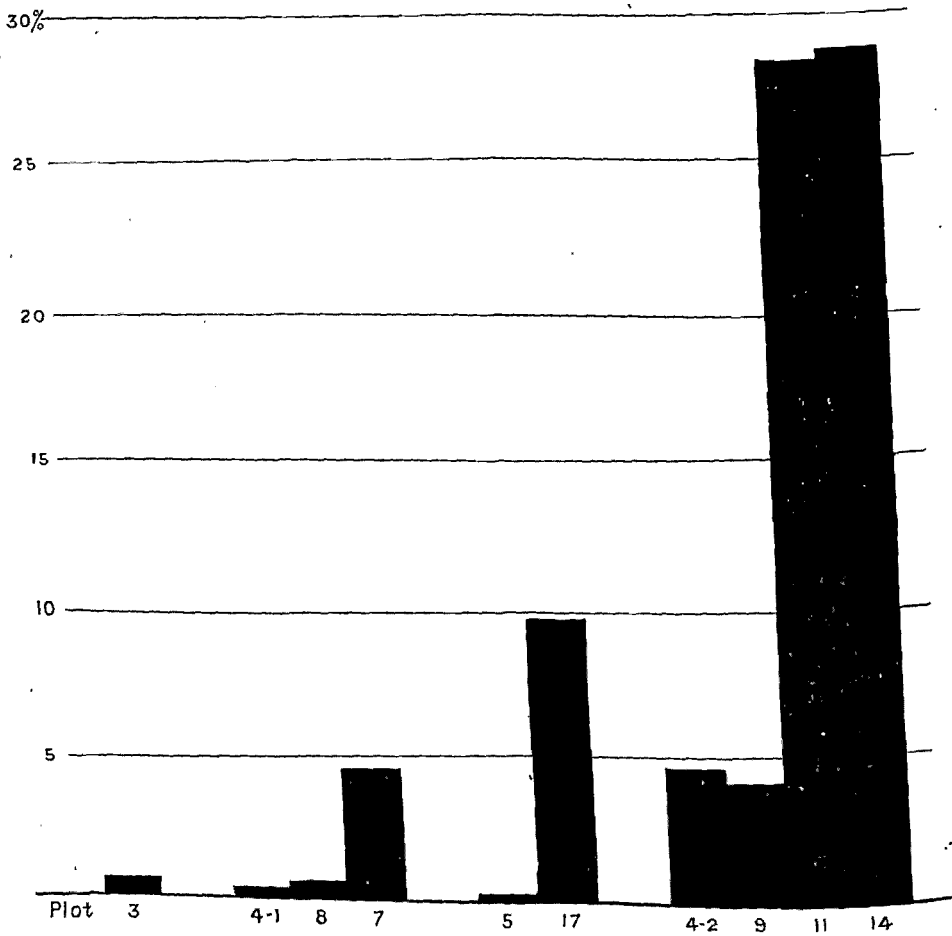


FIG. 34.—Percentage of *Alopecurus pratensis* in the Herbage of the Grass Plots. First Crop, Season 1903.

<i>Unmanured.</i>	<i>Minerals only.</i>	<i>Nitrogen only.</i>	<i>Nitrogen and Minerals.</i>
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts. 9. Complete } 11. Excess N. }
	8. No Potash.	17. Nitrate Soda.	
	7. Complete.		
			14. Complete ; Nit. Soda.

TABLE LXII.—Continued.

GRAMINEÆ—Continued.												
Years	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
<i>Bromus mollis</i> (Soft Brome Grass).												
1862	0.13	0.52	1.38	1.26	0.15	2.12	0.08	0.18	0.33	4.46	1.39	18.04
1867	0.05	0.43	0.43	0.98	...	6.27	...	2.26	0.20	0.11	0.04	17.69
1872	0.01	0.09	0.09	0.04	0.01	4.00	...	0.81	0.02	0.10	0.01	42.10
1877	...	0.01	0.01	0.01	...	1.65	...	0.15	...	...	...	8.02
1903	...	...	...	0.59	0.21	3.42	0.01	0.20	...	0.01	...	22.97
1914	...	...	0.21	2.11	0.67	2.89	0.22	0.14	...	...	...	5.15
<i>Lolium perenne</i> (Perennial Rye-grass).												
1862	6.37	9.28	5.92	3.12	4.58	7.49	3.33	5.09	6.47	4.20	1.37	13.80
1867	4.03	5.24	2.61	2.40	1.39	3.24	1.21	3.23	1.36	1.01	0.08	9.36
1872	2.37	3.12	1.92	0.59	0.69	4.42	0.97	2.94	0.70	1.11	...	5.55
1877	4.55	4.35	7.83	3.02	1.97	7.32	0.09	6.68	0.21	0.16	0.01	2.63
1903	...	0.02	0.12	0.11	0.12	0.02	...	0.54	...	...	...	0.04
1914	0.06	0.12	0.41	0.16	...	0.16	...	1.39	...	...	...	0.08
Total of other Species under 5 per cent. ( <i>Phleum pratense</i> , <i>Aira cæspitosa</i> , <i>Cynosurus cristatus</i> , <i>Festuca pratensis</i> , <i>elatior</i> , and <i>lohiacea</i> ).												
1862	0.23	0.47	2.47	0.27	0.45	0.17	0.37	0.61	0.46	1.42	1.91	0.88
1867	0.13	0.84	0.67	0.86	0.04	0.43	0.15	0.50	0.01	0.07	...	0.20
1872	1.13	1.11	1.36	0.21	0.03	0.72	0.03	0.36	0.04	0.04	...	0.10
1877	1.06	0.82	1.68	1.06	0.15	1.60	...	0.89	0.08	0.01	...	0.34
1903	0.27	0.06	0.57	0.58	0.08	0.04	0.04	0.28	...	...	...	...
1914	0.10	0.06	0.07	0.21	...	...	...	...	...	...	...	...
LEGUMINOSÆ.												
<i>Trifolium repens</i> (White or Dutch Clover).												
1862	0.53	0.61	2.70	3.08	0.01	0.04	0.01	0.05	0.01	0.01	...	0.01
1867	0.21	0.09	0.10	0.47	0.01	0.08	0.01	0.32	0.01	0.01	...	0.01
1872	0.38	0.48	0.25	1.77	0.01	0.06	0.01	0.09	...	...	0.01	...
1877	0.13	0.35	0.10	0.01	0.01	0.01	...	0.01	0.01	...	...	...
1903	0.14	2.82	1.25	4.27	1.68	6.74	...	0.18	0.01	...	...	0.01
1914	0.06	1.31	0.14	0.84	0.15	2.41	...	...	...	...	...	...
<i>Trifolium pratense</i> (Common Red Clover).												
1862	4.48	1.45	7.71	6.84	0.03	0.20	0.04	0.31	0.01	...	...	0.01
1867	2.11	0.17	1.13	4.75	0.01	0.04	0.01	0.26	...	...	...	0.01
1872	1.68	0.11	0.27	1.13	0.04	0.03	...	0.12	0.01	...	...	0.01
1877	2.09	0.30	0.36	1.55	0.08	0.31	...	0.11	...	0.01	...	...
1903	1.44	2.71	1.38	6.41	5.91	5.76	...	0.01	...	...	...	...
1914	1.96	2.98	5.86	4.69	5.11	2.57	0.11	0.14	...	...	...	...
<i>Lotus corniculatus</i> (Bird's Foot Trefoil).												
1862	1.83	0.41	0.15	1.27	0.01	0.02	0.05	0.05	...	...	...	...
1867	2.85	1.23	0.83	0.69	0.08	0.35	0.31	0.12	...	...	0.01	...
1872	5.94	3.71	3.51	0.19	0.06	0.03	0.41	1.16	...	...	...	...
1877	3.95	0.86	1.18	0.04	0.03	0.01	0.14	0.78	...	...	...	...
1903	3.64	7.28	12.24	0.43	2.30	0.01	...	2.28	...	...	...	...
1914	3.31	1.06	1.79	0.63	1.59	0.10	0.17	0.35	...	...	...	...

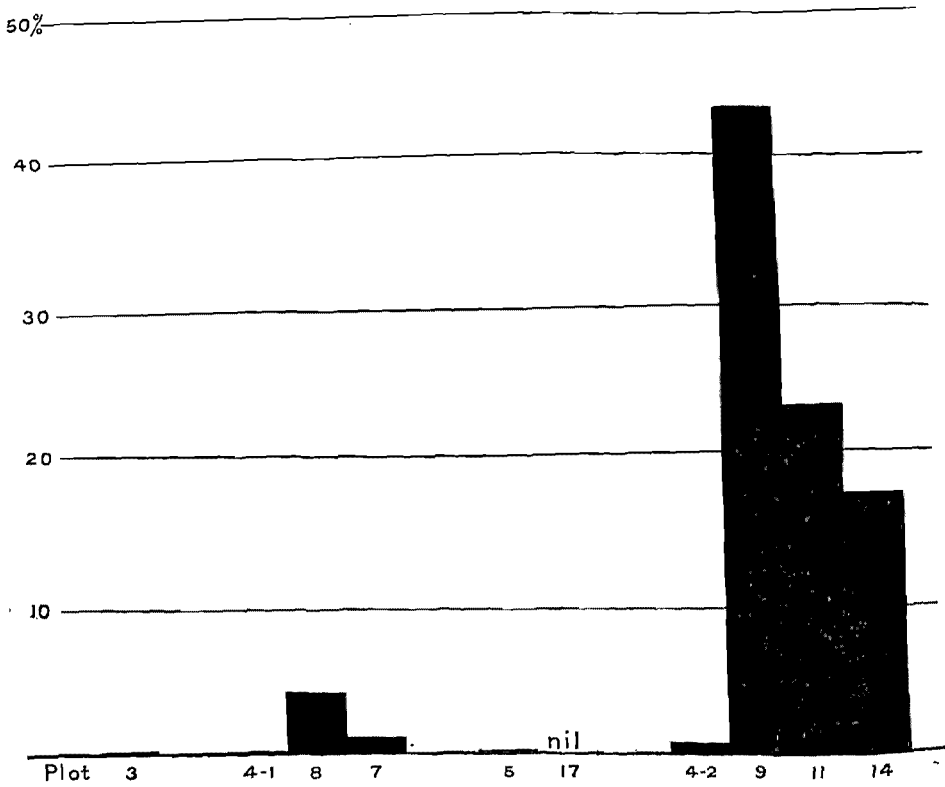


FIG. 35.—Percentage of *Arrhenatherum avenaceum* in the Herbage of the Grass Plots. First Crop, Season 1903.

<i>Unmanured.</i>	<i>Minerals only.</i>	<i>Nitrogen only.</i>	<i>Nitrogen and Minerals.</i>
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash
	8. No Potash.	17 Nitrate Soda.	9. Complete
	7. Complete.		11. Excess N.
			14. Complete; Nit. Soda.

} Amm.-salts.



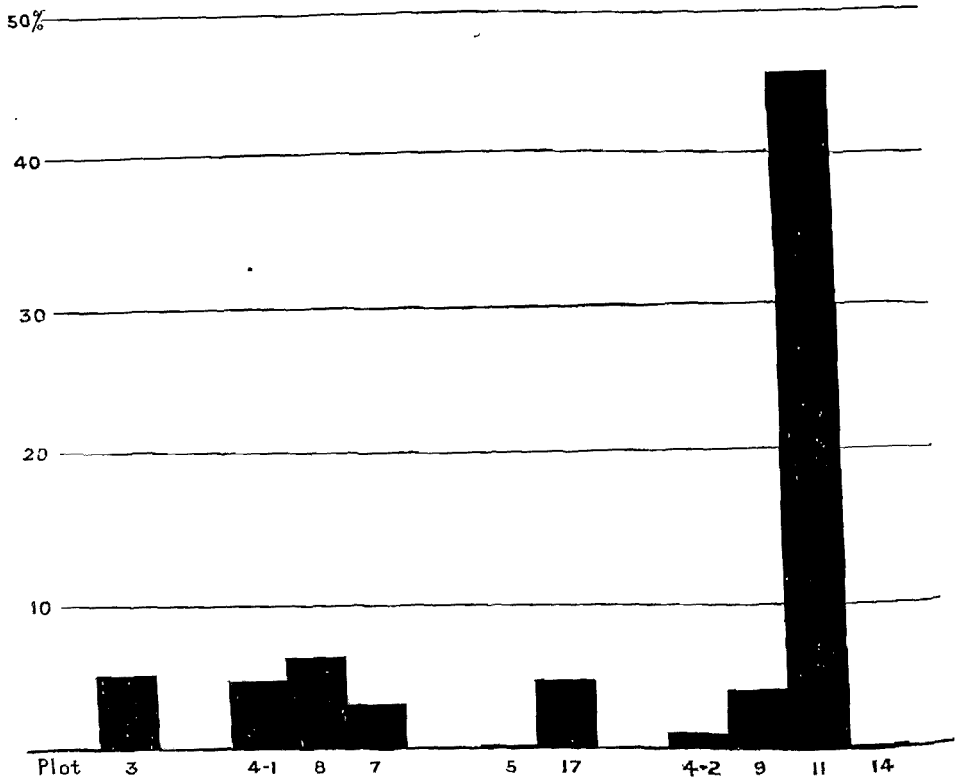


FIG. 38.—Percentage of *Holcus lanatus* in the Herbage of the Grass Plots. First Crop, Season 1903.

<i>Unmanured.</i>	<i>Minerals only.</i> 4-1. Superphosphate. 8. No Potash. 7. Complete.	<i>Nitrogen only.</i> 5. Amm.-salts. 17. Nitrate Soda.	<i>Nitrogen and Minerals.</i> 4-2. No Potash 9. Complete 11. Excess N. 14. Complete; Nit. Soda.
			}
			Amm.-salts.

TABLE LXII.—Continued.

MISCELLANEOUS SPECIES—Continued.												
Years	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
<i>Centaurea nigra</i> (Black Knapweed).												
1862	0.31	0.43	0.22	0.03	...	...	0.01	4.41	0.01	0.04	0.07	...
1867	0.59	0.36	0.45	0.79	1.40	0.17	2.43	4.10	0.21	...	...	0.01
1872	2.11	1.01	0.24	0.27	1.41	2.58	2.18	10.23	1.25	0.02	...	...
1877	1.06	0.66	0.76	0.10	0.44	0.90	0.53	2.32	0.85	...	...	...
1903	4.05	4.77	7.21	1.03	1.35	0.31	0.71	11.20	1.43	...	...	0.03
1914	8.70	8.64	9.21	6.84	6.07	0.94	6.96	8.02	0.13	...	...	...
<i>Achillea millefolium</i> (Yarrow or Milfoil).												
1862	1.53	1.42	0.93	1.69	3.34	2.53	1.33	2.14	1.77	1.95	1.45	0.24
1867	1.16	1.38	4.89	3.10	1.08	1.13	1.09	1.39	1.49	2.03	0.06	0.47
1872	1.78	5.38	9.75	5.23	4.09	2.60	1.05	2.91	1.75	1.50	...	0.21
1877	1.99	3.19	2.76	0.64	1.72	0.58	0.18	1.39	0.27	0.04	0.01	0.65
1903	2.67	1.30	3.50	8.95	7.62	9.95	0.04	2.82	0.01	0.37	...	0.12
1914	0.73	1.55	2.75	2.53	3.11	4.25	0.39	1.19	...	0.10	...	0.12
<i>Leontodon hispidus</i> (Rough Hawkbit).												
1862	0.06	0.59	...	...	...	0.01	...	0.02	...	...	...	...
1867	0.64	0.62	...	0.01	...	0.01	...	0.05	...	...	...	...
1872	1.27	0.11	...	...	...	...	...	0.07	...	...	...	0.01
1877	1.32	0.92	...	...	...	0.01	...	0.25	...	...	...	...
1903	5.93	14.66	0.85	...	...	...	...	3.68	...	...	...	...
1914	17.06	12.43	1.03	...	...	...	...	4.39	...	...	...	...
<i>Plantago lanceolata</i> (Ribwort Plantain).												
1862	7.34	5.63	0.71	0.23	0.06	6.92	0.10	3.35	0.04	0.01	...	0.18
1867	10.73	9.66	1.53	1.10	...	4.67	0.02	4.83	...	0.01	...	0.01
1872	2.66	3.13	0.34	0.07	...	0.23	...	2.41	...	...	...	0.01
1877	3.16	3.78	0.26	0.09	0.01	0.56	...	7.99	0.01	...	...	...
1903	1.98	2.49	5.85	0.05	0.09	0.20	...	10.70	...	...	...	...
1914	3.25	6.77	8.66	0.74	0.11	0.26	0.22	13.87	...	...	...	...
<i>Rumex acetosa</i> (Sorrel).												
1862	1.40	3.94	1.93	2.10	12.11	6.64	9.15	3.57	13.39	5.40	7.02	6.88
1867	1.76	5.47	7.86	8.88	24.27	7.34	15.94	7.53	8.42	10.89	3.96	1.11
1872	1.77	2.81	1.96	1.16	7.51	2.06	7.13	1.58	6.85	4.60	1.09	0.61
1877	1.87	3.37	5.84	6.67	7.66	5.79	2.13	2.56	3.09	3.60	2.25	4.40
1903	2.21	1.51	1.91	3.71	5.24	1.56	14.84	1.80	0.54	2.79	0.13	0.57
1914	0.34	0.68	0.55	0.21	0.26	0.21	1.34	0.35	0.51	4.37	...	0.52
Total of all other Miscellaneous Species.												
1862	4.79	3.35	2.45	3.18	2.37	2.53	1.49	0.66	0.95	0.82	0.25	0.27
1867	9.06	7.84	5.31	4.42	2.46	5.31	2.49	1.91	1.01	0.45	0.01	0.27
1872	6.42	6.38	4.98	2.97	3.24	11.54	3.35	4.11	1.07	0.16	0.02	0.23
1877	4.68	3.32	2.37	2.14	2.03	1.91	2.12	2.58	1.00	0.51	0.20	0.85
1903	6.49	3.95	6.92	6.83	4.25	1.13	1.99	6.67	4.38	0.69	0.02	0.69
1914	3.14	2.06	2.88	2.62	1.46	0.63	3.66	1.17	0.30	0.73	...	2.01

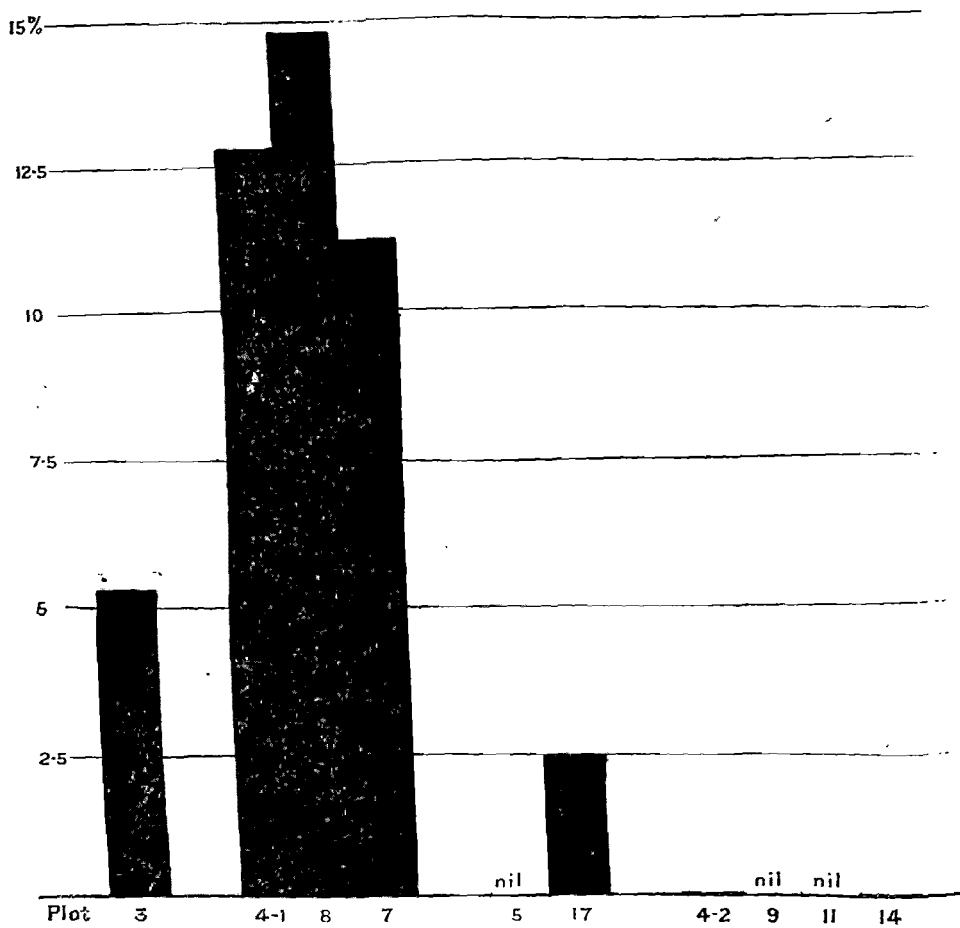


FIG. 37.—Percentage of *Trifolium repens*, *Trifolium pratense*, and *Lotus corniculatus* (together) in the Herbage of the Grass Plots. First Crop, Season 1903.

<i>Unmanured.</i>	<i>Minerals only.</i>	<i>Nitrogen only.</i>	<i>Nitrogen and Minerals.</i>
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-
	8. No Potash.	17. Nitrate Soda.	9. Complete } salts.
	7. Complete.		11. Excess N. }
			14. Complete; Nit. Soda.

TABLE LXII.—Continued.

SUMMARY.

TOTAL PER CENT. OF GRAMINEOUS, LEGUMINOUS, AND OF OTHER ORDERS.												
Years	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
Total of Gramineous Species.												
1862	70·61	74·96	71·69	64·65	80·52	78·26	86·32	81·36	80·31	88·59	89·38	89·52
1867	65·53	66·88	63·03	59·29	62·66	80·02	71·85	75·72	86·13	77·06	94·12	84·25
1872	68·66	67·03	71·56	48·82	79·23	78·76	84·70	73·27	88·65	92·19	98·84	92·87
1877	71·15	71·78	81·19	74·38	79·96	88·45	94·06	75·87	94·63	94·65	97·58	87·81
1903	52·23	43·00	43·50	41·75	35·61	50·05	82·37	56·01	93·65	95·90	99·82	85·64
1914	54·32	55·86	62·75	68·09	62·55	58·76	83·30	68·01	98·56	93·73	100·00	91·21
Total of Leguminous Species.												
1862	8·10	2·79	19·32	24·70	0·28	0·27	0·12	0·42	0·09	0·13	0·01	0·13
1867	5·35	2·83	8·88	12·69	0·10	0·51	0·34	0·70	0·04	0·16	0·01	0·39
1872	8·98	8·61	7·97	39·77	1·58	0·12	0·46	1·38	0·03	0·02	0·01	1·36
1877	8·54	5·53	4·01	18·71	6·68	1·80	0·19	0·91	0·04	0·41	...	0·76
1903	7·77	17·58	18·57	33·15	40·83	28·97	...	2·59	0·01	0·01	...	3·35
1914	5·78	7·46	10·65	16·91	24·23	32·74	0·45	0·56	...	...	...	4·00
Total of other Orders.												
1862	21·29	22·25	8·99	10·65	19·20	21·47	13·56	18·22	19·60	11·28	10·61	10·35
1867	29·12	30·29	28·09	28·02	37·24	19·47	27·81	23·58	13·83	22·78	5·87	5·36
1872	22·36	24·36	20·47	11·41	19·19	21·12	14·84	25·85	11·32	7·79	1·15	5·77
1877	20·31	22·69	14·80	11·91	13·36	14·75	5·75	23·22	5·33	4·94	2·47	11·43
1903	40·00	39·42	37·93	25·12	23·55	20·95	17·65	41·43	6·36	4·11	0·15	11·12
1914	35·58	33·56	25·77	14·63	12·35	7·34	12·69	30·25	1·44	5·30	...	3·80
Number of Species.												
1862	50	46	38	44	34	39	38	33	35	28	28	28
1867	43	46	42	42	32	39	36	47	30	29	18	30
1872	49	49	42	41	39	39	31	43	28	30	16	30
1877	52	45	48	44	38	43	29	49	26	27	15	27
1903	47	44	45	36	39	35	22	41	15	20	10	24
1914	40	33	34	32	32	28	31	30	15	14	7	18

VIII. *The Effect of Season.*

The hay crop probably fluctuates with the seasons more than any of the crops on arable land, because the land does not receive cultivation, which tends to regulate the supply of water to the plant, and especially to preserve it from wasteful evaporation during dry seasons. Not only does the gross weight of crop vary very much, but the character of the herbage alters considerably with the distribution of

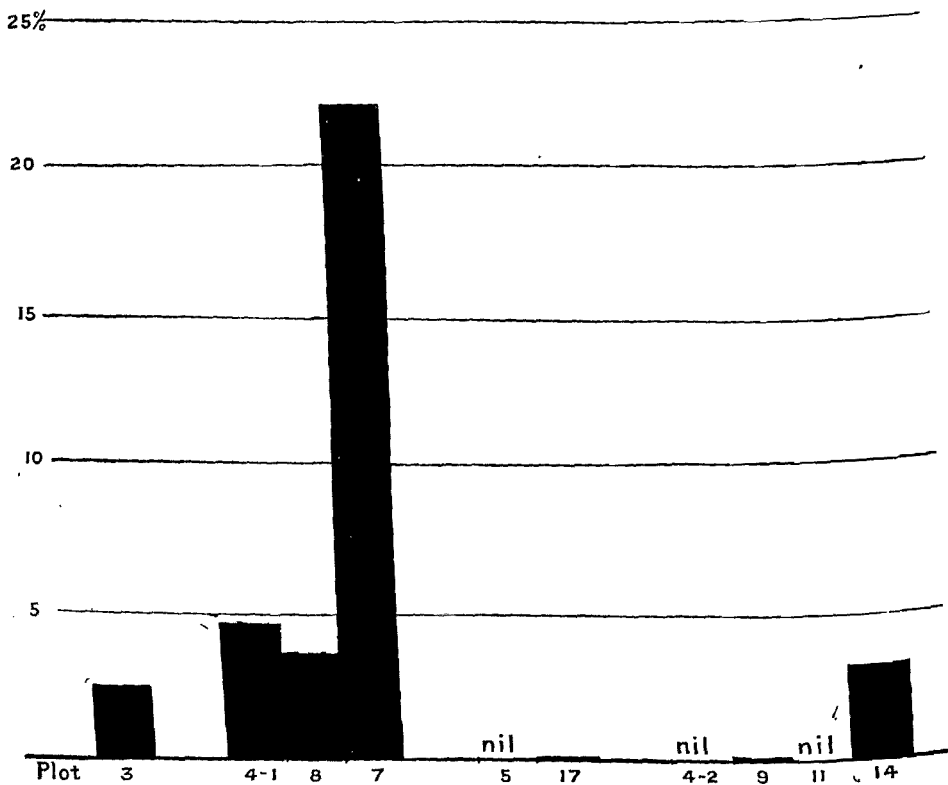


FIG. 88.—Percentage of *Lathyrus pratensis* in the Herbage of the Grass Plots.  
First Crop, Season 1903.

<i>Unmanured.</i>	{	<i>Minerals only.</i>	{	<i>Nitrogen only.</i>	{	<i>Nitrogen and Minerals.</i>
		4-1. Superphosphate.		5. Amm.-salts.		4-2. No Potash
		8. No Potash.		17. Nitrate Soda.		9. Complete
		7. Complete.				11. Excess N.
						14. Complete; Nit. Soda.

the rainfall and temperature. Thus the year 1902 with frequent light rains was especially favourable to the growth of the shallow-rooted *Lathyrus*, and other leguminous plants, the proportion of which was doubled or more on some of the plots. The Table LXIII. shows the monthly rainfalls for the seasons

TABLE LXIII.—*Rothamsted Park Hay. Seasons of highest and lowest Yields compared with Monthly Rainfall.*

Years.	Plot 9. Minerals, and 400 lb. Ammonium- salts.	Plot 14. Minerals, and 550 lb. Nitrate of Soda.	Rainfall.					Total, March to June.
			March.	April.	May.	June.		
10 Highest Yields on Plot 9.								
	Lb.	Lb.	Inches.	Inches.	Inches.	Inches.	Inches.	
1869	7700	8526	1.422	2.129	3.231	1.061	7.843	
1879	7668	5964	1.183	2.790	3.481	5.551	13.005	
1904	7473	7340	1.578	1.252	2.152	0.813	5.795	
1882	7266	7158	1.566	3.925	2.068	3.926	11.485	
1858	7172	5646	0.967	2.439	2.531	0.958	6.895	
1868	6622	7728	1.922	2.187	0.732	0.369	5.210	
1871	6576	6930	1.503	2.890	0.955	3.866	9.214	
1857	6422	...	1.495	2.171	1.088	2.227	6.981	
1862	6402	5718	3.061	2.843	2.909	3.407	12.220	
1856	6363	...	0.994	2.615	4.872	1.742	10.223	
Mean .	6966	6876	1.569	2.524	2.402	2.392	8.887	
10 Lowest Yields on Plot 9.								
	Lb.	Lb.	Inches.	Inches.	Inches.	Inches.	Inches.	
1893	1108	2592	0.424	0.249	1.221	0.999	2.893	
1896	2267	4437	3.754	0.952	0.476	2.250	7.432	
1901	2960	5061	2.565	2.511	1.806	0.841	7.723	
1874	3290	5484	0.652	2.141	1.187	1.593	5.573	
1870	3306	6300	1.789	0.488	1.324	0.979	4.580	
1881	3307	4248	2.152	0.997	1.376	1.633	6.158	
1887	3608	6324	1.755	1.194	2.354	0.709	6.012	
1865	3866	5292	1.435	0.426	3.048	0.914	5.823	
1888	3958	5070	3.125	2.143	1.276	4.867	11.411	
1900	4246	5556	0.982	1.332	1.080	2.634	6.008	
Mean .	3192	5027	1.861	1.243	1.515	1.742	6.361	

giving the highest and the lowest yields on the completely manured Plot 9, also the corresponding yields on Plot 14, which receives an equivalent amount of nitrate of soda instead of the ammonium-salts on Plot 9. Although in a general way it can be seen that a wet late spring is on the

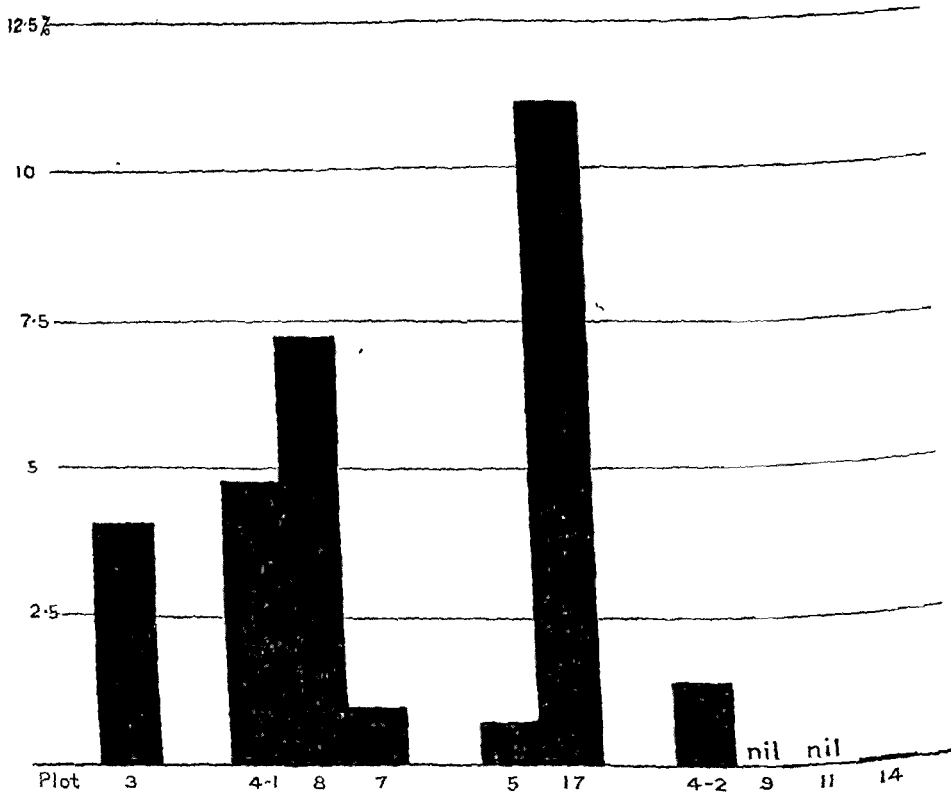


FIG. 39.—Percentage of *Centaurea nigra* in the Herbage of the Grass Plots.  
First Crop, Season 1903.

<i>Unmanured.</i>	<i>Minerals only.</i>	<i>Nitrogen only.</i>	<i>Nitrogen and Minerals.</i>
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts. 9. Complete } 11. Excess N. }
	8. No Potash.	17. Nitrate Soda.	
	7. Complete.		
			14. Complete; Nit. Soda.

whole more favourable to the leguminous plants, it is not easy to trace any connection between the weather, as judged from the meteorological records, and the character of the crop, since so much depends upon the frequency of the rainfalls and the relative predominance of particular species when the most favourable period for growth sets in. In a dry spring the plots receiving nitrate have a great advantage over those receiving ammonium-salts, but this is due to the deep-rooted herbage they carry, rather than to any direct effect of the manure used. As regards rainfall, the critical months are April and May: the rainfall of March appears to affect the crop but little.

#### PRACTICAL CONCLUSIONS

1. It is better to lay up the same land for hay each year, grazing the aftermath only, and, in the same way, always to graze other land, rather than graze and hay in alternate years. In this way we obtain the fullest development of those grasses and clovers which are suited to haying and grazing respectively.

2. For the same reason the system of manuring once adopted should be varied as little as possible, for even manures as similar as nitrate of soda and sulphate of ammonia encourage different kinds of grass.

3. On poor land any large expenditure on manures will be wasted; the character of the herbage must be slowly reformed; a full manuring is only utilised when there are plenty of strong and vigorous grasses or clovers among the vegetation.

4. Land which is growing hay requires a manure which is mainly nitrogenous, whilst pasture requires a mineral manuring.

5. On strong loams, with a good mixed herbage, a dressing of 10 to 15 tons of farmyard manure should be given every fifth year. In the other years a winter manuring (January or February) of 2 cwt. per acre of superphosphate (basic slag on strong clay soils), and 3 cwt. of kainit, with  $1\frac{1}{2}$  cwt.

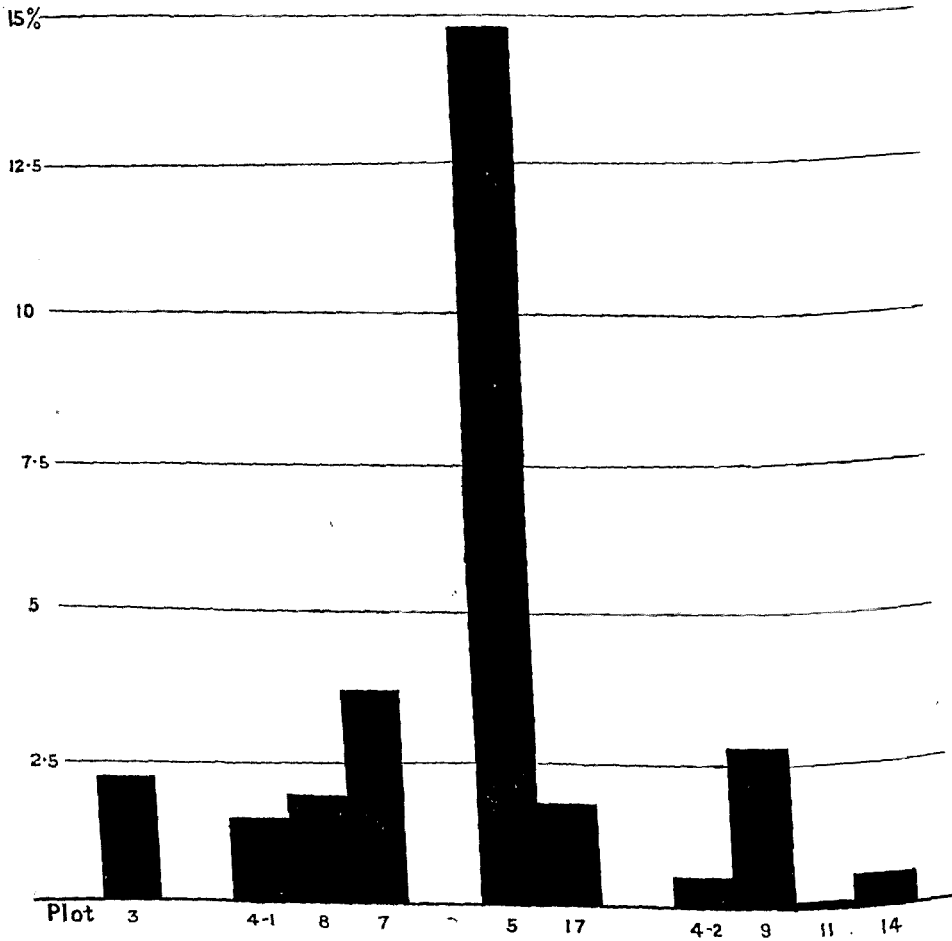


FIG. 40.—Percentage of *Rumex acetosa* in the Herbage of the Grass Plots.  
First Crop, Season 1903.

Unmanured.

Minerals only.  
4-1. Superphosphate.  
8. No Potash.  
7. Complete.

Nitrogen only.  
5. Amm.-salts.  
17. Nitrate Soda.

Nitrogen and Minerals.  
4-2. No Potash } Amm.-  
9. Complete } salts.  
11. Excess N. }  
14. Complete; Nit. & Soda.

of nitrate of soda when the grass begins to grow, will be remunerative.

6. On light dry soils, either sandy or chalky, the nitrogenous manures are the most important; dung, and cake-feeding the aftermath, will best build up a vigorous herbage, and until this is done it will not be wise to spend much money on artificial manures: 1 cwt. of nitrate of soda, 1 cwt. of superphosphate, and 3 cwt. of kainit, being about the best proportion in which to employ them.

7. On all old grass land an occasional dressing of ground lime, at the rate of half a ton per acre, applied in the early winter (best in the year following the dunging), will sweeten the herbage and utilise the reserves of past manuring.

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## CHAPTER X

### EXPERIMENTS UPON CROPS GROWN IN ROTATION, AGDELL FIELD

- I. The Unmanured Plots.
  - II. Effect of the Manures.
  - III. The Effect of the Growth of Clover or Beans on the succeeding Crops.
  - IV. Effect of Manurial Residues on subsequent Crops.
  - V. Gain or loss of Manurial Constituents to the Land.
- Practical Conclusions.                      References.

THE Agdell field, which was put under experiment in the year 1848, differs from the other Rothamsted fields in that it is farmed on a four-course rotation of Swedes, barley, clover (or beans) or fallow, and wheat, instead of growing one crop continuously. It is divided into three main plots, one of which (O) has received no manure, the second (M) mineral manures only (superphosphate alone in the first nine courses), and the third (C) a complete manure, containing the same minerals, but also nitrogen in the form of rape cake and ammonium-salts. The manures are applied to the Swedes only, the other three crops of each course being grown without manure. Each of the three plots was originally subdivided into four, so as to obtain the following comparisons:—(1) Half the plots carried clover or beans as the third crop of the course, and half the plots were bare fallow. This showed the effect of introducing the leguminous crop into the rotation, as compared with the bare fallow. (2) From half the plots the root crops grown in the first course were carted; on the other half the roots were eaten on the land by sheep; or rather, since the land is unsuited to winter folding, the roots were chopped up and ploughed in. This showed the effect on the succeeding crops of barley, etc., of the return of a root crop to the land by folding.

In 1903 the second division was abolished, and since then the three plots have been divided into two only, clover and fallow respectively in the third year: the roots are carted from all plots. Table LXIV. shows the mean results for the five courses 1884-1903 and the two courses 1904-1911.

TABLE LXIV.—Crops grown in rotation, Agdell Field. Mean produce per acre over the five Courses 1884-1903 and the two Courses 1904-1911.

	O.—Unmanured.				M.—Mineral Manures.				C.—Complete Mineral and Nitrogenous Manure.			
	Roots Carted.		Roots Fed.*		Roots Carted.		Roots Fed.*		Roots Carted.		Roots Fed.*	
	Fallow.	Beans or Clover.	Fallow.	Beans or Clover.	Fallow.	Beans or Clover.	Fallow.	Beans or Clover.	Fallow.	Beans or Clover.	Fallow.	Beans or Clover.
1884-1903												
Roots (Swedes), Cwt.	19·9	7·5	25·7	10·6	177·7	213·4	196·6	245·1	416·9	407·2	405·4	370·1
Barley Grain, Bush..	15·6	15·0	17·6	15·1	13·6	19·9	17·7	28·9	19·6	27·6	29·5	34·1
Barley Straw, Lb. .	1204	1303	1322	1213	1033	1422	1278	1961	1434	1959	2258	2621
Clover Hay, Cwt.* .	...	9·0	...	9·7	...	33·2	...	37·7	...	33·8	...	41·8
Bean Corn, Bush.† .	...	15·7	...	16·0	...	28·0	...	28·6	...	19·7	...	19·5
Bean Straw, Lb.† .	...	971	...	979	...	1894	...	1887	...	1273	...	1304
Wheat Grain, Bush..	27·0	25·6	27·2	25·0	31·9	38·4	32·9	41·1	33·8	39·4	36·5	38·8
Wheat Straw, Lb. .	2424	2266	2475	2147	3176	3584	3311	3859	3382	3679	3924	3805
1904-1911												
Roots, Cwt. . . . .	28·4	9·4	...	...	184·1	230·4	...	...	430·9	335·2	...	...
Barley Grain, Bush..	13·4	8·6	...	...	16·6	18·9	...	...	24·9	32·3	...	...
Barley Straw, Lb. .	975	824	...	...	1297	1582	...	...	1779	2299	...	...
Clover Hay, Cwt. . .	...	10·7	...	...	...	53·1	...	...	...	43·1	...	...
Wheat Grain, Bush..	20·1	22·9	...	...	25·4	37·4	...	...	29·1	33·6	...	...
Wheat Straw, Lb. .	2341	2715	...	...	3204	4655	...	...	3617	3785	...	...

\* Mean of 3 courses.

† Mean of 2 courses.

CROPS IN ROTATION, AGDELL FIELD

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## I.—THE UNMANURED PLOTS.

The various crops as grown in rotation are affected very differently by the absence of manure than the same crops are when grown continuously. In the case of the cereals, the crop is maintained far better on the rotation plots that are unmanured than on the similar plots in Broadbalk and Hoosfield, where wheat and barley are grown continuously. The root crop, however, falls to a minimum in the absence of manure, and the mere act of growing in rotation is quite unable to provide sufficient nutriment for the needs of even a small crop. The clover and bean crops also grow very indifferently on the unmanured plots notwithstanding the rotation, though the falling-off is not so marked as in the case of the Swedes.

Although a rotation of crops, by alternating plants of different requirements and different habits (some deep and

TABLE LXV.—*Crops grown in rotation, Agdell Field. Comparison of yield at the beginning of the Experiment, and in later years (1852-1867, 1884-1903, and 1904-1911). Average Total Produce per acre of four Unmanured and four Manured Plots.*

Courses.	Swedes.		Barley.		Beans (or Clover).		Wheat.		Unmanured Produce compared with that by Complete Manure = 100.			
	Un- manured.	Complete Manure.	Un- manured.	Complete Manure.	Un- manured.	Complete Manure.	Un- manured.	Complete Manure.	Swedes.	Barley.	Beans (or Clover).	Wheat.
	Cwt.	Cwt.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.				
2nd to 5th	19·3	263·7	4190	5972	2002	3545	5526	6756	7·3	70·2	56·5	81·8
10th to 14th	19·7	435·4	2163	3662	1450	3592	3979	6033	4·5	59·1	40·4	66·0
15th & 16th*	19·0	383·1	1910	3843	1203	4826	3958	5766	4·7	49·7	24·9	68·6

\* Averages for Plots 1 and 2 Complete Manure, and for Plots 5 and 6 Unmanured.

some shallow-rooting), is able to utilise more thoroughly the nutriment supplied as manure and the initial resources of the soil, it is evident that it cannot enable the crops to dispense with supplies of manure, but that its value largely depends upon the opportunities it affords for cleaning the land and maintaining a proper system of tillage. Table LXV. shows

MAINTENANCE OF YIELD WITHOUT MANURE 193

a comparison between the crops on the unmanured and the completely manured plot for the four courses from 1852-1867, the five courses from 1884-1903, and the two courses from 1904-1911, from which an idea can be obtained of how far

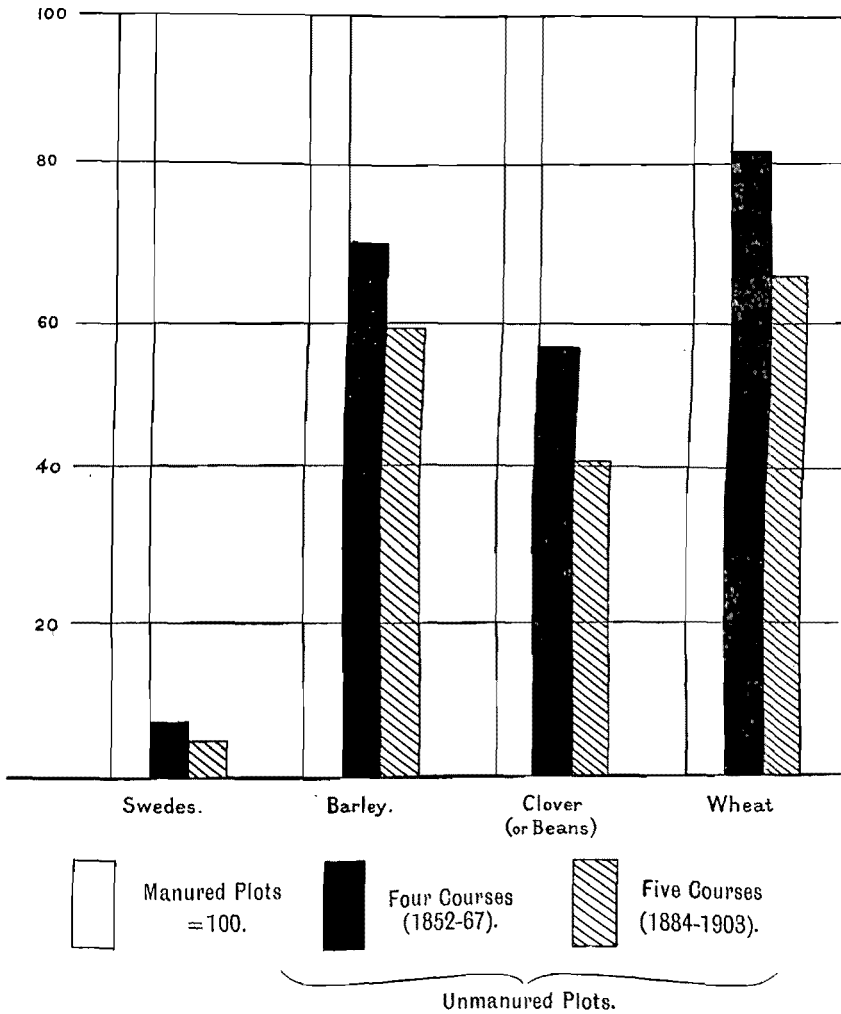


FIG. 41.—Crops Grown in Rotation. Relative Yield on Manured and Unmanured Plots in the earlier and later years of the Experiment.

each crop has been affected during the whole fifty-nine years of the experiment by the continued absence of manure. The same results are shown graphically in Fig. 41.

Since 1884 (Table LXVI.) the crop of Swedes on the unmanured plots has averaged only 15.0 cwt. per acre, and the roots have lost the appearance of Swedes, becoming tap-roots

with hardly any development of bulb. The crop, indeed, fell away to nothing as soon as the manure was discontinued; it was less than 8 per cent. of the crop on the manured plots during the first four courses, and it has fallen to about half that quantity during the later five courses. Swedes have thus very little power of growing upon the reserves of nutriment in the soil, and they are almost wholly dependent upon an immediate supply of manure.

The barley has yielded on the unmanured plots 14·5 bushels of grain and 10·9 cwt. of straw per acre during the last seven courses. This amounts to about 59 per cent. of the yield on the manured for the 10th to the 14th courses, and to 49·7 per cent. for the 15th and 16th courses, whereas for the first four courses the yield on the unmanured plots was about 70 per cent. of that of the manured plots. As compared with the corresponding plots in the same years in Hoos field, where barley is grown continuously, the yield of barley has been much better maintained when grown in rotation. On the Hoos field in the later years the production of the unmanured plots has fallen to 26 per cent. of that of the manured plots, while the rotation barley on the unmanured had only fallen to about 50 per cent. of that on the manured plots, the same years being compared in each case.

On the Rothamsted land it is not found desirable to grow clover every four years, so only six clover crops have been taken during the course of the experiment, beans having been substituted in the other cases. On these leguminous crops the absence of manure has had a very marked effect; the production, which was nearly 60 per cent. of the manured plots in the earlier courses, has fallen to 24 per cent. in the later ones. Thus the leguminous crops are much more affected by the cropping out of the land than is the barley.

The wheat is better able to resist the deterioration of the fertility of the soil than any of the other crops are. The average production during the later courses has been 24·8 bushels per acre on the unmanured plots, as compared with

## WHEAT BEST STANDS ABSENCE OF MANURE 195

11·0 bushels per acre on the unmanured plot in Broadbalk growing wheat continuously, and with 16·9 bushels on the similarly unmanured plot where wheat is grown after a bare fallow. In the earleir period on the rotation field the unmanured plots yielded 82 per cent. of the wheat on the manured plots, but in the later period the production without manure had fallen to less than 70 per cent. of that on the manured plots, whereas in the corresponding later years of the continuous wheat-field the production on the unmanured plot has fallen to 29 per cent. of that on the manured plot. It is clear that the progressive cropping out of the soil is telling upon the wheat, though it will take a very long time before the crop grown in rotation is reduced to the level of the unmanured land that is continuously cropped with wheat.

### II.—EFFECT OF THE MANURES.

The three main plots into which the experimental field is divided receive the following manurial treatment per acre :—

O. Unmanured continuously.

M. 3½ cwt. superphosphate, 500 lb. sulphate of potash, 100 lb. sulphate of soda, and 200 lb. sulphate of magnesia for the Swedes.

C. Minerals as on Plot M., together with 200 lb. ammonium-salts and 2000 lb. rape cake for the Swedes.

TABLE LXVI.—*Effect of Manure on Crops grown in rotation, Agdell Field. Average produce per acre over the seven Courses, 1884-1911.*

	O.	M.	C.
	Unmanured. 5 and 6.	Mineral Manure. 3 and 4.	Complete Manure. 1 and 2.
Roots (Swedes) . . . . Cwt.	15·0	201·4	373·6
Barley Grain . . . . Bush.	14·5	19·4	28·0
Barley Straw . . . . Cwt.	10·9	12·8	18·6
Clover Hay* . . . . Cwt.	9·9	42·3	39·9
Bean Corn† . . . . Bush.	15·8	28·2	19·5
Bean Straw† . . . . Cwt.	8·7	16·9	11·5
Wheat Grain . . . . Bush.	24·8	34·7	35·5
Wheat Straw . . . . Cwt.	21·3	32·2	33·0

\* Average of 7 courses.

† Average of 2 courses.

It should be remembered that each of these three plots was further subdivided into four quarter plots, in the first place the third crop may be clover or a bare fallow, and again the roots were carted off or fed on the land. Now each plot is divided into two half plots, as the roots are carted in all cases.

The effect of the mineral manures without nitrogen is very marked on the roots; during the last seven courses the crop averaged 201 cwt. per acre, as against 15 cwt. per acre only on the unmanured plot. Table LXIV. shows that even on the most impoverished of the quarter plots, that from which the roots were always carted and where a bare fallow was taken after the barley, the production amounted to 178 cwt. from 1884-1903, although the plot had been receiving no nitrogen for thirty-six years previously, nor had any residues of the previous crops, which would contain nitrogen, been returned to the ground. Where the roots had been put back, and where also a leguminous crop was taken in the rotation, the crop amounted to 245 cwt., the increase being due to the extra nitrogen thus returned to the soil. These results illustrate the great dependence of the Swede crop upon a plentiful supply of mineral, and especially of phosphatic, manures; the latter in particular seem to stimulate the development of fibrous roots, thus enabling the plant to utilise the resources of the soil. Again, the cultivation to which the land is subjected for the Swede crop is calculated to nitrify reserves of nitrogenous material in the soil and render the plant more or less independent of a direct supply of nitrogen. Thus, in ordinary farming practice with the land in good condition the Swede crop only requires a small nitrogenous dressing, but should always have a comparatively large amount of phosphoric acid, in order to enable it to make the most of the reserves in the soil and of the dung which is generally used with this crop.

The effect of the mineral dressing has been much less marked on the barley than on the roots; it has only increased the average

crop from 14.5 to 19.4 bushels per acre. This increase again is chiefly found on the plots growing clover and beans, and so receiving nitrogen collected from the air; the two quarter plots which were fallowed after the barley, actually grew till 1903 less than the corresponding unmanured plots. On these latter plots the preceding growth of a comparatively large crop of roots has removed so much nitrogen that the soil is left poorer than on the wholly unmanured plot, which has been taxed less severely, though both are alike in receiving no supply of nitrogen during the whole course of the rotation. From this we may conclude that, in the absence of nitrogen, mineral manures are of no use to the barley crop, the magnitude of which will depend on the amount of nitrogen available, even when the mineral resources of the soil have been considerably drawn upon. In other words, with barley on unmanured land nitrogen starvation sets in long before the deficit in minerals is felt, the reverse being the case with Swedes.

Coming to the leguminous crop, the mineral manures have a very powerful effect, although they are applied a year before the clover is sown and two years before the crop is grown. The increase brought about is from 9.9 to 42.3 cwt. of clover hay, and in the case of beans, from 15.8 bushels of corn and 8.7 cwt. of straw to 28.2 bushels of corn and 16.9 cwt. of straw. This illustrates well the generally accepted fact that the leguminous plants are in the main independent of manurial sources of nitrogen, which element they are able to draw from the atmosphere, especially when they are provided with plenty of mineral plant-food.

In considering the wheat crop, it is necessary to distinguish between the plots which have previously grown clover or beans and those which have been fallowed, because in the former case there has been such an accumulation of nitrogen in the soil that the succeeding wheat crop is very much stimulated. It will be seen that the crops on the fallowed portions average about 25.4 bushels per acre, as against 20.1 bushels per acre on the corresponding unmanured plots, an increase

which must in the main be set down to the mineral dressings received three years earlier in the rotation. Where clover or beans are grown the crop mounts up to nearly 38 bushels per acre, or to the maximum grown even on the plots receiving nitrogen as well as minerals, so thoroughly have the leguminous plants done their work of accumulating nitrogen for the succeeding crop of wheat.

The application of the nitrogen (141 lb. in the shape of rape cake and ammonium-salts) to the Swedes has nearly doubled the crop, the average during the last seven courses having been 18 tons, as against less than 10 tons with the minerals only. Dependent as the Swede crop has been shown to be upon the minerals, the soil of the plots receiving no nitrogenous manure has been so far depleted that nitrification of the reserves of humus still remaining in the soil is not able alone to supply enough available nitrogen for the needs of the crop, as is shown by the increased yield produced by a direct application of nitrogenous manure.

The effect of the nitrogen applied to the Swedes is still very palpable in the barley crop, the yield of which is about 40 per cent. larger on the completely manured plots than on the plots receiving no nitrogen. Coming to the leguminous crop, the nitrogen has no effect; the clover is not better, and the beans are very distinctly worse where it has been applied. This affords very strong evidence of the extent to which leguminous plants are able to feed themselves with nitrogen from the atmosphere and become independent of nitrogen in the soil, an excess of which may even be injurious to their growth.

The manner in which accumulations of nitrogen in the soil interfere with the growth of leguminous plants is curiously seen in another way on this field: one of the commonest weeds among both the barley and the wheat on the unmanured plots and on those receiving only minerals is the little leguminous Black Medick (*Medicago lupulina*), which often almost entirely covers the surface of the ground towards harvest time. This plant, however, is much less abundant, and indeed is

hardly to be seen, on the other plots which receive nitrogen for the Swedes, although no nitrogen has been applied during the years in which the plant in question is growing.

The wheat, which comes last in the rotation, still shows some effect for the nitrogen applied three years previously. If we consider the fallow portions only, there are about 3 bushels more grain produced by the residue of the nitrogenous manuring, so dependent is the wheat crop upon a supply of

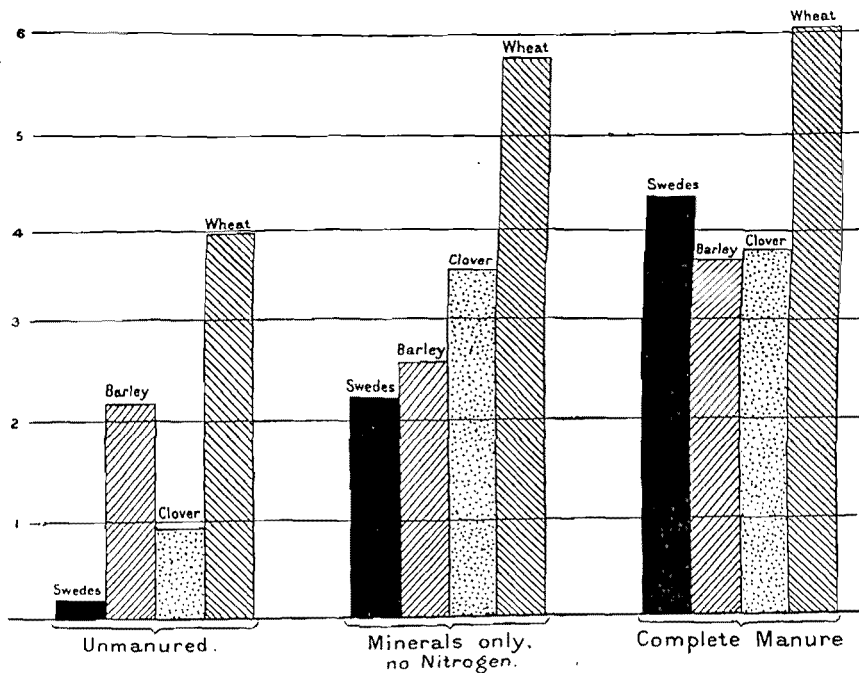


FIG. 42.—Effect of Manure upon Crops grown in Rotation. Total Produce. Averages of Five Courses (1884-1903). Swedes in 100 cwt.; Barley and Wheat in 1000 lb.; and Clover in 10 cwt.

nitrogen. On the portions which grow beans or clover the wheat crop gains so much from the nitrogenous material left by the stubble of these leguminous crops that the effect of the previous nitrogenous manuring is no longer apparent, the average crop being actually highest on the portions receiving only minerals, thus corresponding with the varying yields of the previous leguminous crops rather than with the direct nitrogenous manuring.

Fig. 42 shows in a graphic form the effect of these three

systems—no manure, minerals without nitrogen, and a complete manure—on the successive crops in the rotation.

### III.—THE EFFECT OF THE GROWTH OF CLOVER OR BEANS ON THE SUCCEEDING CROPS.

It has already been stated that one of the main objects of the experimental field is to compare the results of growing a crop like beans or clover as the third item in the rotation instead of taking a bare fallow. Of course, historically, this change from bare fallow to clover marks one of the great advances in agricultural practice, but its complete justification has only been possible in the last few years, since the power of the leguminous plants to fix atmospheric nitrogen has been known. In the Agdell field clover has been grown seven times and beans eight times during the period under experiment. Table LXVII. shows the average crops of each separately, together with the total produce of the succeeding wheat crop on the fallowed and cropped portions respectively.

TABLE LXVII.—*Crops grown in rotation, Agdell Field. Effect of Clover or Beans on the following Wheat Crops. Total produce per acre.*

	Clover Crops.*	Wheat.†			Bean Crops.‡	Wheat.§		
		After Fallow.	After Clover.	Difference due to Clover.		After Fallow.	After Beans.	Difference due to Beans.
	Cwt.	Lb.	Lb.	Per cent.	Lb.	Lb.	Lb.	Per cent.
O. Unmanured	14·0	4028	3696	- 3·2	1838	4907	4373	- 10·9
M. Mineral Manure.	47·0	5147	6052	+ 17·6	2615	5528	5447	- 1·5
C. Complete Manure	50·1	5493	6093	+ 0·9	3177	6092	5929	- 2·7

\* 7 years (1874, '82, '86, '94, 1902, 1906, and 1910).

† 7 years (1875, '88, '87, '95, 1908, 1907, and 1911).

‡ 8 years (1854, '58, '62, '66, '70, '78, '90, and '98).

§ 8 years (1855, '59, '63, '67, '71, '79, '91, and '99).

The beneficial effect of the clover crop is at once apparent from the table. On the unmanured plot the clover crop is a small one, and apparently the nitrogen it has collected from the atmosphere is not sufficient to compensate for the better tilth and nitrification which are induced by a bare fallow. On the plot receiving mineral manures a large bulk of clover is grown, averaging 47 cwt. of clover hay, and notwithstanding that all

this is removed from the land the nitrogen accumulated in the roots and stubble is sufficient to raise the total produce of the wheat from 5147 lb. to 6052 lb., or by 17·6 per cent. On the completely manured plot a still greater crop of clover is obtained, averaging 50 cwt., and this still further increases the wheat crop from 5493 lb. to 6093 lb., or by 0·9 per cent.

With the beans an entirely different result appears; on each of the three plots the bare fallow proves a better preparation for wheat than does the bean crop, after which in all cases the wheat crop is somewhat diminished. On the unmanured plot the average diminution is 11 per cent., on the mineral manured plot it is 1·5 per cent., and on the completely manured plot it is 2·7 per cent. In other words, the bean crop, which is pulled, not cut, does not leave behind any great amount of nitrogen gathered from the atmosphere—not sufficient to compensate for the absence of the summer tillage that the bare fallow receives. These results are even more clearly seen when the crops following the largest clover and bean crops are considered, the results of which are set out in Table LXVIII.

TABLE LXVIII.—*Crops grown in rotation, Agdell Field. Effect of the largest Clover or Bean Crop on the following Wheat Crop. Total produce per acre.*

	Clover, 1910.	Wheat, 1911.			Beans, 1862.	Wheat, 1868.		
		After Fallow.	After Clover.	Difference due to Clover.		After Fallow.	After Beans.	Difference due to Beans.
	Cwt.	Lb.	Lb.	Per cent.	Lb.	Lb.	Lb.	Per cent.
O. Unmanured	17·4	3876	4052	+ 4·5	3603	7222	5231	- 26·9
M. Mineral Manure	64·1	5338	6292	+ 17·9	4033	7910	6090	- 23·0
C. Complete Manure	76·6	5454	6163	+ 13·0	5755	8792	7674	- 12·7

In 1910 the clover on the unmanured plot produced only 17·4 cwt. of hay and caused a barely perceptible increase in the total produce of the wheat, amounting to only 4·5 per cent. On the plot receiving a complete mineral manure, however, a very large crop of clover was obtained, 64·1 cwt. per acre, and this

increased the total produce of the wheat crop from 5338 lb. to 6292 lb., or by 17·9 per cent., the extra grain amounting to 6 bushels per acre. On the completely manured plot a still greater clover crop was obtained, 76·6 cwt. of hay; this in its turn increased the total produce of the wheat crop from 5454 lb. to 6163 lb., or by 13 per cent. The increase of grain in this case was 5 bushels per acre.

Turning now to the bean crop of 1862, the largest of the series, we find that it was also followed by a specially good wheat crop in 1863, but that in each case the wheat was less after the beans than after the bare fallow, the diminution amounting to 26·9 per cent. on the unmanured plot, 23 per

TABLE LXIX.—*Crops grown in rotation, Agdell Field. Effect of Clover (or Beans) on the succeeding Swede and Barley Crops. Mean of six Courses—Produce per acre.*

	10th-15th Courses (1884-1907). Clover (or Beans).	11th to 16th Courses (1888-1911).					
		Root Crops.			Barley.		
		After Fallow.	After Clover or Beans.	Increase due to Clover or Beans.	After Fallow.	After Clover or Beans.	Increase due to Clover or Beans.
	Lb.	Cwt.	Cwt.	Per cent.	Lb.	Lb.	Per cent.
O. Unmanured . . . . .	1284	23·1	10·8	- 62·5	2082	1992	- 4·3
M. Mineral Manure . . . . .	4019	195·3	244·6	+ 25·2	2135	2926	+ 37·1
C. Complete Manure . . . . .	3170	453·8	409·4	- 9·7	3215	3980	+ 23·7

cent. on the plot receiving superphosphate only, and 12·7 per cent. on the completely manured plot. These results can only be interpreted by supposing that the large bean crop, so far from obtaining all the nitrogen it required from the atmosphere, drew extensively upon the resources in the soil, consequently, instead of enriching the land like the clover crop it actually left it poorer than it was before.

Since the growth of clover has such a marked effect on the subsequent crop of wheat, the question of the duration of the benefit caused by the clover naturally arises. Table LXIX. gives a summary of the results during the last six courses

which have been completed, showing a comparison of the roots and the barley after fallow and after clover (or beans) respectively—*i.e.*, of the crops coming in the second and third years after the growth of the leguminous crop.

The results show that where the manuring is with minerals only the effect of the leguminous crop is very marked both in the roots and in the barley, *i.e.*, that the nitrogen introduced by the growth of clover is operative, not only in the wheat which follows it, but also in the roots and the barley which follow the wheat; in fact, in all the crops of the rotation until the clover comes round again. The root crop is increased by 25 per cent., and the barley crop by about 37 per cent., the magnitude of the increase being due to the fact that the leguminous crop represents the only source of nitrogen on this plot. When, however, the manure put on to the Swedes contains nitrogen, the effect of the nitrogen stored up in the soil by the clover crop two seasons before is masked by the fresh nitrogen introduced, and produces no increase of crop. It, however, becomes manifest in the succeeding barley crop, which is 23 per cent. greater on the portion cropped with leguminous plants than on the fallowed portion, so that we can say the value of a clover crop is felt for three years after its growth in all the crops of the rotation, even under the ordinary conditions of farming when a manure introducing large quantities of nitrogen is used once during the rotation. Of course it must be remembered that the above mean results are for the six last courses after ten rotations had been completed, and that as the benefit is doubtless somewhat cumulative from one rotation to the next, the results represent not so much the value of a single clover crop as of its constant introduction into the rotation instead of taking a bare fallow. On the other hand, if we compare the effects of the single crops, we find that the crops of beans, just as they show little effect in the succeeding wheat crops, so also they cause but a small benefit to the roots and barley coming later still. The continuous enrichment of the land shown in the above table has therefore been due in the

main to the seven occasions on which clover has been taken during the sixteen complete courses of the experiment.

The diagram, Fig. 43, shows in a graphic form the benefit to the whole rotation of the growth of clover, even when the root crop receives nitrogenous manures.

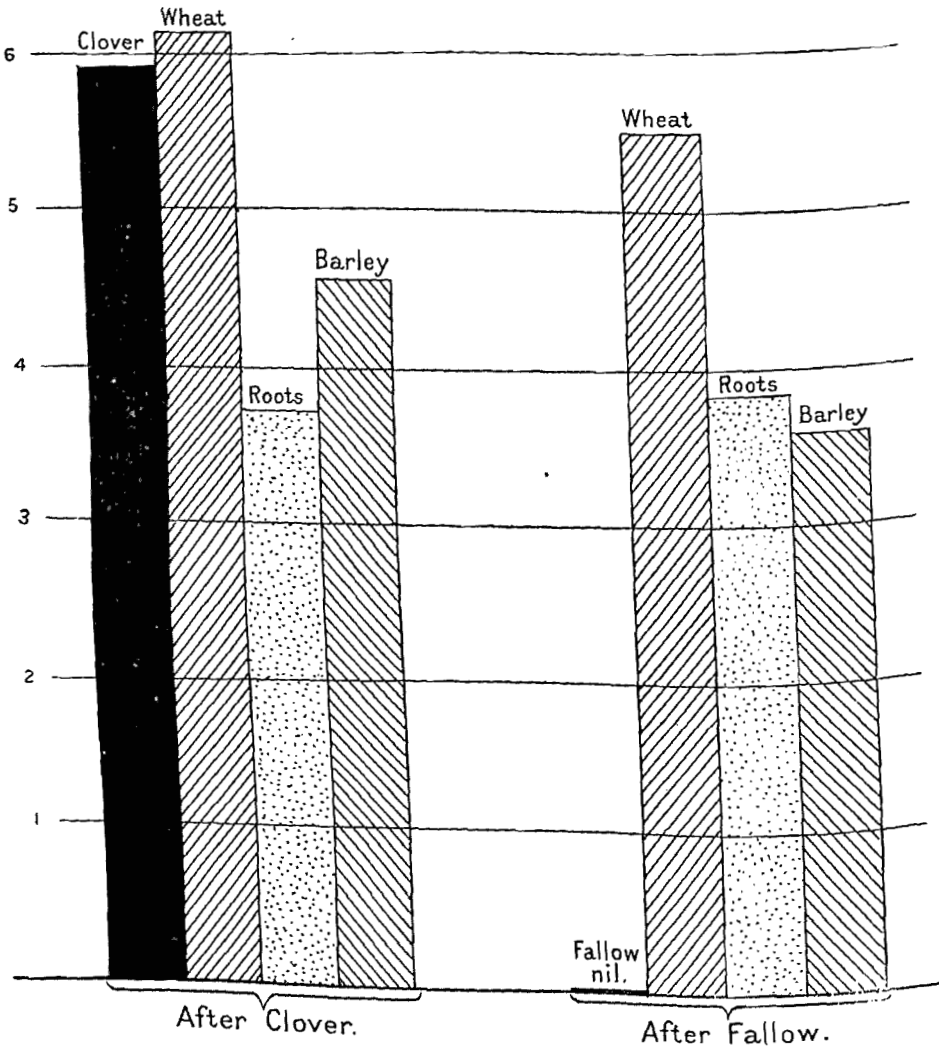


FIG. 43.—Comparative Effect of Clover or Bare Fallow on the succeeding Crops in the Rotation. Total Produce—In 1000 lb. for Clover, Wheat, and Barley, and in 100 cwt. for Roots.

IV.—EFFECT OF MANURIAL RESIDUES ON SUBSEQUENT CROPS.

It has already been stated that the manures on this experimental field are applied only to the root crop, the three

subsequent crops in each course being grown without further manure. We thus obtain a means of ascertaining what residue is left in the land after the removal of the crop to which the manure has been applied. If, for example, we compare the plots receiving minerals only with those receiving minerals and nitrogen, on the fallow portion the addition of nitrogen produces an increase of crop from 186 to 443 cwt. per acre, or of 131 per cent. This crop of roots is entirely removed, but the succeeding barley crop shows a total produce of 2783 lb. on the plot where nitrogen was applied to the roots, against 1970 lb. on the plot without nitrogen; thus the residue of the nitrogen in the ground after one crop had been grown and removed was still able to increase the next crop by 41 per cent.

The following Table (LXX.) shows the summarised results

TABLE LXX.—*Crops grown in rotation, Agdell Field. Total produce per acre. Mean of seven Courses, 1884-1911. Increase due to Nitrogenous Manures applied to the Swede Crop only, and their Residues.*

Manures.	Swedes.	Barley.	Fallow (or Beans or Clover).	Wheat.
Roots carted, Fallow.				
Minerals only . . . . .	Cwt. 186·9	Lb. 1970	Lb. ...	Lb. 5100
Minerals + Nitrogen . . . . .	443	2783	...	5523
Increase { Actual . . . . .	256·1	813	...	423
Per cent. . . . .	131·6	41·2	...	8·3
Roots carted, Beans or Clover.				
Minerals only . . . . .	256·0	2609	3722	6149
Minerals + Nitrogen . . . . .	428·1	3782	3036	6119
Increase { Actual . . . . .	172·1	1173	- 686	- 30
Per cent. . . . .	67·2	41·1	- 18·6	- 4

for the last seven courses on both the fallow and the clover portions.

It will be seen that a nitrogenous dressing consisting of rape cake and ammonium-salts leaves in the ground, after

growing a crop of roots, a residue which increases the barley crop by 41 per cent.; even two years later, after an intervening bare fallow, sufficient still remains to increase the wheat crop by 8·3 per cent. A similar increase in the barley of about 41 per cent. is brought about by the residues of the nitrogenous manuring applied to the Swede crop on the plots which, instead of being fallowed, carry clover or beans as the third crop in the rotation. On the leguminous crop itself, however, the residues of nitrogen still in the soil have a depressing effect, the average production of beans or clover being 18 per cent. less on the plots which receive nitrogen for the Swede crop than on the corresponding plots getting no nitrogen, a result of nitrogenous manuring which has been noted before.

Further evidence of the duration of manurial residues is to be obtained by comparing the plots from which the roots were removed with those to which the roots were returned, and noting the effects on the succeeding crops of the rotation. For this purpose it will be wise to consider only the plots on which the Swedes receive nitrogen as well as the minerals, for on them only is there a crop of Swedes big enough to leave any perceptible residue. Table LXXI. shows the average results

TABLE LXXI.—*Effect of Carting and of Feeding Roots on the Yield of succeeding Crops. No Clover grown.*

	Average Produce per acre.		Relative Yield.	
	Roots Removed.	Roots Fed.	Roots Removed.	Roots Fed.
Swedes . . .	448 cwt.	440·1 cwt.	100	99
Barley . . .	2575 lb.	3951 lb.	100	153
Fallow . . .	5521 lb.	6224 lb.	100	113

(grain and straw) for five courses on the fed and carted portions, where a bare fallow is taken in each course.

Taking the figures in the last column, we see that the effect of the root crop on the succeeding barley is considerable, for

the yield of barley is increased by as much as 53 per cent. through the return of the root crop to the land. The residues have, however, but a small effect two years later on the wheat crop which follows the bare fallow, for where the roots were fed the wheat crop is only 13 per cent. larger than where the roots were carted off. The residual effect has practically disappeared by the fourth year, and when the roots (to which a fresh application of manure is applied) come round again they are little the better for any accumulated residues in the soil, even though the treatment of returning or removing the roots is repeated through thirteen rotations, or a period of fifty-two years.

The next Table (LXXII.) shows the parallel experiment, in which clover or beans were grown in the third year of the course instead of taking a bare fallow.

TABLE LXXII.—*Effect of Carting and of Feeding Roots on the Yield of succeeding Crops. Clover grown.*

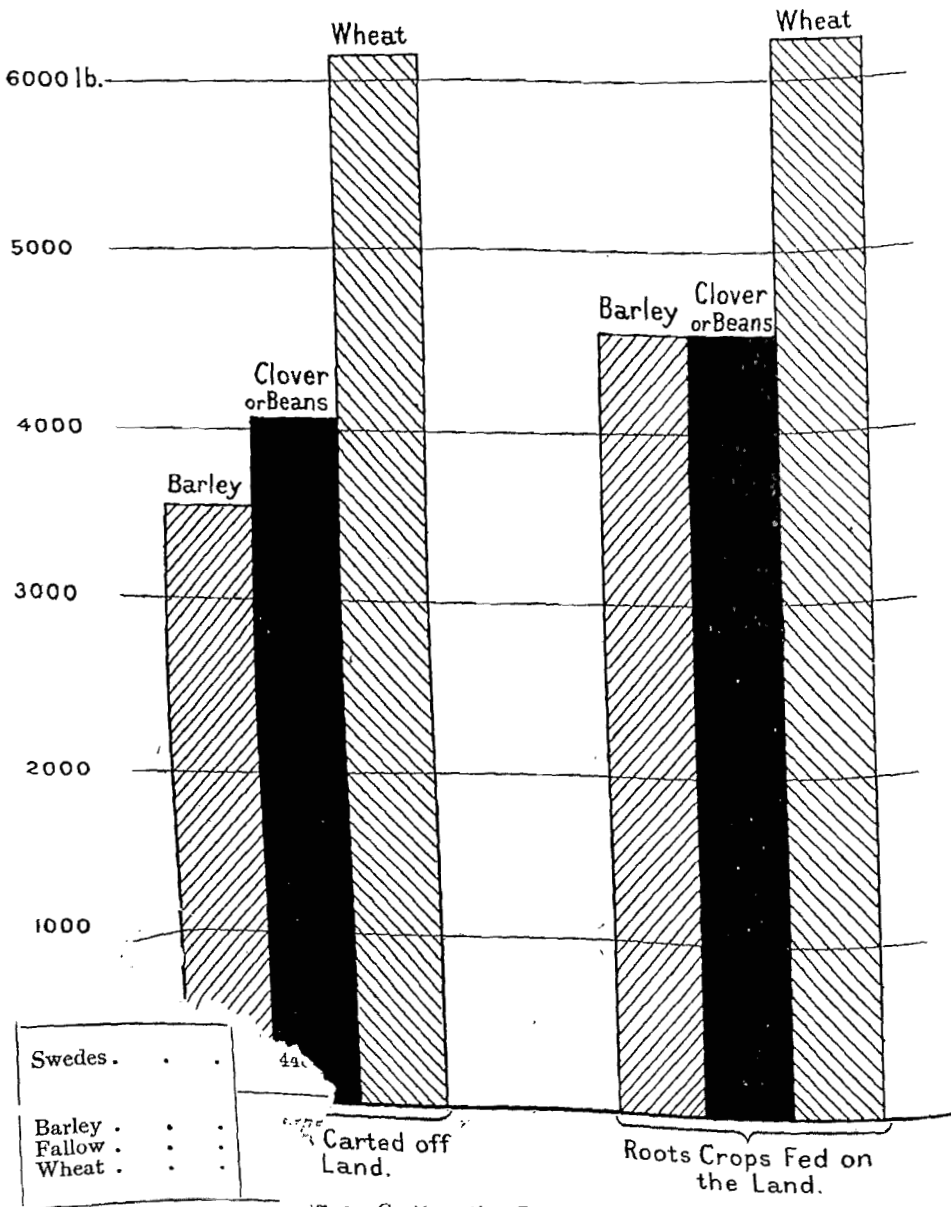
	Average Produce per acre.		Relative Yield.	
	Roots Removed.	Roots Fed.	Roots Removed.	Roots Fed.
Swedes . . .	445 4 cwt.	408·1 cwt.	100	92
Barley . . .	3543 lb.	4579 lb.	100	128
Clover or Beans . .	4066 lb.	4572 lb.	100	109
Wheat . . .	6140 lb.	6246 lb.	100	102

In this case the effect of feeding the roots on the land is plainly visible in the following crop, though the increase is not so great (being 28 per cent. instead of 53 per cent.) until the second rotation includes a bare fallow.

The second crop, clover or beans, is also reducing the net extent, for the residue of the roots produces 3 acre per annum. 9 per cent. Now, however, the new stores of nitrogen introduced by the clover crop practically obliterate the effect of the residues, and the wheat crop is to some extent increased the better for the return of the Swedes to the land. We can consequently deal with,

CROPS GROWN IN ROTATION

The diagram, Fig. 44, shows graphically the effect that feeding off the root crop on the land has on the succeeding



(grain and straw portions, where a  
 Taking the figure ordinary conditions of farming when clover  
 of the root crop is in rotation.

V.—GAIN OR LOSS OF MANURIAL CONSTITUENTS TO THE LAND.

From the analyses which have been made from time to time of the crops on Agdell field it is possible to estimate the quantities of the chief manurial ingredients—nitrogen, phosphoric acid, and potash—which are removed from the soil during a typical rotation. Thus we can form some idea of what will be necessary to maintain the fertility of land under ordinary crop, and whether there are any natural recuperative agencies which restore plant food to the soil.

Table LXXIII. shows the amount of nitrogen removed per acre per annum on the three plots which are fallowed and where also the roots are carted off—where everything is, in fact, removed, and no nitrogen is added except in the one case on Plot C where the Swedes are manured.

TABLE LXXIII.—Nitrogen removed by Crops grown in rotation, Agdell Field. Average of eight Courses, 1852-1883. Roots carted.

	O. Unmanured.	M. Minerals only.	C. Complete Manure.
	Lb.	Lb.	Lb.
Supplied in Manure . . . .	0	0	140
Removed in Crops :—			
Swedes . . . . .	11.5	34.8	78.5
Barley . . . . .	28.1	23.3	39.2
Fallow . . . . .	...	...	...
Wheat . . . . .	36.6	39.0	42.1
Total in rotation . . . .	76.2	97.1	8
Per acre per annum . . . .	19.1	24.3	y 64 lb

It will be seen that on the unmanured plot nitrogenous nitrogen is chiefly effected by the two ce) containing the net has the crop of roots become. The average acre per annum, over the whole four years of the rotation of nitrogen intro- over 19 lb. per acre per annum, which indication that the with the average annual removal of n, has been increased unmanured plot in Broadbalk where whea)nce we can con- after year. When mineral manures are used)re dealing with,

the loss of nitrogen to the soil during the rotation is greater, amounting to over 24 lb. per acre per annum, the increase being almost wholly due to the much larger Swede crop which is obtained by the help of the mineral manures. Coming to the plot which receives a nitrogenous manure for the Swede crop, we find the average removal of nitrogen becomes 40 lb. per acre per annum, a slightly greater quantity than is supplied by the manure, so that the net loss is about 5 lb. of nitrogen per acre per annum, approximately the amount annually restored by the rain. Thus, if we consider this plot alone, an almost exact balance is obtained between the nitrogen supplied and the nitrogen removed, so that the fertility of the land should be closely maintained. There are, however, other sources of loss which the above figures do not take into account—losses by the removal of weeds, losses by the washing away of nitrates, especially during the bare fallow, and possible losses due to the decomposition of nitrogenous materials in the soil with the evolution of their nitrogen as gas. Possible sources of gain are the absorption from the atmosphere of ammonia other than the ammonia washed down in the rain, and the fixation of atmospheric nitrogen by soil bacteria which do not require the co-operation of a leguminous plant. It is difficult to decide whether the fertility of this plot is really falling off or not, so great is the effect of seasons in causing fluctuations in yield which cannot be gauged; the last four root crops have actually been greater than the first four, the wheat has been somewhat less, while the barley has given in the later years less than half the crop of the earlier ones. The seasons in the later years were, however, against the barley crop, so that one can come to no very definite conclusion as to whether the recuperative agencies indicated above are sufficient to compensate for the unestimated but inevitable losses.

Turning now to the plots on which clover or beans are grown, it becomes still more difficult to estimate the gain or loss of nitrogen to the land, since the leguminous crop gains an

amount of nitrogen for the land which we have no means of calculating, but which we know is sufficient to benefit the succeeding crops for at least three years. Table LXXIV. shows the removal of nitrogen per acre per annum on the plots growing beans and clover where the root crop is completely carted away.

TABLE LXXIV.—*Nitrogen removed by Crops grown in rotation, Agdell Field. Average of eight Courses, 1852-1883. Roots carted.*

	O. Unmanured.	M. Minerals only.	C. Complete Manure.
	Lb.	Lb.	Lb.
Supplied in Manure . . . .	0	0	140
Removed in Crops :—			
Swedes . . . . .	7·6	33·3	80·6
Barley . . . . .	30·4	23·5	40·7
Beans or Clover . . . . .	41·4	61·5	89·5
Wheat . . . . .	32·8	35·9	43·7
Total in rotation . . . .	112·2	154·2	254·5
Per acre per annum . . . .	28·1	38·6	63·6

On the plot receiving mineral but no nitrogenous manure the removal of nitrogen is now nearly 40 lb. per acre per annum ; but if we exclude the clover or bean crop as providing its own nitrogen, the loss is only a little over 23 lb. per acre per annum, some of which is undoubtedly replaced by the nitrogen drawn from the atmosphere and left in the roots and stubble of the clover. With the nitrogenous manuring for the Swedes the annual removal of nitrogen amounts to nearly 64 lb. per acre per annum, or again excluding the amount contained in the clover or beans, to about 41 lb., of which the nitrogenous manure used for the Swedes provides 35 lb., reducing the net loss to the soil to about 6 lb. of nitrogen per acre per annum. This is easily compensated for by the amount of nitrogen introduced by the clover crop, and there is every indication that the fertility of this plot, so far from falling off, has been increased somewhat by each completed rotation. Hence we can conclude that fairly strong land, such as we are dealing with,

when farmed on the four-course system will rise rather than fall in fertility if during the rotation it receives manure supplying 150 lb. of nitrogen per acre, even though the roots are wholly removed from the land. Such a quantity of nitrogen would be supplied by 15 tons of fair ordinary dung. It should be, however, remembered that the state of equilibrium thus attained is not a very high one, and that if the land is to be kept in higher "condition," with a generally larger production throughout, then the losses of nitrogen by drainage and otherwise will also be greatly increased. Hence if the higher level of production is to be maintained it will require an additional expenditure of nitrogen as manure, not merely enough to make up for the larger amount removed in the greater crops, but a considerable surplus in order to compensate for the increased wastage.

When the mineral constituents of plant food are considered—the phosphoric acid and potash—there is no difficulty in estimating the annual loss or gain to the soil, because we know that there are no recuperative agencies at work to increase the original stock of such mineral substances in the soil, nor, on the other hand, are the only possible losses, those by drainage, of any moment. The annual draft on the soil can then be estimated with accuracy if we know the amounts of the constituents in question which are contained in the manure supplied and in the crops removed.

On the unmanured plot, from which everything is removed, the loss of phosphoric acid is about 7·5 lb. per acre per annum under the rotation, a figure which is very close to the annual withdrawal of phosphoric acid from the unmanured plots where wheat and barley are respectively grown year after year. On the continuous wheat plot the amount removed in the crop is 8·9 lb. per acre per annum, on the barley it becomes 7·8 lb. per acre per annum. Again, as regards the potash, the average removal from the unmanured plot under rotation is 13·2 lb., whereas the continuous wheat plot similarly unmanured loses 14·3 lb., and the continuous barley plot 11·6 lb. per acre per annum.

REMOVAL OF MINERAL CONSTITUENTS 213

It thus appears that when land is continuously cropped without manure and without the restoration of any parts of the crops grown to the soil, the annual withdrawal of the chief

TABLE LXXV.—*Phosphoric Acid and Potash removed by Crops grown in Rotation. Agdell Field.*

	Phosphoric Acid.		Potash.	
	Unmanured. Fallow. Roots Carted.	Completely Manured. Clover or Beans. Roots Carted.	Unmanured. Fallow. Roots Carted.	Completely Manured. Clover or Beans. Roots Carted.
Removed in :—	Lb.	Lb.	Lb.	Lb.
Swedes . . . . .	1·55	20·19	6·07	78·31
Barley . . . . .	13·11	21·59	18·96	31·49
Fallow, or Beans or Clover . . . . .	...	18·03	...	47·40
Wheat . . . . .	15·40	21·96	27·77	38·29
Total . . . . .	30·06	81·77	52·80	195·49
Supplied in Manure . . . . .	...	64	...	150
Net Loss to Soil . . . . .	30·06	17·77	52·80	45·49
Average Loss to Soil per acre per annum . . . . .	7·52	4·44	13·20	11·37

manurial constituents will be about the same whether the land is put under a rotation or grows a cereal crop every year. Of course the rotation plot in this case is practically growing two cereal crops only in the four years, with a fallow between each, so small is the production of roots in the first year of the course.

Table LXXVI. (p. 214) brings together for comparison the annual losses on the three unmanured plots in question.

As regards the manured plots growing clover or beans, we find that a little more than 80 lb. of phosphoric acid is removed during the four years of the rotation and must be replaced by manure if the fertility of the land is to be maintained. If 15 tons per acre of dung be given during the rotation, more phosphoric acid will be returned than is withdrawn by the crop; but, as the phosphoric acid in dung is

not in a very active form and as the growth of Swedes is very specially dependent on an abundant and active supply of phosphoric acid, it would probably be necessary to use 4 cwt.

TABLE LXXVI.—*Fertilising Constituents removed under various systems of Cropping. Unmanured Soils.*

	Removed in Crops per acre per annum.		
	Nitrogen.	Phosphoric Acid.	Potash.
	Lb.	Lb.	Lb.
Agdell—Rotation (Swedes, Barley, Fallow, Wheat)	19·1	7·52	13·20
Broadbalk—Continuous Wheat . . . . .	17·0	8·93	14·29
Hoos—Continuous Barley . . . . .	17·7	7·80	11·64

or so of superphosphate per acre if a good average crop of roots is to be obtained. The withdrawals of potash from the soil during the rotation are more considerable, amounting to nearly 200 lb. per acre, which in this experiment are only partially replaced by the 150 lb. given in the manure for the Swedes. We can assume, however, that even if this is not supplied by the 15 tons of farmyard manure, which we have been assuming as necessary to maintain both an average yield and the fertility of the land, yet it will not be necessary to afford any artificial supply of potash on a soil like that of Rothamsted. The reserves of potash in such a strong soil are enormous—at least 50,000 lb. per acre in the top 9 inches of soil, of which 12,000 lb. is soluble in hydrochloric acid—and a little of it becomes available every year under the action of the weathering induced by cultivation.

#### PRACTICAL CONCLUSIONS

The following conclusions may be drawn from an examination of the results yielded by the Agdell Rotation Field:—

1. On land continuously cropped without manure the Swede crop is the first to feel the want of manure, the yield being reduced to a minimum almost immediately. The leguminous

crops fall off more slowly, and the cereals, especially the wheat, maintain a fair production for a long period.

2. The unmanured wheat and barley grown in rotation continue to give much greater produce than they do on land similarly unmanured but growing the same crops year after year. This is, however, chiefly in virtue of the two fallowings the land receives during the four-years' course, the unmanured land losing about the same amount of plant food in the one case as in the other.

3. On the manured plots the yield of Swedes is determined by both phosphatic and nitrogenous manure, chiefly by the former; the yield of cereals is determined by the available nitrogen in the soil.

Leguminous crops like clover and beans are dependent on the supply of minerals, particularly of potash, and are even somewhat decreased by the presence of much nitrogen in the soil.

4. The inclusion of a clover crop in the rotation, besides providing a crop of hay, leaves the land so much richer in nitrogen that the succeeding wheat crop is greatly increased. The good effect of the clover persists and may be traced through all the crops of the rotation. With beans in place of the clover, no beneficial effect is produced on the succeeding crops.

5. The effect of such residues as are left by an organic manure like rape cake applied to the Swedes, or those left on restoring the Swedes to the land, or the residues left by a clover crop, is to be traced in the three following crops at least. In the third crop they are, however, becoming small, and even in the second year after the application of the manure the effect of the residues becomes masked by any new addition of nitrogenous manure, although they may still remain and go to build up the "condition" of the soil.

6. The losses of nitrogen to strong land farmed on the four-course system are almost made up by the growth of a crop of clover, and will be more than repaired by a dressing of 15 tons

of farmyard manure or its equivalent during the rotation. The losses of phosphoric acid and potash would be similarly made up, though it is well also to use about 50 lb. of phosphoric acid per acre for the Swede crop, which is specially dependent on a large quantity of available phosphoric acid.

7. As the standard of farming is raised, however, it is necessary to give further supplies of nitrogen and corresponding increases in the supplies of phosphates and potash.

#### REFERENCES

- "Rotation of Crops." *Jour. Roy. Ag. Soc.*, 55 (1894), 585. *Rothamsted Memoirs*, Vol. VII., No. 7.

## CHAPTER XI

### NITRIFICATION AND THE COMPOSITION OF DRAINAGE WATERS

- I. The Process of Nitrification.
  - II. Denitrification.
  - III. Nitrates in Cultivated Soils.
  - IV. Nitrates in Manured and Cropped Soils.
  - V. The Nitrates in Drainage Waters.
  - VI. Other Constituents of Drainage Waters.
- References.

#### I.—THE PROCESS OF NITRIFICATION.

THE fact that cultivated soils could induce the conversion of organic matter containing nitrogen into nitrates has been known for a long time, indeed it was for many years utilised on a commercial scale for the production of nitre. Many of the conditions under which nitrification takes place had been worked out by the men in charge of the old saltpetre beds before Boussingault and other investigators considered them afresh from the point of view of agriculture. The presence of calcium carbonate or some other base, the aëration of the soil, warmth, and a certain proportion of water had been shown to be necessary, while it was known that much organic matter was injurious. That the action is brought about by a living organism, was first established by the experiments of Schloesing and Müntz in 1877; and on the appearance of their paper, Warington, who was then working in the Rothamsted laboratory on the subject of nitrates in the soil, proceeded to a further investigation of this important subject. His first experiments confirmed the conclusions reached by Schloesing and Müntz, and showed that the amount of nitrates

in a soil increased when pure air was led through it, but that no increase was observable when the air contained a trace of an antiseptic like chloroform or carbon bisulphide. Further experiments cast light on the conditions under which the nitrogen in ammonium-salts would thus pass over into nitrates—a preliminary seeding from a previously nitrifying solution or from soil or natural waters is necessary—bright light inhibits the process, and the drying up of a soil, even at the ordinary temperature of a room, is sufficient to destroy the agent of the change. All these facts showed that the change to nitrate was effected by living organisms present in the soil and in natural waters. It was also shown that certain food substances, particularly phosphoric acid, are required in the nitrifying solution. About the same time also, Munro showed that the organism can obtain its carbon from purely inorganic sources like the carbonates of ammonia or calcium, acquiring the necessary energy for splitting up the carbon dioxide from the combustion of the ammonia to nitrous and nitric acid. This remarkable fact was afterwards more rigorously demonstrated by Winogradsky, who established a relation of about thirty-five to one between the nitrogen oxidised and the carbon assimilated.

In the course of Warington's experiments he observed that when a comparatively strong ammoniacal solution (containing also phosphates, etc.) was seeded from a soil, the first product of the oxidation was largely, if not wholly, nitrites, and that these nitrites were converted into nitrates at a later stage when most of the original ammonia had been oxidised. This seemed to indicate that the reaction takes place in two stages, a preliminary oxidation to nitrite being followed by a second independent change of the nitrite into nitrate. Warington succeeded in separating by repeated cultivations one agent that would only carry on the first oxidation from ammonia to nitrite, and a second that would oxidise nitrite into nitrate but would not attack the original ammoniacal solution. Warington was not able at that time to isolate in a pure

state the organisms respectively carrying on these reactions, but his experiments proved that the ordinary process of nitrification in soil, etc., must be due to two distinct organisms, the nitrous and nitric, each incapable of doing the work of the other. Soon afterwards Warington's conclusions were confirmed by Winogradsky, who succeeded by a new method in preparing pure cultures of the two organisms.

The position in which Warington's investigations left the question of nitrification has not been materially advanced since; the process is carried out by two distinct organisms present in enormous numbers in all cultivated soils, being only absent from soils possessing an acid reaction like peat. The action of these organisms is dependent on certain conditions of temperature and aëration, on a supply of inorganic food like phosphates, on the presence of a base and on the absence of any excess of soluble organic matter.

## II.—DENITRIFICATION.

During the progress of the investigations on nitrification Warington found that under certain conditions soils possessed the power of destroying any nitrates which had been formed previously. This had been observed before, and shown to be due to the action of sundry living organisms which are universally distributed in natural waters, sewage, and soil. The main conditions necessary for the development of this reducing action are the absence of oxygen and the presence of a sufficiency of readily oxidisable organic matter; it will then depend on the conditions to which the soil is subjected whether the nitrate-making or the nitrate-destroying organisms become active. Warington, for example, showed that if an ordinary soil were deprived of air by keeping it in a water-logged condition, any nitrates added to it would be rapidly destroyed with the evolution of nitrogen gas.

The action of a number of organisms was studied by introducing them into beef broth containing some nitrate and protected from the access of oxygen by a layer of paraffin oil.

Under these conditions, of thirty-seven distinct organisms tested, nineteen reduced the nitrate to nitrite, one of them producing nitrogen gas also, three brought about some slight reduction, and fifteen were without action on the nitrate. Reduction to a nitrite was the most general reaction, but other organisms have been found capable of carrying the reduction further to nitric or nitrous oxide, or even to nitrogen gas.

It has been supposed that considerable losses of nitrogen are likely to accrue from this cause whenever nitrate of soda is used as a manure in conjunction with organic materials like dung. But, notwithstanding the presence of denitrifying bacteria in the soil, the conditions under which they become active—absence of air, a high temperature and the presence of large quantities of soluble organic matter—are so rarely realised that denitrification probably plays no large part in practice. For example, on the Rothamsted mangold plots, where large quantities of nitrate of soda are used in conjunction with dung applied every year, the recovery in the crop of the nitrogen supplied in the nitrate compares favourably with the proportion recovered when nitrate of soda alone is used (see pp. 113-14). In other words, the nitrate of soda produces almost as large an increase when added to a dunged as to an unmanured plot, hence very little of its nitrogen can have been wastefully liberated as gas.

Besides denitrification proper another type of loss of nitrogen occurs. Under partial aerobic conditions the bacterial decomposition of organic bodies containing nitrogen may result in the loss of nitrogen as free gas. Such actions probably go on in soil, and serve to account for the fact that there seems to be a limit to the accumulation of nitrogen in soils, because the destructive changes proceed with greater rapidity as the amount of organic matter in the soil increases and provides a richer medium for the development of these bacteria. For example, it is found that the amount of nitrogen accumulated in the soil of the Park, which has been in grass from time immemorial, shows no

tendency to increase and is but little higher than the proportion in the soil of other adjoining meadows which have only been laid down to grass for thirty years or so. Again, in the Broadbalk wheat field, the plot which receives farmyard manure is supplied annually with far more nitrogen than is removed in the crop. During the earlier years of the experiments there was in consequence a rapid rise in the proportion of nitrogen in the soil, but this rise has diminished, and has been latterly by no means equal to the annual increment of nitrogen. A state of equilibrium is eventually attained, when the destructive agencies find the conditions so favourable for their development that the quantity of nitrogen compounds broken down to the state of gas becomes equal to the surplus of combined nitrogen that is added year by year.

### III.—NITRATES IN CULTIVATED SOILS.

The nitrifying organisms are in the main present only in the surface soil which is subject to cultivation; at depths greater than 9 inches from the surface the organisms become more scanty and less effective in inducing nitrification in a suitable medium. During the sampling of several of the Rothamsted soils Warington took advantage of the pits dug into the subsoil to obtain small samples of the undisturbed subsoil, portions of which were then introduced into solutions capable of undergoing nitrification. It was found that the nitrifying organisms were present in all the samples down to 3 feet from the surface; at 6 feet, where the subsoil was clay, half the samples failed to induce nitrification, at 8 feet the clay subsoil showed no evidence of the presence of nitrifying organisms. Whenever the subsoil passed into the chalk rock, which in one case extended to within 5 feet of the surface, no nitrifying organisms were found. Practically the whole of the nitrification going on in a comparatively close soil like that of Rothamsted takes place in the first 9 inches which gets stirred about and aerated by the action of the plough.

It will now be realised that the most favourable conditions

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for nitrification occur when the land is subjected to a bare summer's fallow; the land is being thoroughly worked, the temperature is high through the complete exposure to the sun's rays, and the soil also retains sufficient moisture for nitrification because it is not being dried by the growth of a crop. The favourable results accruing from a bare fallow on strong land have already been discussed, and though they are in part due to the freedom from weeds and the improved tilth of the soil, the main effect must be attributed to the accumulation of nitrates during the summer.

The following table shows the amount of nitrogen as nitrate found in various Rothamsted soils after fallowing:—

TABLE LXXVII.—*Effect of Fallowing—Nitrogen as Nitrates, lb. per acre.\**

	Alternate Wheat and Fallow.				Continuous Wheat.		Rotation Field.	
	Fallow Portion.				After Crop		Super. only.	Complete Manure.
	Oct 1878.	March 1881.	July 1883.	July 1884.	Oct. 1881.	Oct. 1893.	Oct. 1878.	Oct. 1878.
First 9 inches . . .	28.5	7.0	19.4	17.1	9.9	9.6	22.3	30.0
Second „ . . .	5.2	3.3	8.0	3.6	5.2	9.2	14.0	18.8
Third „ . . .	...	3.1	2.4	2.7	2.8	2.7	...	...

The accumulation of nitrates in the surface soil of the uncropped land as the summer advances is to be seen very plainly from the figures: the lowest amount of nitrate was in the March sample, and both the July samples were poorer than that drawn in October. In October also the continuous wheat land had been broken up, and nitrification thus started afresh. It is also plain that the fallow land was much richer in nitrates than the plot which had been under continuous crop, although the accumulation of nitrates was greater on the last plot where the land had been manured and was in good condition than on the other plots, all of which had long been unmanured.

\* I have retained these figures (obtained by Warington) for their historic interest. More extended recent observations confirm them. (See p. 239 for References.)

It has already been pointed out in dealing with the wheat crop (p. 63) that the increased crop after fallow is almost wholly dependent on the retention in the soil of the nitrates thus formed in the summer. Should a wet autumn and early winter succeed, the nitrates are washed so far down in the subsoil as to be out of reach of the crop, which then shows a very small return for the previous summer fallowing.

The rapidity with which nitrification may take place after harvest is also noticeable in the table. For three months or so before the removal of the wheat crop the soil in which it is growing contains only little nitrates, but if rain falls when the ground has been broken up after harvest the conditions become extremely favourable to nitrification, because the soil is warm and well aerated by stirring, and possesses a suitable degree of moisture. Hence heavy autumnal rains, before the land is again occupied by a crop to take up the nitrates, may easily result in serious loss to the land, and some quick-growing covering crop like mustard is valuable, because it seizes upon the ready formed nitrates. At a later date the nitrogenous compounds the mustard has formed from the nitrates, which would otherwise have been washed away, are returned to the land, either by being ploughed in or fed off, and become available on their decay for the nutrition of the succeeding crop. Even a free growth of weeds on the stubble will diminish the loss of nitrates to the land.

#### IV.—NITRATES IN MANURED AND CROPPED SOILS.

In several instances, as, for example, in the Broadbalk field in 1893, soil samples have been drawn to depths of 9 feet, and the distribution of the nitrates in the successive 9 inches determined. Table LXXVIII. shows the results for certain of the plots sampled in October of that year, after a very dry summer yielding a crop much below the average, and also after a fall of about  $4\frac{1}{2}$  inches of rain between harvest and the time of sampling.

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TABLE LXXVIII.—*Nitrogen as Nitrates in Broadbalk Wheat Soils, October 1893. Lb. per acre.*

Plot	8.	2B.	19.	5.	6.	7.	8.	16.
	Un-manured.	Dunged.	Rape Cake.	Minerals only.	Minerals +48 lb. N. as Amm.-salts.	Minerals +88 lb. N. as Amm.-salts.	Minerals +120 lb. N. as Amm.-salts.	Minerals +86 lb. N. as Sod. Nit.
1st 9 inches .	9.64	10.53	22.06	10.53	14.13	14.96	17.40	13.59
2nd " .	9.22	45.36	24.36	6.36	12.74	19.21	29.17	42.58
3rd " .	2.74	12.25	14.18	2.23	5.31	8.54	8.71	20.77
4th " .	...	...	...	0.95	2.98	5.32	8.71	13.03
5th " .	...	...	...	1.00	3.47	4.64	8.51	7.82
6th " .	...	...	...	0.71	3.72	4.40	7.46	5.96
7th " .	...	...	...	1.03	3.25	4.51	7.99	5.45
8th " .	...	...	...	0.92	1.89	4.02	7.60	6.28
9th " .	...	...	...	0.87	2.46	4.29	6.13	...
10th " .	...	...	...	0.57	2.16	4.38	5.64	...
Total 1 to 90 .	...	...	...	25.17	52.61	74.27	107.32	115.48*

\* To 72 inches only.

It has already been pointed out that nitrification is practically confined to the surface soil, where only do the desirable conditions prevail of numerous organisms, free aëration and stirring of the soil, and nitrogenous matter easily attackable by bacteria. This opinion is also borne out by the fact that the drain-gauge with soil 60 inches deep yields practically the same amount of nitrate as the shallower gauge where the soil is only 20 inches deep. From this it follows that the nitrates to be found in the lower depths of the subsoil are all derived from the surface, and have been washed down with the rain.

It will be noticed that in most cases shown in the table the second 9 inches contains a larger amount of nitrates than the surface soil, in some instances even the third 9 inches are richer than the surface. This is merely due to the downward displacement of the nitrates produced after the harvest by the heavy rain which had fallen immediately before sampling. It will also be noticed that in several cases there is a break in continuity in the amount of nitrates between the third and fourth depths. This is probably due to the tile drains, which lie at about this depth and remove the drainage water charged with

nitrates. Such a break in composition is not seen in the samples drawn from other fields which are not tile-drained.

The character of the manuring applied to the surface soil is well seen in the amount of nitrates in the subsoil; for example, Plots 5, 6, 7, 8 form a series, all getting the same mineral manure, but Plot 5 has no nitrogen, while Plots 6, 7, and 8 receive successive increments of ammonium-salts. Down to the depth of 9 feet the samples contain nitrogen as nitrate in approximately the same proportions as it is applied to the surface in the form of ammonium-salts. Again, the total amount of nitrogen as nitrate contained in the whole depth below Plots 6, 7, and 8, as compared with that present below Plot 5 receiving no nitrogen, is much the same as the quantity of nitrogen applied as manure less the amount removed in the crop of 1893.

TABLE LXXIX.—*Nitrogen, lb. per acre, 1893.*

Plot.	5.	6.	7.	8.	16.
As Nitrate in Soil to depth of 90 inches .	25·2	52·6	74·3	107·3	115·5*
Excess of Nitrate over Plot 5 . . . .	...	27·4	49·1	82·1	90·3
Nitrogen in Crop, excess over Plot 5 . . .	...	8·7	12·9	14·8	11·7
Nitrogen accounted for in Soil and Crop, excess over Plot 5 . . . .	...	36·1	62·0	96·9	102·0
Nitrogen supplied in Manure . . . .	...	43	86	129	86

\* 72 inches only.

Thus we have evidence that practically the whole of the nitrogen supplied as ammonium-salts is nitrified during the season of growth of the wheat, and whatever is not removed by the plant gets washed down as nitrate into the subsoil, and may be either intercepted by the tile drainage, if any, or find its way into the general stock of underground water. Just in the same way the nitrate supplied to Plot 16 in excess of the requirements of the plant gets also washed down to a considerable depth in the subsoil.

The large quantity of deep-seated nitrate shown in the analyses is no longer available for crops on the Rothamsted

soil, probably because the closeness of texture permits but little capillary movement of water to take place. This we learn from the comparison of the yields on Plot 5, receiving minerals but no nitrogen every year, and on Plot 17 or 18, which receives alternately minerals and ammonium-salts. As has already been pointed out (p. 52), in the years this plot 17 or 18 receives minerals but no nitrogen, its crop sinks almost exactly to the level of the crop on Plot 5, although it had received 86 lb. of nitrogen as ammonium-salts the year before. Clearly, then, on the Rothamsted soil ammonium-salts are not retained as such for more than the season of application, nor are the nitrates resulting from them able to return to the surface to feed the succeeding crop. On other soils of better texture for allowing the movements of water by capillarity it is possible that the nitrates in the subsoil water may return to the surface and be of service to the crop.

It must not be supposed, however, that dressings of manures like nitrate of soda and sulphate of ammonia, which so readily wash away as nitrates, are entirely without action on the succeeding crops. Because of the very fact that they cause a large growth, there is left behind in the soil a correspondingly large development of root and stubble, which will decay for the benefit of succeeding crops. Especially is this the case where some considerable proportion of the crop grown is not harvested, but is returned at once to the land, as is done, for example, with the leaves of mangolds or the haulm of potatoes. A striking example is seen at Rothamsted, on the plots which grew potatoes for twenty-six years, from 1876 to 1901, and were then sown with barley without further manuring.

Table LXXX. shows the total produce (grain and straw) of the first and second crops (barley) and the third crop (oats), after the manuring had been discontinued.

It will be seen that the change from potatoes to barley was followed by enormous crops of grain wherever nitrogenous manure has been used for the potatoes; the two plots which had previously been dunged gave over 70 bushels of grain per

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acre; the four plots which had received nitrogen as either nitrate of soda or ammonium-salts gave somewhat less, but still over 60 bushels; while the four plots without nitrogen in

TABLE LXXX.—*Total produce without Manure, following Potatoes manured for 26 years.*

Plot.	Manure applied to the Potatoes, 1876-1901.	Lb. per acre.		
		Barley.		Oats.
		1902.	1903.	1904.
1	Unmanured . . . . .	3602	1063	2331
2	Unmanured, 1882 and since, previously Dung . . . . .	3804	1836	2129
3	Dung alone, 1883 and since . . . . .	9024	6030	5492
4	Dung alone, 1883 and since . . . . .	9072	5937	5974
5	86 lb. N. as Ammonium-salts . . . . .	6981	2066	2211
6	86 lb. N. as Sodium Nitrate . . . . .	7692	1934	2236
7	86 lb. N. as Ammonium-salts + Minerals . . . . .	7792	3207	3024
8	86 lb. N. as Sodium Nitrate + Minerals . . . . .	8253	3187	3045
9	Superphosphate only . . . . .	3720	1617	2089
10	Complete Minerals . . . . .	2953	1586	2056

previous years gave between 25 and 35 bushels. In the following season these differences were still to be seen, and the leading position of the previously dunged plots was naturally more manifest than ever; while in the third season (oats) after the manuring had been discontinued, the order of the plots remained the same, although only the dunged plots now grew a large crop.

That the increase on the plots which had previously received nitrate of soda or ammonium-salts was due to crop residues rather than to the return of nitrates derived from the manure and stored in the subsoil, is probable from the superiority of the crops on Plots 7 and 8, where minerals had accompanied the nitrogenous manures, over Plots 5 and 6, where the same nitrogenous manures had been used alone. When residues are being cropped out, the size of the cereal crop grown is almost wholly determined by the available nitrogenous supply, and Plots 7 and 8, which formerly grew the larger crops of potatoes, give better yields than Plots 5 and 6, although they had initially the same supply of nitrogen. On

the other hand, the rapid decline in the production of Plots 5, 6, 7, and 8, following the discontinuance of the manure, is more consistent with the existence of a residue of nitrate rather than of slowly-decaying organic material derived from the haulm of the potatoes.

Soil samples down to a depth of six times 9 inches were taken from some of these plots in February 1903, after the first barley crop had been removed. The following table shows the average figures obtained.

TABLE LXXXI.—*Nitrogen as Nitrates per million in dry Soil of former Potato Plots, February 1903.*

Depth of Soil.	Unmanured.	Dunged.	Ammonium-salts only.	Nitrate of Soda only.
	Plot 1.	Plot 3.	Plot 5.	Plot 6.
1st 9 inches . . .	1·92	8·75	1·63	1·68
2nd " . . .	1·68	5·13	1·94	2·03
3rd " . . .	0·78	2·97	1·18	1·21
4th " . . .	0·76	2·23	3·18	0·86
5th " . . .	0·67	1·47	2·14	1·67
6th " . . .	0·58	3·24	5·75	3·67
Means .	1·06	3·97	2·64	1·85

In this case the samples were taken in the early spring after a winter of fair rainfall, which had distributed the nitrates throughout the soil; the total, however, present in the first six depths roughly corresponds to the variations in the barley crop of 1903 which followed.

One striking fact in connection with these and similar determinations, is the absence of any lateral diffusion of the nitrates in the subsoil water beneath the plots. The Broadbalk wheat plots, for example, are comparatively narrow, being about 7 yards in breadth, separated by paths of 4 feet in width. Yet, as is seen in Table LXXVIII., Plot 5, which receives no nitrogen, shows no trace of the influx of nitrates by diffusion from the much richer subsoil water below the immediately contiguous Plot 6, even down to the depth of 9 feet. Just

in the same way the amount of nitrates present at each depth in the subsoil water below Plots 6, 7, and 8, is perfectly distinct and characteristic of the manuring applied to the surface.

Additional evidence of the lack of lateral diffusion of the nitrates in the soil water is to be seen in the permanent grass plots; although no path separates the plots receiving nitrate of soda from the neighbouring plots, the characteristic vegetation induced by the nitrate of soda manuring shows no tendency to stray across the division line. For example, Plot 14, receiving a complete manure containing 550 lb. per acre of nitrate of soda, is immediately contiguous to Plot 1, receiving nitrogen only as ammonium-salts; the vegetation on the two plots is in marked contrast, yet the dividing line is singularly sharp, and, despite the many years Plot 14 has received this last dressing of nitrate of soda, there is not the least sign of its diffusion into the subsoil below the adjoining plot.

#### V.—THE NITRATES IN DRAINAGE WATERS.

The processes of nitrification in soils can also be studied by the examination of the drainage water beneath cultivated land. It has long been known that all the soluble compounds of nitrogen are retained by the soil with the exception of the nitrates, hence an examination of the amount of nitrates present in the water reaching the drains will throw light on the rate at which nitrates are produced in the soil, and on their ultimate fate.

At Rothamsted the water which percolates through the drain-gauges is stored, and the nitrates are regularly determined in proportionate samples representing the percolation for the month. These results have been combined for twenty-six years, 1878-1903, and the averages are set out in the accompanying curves (Fig. 45), which show the rainfall, the percolation in inches through 20 inches of bare soil, the concentration of the percolating water in parts of nitric nitrogen per million, and the total amount of nitric nitrogen reduced to lb. per acre.

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Neither the percolation nor the total quantity of nitrogen removed differ much for the 40-inch and the 60-inch gauges; but owing to the greater amount of water retained by the deeper

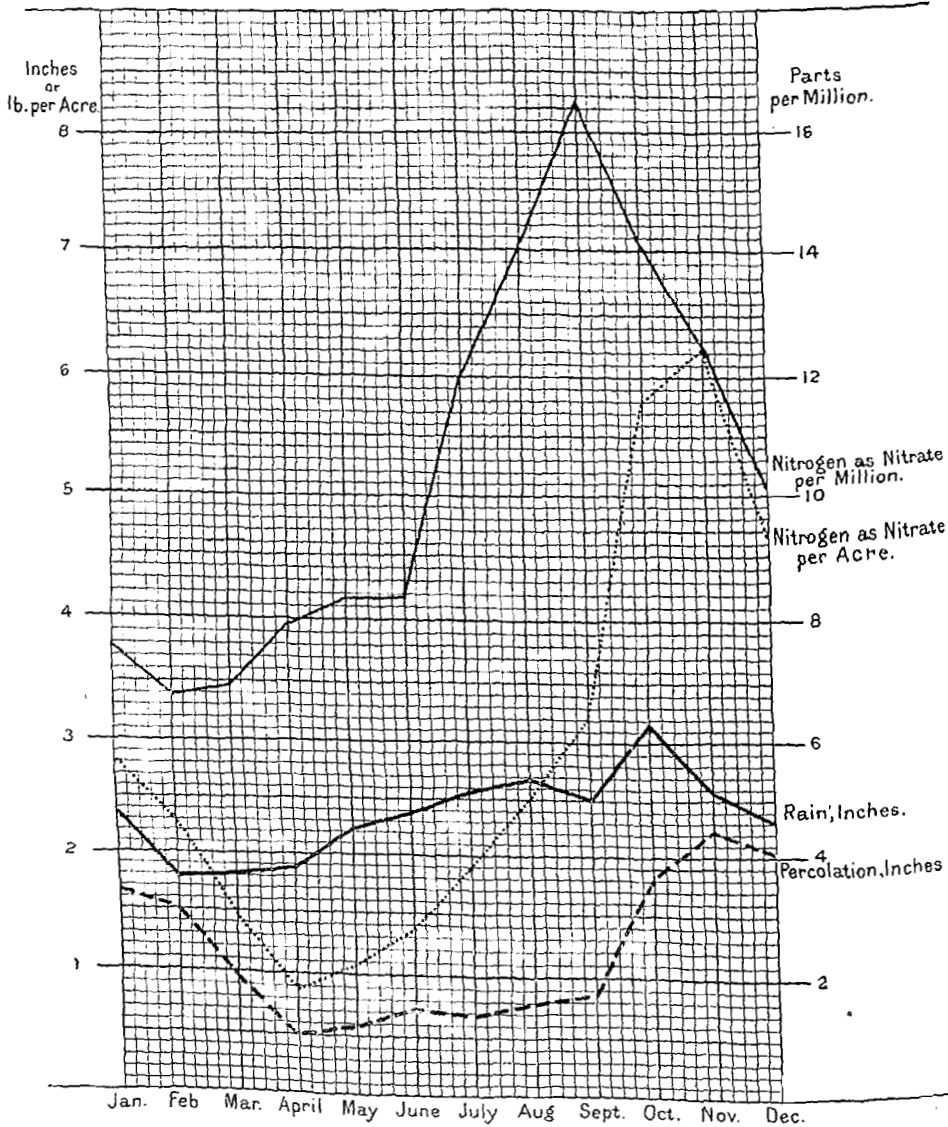


FIG. 45.—Rainfall, Percolation, and Nitrogen as Nitrate in Drainage through 20 inches of Soil. Rothamsted. 26 years (1878-1903).

soil the drainage from the 60-inch gauge is more uniform in concentration throughout the year, the main discharge also comes a little later in the year.

Inspection of the curves shows how great is the variation

from month to month in both the concentration of the drainage water and the loss of nitrate. The concentration is at its lowest in February, a time of year when the soil is still at a very low temperature and has been thoroughly washed by the winter's rains. In April the concentration has increased but little, and this combined with a smaller percolation results in the minimum loss of nitrates for the year in this month. The rise in concentration is still slow until July, when there is a considerable jump, the concentration reaching its maximum in September. The maximum loss of nitrates comes as soon after this point as the rainfall is abundant enough to wash through the soil; on the average the greatest annual loss of nitrates takes place in November, from which time onwards both concentration and total loss diminish. All these results refer to soil which is kept bare and uncropped, where in consequence the percolation is at a maximum, and where also there are no growing crops to take up the nitrates as they are produced. The effects to be seen under more ordinary conditions can be followed in the analyses of the drainage waters from the Broadbalk wheat field, under each plot of which runs a tile drain at a depth of from 2 feet to 2 feet 6 inches. These drains all debouch into a cross trench at the bottom of the field, and a record is kept of the occasions upon which there is any flow from the drains. Determinations of the nitrates contained in the waters are also made, but as it is impossible to withdraw an aliquot sample of the whole flow of the drain, and as also during any particular running the concentration is always changing, the earlier discharge being sometimes stronger and sometimes weaker than the later, it is impossible to make any exact account of the quantity of nitrogen removed by each drain. By combining, however, the results obtained over the whole period of the determinations, an approximate idea of the concentration of the discharge may be obtained. Other considerations lead one to suppose that the discharge from the drains does not represent, either in quantity or concentration,

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the water that may be supposed to pass into the subsoil at the depth of the drain. The results, however, are probably comparatively true from plot to plot.

Table LXXXII. shows the average concentration of the nitrates in the drainage water from four of the wheat plots, and

TABLE LXXXII.—*Nitrogen per million parts of Broadbalk Drainage Water.*

	Plot 8. Unmanured.	Plot 7. Minerals + Sulphate of Ammonia in Spring.	Plot 9. Minerals + Nitrate of Soda.	Plot 15. Minerals + Sulphate of Ammonia in Autumn.
September . . . . .	3.9	7.8	10.5	7.8
October . . . . .	5.0	8.8	12.8	16.9
November . . . . .	7.0	17.7	14.7	44.0
December . . . . .	5.9	20.5	17.7	50.3
January . . . . .	4.2	12.7	9.0	23.7
February . . . . .	4.0	8.1	9.2	17.7
March . . . . .	2.6	9.4	12.2	12.9
April . . . . .	1.7	14.3	30.5	9.6
May . . . . .	0.7	8.4	9.1	6.5
June . . . . .	0	8.8	6.8	1.3
July . . . . .	0.5	3.2	8.0	2.5
August . . . . .	0.9	7.4	4.3	2.7

Table LXXXIII. the average number of days in each month on which the drains of the same plots run.

TABLE LXXXIII.—*Number of Days with Drainage, Broadbalk Field. Average over 36 years.*

	Plot 8.	Plot 7.	Plot 9.	Plot 15.
September . . . . .	16	12	14	8
October . . . . .	64	51	53	35
November . . . . .	94	84	86	54
December . . . . .	107	103	107	58
January . . . . .	103	111	116	60
February . . . . .	69	73	77	45
March . . . . .	50	43	56	23
April . . . . .	21	21	18	9
May . . . . .	16	12	17	9
June . . . . .	17	10	9	6
July . . . . .	15	9	9	7
August . . . . .	13	11	10	6

Considering first the unmanured plot, but little drainage takes place during the summer months, May to August, because of the drying action of the crop upon the land. At the same time the concentration of such water as does find its way

through into the drain is very low, so thoroughly have the nitrates been removed by the growing crop. From September onwards, however, to February, the concentration of the water is comparatively high, and as the drains begin to run freely during this period when the crop is off the ground, great losses of nitrate are likely to occur. Nitrification goes on throughout the winter; even in years when the rainfall of the early autumn is so excessive as to wash the soil clean of all nitrates produced during the first nitrification following the removal of the crop, yet fresh nitrates are still produced in considerable quantity, and find their way into the drains in December and January. Nothing, in fact, short of the absolute freezing of the ground stops the production of nitrate and its consequent loss whenever the rainfall is heavy enough to wash through into the subsoil.

If the results obtained on the drainage water from the manured plots be examined, it will be seen that nitrification of manures like ammonium-salts is extremely rapid; if there is any percolation, nitrates begin to appear in the drainage water immediately after the application of the manure. Even in autumn an application of ammonium-salts is converted into nitrate in a very short time, as may be seen from the following series of analyses of the water running from the drain below Plot 15, in October 1880.

On October 25th of that year, mixed ammonium-salts containing 86 lb. of nitrogen and 119 lb. of chlorine per acre were applied to Plot 15 and ploughed in. Heavy rain followed, so that on October 27th the drain beneath the plot was running; other rain fell at short intervals, and yielded the series of samples set out in the table. It will be noticed that in the first runnings, taken within forty hours of the application of the manure, some ammonia was to be found. This is a very exceptional occurrence, but the large excess in which the chlorine was present in the water showed that the decomposition of the ammonium chloride and retention of the ammonia by the soil had progressed considerably.

Nitrification had also set in, since the earliest running contained nearly twice as much nitric nitrogen as was found in the sample taken a fortnight earlier, before the application of the manure. The proportion of nitrate continued to increase, and reached its maximum in the discharge three weeks later, by which time the nitrification of the ammonium-salts must have been far advanced towards its completion.

TABLE LXXXIV.—*Nitrogen and Chlorine in Drainage Water from Plot 15. Parts per million.*

	Nitrogen as Ammonia.	Nitrogen as Nitrates.	Chlorine.	Nitrogen as Nitrates to 100 Chlorine.
1880. October 10 . . . . .	None	8.2	22.7	37.0
1880. October 27, 6.30 A.M. . . . .	9.0	13.5	146.4	9.2
1880. October 27, 1 P.M. . . . .	6.5	12.9	116.6	11.1
1880. October 23 . . . . .	2.5	16.7	95.3	17.5
1880. October 29 . . . . .	1.5	16.9	80.8	20.9
1880. November 15, 16 . . . . .	None	50.8	54.2	93.7
1880. November 19, 26 . . . . .	None	34.6	47.6	72.7
1880. December 22, 29, 30 . . . . .	None	21.7	23.2	93.5
1881. February 2, 8, 10. . . . .	None	22.9	19.4	118.0

The last column of the Table shows the relation between the nitric nitrogen and the chlorine in the drainage water. The chlorine is derived from the ammonium-salts of the manure, and as it is in no way retained by the soil its appearance in the drainage indicates the movements of soluble salts in the soil independently of the production of nitrates. In the earlier runnings the chlorine was present in great excess, being immediately derived from the manure; in the later months the proportion fell as it became washed out, and by December it had again reached the normal level it had showed before the manure was put on. Meantime the proportion of nitrate was being maintained by constant nitrification in the soil, so that the ratio of nitric nitrogen to chlorine in the drainage water rose rapidly towards the end of the winter.

When ammonium-salts are applied as a top-dressing in the

spring, as is now more generally the case, the losses of nitrates are very much reduced; not only is the temperature of the soil lower, so that nitrification takes place more slowly, but the growing crop both diminishes the percolation and takes up the nitrates as fast as they are produced. The figures, however, for Plot 7 and Plot 9, Table LXXXII., show some rise in the concentration of the drainage water in the early spring, following the application of manure.

By combining the figures obtained for the concentration of the water flowing from the Broadbalk field drains with the amounts of water percolating through the drain-gauge containing 60 inches of bare soil (see p. 22), an estimate can

TABLE LXXXV.—*Nitric Nitrogen in Drainage Water. Lb. per acre.*

Plot.	Manuring per acre.	1870-80.		1880-81.	
		Spring Sowing to Harvest.	Harvest to Spring Sowing.	Spring Sowing to Harvest.	Harvest to Spring Sowing.
3	Unmanured . . . . .	1.7	10.8	0.6	17.1
5	Minerals only . . . . .	1.6	13.3	0.7	17.7
6	Minerals + 200 lb. Ammonium-salts . . . . .	10.1	12.6	2.2	19.8
7	Do. + 400 lb. do. . . . .	18.3	12.6	4.3	21.4
9	Do. + 550 lb. Nitrate of Soda . . . . .	45.0	15.6	15.0	41.0
10	400 lb. Ammonium-salts alone . . . . .	42.9	14.3	7.4	35.2
11	400 lb. do. + Superphosphate . . . . .	28.3	17.7	3.4	29.6
12	400 lb. do. do. and Sulph. Soda . . . . .	21.2	17.5	3.3	27.2
13	400 lb. do. do. and Sulph. Pot. . . . .	19.0	16.4	3.7	25.3
14	400 lb. do. do. and Sulph. Mag. . . . .	26.0	16.8	4.2	25.9
15	Minerals + 400 lb. Amm.-salts in Autumn . . . . .	9.6	59.9	3.4	74.9
	Estimated Drainage—Inches	11.1	4.7	1.8	18.8

be formed of the losses to the land by drainage under each system of manuring, an estimate rendered erroneous because it does not take into account the drying effect of the crop. However, the figures thus obtained, though imperfect, are instructive, and are set out in Table LXXXV. for two years, each divided into two periods: first, from the date of sowing the nitrogenous manures up to harvest; secondly, from harvest round again to the sowing of the manures in spring.

The seasons were rather exceptional, the summer rainfall

and drainage in 1879 and the winter rainfall in the following year being both above the average. It will be seen that the loss was greatest from Plot 9, receiving 550 lb. of nitrate of soda, and this excess of loss was chiefly in the summer drainage water: the figures are, however, exaggerated by the fact that half the nitrate plot received no mineral manures, and therefore grew but a scanty crop. The losses during the winter months are more nearly the same for all plots, and represent to a large degree the nitrification of the organic residues in the soil. The losses from the plots receiving minerals and varying amounts of ammonium-salts (Plots 5, 6, and 7) increased with each application of nitrogen; the losses from the plots receiving ammonia and various mineral manures (Plots 10, 11, 12, 13, and 14) diminished as the mineral manure became a more complete plant food, because the greater growth of crop which resulted removed more of the nitrates as they were formed, besides hindering nitrification by drying the surface soil.

Perhaps the most striking result that emerges from these analyses of the drainage waters is the rapidity with which nitrification takes place of such substances as the salts of ammonia; even in the colder autumnal and winter soils nitrification is so active that great losses of nitrogen are sure to occur if such manures are applied in the autumn, hence the justification for using ammonium-salts only as a spring dressing. It also serves to show that any differences in the effectiveness of the nitrogen of nitrate of soda and of ammonium-salts is most likely to be due to the differences in habit of growth of the plant induced by the two manures, since the conversion of the ammonium-salts into nitrate is so easily and completely effected except in such soils as are short of the base necessary for nitrification. Only in the wheat experiments is there any indication that a wet and cold year may so check nitrification as to make the ammonium-salts a less valuable source of nitrogen than usual. Again, we see how cereals, and especially wheat, are specially dependent on artificial supplies of nitrogen, and have earned the character of being exhausting

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crops. Their growth is almost completed before nitrification has reached its greatest activity (from flowering time onwards the cereals take no more nitrogen from the soil), and being harvested in August or early September, they leave the ground bare at a time of rapid nitrate formation, thus exposing it to all the risks of washing away by the autumnal rains.

### VI.—OTHER CONSTITUENTS OF DRAINAGE WATERS.

Complete analyses of the mineral constituents of the waters draining from the various Broadbalk plots were made at various times by the late Dr Voelcker and by Sir Edward Frankland; these analyses still constitute almost our only information as to direct losses of the land by drainage.

Table LXXXVI. gives an average of the five analyses made during the years 1866, 1867, and 1868.

TABLE LXXXVI.—*Composition of Drainage Waters from the Broadbalk Wheat Plots, in parts per million (Dr A. Voelcker). Mean of five (or fewer) Collections—December 6, 1866; May 21, 1867; January 13, April 21, and December 29, 1868.*

Plot.	Peroxide of Iron.	Lime.	Magnesia.	Potash.	Soda.	Chlorine.	Sulphuric Acid.	Phosphoric Acid.	Soluble Silica.	Nitrogen as		Loss by Ignition, CO <sub>2</sub> , and Difference.	Total Solid Matter.
										Ammonia.	Nitric Acid.		
2	2.6	147.4	4.9	5.4	13.7	20.7	106.1	...	35.7	0.16	16.1	77.4	476.1
3-4	5.7	98.1	5.1	1.7	6.0	10.7	24.7	0.63	10.9	0.12	3.9	67.7	246.4
5	4.4	124.3	6.4	5.4	11.7	11.1	66.3	0.91	15.4	0.13	5.1	60.1	326.0
6	2.7	143.9	7.9	4.4	10.7	20.7	73.3	1.54	24.7	0.20	8.5	84.6	407.6
7	8.1	181.4	8.3	2.9	10.9	26.1	90.1	0.91	17.0	0.07	14.0	92.6	492.4
8	2.7	197.3	8.9	2.7	10.6	39.4	89.7	0.17	20.9	0.27	16.9	110.7	548.4
9	5.1	118.1	5.9	4.1	56.1	12.0	41.0	...	10.6	0.24	18.4	99.7	423.9
10	4.0	154.1	7.4	1.9	7.1	32.0	44.4	1.44	12.7	0.08	13.9	87.0	406.9
11	3.4	165.6	7.3	1.0	6.6	31.6	54.3	1.66	11.3	0.17	15.3	83.9	425.9
12	3.6	191.6	6.6	2.7	24.6	30.9	96.7	1.26	17.9	0.30	15.1	96.6	530.9
13	3.7	201.4	9.3	3.3	6.1	36.6	86.9	1.09	23.3	0.16	17.4	100.1	544.3
14	3.7	226.7	11.6	1.0	5.6	39.4	99.7	1.01	14.0	0.09	19.2	121.6	598.6
15	3.4	201.1	7.9	5.3	14.3	24.6	123.9	1.54	22.1	0.11	24.2	87.6	585.3
16	3.0	117.1	5.3	2.4	5.1	11.4	21.9	0.91	17.0	0.09	7.0	75.4	286.7

As regards constituents of manurial value, it has already been noted that practically no nitrogenous compounds occur in drainage water except the nitrates; phosphoric acid is

also present in but small amounts, even in the plots receiving a great annual excess of this substance, while potash was found in slightly greater quantities. The mean annual loss, however, cannot be estimated at more than about 2 lb. of phosphoric acid and 10 lb. of potash per acre, both of which in normal cases would be arrested in the subsoil below the drains. Dr Bernard Dyer's analyses of the Rothamsted soils and subsoils would also indicate that all the excess of phosphoric acid, applied as a manure and not removed in the crop, still remains in the soil very near the surface, the potash having sunk a little further, and being present to some degree in the third depth of 9 inches below the surface.

The chief constituent of the drainage water from the unmanured plots consists of calcium carbonate, the amount of which is increased in the water from the dunged plot, owing to the greater production of carbonic acid from the decay of the dung and crop residues. Where ammonium-salts like the sulphate and chloride are applied as a manure the soil suffers a great loss of calcium carbonate, the calcium being removed in the drainage water combined with the sulphuric or hydrochloric acid of the manure. This reaction is the necessary precedent to the arrest of the ammonia in the soil and its subsequent nitrification. In the absence of a sufficiency of calcium carbonate in the soil to bring about this reaction, ammonium-salts become injurious to plant life. The salts of potassium, like the sulphate and chloride, may also increase the loss of calcium carbonate to the soil, for they react with it in the same way as do the ammonium-salts, forming calcium sulphate and chloride, which are no longer retained by the soil.

Since the healthy condition of the soil depends on a due proportion of calcium carbonate being present, these losses caused by the use of natural and artificial manures are of the greatest importance; many of our fertile soils may easily lose much of their power of producing crops unless their proportion of calcium carbonate is restored by judicious liming at intervals.

Determinations of the calcium carbonate in samples of the

## REMOVAL OF LIME IN DRAINAGE WATERS · 239

soil taken at various intervals between 1865 and 1904 indicate that on the unmanured plots the normal loss of calcium carbonate in the drainage water amounts to about 1000 lbs. per acre. When ammonium-salts are used as a manure, the loss is increased by the amount required to combine with the combined acid in the manure. The calcium carbonate, however, which is required for nitrification, gets returned to the soil by the growth of the plant itself, and by the decay of calcium compounds in the crop residues.

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## CHAPTER XII

### THE FEEDING EXPERIMENTS

- I. Relative Value of Nitrogenous and Non-nitrogenous Constituents of Food.
  - II. Relation of Nitrogenous Food to Work.
  - III. The Source of Fat in the Animal Body.
  - IV. Relation of Food Consumed to Live-weight Increase.
  - V. The Composition of Oxen, Sheep, and Pigs, and of their Increase during Fattening.
  - VI. The Manure Value of Foods.
  - VII. Miscellaneous Feeding Experiments.
- References.

#### I.—RELATIVE VALUE OF NITROGENOUS AND NON-NITROGENOUS CONSTITUENTS OF FOOD.

At the date of the inception of the Rothamsted Experiments even less was known about the laws of the nutrition of animals than of crops, though the question had excited more interest on the Continent than in England. Here attention had been in the main concentrated upon the animal; it had been the object of breeders and graziers to develop races of stock that would give the least waste and the largest proportion of useful meat to live weight. To this end early maturity had also been successfully sought, thus economising the food used merely in keeping the animal alive without increasing its weight. On the Continent, however, even in the eighteenth century, attention had been rather directed to the character of the food, and especially to obtaining a measure of the comparative value of different foods, with the view of ascertaining how far one could replace another.

As an example of what was going forward, Thær's "hay

values" may be instanced; in 1809 he published a table of all the recognised cattle foods, ranged in order and marked to show how much of each was equivalent to 100 parts of hay taken as a standard. Thayer's hay values were based partly on his own experience as a practical man and partly on attempts, very imperfect in the then state of chemical knowledge, to estimate by analysis the nutritive constituents of the foods. Boussingault's investigations were the earliest serious attempts to apply scientific principles to the feeding of animals; the importance of the nitrogenous constituents of food had now become clear, so his first work consisted in determining the proportion of nitrogen present in a large number of feeding materials. Careful practical trials were then made with a few selected foods, and as a result he published a revised table of hay values, based on the amount of nitrogen the foods contained, and checked to some extent by his practical experience. His experiments led Boussingault to bring into prominence the non-nitrogenous constituents of food, but in general his conclusions were that the comparative values of food-stuffs are determined rather by their nitrogenous than by their non-nitrogenous constituents. In this subject Boussingault's was the pioneer work, and Liebig, who in many respects must be regarded as the originator of any general theory of animal nutrition, in the main arrived at his deductions from Boussingault's results. Liebig also, and perhaps even more strongly than Boussingault, looked at the nitrogenous matter as the most important constituent of food for the production of both increase and of work.

In this position was the science of animal nutrition when Lawes and Gilbert began their experiments on feeding, and naturally the direction their experiments took was mainly determined by the views then prevailing. The most notable characteristic of the Rothamsted experiments on animals was that from the first they were concerned with animals increasing in weight rather than with animals whose food rations were adjusted to maintain them in a constant condition. The

practical side was thus prominent: they were trying to give a scientific basis to the work of the grazier by ascertaining to what source the increased weight of an animal was due, and how it might be produced most rapidly and economically.

The first set of feeding experiments at Rothamsted dealt with the relation between food consumed and live-weight increase produced. Selected pens of the various animals were fed upon specified rations of different foods, one of which was always fed *ad libitum*, so that the exact composition of the ultimate ration was determined by the animal itself. The nitrogen and dry matter in the food was determined, and the weight of manure produced both in a fresh and dry condition was ascertained. In all, about 600 sheep were employed in the experiments, 160 pigs, and 200 oxen, many of the latter being fattened on the Duke of Bedford's farm at Woburn.

The experiments with sheep came first, and tended to show that the prevailing impression of the special importance to be attached to the nitrogenous constituents of food was not correct, but that it was rather the supply of non-nitrogenous food which regulated both the amount of food consumed by a given live weight in a given time and also the increase in live weight produced. Of course, at that time it was not possible to distinguish between the digestible and the indigestible portions of the food, nor was any attempt made to estimate in the different foods the relative proportions of albuminoid nitrogen and of such nitrogen compounds as the amides, etc., which are abundant in roots, but of whose feeding value nothing was known. That the exactitude of their experiments was limited by these considerations, was pointed out by Lawes and Gilbert; at the same time, the corrections necessary would not invalidate the soundness of the general conclusions they drew. The experiments on pigs indicated still more clearly that the carbohydrates were chiefly concerned in both the maintenance and in the increase in live weight of the pigs, also that very great variations in the amount of albuminoids consumed were without much effect on the result,

when once the necessary minimum of nitrogenous matter in the ration had been passed. The rations fed to the various lots of pigs were so arranged as to supply very different proportions of nitrogenous and starchy food. In some cases the food was mainly highly nitrogenous bean or lentil meal, in others very starchy barley meal or maize was employed; in another set

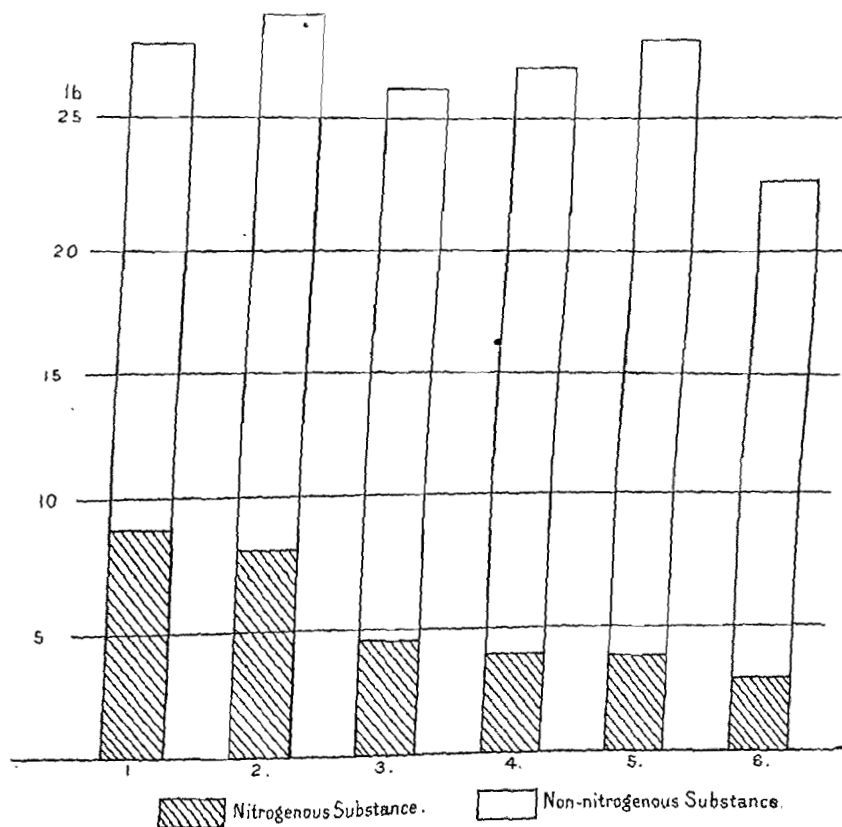


FIG. 46.—Dry Matter and Nitrogenous Substance consumed per 100 lb. Live Weight per week. Pigs.

1. Bean and Lentil Meal, *ad lib.*
2. Maize Meal, limited. Bean and Lentil Meal, *ad lib.*
3. Bean and Lentil Meal, limited. Maize Meal, *ad lib.*
4. Bran, limited. Maize Meal, *ad lib.*
5. Barley Meal, *ad lib.*
6. Maize Meal, *ad lib.*

of experiments, actual starch or sugar was added to the rations. In all cases the pigs had an *ad libitum* supply of one food or other, so that they could regulate the amount and to some extent the composition of their diet.

The diagrams, Figs. 46 and 47, show, from some of these results obtained with pigs, the amount of dry organic matter required to produce 100 lb. of increase, and also the proportion of it which can be reckoned as nitrogenous matter.

It will be seen from these diagrams that, speaking broadly, neither the amount of dry food-stuff required for maintenance

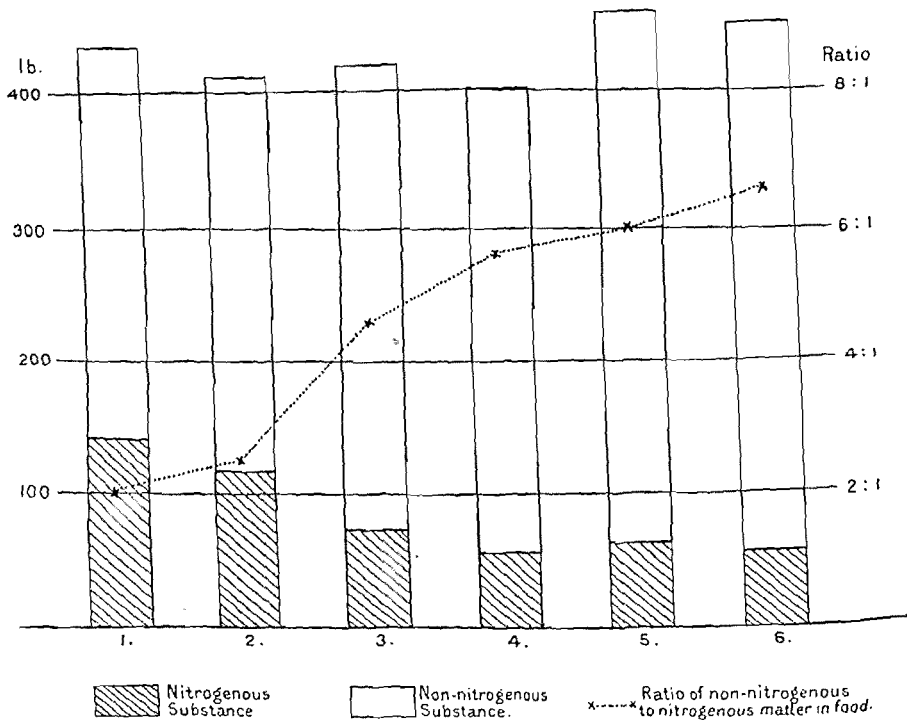


FIG. 47.—Nitrogenous and Non-nitrogenous Matter in Food required to produce 100 lb. Live-weight Increase. Figs.

1. Bean and Lentil Meal, *ad lib.*
2. Maize Meal, limited. Bean and Lentil Meal, *ad lib.*
3. Bean and Lentil Meal, limited. Maize Meal, *ad lib.*
4. Bran, limited. Maize Meal, *ad lib.*
5. Barley Meal, *ad lib.*
6. Maize Meal, *ad lib.*

per 100 lb. live weight of the animal nor the amount required to produce 100 lb. increase in the live weight varied very widely, whatever the character of the foods consumed. The amount of nitrogenous substance did, however, show a very wide range of variation, hence whatever was consumed above a certain minimum could have been replaced without loss by purely non-

nitrogenous organic matter. In other words, the non-nitrogenous compounds are the main items to be taken into account in making up the value of a cattle food, which value cannot be estimated on a basis of its nitrogen content only.

## II.—RELATION OF NITROGENOUS FOOD TO WORK.

The very special importance that was originally attached to the nitrogenous constituents of food was also seen in the views of Liebig with regard to the source of the work, either external or internal, performed by an animal. He put forward the view that the amount of work done was determined by the amount of nitrogenous material transformed in the body, and therefore that it could be measured by the amount of nitrogen appearing in the urine, since the albuminoids and other nitrogen compounds in food which are digested and undergo change in the animal are excreted as urea. Lawes and Gilbert, by their studies of human dietaries, were led to conclude that this view was mistaken, and that the fats and carbohydrates, which are oxidised and leave the body in the respiration products, supply the energy for the work performed in and by the body. Two experiments with pigs, carried out in 1854 and 1862 respectively, were adduced as further evidence. The pigs were confined in a frame; the nitrogen in the food and the nitrogen excreted in urine and fæces respectively were determined. The food was so adjusted that one pig received about twice as much nitrogen as the other (Table LXXXVII.).

The animals were obviously under equal conditions as regards exercise, both being at rest, yet in each experiment the animal receiving the highly nitrogenous diet excreted rather more than twice as much nitrogen as urea. Thus the amount of nitrogen in the urine, which measures the amount of albuminoids oxidised, could hardly be taken as a measure of the amount of work performed by the respective animals.

The question was afterwards systematically attacked in various directions by other investigators, and direct proof was obtained that the energy required to carry on work is

derived from the oxidation of the food constituents, either albuminoids, fats, or carbohydrates being available for the purpose, though as a rule the two latter are utilised. The

TABLE LXXXVII.—*Experiments at Rothamsted with Pigs in 1854 and 1862. Quantities per head per day.*

Period.	Foods.	Nitrogen in Food.	Urea Voided.	Nitrogen in Urea.
June to August 1854.				
Days.		Grams.	Grams.	Grams.
3	No. 1. Lentil Meal . . .	123.0	134.0	62.6
3	No. 2. Barley Meal . . .	58.9	61.5	28.7
10	No. 1. Lentil Meal . . .	120.6	141.0	65.8
10	No. 2. Barley Meal . . .	51.2	52.1	24.3
August to September 1862.				
10	No. 1. Barley and Bran . . .	41.6	43.6	20.4
10	No. 2. Beans and Bran . . .	66.0	89.6	41.8
5	No. 1. Barley and Bran . . .	46.2	52.3	24.4
5	No. 2. Beans and Bran . . .	82.5	116.6	54.4

amount of energy obtainable from each food can be directly measured by the heat it will generate when burnt, and provided the animal receives enough nitrogenous material to repair the normal waste of tissue, the energy required to do work can be wholly derived from the combustion of non-nitrogenous materials. However, when the output of work has to be rapid and at high pressure, it has been found advisable to include a fairly high proportion of easily digestible and concentrated albuminoids in the food; as Lawes and Gilbert put it in 1852, "a somewhat concentrated supply of nitrogen does, however, in some cases, seem to be required when the system is over-taxed."

### III.—THE SOURCE OF FAT IN THE ANIMAL BODY.

The source of the fat stored up in animals, or given out as milk, was also for a long time a matter of considerable contro-

## FAT DERIVED FROM CARBOHYDRATES 247

versy. It was clear that the fat supplied in the food was in many cases, especially with herbivora, insufficient to supply all the fat produced by the animal, and though Liebig on general grounds argued that the starch, sugar, and other carbohydrates of the food could be elaborated into fat, for some time the view was held that the extra fat could only come from the transformation of albuminoids. This view was strongly opposed by Lawes and Gilbert, whose experiments upon the fattening of pigs showed that the animals put on far more fat than could be made up from the whole of the fat and albuminoids in the foods. To take one example, pigs were fed upon maize meal or barley meal *ad lib.*, with the following results:—

TABLE LXXXVIII.

	Maize Meal	Barley Meal
Number of Animals . . . . .	3	3
Duration of Experiment . . . . . Weeks	8	9
Original Live Weight per head . . . . . Lb.	144	148
Increase in Live Weight . . . . . Lb.	73	97
Per 100 increase in Live Weight.		
(1) Albuminoids in Food . . . . .	57	64
(2) Albuminoids in increased Live Weight . . . . .	5·3	6·5
(3) Leaving Albuminoids available for Fat Formation . . . . .	51·7	57·5
(4) Fat in increased Live Weight . . . . .	79·0	71·2
(5) Fat in Food . . . . .	26·3	12·4
(6) Fat formed during the Experiment . . . . .	52·7	58·8
Carbon in Fat formed (6) . . . . .	40·6	45·3
Carbon in Food Albuminoids (3), less Carbon excreted in Urea . . . . .	24·7	27·4
Carbon in Fat formed during Experiment, not derivable from Fat or Albuminoid . . . . .	15·9	17·9
Relation of last item to the Carbon of Fat formed during the Experiment	39·2%	39·5%

Thus, after crediting the fat put on by the animal during the experiment with the whole of the fat in the food, and with the maximum that could by any possibility be generated out of the albuminoids in the food, there still remains about 40 per cent.

of the fat formed which could only have come from carbohydrates in the food. Similar but less decisive evidence was adduced from the sheep-feeding experiments, and the view which Lawes and Gilbert maintained on these grounds has since been amply confirmed by the experiments of Kühn and others.

#### IV.—RELATION OF FOOD CONSUMED TO LIVE-WEIGHT INCREASE.

Taking the ordinary foods available on the farm, Lawes and Gilbert found that oxen, sheep, and pigs differed greatly in their powers of consuming food, and in the rate at which their live weights would increase. During the whole fattening period oxen will consume per 1000 lb. of live weight 120 to 150 lb. of dry food per week (*e.g.*, in the experiments, 25 lb. cake, 60 lb. clover hay, and 350 lb. Swedes), and should produce about 10 lb. live-weight increase per week. Sheep, per 1000 lb. live weight, will consume in the same time about 150-160 lb. of dry food (44 lb. cake, 52 lb. clover hay, and 70 lb. Swedes) for a production of 17-18 lb. increase per week. The same live weight of pigs, consuming 260-280 lb. of dry food (300 lb. barley meal), will produce 50-60 lb. increase.

These results may be expressed in a table as follows :—

TABLE LXXXIX.

	Number of Experiments.	Number of Animals.	Average duration of Experiment.	Dry Substance of Food consumed.			Increase per 1000 lb. Live Weight per week.	Dry Manure* per 1000 lb. Live Weight per week.
				Per Head per week.	Per 1000 lb. Live Weight per week.	To produce 1 lb. Increase in Live Weight.		
Oxen .	27	112	Days. 87	Lb. 146½	Lb. 121	Lb. 13·0	Lb. 9·4	Lb. 50
Sheep .	19	307	143	20½	159	9·2	17·2	54
Pigs .	33	104	58	48	270	4·8	56·2	63

\* Dry Matter of Solid Excrement and Urine exclusive of Litter.

These estimates, drawn up from a very large number of trials carried out in the ordinary way of farming, have been generally verified by the later exact work of the German experi-

menters, if allowance be made for the superior fattening qualities of the English stock. Probably at the present day both the estimates of the amount of food required per diem and the rate of increase should be raised, because of the improvements that have been effected in the breeds of our sheep and cattle. The modern farm animal is in fact a more efficient meat-producing machine than it was fifty years ago, capable of dealing with more food and of growing more rapidly to maturity, thus shortening the time during which food has to be consumed for purposes of pure maintenance only. It is in this direction that new experiments and additional data are generally needed, for we know nothing of the relative capacities of modern breeds of farm animals as meat producers or of their digestive powers for various foods. Due economy in feeding is only possible if the practical man can check his opinions by reference from time to time to exact determinations of the requirements of different animals at various stages of their growth.

Others of the pig experiments showed how much less of the food is utilised for increase as the fattening advances, partly because as the animal increases in size it consumes more food for purposes of warmth and internal work than before, partly also because the increase made during the latter period is more fatty and therefore drier than in the earlier stages.

The following table shows the rates of increase of pigs fed

TABLE XC.—*Fattening Pigs. Weekly Consumption of Food, and rate of Increase.*

	Food Consumed.		Increase in Live Weight.		Food producing 100 lb. of Increase.
	Per Head.	Per 100 lb. Live Weight.	Per Head.	Per 100 lb. Live Weight.	
	Lb.	Lb.	Lb.	Lb.	Lb.
First Fortnight . . .	60.1	39.7	15.5	10.3	339
Second Fortnight . . .	67.5	36.7	17.4	9.4	339
Third Fortnight . . .	66.4	30.9	13.2	6.2	502
Fourth Fortnight . . .	66.0	27.4	12.9	5.4	511
Fifth Fortnight . . .	69.6	26.3	11.3	4.2	621
Mean . . .	65.9	32.0	14.1	6.8	469

on an unlimited supply of barley meal together with a fixed ration of 1 lb. per head of pea meal per diem.

V.—THE COMPOSITION OF OXEN, SHEEP, AND PIGS, AND OF THEIR INCREASE DURING FATTENING.

The most important work carried out at Rothamsted on the nutrition of animals was the determination of the composition of ten farm animals in different stages of growth and fattening.

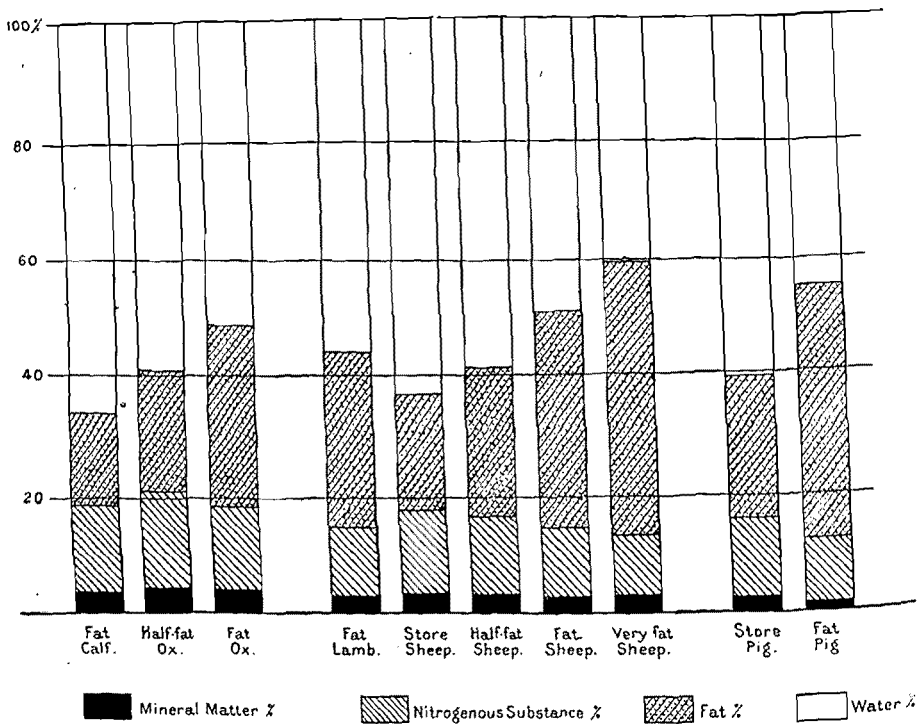


FIG. 48.—Percentage Composition of the Whole Bodies of Oxen, Sheep, and Pigs.

For this purpose the following animals were selected—a fat calf, a half-fat and a fat ox; a fat lamb, a store sheep, three others in the half-fat, fat, and very fat condition; a store and a fat pig. These animals after slaughter were carefully divided, and the weights of the carcass and different parts of the offal were determined. Afterwards the proportions of water, fat, nitrogen, and ash in each part were determined, the composition of the ash of each part being determined later. A summary of the results is set out in Table XCI., while the diagram (Fig. 48) shows graphically the composition of the entire animals.

PERCENTAGE COMPOSITION

TABLE XCI.—Percentage Composition of the Carcasses, the Offal, and the Entire Bodies of ten Animals of different descriptions, or in different conditions of Maturity.

Description of Animal.	Mineral Matter (Ash).	Nitrogenous Substance.	Fat.	Total Dry Substance.	Water.	Contents of Stomachs and Intestines (Moist State).
Per cent. in Carcass.						
Fat Calf . . . . .	4.48	16.6	16.6	37.7	62.3	...
Half-fat Ox . . . . .	5.56	17.8	22.6	46.0	54.0	...
Fat Ox . . . . .	4.56	15.0	34.8	54.4	45.6	...
Fat Lamb . . . . .	3.63	10.9	36.9	51.4	48.6	...
Store Sheep . . . . .	4.36	14.5	23.8	42.7	57.3	...
Half-fat Old Sheep . . . . .	4.13	14.9	31.3	50.3	49.7	...
Fat Sheep . . . . .	3.45	11.5	45.4	60.3	39.7	...
Extra Fat Sheep . . . . .	2.77	9.1	55.1	67.0	33.0	...
Store Pig . . . . .	2.57	14.0	28.1	44.7	55.3	...
Fat Pig . . . . .	1.40	10.5	49.5	61.4	38.6	...
Mean of all . . . . .	3.69	13.5	34.4	51.6	48.4	
Per cent. in Offal (excluding Contents of Stomachs and Intestines).						
Fat Calf . . . . .	3.41	17.1	14.6	35.1	64.9	...
Half-fat Ox . . . . .	4.05	20.6	15.7	40.4	59.6	...
Fat Ox . . . . .	3.40	17.5	26.3	47.2	52.8	...
Fat Lamb . . . . .	2.45	18.9	20.1	41.5	58.5	...
Store Sheep . . . . .	2.19	18.0	16.1	36.3	63.7	...
Half-fat Old Sheep . . . . .	2.72	17.7	18.5	38.9	61.1	...
Fat Sheep . . . . .	2.32	16.1	26.4	44.8	55.2	...
Extra Fat Sheep . . . . .	3.64	16.8	34.5	54.9	45.1	...
Store Pig . . . . .	3.07	14.0	15.0	32.1	67.9	...
Fat Pig . . . . .	2.97	14.8	22.8	40.6	59.4	...
Mean of all . . . . .	3.02	17.2	21.0	41.2	58.8	...
Per cent. in the Entire Animal (Fatted Live Weight).						
Fat Calf . . . . .	3.80	15.2	14.8	33.3	63.0	3.17
Half-fat Ox . . . . .	4.66	16.6	19.1	40.3	51.5	3.19
Fat Ox . . . . .	3.92	14.5	30.1	43.5	45.5	5.98
Fat Lamb . . . . .	2.94	12.3	28.5	43.7	47.8	3.54
Store Sheep . . . . .	3.16	14.8	18.7	36.7	57.3	6.00
Half-fat Old Sheep . . . . .	3.17	14.0	23.5	40.7	50.2	9.05
Fat Sheep . . . . .	2.81	12.2	35.6	50.6	43.4	6.02
Extra Fat Sheep . . . . .	2.90	10.9	45.8	59.6	35.2	5.13
Store Pig . . . . .	2.67	13.7	23.3	39.7	55.1	5.22
Fat Pig . . . . .	1.65	10.9	42.2	54.7	41.3	3.97
Mean of all . . . . .	3.17	13.5	28.2	44.9	49.0	6.13

It is obvious that from these results a great deal of evidence can be obtained as to what goes on during the fattening process, if we can assume that the particular animals selected for analysis are typical of the ordinary run of live stock and represent the normal change in composition of fattening animals. It is obvious, for example, that the fattening process is properly so called; even animals in the store condition contain rather more fat than nitrogenous substance, but as the fattening process advances the proportion of fat to albuminoid rises until it becomes two or even three times as great. Of course the gross amount of albuminoid in the animal continues to increase somewhat, but the increase in the fat is so much greater that the proportion of albuminoid in the finished animal has been reduced. It will be seen also that the fat animal contains less water than the same animal in the store condition; lean meat possesses, in fact, a considerably higher proportion of water than fat does, so that the accumulation of fat tends to reduce the proportion of water in the whole body.

From the figures obtained in these experiments the composition of the live-weight increase during fattening can be deduced. This is set out graphically in the diagram Fig. 49, from which it will again be seen how much of the weight put on by an animal during fattening is made up of fat itself. In oxen, when the fattening process begins while they are young, as is generally the case nowadays, the increase of weight will consist of about one-third water and two-thirds dry substance, the latter being made up of about 15 per cent. of nitrogenous matter and 75-80 per cent. of fat. For the final fattening stage, when the animal is full grown, about three-quarters of the increase will be dry matter, containing only about 10 per cent. of nitrogenous matter and 90 per cent. of fat.

In the case of sheep, rather more mineral matter is contained in the fattening increase, because of the large content of wool in alkaline salts; but despite the nitrogenous nature of wool, the amount of nitrogenous matter in the increase is less for sheep

# COMPOSITION OF INCREASE IN WEIGHT 253

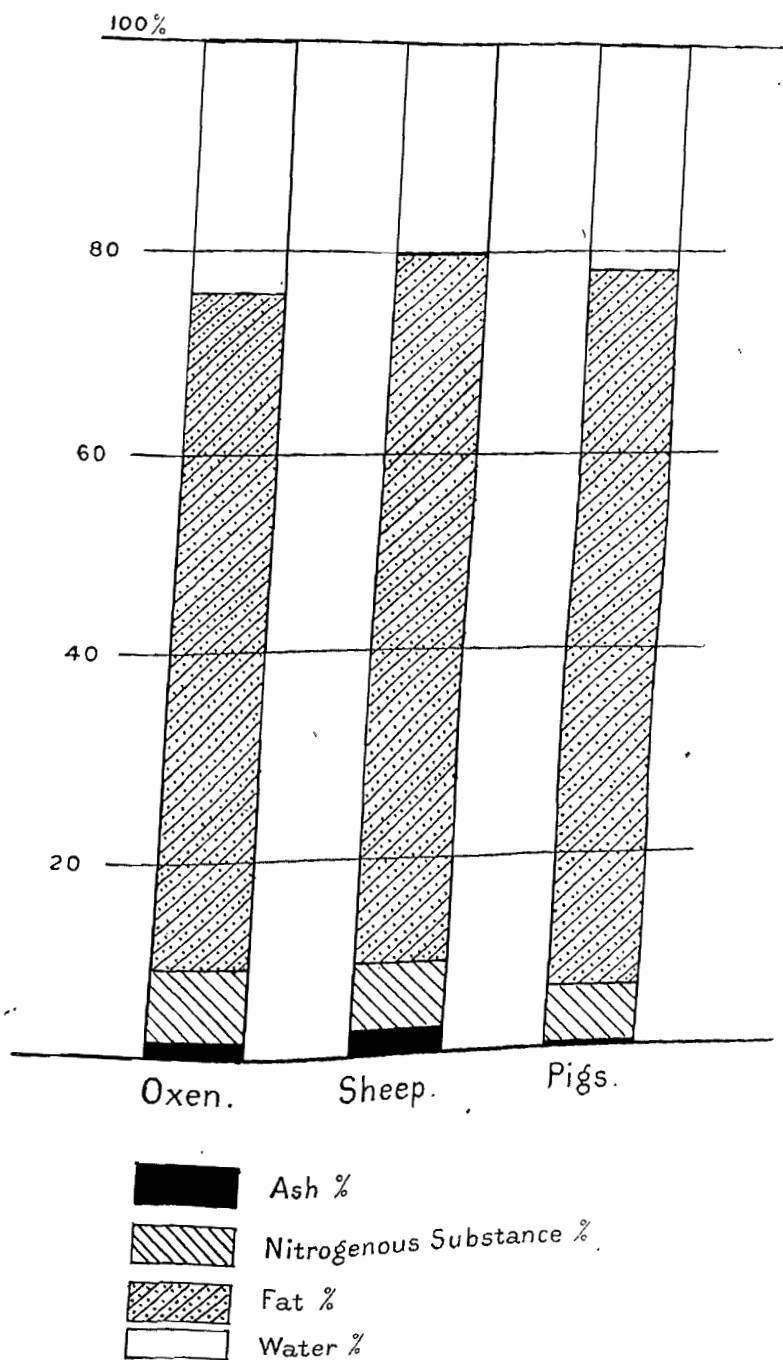


FIG. 49.—Oxen, Sheep, and Pigs. Composition of Increase in Fattening.

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than for oxen, the balance being made up by an extra proportion of fat, which may amount to 75 per cent. of the increase. In the case of really fat pigs the increase will contain about 70 per cent. of fat and 7 per cent. of nitrogenous matter, being even less nitrogenous and more fatty than with sheep.

These experiments on the composition of whole animals, which form the fundamental basis of our knowledge of the nature of the animal's body and of the changes taking place during growth and fattening, have never been repeated.

#### VI.—THE MANURE VALUE OF FOODS.

In order to form any estimate of the value of different cattle foods, it is of much importance to know how far their various manurial constituents—nitrogen, phosphoric acid, and potash—find their way into the manure heap, and so back to the farm.

In the experiments previously described it is seen how small a proportion of the nitrogenous constituents of food is retained in the increased live weight of the animal during fattening, by far the largest portion being passed undigested into the fæces, or excreted as urea in the urine. When the animal is producing milk, however, a much larger proportion of the nitrogen will be removed in the milk than is retained in fattening increase, and the manure made will be correspondingly poorer. At the other extreme is the case of a working horse or a store beast not gaining in weight, when the whole of the nitrogen supplied in the food will be voided in the fæces or the urine.

As regards the mineral matters of the food, after the animal has withdrawn a certain small proportion for increase or for milk, the remainder must find its way into the manure; but in the case of the nitrogenous compounds there is always the possibility of loss, because some of the nitrogen may pass into volatile ammonia, or even into gaseous nitrogen, during the vital processes.

The question of the existence of this loss was investigated

at Rothamsted in 1854 with pigs, the animals being confined in a frame resting upon a sloping zinc bottom. They were watched day and night during the experimental period, and the voidings were collected as soon as passed, and analysed at regular intervals for dry matter, ash, and nitrogen. The results were, however, not satisfactory; there was a considerable portion of the nitrogen of the food unaccounted for in either the increase of weight or in the excrements. The results seemed to show that the loss was probably due to the difficulties of proper collection and analysis of the excreta, so that the experiment was repeated with greater precautions in 1862. This time the losses of nitrogen were much reduced, and when allowance was made for the many unavoidable sources of error, the results supported the idea that the whole of the nitrogen of the food not stored up as increase passed over into the manure. Other experiments were made with sheep; but again it was impossible to avoid some mechanical losses, and to eliminate the uncertainty due to lack of exact knowledge of the composition of the animal at the beginning and close of the experiment.

Later experiments on the Continent have indeed set the point at rest, and shown that there is no decomposition of nitrogenous matter of the food into nitrogen gas during the vital processes, but that the whole of the digested nitrogen which is not utilised for increase, milk, etc., is voided in the urine.

The practical question which greatly occupied the attention of Lawes and Gilbert was that of the manure value of the many purchased cattle foods commonly used in this country, and particularly the compensation to be paid to an outgoing tenant for their consumption in the latter years of his tenancy, before he could be supposed to have obtained a return from them in the shape of the crop. Lawes and Gilbert therefore prepared a table showing the composition of most of the cattle foods commonly in use, and calculated what proportion of the nitrogen, phosphoric acid, and potash present would under normal conditions be retained by fattening stock consuming the

food. Thus when stock consume linseed cake, Lawes and Gilbert calculated that every 6 lb. of food produced 1 lb. increase in live weight containing 1·27 per cent. of nitrogen; so that if 1 ton were consumed, out of the 106·4 lb. of nitrogen in the cake the animals would retain 4·74 lb., and pass on to the manure 101·66 lb. The same ton of linseed cake would contain 44·8 lb. of phosphoric acid, of which the fattening animal would only retain 3·21 lb., and 31·4 lb. of potash, of which the animal would only retain 0·4 lb.

When dealing, however, with less concentrated foods the amount required to produce 1 lb. of increase would be much greater and the toll taken by the animal of the nitrogen in the food would also increase. For example, 1 ton of oat straw contains 11·2 lb. of nitrogen, of which the animal would retain 1·6 lb. and pass on 9·6 lb. to the manure—only 86 per cent. of that which had been fed instead of over 95 per cent., as in the case of linseed cake.

From data of this kind Lawes and Gilbert were able to calculate for each of the named foods the amount of nitrogen, phosphoric acid, and potash which would go to the manure. The experiments before mentioned had gone to show that there is no loss of nitrogen during the actual feeding process. However, it had been ascertained that even under the best conditions (as in the cattle-feeding experiments at Woburn before alluded to) there were great losses of nitrogen in making the dung before the manure reached the land, these losses being due in the main to the volatilisation of ammonia resulting from the rapid fermentation of the urea. Such losses, too, fall upon the urea, the most valuable part of the excreta, since the undigested food residues in the fæces decay so slowly in the ground as to have a lower manure value. Very few data existed from which to determine how large these losses are under ordinary farming conditions, but Lawes and Gilbert felt safe in assuming that at least one-half of the manurial material voided by the animal is lost during the making and storage of the dung, and does not come back to the land in the manure.

The compensation table they drew up showed (1) the amount of nitrogen, phosphoric acid, and potash in the food itself; (2) the amount passed by the animal after taking out what it required for its own fattening increase; (3) the value of this voided material at the current prices of these constituents in manures, or as they called it, the "original manure value" of the food. They then proceeded to arrange a compensation table on the basis of allowing the outgoing tenant half this original manure value, *i.e.*, assuming that only half of the manure material voided by the animal would be found by the incoming tenant in the manure heap he was taking over. This compensation value was further diminished by one-third for each additional year between the date when the food was consumed and the expiration of the tenancy; thus the compensation value of food consumed in the last year of the tenancy would be half of the original manure value, and it would become one-half less one-third of itself (or one-third of the original manure value) for food consumed in the second year before the tenancy ended, and so on by steps of one-third less for each earlier year. These tables were based on the composition of the fattening increase as ascertained in the previous experiments. Other tables were drawn up for milch cows, which take a much greater toll of the food consumed.

These compensation tables never passed into general use, partly because of the somewhat complex character of the argument and the long period previous to the expiration of the tenancy over which they allowed compensation to be claimed for the consumption of purchase food. They have, however, brought into prominence the great errors introduced by the common custom of paying half the purchase price of the food consumed during the last year only of the tenancy, since the manure value of a food is quite independent of its food value and price in the market. Decorticated cotton cake, for example, has the highest manure value of any substance commonly used for food, yet it can be purchased more cheaply than linseed cake, which has a much lower manure value. Maize, again, however

valuable as a food because of the carbohydrates and fat it contains, has but a low manure value, since it is comparatively poor in nitrogen and ash constituents. Thus the custom of paying half the last year's cake bill would result in paying too highly for linseed cake and maize and too little for cotton cake consumed on the farm.

As an appreciation of these facts gradually spread among practical men in consequence of the Rothamsted publications, and as recently legislation rendered it imperative to put this question of compensation due to the outgoing tenant on a sound scientific basis, the matter has latterly received more attention from farmers and professional valuers. More data have also been accumulated as to the nature and extent of the inevitable losses of nitrogen in manure making, so that it has been possible to construct a modified version of the original compensation table, which now seems to be generally accepted in principle by the valuers chiefly concerned.

#### VII.—MISCELLANEOUS FEEDING EXPERIMENTS.

The above summary by no means exhausts the many experiments upon animal feeding which were carried on at Rothamsted. One set of trials, for example, was arranged to test the relative values of starch and sugar as foods, with the result that they were found to be sensibly equal, as we should nowadays expect in the light of the equal calorific value and similar chemical composition of these foods.

Other trials chiefly dealt with practical points, as for example the long series of trials on the comparative fattening qualities of different breeds of sheep—Hampshires, Southdowns, Cotswolds, Leicesters, and crossbred Leicester-Southdowns being selected for the purpose.

Experiments on the use of condiments in cattle feeding proved of great practical value, as they showed the exaggerated nature of the claims which were being advanced by the manufacturers of some of the patented cattle foods.

Other feeding experiments dealt with the comparative value

of sewage-irrigated and ordinary meadow grass, with the use of malted foods, with the value of ensilage; but these will be dealt with separately.

Speaking generally, these feeding experiments of Lawes and Gilbert, while they will not bear the exact analysis to which later experiments carried out in respiration chambers can be subjected, so that the digestibility of the foods and the portions which go to maintenance, increase, and work respectively can be ascertained, yet gave a sound general idea of the broad principles of animal nutrition as they affect the farmer. They are noteworthy for the intuition with which correct opinions of the general processes were deduced by statistical means from experiments carried out in the main under ordinary farming conditions, opinions which have in all cases been abundantly verified by later and more accurate research.

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## CHAPTER XIII

### MISCELLANEOUS ENQUIRIES

- I. Experiments upon Sewage Irrigation.
- II. Experiments upon Malt and Barley.
- III. Experiments upon Ensilage.
- IV. The Composition of Wheat Grain and its Mill Products.  
References.

#### I.—EXPERIMENTS UPON SEWAGE IRRIGATION.

FROM time to time the Rothamsted investigators were called upon for work dealing with various debatable questions of public importance more or less connected with agriculture. For example, Lawes was appointed a member of the Royal Commission which was charged in 1857 "to inquire into the best mode of distributing the sewage of towns, and applying it to beneficial and profitable uses." The application of sewage to land was naturally one of the subjects of enquiry, and was entrusted to a sub-committee consisting of Lawes and Way, who carried on during 1861-64 experiments at Rugby on the growth of grass with and without sewage treatment, and on the value of the sewage-irrigated grass for feeding stock. The experimental station at Rothamsted was much occupied with the superintendence of these experiments and with the analytical and statistical work involved. The general conclusion from the experiments was that broadcast irrigation on grass land was the best way of dealing with sewage, the highest returns being obtained when large quantities of sewage, as much as 9000 tons per acre, were employed.

As to the grass—that grown in sewage was found to be more watery than the unsewaged grass; hence, of equal weights of green grass, the unsewaged produced the most increase in fattening oxen. But calculated on a basis of equal weights of dry matter, the sewage-irrigated grass gave the better results. The best returns were, however, obtained when the grass was fed to milking cows; sewage irrigation was found to increase the amount of milk which could be produced from 1 acre of land three- or four-fold. The herbage of the sewage-irrigated meadows was found to change rapidly; the Leguminosæ disappeared, as did most of the miscellaneous species, while the grasses became restricted to two or three vigorous species, which constituted the whole vegetation, such as rough-stalked meadow grass, couch grass, cocksfoot, Yorkshire fog, and rye grass.

## II.—EXPERIMENTS UPON MALT AND BARLEY.

In 1863, at the request of the Board of Trade, experiments were undertaken to ascertain the relative feeding value of malt and of the barley from which it was made, so as to see if anything was gained by the process of malting. It had often been asserted, and was the opinion of many practical graziers, that even if there were some loss in the process of converting barley into malt, yet the superior digestibility of the malt and its action upon the other items of the whole food more than compensated for this loss.

The investigation was divided into two stages—(1) an enquiry into the nature and amount of the losses during the malting process; (2) a comparison of the food value of the resulting malt and of the original barley.

Two lots of barley were selected for the experiment, one a malting barley of fair quality, the other a thinner, more nitrogenous barley, such as would only be used for feeding. The malting was done in the ordinary way, at Hertford, and samples of 25 lb. each were taken of the grain before steeping, when thrown out after steeping, at intervals during growth, and

finally after drying and screening; these samples being sent to Rothamsted for analysis.

The results are summarised in the following table, which shows for each sample the changes during the various stages, as calculated back to 100 parts in the original material.

TABLE XCII.—*Loss of Constituents at certain Stages, and at the conclusion of the Malting Process. Proportion to 100 before Steeping.*

	Barley before Steeping.	As thrown from the Couch.	Eight days on the Floor.	Final Products sent to the Kiln.			Loss.
				Screened Malt.	Malt Dust.	Total.	
Barley No. 1.							
As Sampled . . . . .	100	143.2	135.4	78.93	2.20	81.13	18.87
Total Dry or Solid Matter . . . . .	100	99.6	95.9	89.45	2.35	91.80	8.20
Non-nitrogenous Organic Matter . . . . .	100	99.9	95.7	89.66	1.74	91.40	8.60
Nitrogenous Matter . . . . .	100	99.6	99.0	90.61	6.45	97.06	2.94
Mineral Matter . . . . .	100	90.3	89.4	77.68	7.94	85.62	14.38
Barley No. 2.							
As Sampled . . . . .	100	147.2	138.7	74.62	3.21	77.83	22.17
Total Dry or Solid Matter . . . . .	100	99.3	96.1	87.78	3.41	91.19	8.81
Non-nitrogenous Organic Matter . . . . .	100	99.5	95.8	88.19	2.62	90.81	9.19
Nitrogenous Matter . . . . .	100	98.3	97.1	85.52	7.14	92.66	7.34
Mineral Matter . . . . .	100	100.0	102.5	84.76	12.02	96.78	3.22

For example, dealing with sample No. 1, we see that 100 parts of grain yielded 79 parts of malt and 2.2 of malt dust, a loss of weight of nearly 19 per cent. This loss was, however, largely water, for the next row of figures shows that of 100 parts of dry matter in the original material 91.8 were recovered in the malt and malt dust. During steeping 0.4 per cent. of dry matter was lost, consisting of mineral matter (largely dirt washed off the grain), a little nitrogenous matter, and the ready-formed sugar in the barley. During the process of growing on the floor something over 4 per cent. of dry matter is lost; the table, for instance, shows a fall from 99.6 parts of the original dry matter to 95.9 parts, by the eighth day. This loss is due to the respiration process accompanying growth, and represents

the combustion of a certain amount of starch into carbonic acid and water, which escape into the air. During the kilning and drying process there is a further loss of dry matter, this time mainly a mechanical loss due to malt dust, which falls through the wire floor into the fire.

The further figures show that of the nitrogenous materials there is a little loss by solution in the steep-water, but little or none upon the floor, where there will be no production of free nitrogen as long as the germination process is proceeding properly. The chief loss of nitrogenous material is mechanical, in the drying and screening process. Similarly with the mineral matter: after the first loss in the steep no others are possible save those of a mechanical nature. It should be noticed, however, how much of the nitrogen and mineral matter passes into the malt dust; the young shoots of the barley plant are comparatively far richer in nitrogen and mineral matter than the whole grain. The other changes, which take place during malting and are not shown in this table, would be the incipient conversion of some of the starch into malt sugar (it is well known that malt possesses a comparatively sweet taste) and the migration of a large portion of the albuminoids of the grain into soluble nitrogenous compounds, chiefly amides and amino acids, the nutritive value of which is certainly less than that of the albuminoids from which they were derived. The malt also contains large amounts of diastase, the enzyme which converts starch into sugar during "mashing," the next brewing process.

The figures thus obtained for the changes during the malting process agree with those generally accepted by maltsters to-day, who expect to lose 10-11 per cent. of material (dry weight), distributed as follows:—

Loss in steep . . . . .	1 per cent.
Loss by respiration . . . . .	4-5 "
Malt dust . . . . .	4 "
Waste . . . . .	1 "

The waste has been diminished by the employment of tiled

floors to the kiln instead of woven wire, but the great loss by respiration is a necessary part of the process.

The problem then remaining was to ascertain if the inevitable loss thus produced in the dry matter of the original barley would be compensated for by an increased digestibility of the malt. Experiments with stock were made as follows:—

- (1) Milch cows, two lots of ten, each animal receiving either 3 lb. of barley or its equivalent in malt per diem. The experiment lasted for 10 weeks, and the amount of milk produced and the live weight of the cows were recorded. The general ration to which the barley or malt was added consisted of 2 lb. rape cake, 2 lb. bean meal, 14 lb. clover chaff, 7 or 8 lb. straw chaff, and 50 lb. Swedes per head per diem.
- (2) Two lots of three-year-old bullocks were fattened, receiving respectively either 4 lb. barley No. 2 or its equivalent in malt, in addition to a general ration of clover chaff, cake, and Swedes *ad lib.* The experiment lasted 20 weeks.
- (3) Five lots of twelve Hampshire Down wether lambs under cover. Lot 1 had for 16 weeks  $\frac{3}{4}$  lb. and for 4 weeks 1 lb. barley No. 1, per head per diem. Lot 2 had an equivalent in malt from barley No. 1. Lot 3 had similarly  $\frac{3}{4}$  and then 1 lb. of barley No. 2. Lot 4 had the equivalent in malt. Lot 5 had the same weights of a mixture of two parts unmalted and one part malted barley No. 2. The general ration was 1 lb. of clover chaff, and cut Swedes *ad lib.*
- (4) Six lots of eight pigs for 10 weeks. Lot 1 had unmalted barley No. 1 *ad lib.* Lot 2 had the malt from the same barley, also *ad lib.* Lot 3 had both barley No. 1 and its malt separately *ad lib.* Lots 4, 5, 6 were similar, save that barley No. 2 and its malt were substituted. All the pigs in addition had 1 lb. each of pea meal per diem.

In all these trials the final differences in the weights of the

comparative lots, receiving on the one hand barley and on the other an equal quantity turned into malt, were small, and not much removed from the inevitable error in experiments of this kind. But, as a rule, the differences were in favour of the barley, so that we may conclude that nothing had been gained by the changes which the malt had undergone which would compensate for the loss of dry matter. This is indeed what we should have expected; we now know that the whole of the barley is easily digestible except a certain amount of husk. This husk is unaffected by the malting process, and is not rendered thereby more digestible. The malting changes, in fact, consist in a destruction of some of the most soluble and readily digestible carbohydrates, together with a transformation of albuminoid into amides and other nitrogen compounds of less nutritive value. Thus the general conclusion may be drawn that it is not economical to malt grain before using it as food for stock; since, putting on one side the cost of the malting process, the result is only a loss of some of the most valuable parts of the grain.

It has, however, been pointed out by Dr H. T. Brown that there may still be some foundation for the graziers' high opinion of a little malt in a mixed diet.

The greater part of the kernel of the grain of cereals consists of starch-containing cells, which are invested by a thin cellulosic membrane. As long as this membrane remains intact it constitutes a formidable barrier to the free action of the starch-dissolving enzyme of the pancreatic fluid, which plays such an important part in the dissolution of the solid starch-granules when once the food has passed the pyloric orifice.

There does not appear to be any provision in the digestive tract of the herbivora for the secretion of an enzyme capable of attacking this investing membrane, the dissolution of which under ordinary conditions is brought about in the stomach by an enzyme pre-existent in the grain. Under certain conditions this enzyme, *cytase*, may either be absent from the food-grain or present only in minimal quantity, in which case the addition to

the food of a material rich in cytase may be expected indirectly to aid the more ready dissolution and assimilation of the starch. Such a material is malt, provided it has not been kiln-dried at too high a temperature, for, during the process of germination to which it has been subjected, there is a considerable production of cytase in the grain. But the rations used in these experiments were not rich in cellulose material, consequently there was no real test of whether the extra cytase brought in by the malt would have any beneficial effect.

### III.—EXPERIMENTS UPON ENSILAGE.

During the early eighties in the last century, owing to a succession of wet summers, the question of ensilage came prominently before the agricultural public, and farmers were urged to convert their grass and forage crops into silage instead of running the risks of loss and of wasted time incident to the operation of hay-making. Silos were built on various principles all over the country, but before the system had made any real headway, the cycle of dry seasons, which began with 1887, set in, and farmers no longer felt the want of the process. Latterly, with the growth of forage maize in the drier districts of the country, the making of silage has been revived somewhat, the idea being to utilise maize silage instead of roots, as is so largely done in the eastern states of America.

Experiments on silage were begun at Rothamsted in 1884 with the construction of two rectangular tanks calculated to hold about 100 tons of silage each. These were filled—one with red clover, both first and second crop, and the other with meadow grass; the materials were chaffed and weighed as put in, and a number of samples were taken from which to ascertain the average composition of the mixture entering the silo. The silos were emptied between December and the following April, when in the same way the material leaving each silo was weighed and sampled. The analytical results were not wholly satisfactory as far as the determination went of the loss of dry matter during the making of the silage. Such material, both

as put in and as taken out, is subject to such variations in water-content that a very large number of samples are required from which to obtain a fair average for the composition of the whole.

The results indicated that the losses were not so great as was then commonly supposed; not more than 5 per cent. of the total dry matter of the clover, and about 15 per cent. of the dry matter of the grass appeared to be lost. The analyses also indicated a certain loss of nitrogenous matter; the chief change, however, consisted in a conversion of a large proportion of the albuminoids into nitrogenous compounds of lower grade, amides and kindred bodies. The loss of dry matter chiefly fell upon the non-nitrogenous constituents, but the evidence was all against the idea that any of the woody fibre was converted into a more soluble and digestible form.

The next step in the experiments consisted in testing the feeding value of the silage produced, and for this purpose experiments were made both with fattening oxen and with cows in milk. Two lots of five oxen were picked out and fed with 6 lb. cake and  $4\frac{1}{2}$  lb. barley meal each per diem. In addition, the beasts in one lot received 65 lb. of clover silage, and the beasts in the other lot 12 lb. of clover chaff and 50 lb. of Swedes. The experiment lasted 114 days.

The final result was slightly in favour of the silage; the beasts receiving silage made an average increase of 15.6 lb. per week per 1000 lb. mean live-weight, as against a corresponding increase of 14.8 lb. made by the beasts receiving roots and chaffed hay.

In the other experiment with milch cows, two lots each of 20 cows were selected, so as to obtain them as nearly as possible with equal milk yields and equally advanced in the lactation period in each lot. This could hardly be realised with exactitude, especially as fresh cows had to be brought in during the experiment. Of concentrated food each cow received 4 lb. cake, 4 lb. bran, and 10 lb. chaff (hay and straw mixed). The silage lot got from 42 to 50 lb. of clover silage, the others 75 to

90 lb. of mangolds, quantities arranged to supply each lot with equal amounts of dry matter. The experiment lasted 13 weeks, and was immediately continued for another 6 weeks with meadow-grass silage, a reduction being made in the chaff from 10 to 7 lb., because of the larger amounts of woody fibre introduced by the grass silage.

The result seemed to show that the cows on the clover silage tended to fatten rather more than those on the mangolds; though giving slightly less milk they gained in live weight, while the mangold-fed cows lost slightly in weight.

With meadow-grass silage, however, there was not the same tendency to fatten, the cows losing weight; the milk yield was practically equal from the two lots of cows. When analysed, the milk of the mangold-fed cows always showed a higher percentage of both total solids and of butter fat than that of the silage-fed cows.

The general conclusions reached were, that good food would make good silage without much more loss of dry matter than usually takes place in hay-making, etc.; also, that good silage is a useful food for both fattening oxen and cows in milk. It did not seem likely, however, that it would pay farmers to grow crops specially for silage rather than to grow roots.

#### IV.—THE COMPOSITION OF WHEAT GRAIN AND ITS MILL PRODUCTS.

The question of the food value of the various materials grown on the experimental plots was one always before Lawes and Gilbert. Particularly they were preoccupied with anything relating to the production of wheat and its variations in composition due to soil, season, or climate. The original plan of their investigations included a study of the influence of season and manuring upon the composition of the wheat grain, and a further study of the varieties of wheat and their adaptation to various climates and localities in the great range of the earth's surface over which wheat is grown.

In a paper published in 1857 they gave the results of a series of experimental millings of wheat grain from three of the plots—the unmanured plot, that which receives nitrogen only in the shape of ammonium-salts, and one that is completely manured with both minerals and ammonium-salts. The grinding was done by an ordinary millstone, then the only method of grinding wheat. Figures were obtained showing the relative weights of the nine mill products—flour of various grades of fineness, tails, sharps, pollard, and bran—figures which are unfortunately of little interest nowadays since the roller-milling which has become universal has introduced quite a different series of separations. Roller-milling, also, no longer bruises the bran in the way that was inevitable with stone grinding, so that the composition even of the finest products has been to some extent altered. Further determinations were then made of the dry matter, ash, nitrogen, and phosphoric acid in the various products, as had previously been done for several seasons with the whole grain. The results showed that the percentage of nitrogen was lowest in the products at the head of the dressing-machine, *i.e.*, in the flour itself, but increased considerably in the more branny portions, being at its highest in the sixth product, the so-called “coarse sharps.” The ash increased to a still greater degree in the coarser portions, being ten times as great in the coarsest bran as in the finest flour, and the percentage of phosphoric acid augmented with the increase in the percentage of ash.

But Lawes and Gilbert protested most strongly against the idea which was then beginning to be held, and which has never ceased to be promulgated as a sort of creed—that the whole meal of the wheat grain is the most nutritive food, and that ordinary white bread is deprived of much of its value because of the removal of the bran.

For example, Gilbert wrote in 1881: “The higher percentage of nitrogen in bran than in fine flour has frequently led to the recommendation of the coarser breads as more nutritious than the finer. We have already seen that the

more branny portions of the grain also contain a much larger percentage of mineral matter. . . . It is, however, we think, very questionable whether, upon such data alone, a valid opinion can be formed of the comparative values, as food, of bread made from the finer or coarser flours from one and the same grain. . . . Again, it is an indisputable fact that branny particles, when admitted into the flour in the degree of imperfect division in which our ordinary milling processes leave them, very considerably increase the peristaltic action, and hence the alimentary canal is cleared much more rapidly of its contents. It is also well known that the poorer classes almost invariably prefer the whiter bread; and among some of them who work the hardest, and who, consequently, would soonest appreciate a difference in nutritive quality (navvies for example), it is distinctly stated that their preference for the whiter bread is founded on the fact that the browner passes through them too rapidly, consequently before their systems have extracted from it as much nutritious matter as it ought to yield them. It is freely granted that much useful nutritious matter is, in the first instance, lost as human food, in the abandonment of 15 to 20 per cent. of our wheat grain to the lower animals. It should be remembered, however, that the amount of food so applied is by no means entirely wasted. And further, we think it more than doubtful, even admitting that an increased proportion of mineral and nitrogenous constituents would be an advantage, whether, unless the branny particles could be either excluded, or so reduced as to prevent the clearing action above alluded to, more nutriment would not be lost to the system by this action than would be gained by the introduction into the body, coincidentally with it, of a larger actual amount of supposed nutritious matters. In fact, all experience tends to show that the state, as well as the chemical composition of our food, must be considered; in other words, that its digestibility, and aptitude for assimilation, are not less important qualities than its ultimate composition.

“Of course, if the branny portions were reduced to a

perfect state of fineness, and it were found that this prevented the aperient action, and that other evils were not induced, or better still, if more of the food material can be separated from the bran, and in either case without more cost than the saving would be worth, there might be some advantage. But, to suppose that whole wheat meal, as ordinarily prepared, is, as has generally been assumed, weight for weight, more nutritious than ordinary bread-flour, is an utter fallacy, founded on theoretical text-book dicta: not only entirely unsupported by experience, but inconsistent with it. In fact, it is just the poorer fed and the harder working that should have the ordinary flour bread rather than the whole-meal bread as hitherto prepared, and it is the over-fed and the sedentary that should have such whole-meal bread. Lastly, if the whole grain were finely ground, it is by no means certain that the percentage of really nutritive nitrogenous matters would be higher than in ordinary bread-flour, and it is quite a question whether the excess of earthy phosphates would not then be injurious."

The persistent idea that the branny portions of the grain possess a higher nutritive value comes from trusting in the crude chemical view of a century ago, that the percentage of nitrogen alone measures the value of a food, without taking any account of its digestibility and the amount of these nitrogenous materials which can be assimilated by the body. As to the extra value of the phosphoric acid, there is no evidence to show that the ordinary dietaries are in any way deficient in phosphates. The whole subject has, during the last few years, been elaborately tested experimentally in the course of the nutrition investigations of the United States Department of Agriculture, with the result that Lawes and Gilbert's opinion of the superior nutritive value of white bread has been fully confirmed.

The other question raised by Lawes and Gilbert in the 1857 paper, that of the effect of the different systems of manuring upon the baking quality of the wheat and the differences in

composition between English and foreign-grown wheat, was again in 1904 made the subject of investigation at Rothamsted. It was found that these qualities were very little influenced by manuring, but that to a considerable extent they are inherent in the plant itself. The problem of controlling the milling quality is thus one for the plant breeder, and from this point of view it has been studied by Biffen at Cambridge and by others.

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## CHAPTER XIV

### THE RECENT WORK ON THE BIOCHEMICAL PROCESSES OF THE SOIL

I. Soil Protozoa.  
II. Sick Soils.

III. Biochemical Reactions.  
References.

REFERENCE has already been made to the fact that nitrification, the process by which the nitrate indispensable to plant growth is made in the soil, is the work of micro-organisms. The investigations of Schloesing and Müntz, of Warington and of Winogradsky, led to a prodigious number of others, and soil bacteriology has now grown into a very large subject. It is now known that the soil is teeming with life, and that a single saltspoonful of it contains millions of organisms, living, working, and multiplying, and among other activities bringing about various changes absolutely indispensable to plant growth.

The development of the subject has taken place in three directions. Efforts have been made to discover and then to describe the organisms concerned in the processes. Chemists have tried to find out the steps by which the decomposition proceeds. At Rothamsted investigation has been directed to the discovery of the conditions under which the organisms live and work, with the view of ultimately obtaining some degree of control over them.

So impressed were the earlier investigators with the great part played by bacteria, that these came to be tacitly regarded as the only organisms concerned. But a number of difficulties and anomalies arose when the work was carried from the laboratory into the field, and efforts were made to connect the

field observations with the known activities of bacteria. The recent work at Rothamsted has satisfactorily explained these difficulties by showing that the micro-organic population must be regarded not as one, but as two or more groups, some of which are detrimental to the useful organisms concerned in the processes of ammonia and nitrate formation.

The investigation began in the first instance as the result of an accident. In virtue of its large population of micro-organisms soil absorbs a considerable quantity of oxygen and evolves a corresponding amount of carbon dioxide. An experiment had been arranged to demonstrate the well-known fact that soil heated to 130° C., and therefore completely devoid of micro-organisms, lost much of its power of absorbing oxygen. By an accident the autoclave was not available, and the soil was only heated in the steam oven, and it gave the remarkable result that its power of absorbing oxygen showed a considerable increase. Now the steam oven did not kill all the organisms, but spared those capable of forming spores, *i.e.*, sterilisation was only partial. Partial sterilisation by means of volatile antiseptics gave the same result. The conclusion was drawn that partial sterilisation increased the bacterial activity, and consequently the amount of decomposition. The increased quantity of plant food thus formed is shown by the amounts taken up by the plant. Table XCIII. contains a typical series of results:—

TABLE XCIII.—*Weight and Composition of Crops grown on Partially Sterilised Soils.*

	Dry Weight of Crop.	Percentage Composition of Dry Matter.			Weight of Nutrients taken by the Plant from Soil, grams.		
	Grams.	N.	P <sub>2</sub> O <sub>5</sub> .	K <sub>2</sub> O.	N.	P <sub>2</sub> O <sub>5</sub> .	K <sub>2</sub> O.
Buckwheat.							
Untreated Soil . . .	18·14	2·75	1·81	5·62	·499	·339	1·019
Soil treated with Carbon Disulphide. . .	23·27	3·15	2·34	5·97	·733	·544	1·389
Mustard.							
Untreated Soil . . .	15·88	2·30	1·00	4·20	·367	·159	·668
Heated Soil . . .	24·33	4·43	20·8	5·02	1·077	·506	1·221

Further investigations led to the following conclusions : \*—

1. Partial sterilisation of soil, *i.e.*, heating to a temperature of 60° C. or more, or treatment for a short time with vapours of antiseptics such as toluene, causes first a fall, then a rise in bacterial numbers. The rise sets in soon after the antiseptic has been removed and the soil conditions are once more favourable for bacterial development; it goes on till the numbers considerably exceed those present in the original soil (Tables XCIV. and XCV.).

TABLE XCIV.—Numbers of Bacteria and Amounts of Ammonia Production in Partially Sterilised Soils.

	Numbers of Organisms per gram of Dry Soil, in millions, Gelatin Plate Cultures.			Ammonia produced in 9 days, in parts per million of Dry Soil.
	At beginning.	After 9 days.	Increase during 9 days.	
Untreated Soil . . . . .	6·7	9·8	3·1	0·7
Soil heated to 98° . . . . .	·0003	6·3	6·3†	3·2†
Soil treated with Toluene, which was subsequently evaporated . . . . .	2·6	40·6	38·0	17·1
Soil treated with Toluene, which was left in . . . . .	2·3	2·6	0·3	5·5

† After 4 days.

TABLE XCV.—Ammonia and Nitrate accumulating in a Soil kept twenty-three days at about 15° C. in a moist condition; parts per million of Dry Soil.

	Nitrogen present as Ammonia.		Nitrogen present as Nitrate.		Total Nitrogen present as Ammonia and Nitrate.		
	At beginning.	After 23 days.	At beginning.	After 23 days.	At beginning	After 23 days.	Gain in 23 days
Untreated Soil . . . . .	1·8	1·7	12	16	13·8	17·7	3·9
Soil heated 2 hours to 98° C. . . . .	6·5	43·8	13	12	19·5	55·8	36·3
Soil treated with Toluene, which was then evaporated . . . . .	5·0	27·8	12	12	17·0	39·8	22·8
Soil treated with Toluene, which was not removed . . . . .	7·2	14·5	11	10	18·2	24·5	6·3

2. Simultaneously there is a marked increase in the rate of accumulation of ammonia. This sets in as soon as the bacterial numbers begin to rise, and the connection between

\* The details are given in two papers by Russell and Hutchinson in *J. Agric. Sci.*, 3 (1909), 111-144, and 5 (1913), 152-221.

the two quantities is normally so close as to indicate a causal relationship; the increased ammonia production is, therefore, attributed to the increased numbers of bacteria. There is no disappearance of nitrate; the ammonia is formed from organic nitrogen compounds.

3. The increase in bacterial numbers is the result of improvement in the soil as a medium for bacterial growth and not an improvement in the bacterial flora. Indeed, the new flora *per se* is less able to attain high numbers than the old. This is shown by the fact that the old flora, when reintroduced into partially sterilised soil, attains higher numbers and effects more decomposition than the new flora. Partially sterilised soil plus 0.5 per cent. of untreated soil, or an unfiltered aqueous extract of untreated soil, soon contains higher bacterial numbers per gram and accumulates ammonia at a faster rate than partially sterilised soil alone.

4. The improvement in the soil brought about by partial sterilisation is permanent, the high bacterial numbers being kept up even for 200 days or more. The improvement, therefore, did not consist in the removal of the products of bacterial activity, because there is much more activity in partially sterilised soil than in untreated soil. Further evidence is afforded by the fact that a second treatment of the soil some months after the first produces little or no effect.

It is evident from (3) and (4) that the factor limiting bacterial numbers in ordinary soils is not bacterial, nor is it any product of bacterial activity, nor does it arise spontaneously in soils.

5. But if some of the untreated soil is introduced into partially sterilised soil, the bacterial numbers, after the initial rise (see (3)), begin to fall. The effect is rather variable, but is usually most marked in moist soils that have been well supplied with organic manures; *e.g.*, in dunged soils, greenhouse soils, sewage farm soils, etc. Thus the limiting factor can be reintroduced from untreated soils. (Table XCVI.).

6. Evidence of the action of the limiting factor in untreated

soils is obtained by studying the effect of temperature on bacterial numbers. Untreated soils were maintained at 10°, 20, 30 C., etc., in a well moistened aerated condition, and periodical counts were made of the numbers of bacteria per gram. Rise in temperature rarely caused any increase in bacterial numbers; sometimes it had no action, often it caused

TABLE XCVI.—*Effect of introducing Untreated Soil into Partially Sterilised Soil.*

	Gain in Ammonia and Nitrate in 57 days.	Number of Bacteria in millions, per gram of Dry Soil.		
		After 20 days.	After 38 days.	After 61 days.
Toluened Soil alone	24·3	28·0	31·8	60·1
Toluened Soil + extract from Untreated Soil	43·7	61·3	45·2	166·6
Toluened Soil + 5 per cent. Untreated Soil	20·3	32·0	46·9	48·0

a fall. But after the soil was partially sterilised the bacterial numbers showed the normal increase with increasing temperatures. Similar results were obtained by varying the amount of moisture but keeping the temperature constant (20° C.). The bacterial numbers in untreated soil behaved erratically, and tended rather to fall than to rise when the conditions were made more favourable to trophic life; on the other hand, in partially sterilised soil, the bacterial numbers steadily increased with increasing moisture content. Again, when untreated soils are stored in the laboratory or glass-house under varying conditions of temperature and of moisture content the bacterial numbers fluctuate erratically; when partially sterilised soils are thus stored the fluctuations are regular.

7. When the curves obtained in (6) are examined, it becomes evident that the limiting factor in the untreated soils is not the lack of anything\* but the presence of something active.

8. This factor, as already shown, is put out of action by

\* The soils included fertile loams well supplied with organic matter, calcium carbonate, phosphates, etc.

antiseptics and by heating the soil to 60° C., and once out of action it does not reappear. Less drastic methods of treating the soil put it out for a time, but not permanently; *e.g.*, heating to 50°, rapid drying at 35°, treatment with organic vapours less toxic than toluene (*e.g.*, hexane), incomplete treatment with toluene. In all these cases the rise induced in the bacterial numbers per gram is less in amount than after toluene treatment, and is not permanent; the factor sets up again. As a general rule, if the nitrifying organisms are killed the limiting factor is also extinguished; if they are only temporarily suppressed, the factor also is only put out for a time.

9. The properties of the limiting factor are:—

(a) It is active and not a lack of something (see (7) ).

(b) It is not bacterial (see (3) and (4) ).

(c) It is extinguished by heat or poisons, and does not reappear if the treatment has sufficed to kill sensitive and non-spore-forming organisms; it may appear, however, if the treatment has not been sufficient to do this.

(d) It can be reintroduced into soils from which it has been permanently extinguished by the addition of a little untreated soil.

(e) It develops more slowly than bacteria, and for some time may show little or no effect; then it causes a marked reduction in the numbers of bacteria, and its final effect is out of all proportion to the amount introduced.

(f) It is favoured by conditions favourable to trophic life in soil, and finally becomes so active that the bacteria become unduly depressed. This is one of the conditions obtaining in glasshouse "sick" soils.\*

It is difficult to see what agent other than a living organism can fulfil these conditions. Search was, therefore, made for larger organisms capable of destroying bacteria, and considerable numbers of protozoa were found. The ciliates and amœbæ are killed by partial sterilisation. Whenever they are killed the detrimental factor is found to be put out of action, the

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\* This is dealt with fully in *J. Agric. Sci.*, 5 (1912), 27-47, 86-111.

bacterial numbers rise and maintain a high level. Whenever the detrimental factor is not put out of action, the protozoa are not killed. To these rules we have found no exception. Further, intermediate effects are obtained when a series of organic liquids of varying degrees of toxicity is used in quantities gradually increasing from small ineffective up to completely effective doses. The detrimental factor is not completely suppressed but sets up again after a time, so that the rise in bacterial numbers is not sustained. But the parallelism with ciliates and amœbæ is still preserved : they are completely killed when the detrimental factor is completely put out of action ; they are not completely killed, but only suppressed to a greater or less degree, when the detrimental factor is only partly put out of action.

Now this parallelism between the properties of the detrimental factor and the protozoa is not proof that the protozoa constitute the limiting factor, but it affords sufficient presumptive evidence to justify further examination. The obvious test of adding cultures of protozoa to partially sterilised soil was made, but no depression in bacterial numbers was obtained ; instead there was sometimes a rise. But in view of the history of investigations on malaria and other protozoan diseases no great significance was attached to this early failure.

At this stage the investigation was divided into two parts :—

1. The study of the soil protozoa.
2. The effects of the limiting factor on the biochemical processes on the soil.

No attempt had ever been made in any of the above experiments to identify the protozoa, or even to ascertain whether any particular form existed in the soil in the trophic state or as cysts. The variety of forms was considerable, and it soon became evident that a definite protozoological survey of the soil was required.

This was accordingly put in hand. In order to give the

survey as permanent a value as possible the investigations were not confined to the narrow issue whether soil protozoa do or do not interfere with soil bacteria, but they were put on the broader and safer lines of ascertaining whether a trophic protozoan fauna normally occurs in soil, and, if so, how the protozoa live, and what is their relation to other soil inhabitants.

The first experiments were made by Goodey\* mainly with ciliates, and indicated that these organisms were present only as cysts. Subsequent investigations, however, by Martin and Lewin established the following conclusions: † —

1. A protozoan fauna in a trophic state normally occurs in soils.

2. The trophic fauna found in the soil differs from that developing when soil is inoculated into hay infusions: the forms which appear to predominate in the soil do not predominate in the hay infusions, and *vice versa*, the forms predominating in the hay infusions do not necessarily figure largely in the soil.

3. The trophic fauna is most readily demonstrated, and is therefore presumably most numerous, in moist soils well supplied with organic manures; *e.g.*, in dunged soils, greenhouse soils, sewage soils, and especially glass-house "sick" soils.

Finally, the latest experiments by Goodey‡ have shown that when this trophic fauna is introduced into partially sterilised soils the bacterial numbers are brought down. The earliest attempts to carry out this experiment failed, as already stated, only one successful experiment by Cunningham§ being on record. It was not till Goodey discovered the conditions for successful inoculation that it could be carried out. Goodey found that mass cultures of protozoa failed when introduced

\* Goodey, *Roy. Soc. Proc.*, B. 86 (1913), 427-451.

† Martin and Lewin, *Phil. Trans.*, 205 (1914), 77-94; and *J. Agric. Sci.*, 7 (1915), 106-119.

‡ Goodey, *Roy. Soc. Proc.*, B. 89 (1916), 297-314.

§ *Centr. Bakt. Par.*, August 1914, and *J. Agric. Sci.*, 7 (1915), 49-74.

has already been observed by practical men in various countries that certain soil conditions harmful to the growth of organisms were ultimately beneficial to productiveness, such as long continued and severe frosts, long drought (especially if associated with hot weather), sufficient heat, treatment with appropriate dressings of lime, gas lime, carbon disulphide, etc.

Further, it has been observed that conditions which are undoubtedly favourable to life, such as the combination of warmth, moisture, and organic manures found in glass-houses, lead to reduced productiveness after a time. This phenomena is spoken of as "sickness" by the practical man.

It is difficult to account for these results on the old view that the useful plant food-making bacteria are the only active micro-organisms in the soil. On the other hand, the new view that detrimental organisms are also present readily explains the observed facts.

The "sickness" that affects the soil of glass-houses run at a high pitch (such as cucumber houses), and less slowly at a lower pitch (such as tomato houses), has been investigated in some detail owing to its great technical importance. It was traced to two causes: an accumulation of various pests, and an abnormal development, especially in cucumber houses, of the factor detrimental to bacteria. The properties of this factor show that it is identical in character with that present in normal soil, and strongly indicate its biological nature. No evidence of a soluble toxin could be obtained. On the other hand, some remarkably interesting protozoa and allied organisms have been picked out from these sick soils and described by Martin, Lewin, and Goodey. Finally, it has been shown that the whole trouble can be cured by partial sterilisation, and methods suitable for large-scale work have been investigated and are now in use in practice. Steam heat at present proves most convenient, but the suitability and detailed effects of lime have been studied by Hutchinson and M'Lennan, and of various antiseptics by Buddin.

While these laboratory investigations are going on, a detailed

study of the processes taking place in field soils is also in progress, and frequent determinations are made of the quantity of nitrate present. But as soon as we turn to the field conditions and try to follow the production of nitrate in the soil, matters are complicated by the fact that the nitrates produced do not all remain in the soil, but are liable to be washed out or taken up by plants. Analytical determinations, therefore, only give the difference between the amount formed and the amount lost; they do not show how much is actually produced, nor give the rate of production that we desire to obtain. For some time we could see no way of getting over this difficulty, but a simple solution was ultimately found. It is evident that if the curves showing the amount of some other substance *produced in the same way as the nitrate, but lost in a different way*, are of the same general shape as the nitrate curves, then the shape is due mainly to the production factors; if, on the other hand, the two sets of curves are different in shape, then the loss factors control the situation. The carbon dioxide in the soil air satisfies these requirements; it is produced like the nitrates, by bacterial action, but it is lost largely by gaseous diffusion, and only in very bad weather by leaching. Carbon dioxide was therefore determined simultaneously with nitrates, and the curves show a marked similarity except that the increases in nitrate come later. Thus we may conclude that the curves both for nitrate and carbon dioxide are in the main production curves.

The amount of carbon dioxide in the soil air, which, as we have just seen, indicates the rate at which it is produced, follows the soil temperature during the winter months, but not during the summer; indeed, during hot weather the amount is distinctly low. It shows some connection with the moisture content, but it is more closely related to the rainfall. Rain is a saturated solution of oxygen, and when it falls on the soil it not only supplies the needful water but also renews the stock of dissolved oxygen, and thus gives the micro-organisms and the plant roots new leases of activity.

These observations throw important light on the effects of season and climate on the production of nitrate in the soil. It is notoriously difficult to generalise about seasonal effects, but as a rule the activity of micro-organisms is greatest in late spring and in autumn, and lowest in summer and winter.

The winter minimum is easily intelligible: the low temperature limits the activity of the organisms, and as we have already seen, any rise in temperature immediately evokes a response, so that the curves for the production of carbon dioxide run closely parallel to the temperature curve.

The spring maximum is remarkably interesting. It begins to show itself when the soil is drying after the cold and wetness of the winter, and when the sunny days first cause the temperature to rise. Three factors seem to be involved. During winter the cold and the general unfavourable conditions have had their partial sterilising effect on the soil population, and also have resulted in a certain amount of disintegration of the soil organic matter. Everything is therefore ready for a great outburst of activity.

But in our climate this does not come suddenly. Before the soil can be warm it has to be dry, and by the time it is warm enough for much bacterial action the chances are that it has dried too much. It is therefore necessary to wait for rain to supply the needful water and to renew the dissolved oxygen in the water round the soil particles. It appears to be this combination of temperature, moisture and oxygen supply, following on the beneficent changes effected in the winter months in the soil organic matter and the soil population, that causes the great outburst of soil life in spring.

The summer minimum may be attributed to dryness, and the autumn maximum to the effect of rain coming after the heat and drought of the summer.

In consequence of these various activities the soil is left pretty rich in nitrates at the end of the autumn, provided the summer has been reasonably dry. If these remain they form a good supply for the young plants of the following season.

But in a wet winter part is washed out and the young plant is deprived of some of its food. We thus have part of the explanation of the harmful effect of a wet winter, and one of the reasons why the husbandman in all ages has hoped for dry winters. "A wet summer and a fine winter," to quote from the *Georgics*, "should be the farmers' prayer. From winter dust comes great joy to the corn, joy to the land. No tillage gives Mysia such cause for boasting, or Gargarus for wondering at his own harvest."\* English farmers would ask for the wet spring instead of the wet summer, but they would agree entirely as to the winter, and out of their experience they have evolved a variety of similar expressions. Again the man of science has annotated the poet, and Sir Napier Shaw has worked out a mathematical expression showing how much damage is done on an average by winter rain.

The trouble can be met by a system of green manuring, whereby plants are grown in the autumn to take up the nitrates, and are then ploughed into the land ready for the operation of the soil organisms in spring. A field experiment with this purpose in view has been put in hand.

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\* *Georgics*, Bk. I., ll. 100-103.

## CHAPTER XV

### SECONDARY ACTIONS OF ARTIFICIAL MANURES UPON THE SOIL

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|---------------------------------|--------------------------------------|
| I. Loss of Calcium Carbonate.   | IV. Action of the Plant on the Soil. |
| II. Soil Acidity.               | V. Final Considerations.             |
| III. Nitrate of Soda and Tilth. | Reference.                           |

THE study of the interaction between the fertilising constituents of manures and the soil begins with a paper by J. T. Way in the *Journal of the Royal Agricultural Society for 1850* (I. vol. xi., p. 313), which was followed by a second paper two years later, and then by further work by A. Voelcker. These investigations led to the conclusions, generally adopted and acted upon, that on ordinary land the fertilising constituents of manures are promptly absorbed by the soil, and no loss need be feared except of nitrates and the compounds of nitrogen which rapidly change into nitrates.

Way fixed upon the double silicates in the soil—the so-called zeolites—as the agencies causing the absorption of both ammonia and potash salts, though he also showed that humus must have an effect in the same direction, because of the great absorptive powers of all soils rich in humus. As regards the zeolites, the action is intelligible enough; these bodies are complicated double silicates of alumina and various bases, of which lime is the chief; in contact with a weak solution of a salt of ammonia, the lime and ammonia change place, an insoluble zeolite containing ammonia being formed on one side, and on the other a lime salt which goes into solution. Way himself, in a later paper, concluded that carbonate of lime in the soil did not intervene in the process; but in later years, as it appeared that sulphate of ammonia reduced the stock of carbonate of lime in the soil, it began to be thought that there must be a direct interaction between sulphate of ammonia and

the carbonate of lime, instead of the zeolites, as soon as the former was applied to the soil.

That the use of ammonium-salts as manure does directly cause the removal of carbonate of lime from the soil may be learnt from a detailed examination of the amounts present in the soils taken from the Rothamsted plots at successive dates during their history. At Rothamsted the carbonate of lime in the soil, the amount of which varies from about 2 to about 5 per cent. in different fields, is all of artificial origin; for though the "red clay with flints," the drift formation out of which has arisen the soil at Rothamsted, rests on the solid chalk rock at a depth of 10 to 15 feet below, yet both soil and subsoil in a natural state are almost wholly lacking in carbonate of lime. Such natural soil may be found on the neighbouring Harpenden Common, which has never been cultivated nor subject to any improvements; and again on the grass land and a few of the other arable fields on the estate; in all these cases analysis shows only about one-tenth per cent. of carbonate of lime in either soil or subsoil until the underlying chalk rock is reached. It is, however, on record that up to the early years of the nineteenth century it was a regular custom in Hertfordshire farming on this hill land to sink pits through the clay into the chalk, extract the chalk, and spread a layer representing six to ten tons per acre over the arable land, the process being repeated at intervals of a few years. The "dells" or hollows in the fields, which represent the fallen-in pits, are evidence to-day of the old practice, and much of the friability and dryness of this heavy land, through which alone it has been possible to keep it under the plough, is due to the work thus done for the present generation of farmers during the seventeenth and eighteenth centuries or even earlier. As a consequence, the surface soil of the Rothamsted arable fields now contains 2 per cent. or more of carbonate of lime, visible to some extent as tiny rounded fragments from the size of a pin-head to that of a pea, but mainly present in particles too small to be seen: the subsoil, however, contains

none of this carbonate of lime, it has remained only in the layer stirred by the plough, and has never worked downwards. The old maxim that lime sinks in the soil is only true of lime on pastures, where it is buried by the slow but persistent action of earthworms bringing up mould to the surface; in arable land, as the Rothamsted analyses prove, the lime wastes but does not sink. The very special distribution of carbonate of lime in the Rothamsted soil affords, however, an exceptional opportunity of studying the rate at which this important soil constituent is removed by natural causes, and also of how the natural removal is decreased or accelerated by the constant use of certain artificial manures. Samples of soil from the Rothamsted plots were not taken at the very beginning of the experiments, at least none have been preserved; the earliest which are available date from 1856, and later samples from the same Broadbalk field were taken in 1865, 1881, 1893, and 1904. Samples from the other fields date back to 1867, 1868, and 1873, so that in four cases we can ascertain the effect of thirty years' action of the manures—a long enough period to make the change in composition perceptible in the analyses. Of course, there are many sources of error in the analytical figures; soil sampling is never a very accurate process, and in comparing samples taken at long intervals, a new error is introduced by possible changes in the consolidation of the ground. But the figures agree better than might have been expected, and the results may be regarded as accurate to within 20 per cent. or so. Table XCVII. shows the actual amounts of carbonate of lime, calculated as pounds per acre, in the surface soil from certain of the plots in the various Rothamsted fields at the dates given, while the last column of the table gives the average annual loss deduced from these figures.

It will be seen that the unmanured plots agree fairly well in showing a loss of 800-1000 lb of carbonate of lime per acre, due to the washing action of the rain alone, or rather to the solvent action of rain-water after it has become charged

with carbonic acid exhaled from the roots or arising from the decay of organic matter in the soil. Of course, there are many factors which might modify this figure in other soils; it must to some extent depend on the actual amount of carbonate of lime in the soil, on the magnitude of the drainage through the soil—this being lessened with larger crops on normally manured land—and also on the proportion of carbonic acid in the soil gases, which proportion would be increased with manured soil and larger crops. Still these are the best, indeed the only figures available to show the loss of carbonate of lime that arable land is likely to suffer, and we may now

TABLE XCVII.—*Loss of Carbonate of Lime from Rothamsted Salts.*

Field.	Plot.	Manuring.	Carbonate of Lime (lb. per acre).		
			Earliest Date.	1904.	Average Annual Loss.
Broadbalk, 1865 .	3	Unmanured .	110,500	90,200	800
	2b	Dunged . . .	100,400	85,100	590
	6, 7, 8, 10	Ammonium-salts	85,300	61,800	1,100
	9	Nitrate of Soda .	106,000	92,700	565
Hoos, 1881 . . .	10	Unmanured .	86,800	68,900	1,000*
	1 and 4 A	Ammonium-salts	54,300	37,500	775
	1 and 4 N	Nitrate of Soda .	59,500	42,500	595
Agdell, 1867 . .	...	Unmanured .	159,400	117,700	930
Little Hoos, 1873	...	Unmanured .	103,000	70,500	1,046

\* Another plot, more fairly comparable with the plots which follow, lost at the rate of 675 lb. per acre.

proceed to consider how far the loss is affected by the use of ammonium-salts as manures. At Rothamsted a mixture of sulphate and muriate of ammonia has always been employed, and though certain minor differences may be traced in the action of the two fertilisers, in the main the two together will behave towards the soil of the plant just like sulphate of ammonia alone, though in a slightly more concentrated form. The table only gives a selection of the plots from which results are available (for details see Hall and Miller, *Proc. Roy. Soc.*, B. 77 (1907), 1), but it is clear that the use of ammonium-salts causes increased washing out of the carbonate of lime; in fact, from the original figures

we may calculate an average figure of 117 lb. of carbonate of lime removed from each 200 lb. of ammonium-salt applied. This figure would indicate that the carbonate of lime removed is the chemical equivalent of the ammonium-salts supplied as manure, which suggests that when they reach the soil they begin by reacting with the carbonate of lime, and not with the zeolites as originally suggested by Way. However, direct experiments made to test this point (Hall and Gimmingham, *Trans. Chem. Soc.*, 91 (1907), 677) showed that though some interaction will take place between the ammonium-salts in solution and carbonate of lime, the zeolites bring about by far the greater part of the change, even when the carbonate of lime constitutes as much as 20 per cent. of the soil. Probably the carbonate of lime is brought into the action later, when the ammonia is liberated from its zeolitic compound in order to be converted into nitrate or taken up directly by the plant; the question is in any case only of technical interest, since there is no doubt about the final result that the ammonium sulphate behaves like an acid, and removes from the soil whatever amount of carbonate of lime is required to combine with the sulphuric acid it contains.

So far the matter of the wastage of carbonate of lime is clear enough; but another problem was set up when Dr J. A. Voelcker observed that the soil of the permanent wheat and barley crops at Woburn, which had been receiving ammonium salts for about twenty years, had become actually acid to litmus paper (see *Jour. Roy. Ag. Soc.*, 60 (1899), 515, and 62 (1901), 286). The acidity thus developed rendered the land unable to carry barley, though its capacity to do so was restored by a comparatively small dressing of two tons of lime to the acre. Naturally acid soils had been known before, chiefly in peaty water-logged areas, but this was the first example recorded of a soil becoming acid through a particular course of treatment. That the acidity had developed upon the Woburn plots and not at Rothamsted, where the

same manuring had been continued for even longer periods, was obviously due to the fact that the soil at Woburn contained practically no carbonate of lime at the beginning of the experiments. Analyses show less than one-tenth per cent., and even this minute proportion was probably largely over-estimated.

Thus in the Woburn soil there is no base present to maintain the neutrality should any agency arise to produce acid, whereas in the Rothamsted arable soils, as we have seen, there has always been sufficient carbonate of lime to keep up a neutral condition and put out of action any acid as fast as it was produced. However, it was observed later that one of the Rothamsted fields did contain plots on which the soil had become acid through the application of ammonium salts year after year for a long period; this was the Park grass field which is cut for hay every year. Now there is no record of the Park having ever carried anything but grass, and analyses of the soil at the margins of the plots where no experimental treatment had been given, showed that this was one of the pieces of land which had never received the regular chalkings to which allusion has been made earlier. The soil, therefore, of the grass plots had started with but a small proportion of carbonate of lime, an amount comparable with that present in the Woburn soil at the outset of the experiments there, and the acidity has developed itself on this soil just as it has at Woburn.

It is not clear at first sight how free acid can arise by the interaction of ammonium-salts with any of the constituents of the soil; ammonium sulphate and chloride are both neutral salts in which acid and base are firmly combined at ordinary temperatures. Certain physical and chemical possibilities had been suggested, and these were first examined in some detail (see Hall and Gimingham, *loc. cit.*), using clay, sand, humus, and other soil constituents separately, but without detecting any process which would give rise to free acid. On sand the ammonium-salts had no action; with clay an

interchange of bases between the salt and the zeolites took place as already described, but the resulting liquid remained perfectly neutral; with humus a similar interchange took place, also giving rise to no free acid. The humus of normal soils consists of calcium salts of the indefinite acids grouped together as humic acid; when attacked by a solution of ammonium sulphate or chloride, calcium comes out into the solution, while an equivalent amount of ammonium goes into combination with the humic acid. Even when the mixtures of humus and ammonium-salts were repeatedly evaporated to dryness in a current of air or carbon dioxide to represent in an exaggerated way conditions which might occur in the soil, no production of free acid took place. In consequence of these failures, search was then made for some living agency in the soil which would set free acid from ammonium-salts, and small quantities of the acid soils from the Rothamsted grass plots were introduced into nutrient solutions containing ammonium-salts and organic matter. A clue was at once obtained to the actions going on in the field, for the soils were found to induce in the nutrient medium a very rapid and abundant growth of moulds and other minute fungi, the development of which was accompanied by an increasing acidity in the culture liquid. The moulds require nitrogen for their nutrition, and in order to obtain it they split up the ammonium-salts and set free the acid. It was shown that the degree of acidity thus generated corresponded approximately to that prevailing in the water in the soil of the acid plots at Rothamsted soon after the application of the ammonium-salts in the spring, being such as could be produced by the liberation of the acids contained in the manurial salts. The surface soil of these plots was found to be swarming with microscopic fungi, and several species were separated and identified, all of which would attack ammonium-salts and liberate acids, though to a different degree. Further examination of the Rothamsted acid grass soils showed that in addition to the small quantity of acid

which could be extracted by water, the amount of which was greatest in the spring soon after the application of the manures and diminished as the year progressed, there was present a much larger quantity of comparatively insoluble free humic acid. Clearly this had arisen by the action of the mineral acids, set free year by year from the ammonium-salts, upon the neutral humus or calcium humate originally present in the soil, and the humic acid had been able to accumulate because it is but slightly soluble in water. Without discussing the other details bearing upon the question (see Hall, Miller, and Gimingham, *Proc. Roy. Soc., B.* 80 (1908), 196), it became pretty clear that the acidity of the Rothamsted grass soils has arisen from the action of various micro-fungi upon the ammonium-salts that had been annually applied to these plots; such fungi have become very abundant in the soil, and are able to attack ammonium-salts and set free the acid, taking the ammonia to themselves to supply the nitrogen they require for nutrition. At Rothamsted the acid soils have not been rendered absolutely sterile; the ground is still covered by herbage, but it has a very unhealthy appearance, and resembles in the most interesting manner the vegetation of naturally acid soils. The grasses have a characteristic dark ugly colour and grow in tufts with bare spaces between, the surface of the ground in these bare spaces being occupied by a layer of peaty vegetable matter, as though the dead grass had been unable to decay in the normal manner. Half of each of the plots has been limed—2000 lb. per acre of ground lime having been applied in January 1903, and again in January 1907. Table XCVIII. shows the great increase of crop which has followed the liming, the effect of which is also seen in the restoration of the herbage to a normal appearance and a close sward, accompanied by the disappearance of the peaty layer.

The cause of the comparative infertility of the acid soils must be set down to the fact that they are permeated by the micro-fungi which can grow in an acid medium, whereas the

bacteria which normally people the soil and require a neutral medium for their growth are largely pushed out. The fungi in question compete with the higher plants like the grass for the manure applied to the soil, and being active and abundant, they take so much that the crop suffers. At the same time, the higher plants are doubtless injuriously affected by the suppression of many kinds of bacteria which are useful in preparing food for the crop. For example, the nitrifying bacteria, which change ammonia in the soil first into nitrites and then into nitrates, are wholly inhibited by a very slightly acid medium. A number of experiments were made to ascertain if nitrification was still going on in these acid

TABLE XCVIII.—*Effect of Lime upon Rothamsted Grass Plots.*

Relative Yield of Hay on the Limed Portions, the Unlimed Part being taken as 100.								
Plot.	Manuring.	1908.	1904.	1905.	1906.	1907.	1908.	1909.
4-2	400 lb. Ammonium-salts + super	124	111	134	118	113	127	237
9	400 lb. Ammonium-salts + Complete Minerals.	121	110	142	128	106	118	150
11-1	600 lb. Ammonium-salts + Complete Minerals.	115	103	206	120	167	115	119

Rothamsted soils, both by testing for the organisms which cause nitrification, and by putting large samples of the soil under conditions favourable to nitrification and seeing if any nitrates were found. Small fragments of the acid soils rarely showed the presence of the organisms, but the bulk samples in all cases but one did gain some nitrates during the course of the experiment, showing that the process of nitrification was not entirely suspended. Extracts from the soil, however, refused to form nitrates even when fresh active organisms were introduced. On the whole, the evidence points to the fact that a little nitrification is going on in the soils, because a few tiny fragments of carbonate of lime exist here and there, and maintain a neutral condition in the soil with which they are in immediate contact. These nuclei serve to keep a limited

number of the organisms still active, but in the main the process of nitrification is at a standstill and no nitrates are being produced. Now the generally received opinion is that such normal plants as constitute our crops take in their nitrogen only in the form of nitrate, so that the freedom of their growth is entirely dependent on the rate at which the nitrifying organisms in the soil first do the work of manufacturing nitrates. This is probably too hard and fast an opinion. Without doubt most plants feed on nitrates for choice, and soils contain very much more nitrates than ammonia, because as fast as the latter is set free by the bacteria which split up other nitrogenous compounds in the soil into ammonia, it is seized upon by the nitrifying bacteria and converted into nitrates. But there are not wanting experiments to show that many plants, especially cereals, are capable of utilising the nitrogen of ammonium compounds directly, and later experimenters (Hutchinson and Miller, *J. Agric. Sci.*, 3 (1909), 179) have succeeded in growing plants with ammonium-salts as the sole source of nitrogen under absolutely sterile conditions, excluding all bacteria which could change the ammonia into other compounds. Most plants, however, prefer nitrates to ammonia as their source of nitrogen, and the reduced yield on the acid soils may be partly due to the fact that the grass is driven to feed on ammonium compounds instead of the more usual nitrates. The cause of the infertility of the acid soils cannot, however, be regarded as completely established; the competition of the fungi for the manures is doubtless a factor in the result, but that would hardly seem to account for the total failure of barley on the Woburn plots. It was surmised that the fungi might produce substances poisonous to the growth of the higher plants, but experiments to test this point have so far yielded a negative result.

Another example of these secondary actions between fertilisers and the soil, which are not immediately apparent, is afforded by nitrate of soda. The relation of nitrate of soda to the plant may be regarded as the simplest possible; we

know that the compound need undergo no change in order to feed the plant, it can be taken up directly and has a very immediate nutritive effect. Similarly it has little apparent action upon the soil; nitrate of soda is not only readily soluble in water, but it does not enter into combination with any of the soil constituents, and is therefore not retained, but is washed out at once when there is any drainage through the soil. There is without doubt some interchange of bases between the soda of the manure and the other bases in the soil zeolites, because a dressing of nitrate of soda always assists the plant to obtain potash from the soil; but the nitrate part of the salt suffers no change whatever before its absorption by plants and other organisms. Yet it is very clear that nitrate of soda has some action upon heavy soils, for all farmers upon clay recognise that the use of nitrate of soda leaves the land very wet and sticky. This is perhaps most apparent in districts where early vegetables are grown, as in the Evesham country and in Cornwall, for there the market gardeners, who are trying to push on early cabbages and broccoli to secure the earliest possible market, use quantities of nitrate of soda which seem incredible to the ordinary farmer, as much as 10 and 15 cwt. per acre. Such a dressing is apt to leave the land in a terrible state of bad tilth, from which it takes some time to recover. Some of the Rothamsted plots show exactly the same result; the bad texture of the soil, where nitrate of soda has been applied regularly in large quantities, is not perhaps so marked on the wheat field as it is on the mangold field, but there the nitrate plots are excessively wet and sticky after rain, and dry with a hard glazed surface that marks off the plots to the eye from a considerable distance. In either wet or dry weather the nitrate plots can at once be distinguished on walking over them by their tread and feel to the sole of the foot. It is unnecessary to multiply instances, as the effect is pretty generally recognised; usually it has been explained as due to the attraction of nitrate of soda for moisture. Nitrate of soda is always damp because of its fondness for water, and a bag of the salt left standing

in an ordinary damp manure shed will sometimes be found standing in a pool of liquid, a solution formed by the water which the contents have absorbed from the atmosphere. Such an explanation of the wetness of soil dressed with nitrate of soda is entirely inadequate, because the extra quantity of water retained by the soil from such a cause would be imperceptible. Suppose as much as a ton of nitrate of soda per acre was applied, that it absorbed its own weight of water, and again remained wholly in the surface layer of the land 9 inches deep, the water retained by the whole ton of nitrate of soda would not amount to more than one in a thousand of soil, and could not cause the slightest difference to the texture. Moreover, determinations have been made of the water actually present in the Rothamsted soils on the mangold plots, and no differences that could affect the behaviour of the soil have ever been detected. The altered appearance and the greater apparent wetness must therefore be due to some other cause. Mechanical analyses were next made of the soils. It seemed possible that the greater stickiness of the nitrated soils might be due to a general disintegration of the soil into finer particles, brought about by the long-continued action of the fertiliser. But it was surprising to find that the nitrated soils were distinctly and regularly coarser, that is to say, they had been

TABLE XCIX.—*Mechanical Analyses of Rothamsted Soils, with and without Sodium Nitrate.*

Percentages after Ignition.		
Mean of Five Plots.	No Sodium Nitrate.	With Sodium Nitrate.
Fine Gravel . . . . .	2·2	2·1
Coarse Sand . . . . .	6·1	6·7
Fine Sand . . . . .	18·8	18·8
Silt . . . . .	29·5	29·9
Fine Silt . . . . .	14·0	13·9
Clay . . . . .	17·9	15·0

deprived of some of their finer particles. Table XCIX. gives the average mechanical analyses of five pairs of plots from the

different Rothamsted fields; in each pair there was a plot receiving nitrate of soda to compare with one receiving ammonium-salts, while the other treatment was identical on both plots.

It will be seen that the percentage of clay is distinctly less on the plots which had received nitrate of soda, and though the difference may not appear to be great, it is without doubt a real one, because it was found to exist in each pair of soils used in the comparison (see *Trans. Chem. Soc.*, 85, 1904, 964), and it is contrary to what would have been expected from the behaviour of the soils. Of the reality of the differences we have, moreover, another indication in the fact that when the tile drains, which are laid beneath the whole length of the narrow strips constituting the plots on the Broadbalk wheat field, begin to run, the water flowing from the drains beneath the nitrate plots is always faintly turbid and carries a very light cloud of fine mud, whereas the water from the plots receiving ammonium-salts is always crystal-clear. Evidently the washing out of the finest clay particles which we see going on in the drainage water has been so continuous that the quantity remaining in the soil has been definitely reduced by the 1 to 5 per cent. shown in the different analyses. It is also evidence in the same direction to find that in the earlier years of the experiment the drain beneath the unmanured plot ran more frequently than that below the nitrate of soda plot, whereas of late years, since so much of the finest stuff has been washed out, the drains have been running more frequently beneath the nitrate plots.

The turbid aspect of the drainage water from the two sets of plots suggested another experiment, which provided the clue to the different texture of the two plots. Small equal portions of soil from the plots were weighed out, and each was shaken up with a large bulk of pure water; the resulting muddy liquids were then put to stand separately in similar tall jars. A certain time is occupied before the suspended soil falls to the bottom of the jar and leaves the water clear above;

the finest particles of clay usually keep the water somewhat troubled for a day or two before they settle out completely. But if the settlement of soil from the unmanured plots or from the plots receiving ammonium-salts was complete in two days, it would take three or four days, or sometimes an indefinite time, to bring about the same clearness in the jars containing soil from the nitrated plots. Now it had previously been proved that there were fewer of the finest particles in the nitrated soils, so that they should settle more quickly and more completely were there not some other factor at work hindering the precipitation.

The settlement of clay from its turbid suspensions in water has been frequently investigated, because it finds a good many practical applications in such matters as the texture of the soil, the fitness of clay for pottery and brick-making, etc., and the important facts are that acids or certain salts hasten the settlement greatly, whereas alkalis will retard or even entirely prevent it. It is well known, for example, how a little alum will bring about the clearing of turbid water, and a trace of acid or of some salt of lime will produce the same effect almost as rapidly. The process can be watched under the microscope; as soon as the acid or salt is introduced, the very fine particles, which before were moving about in the liquid without ever coalescing, suddenly rush together and flocculate or coagulate into comparatively large and heavy groups which will fall rapidly through the liquid. In clay soils that are in good tilth the very fine particles are grouped together in this flocculated condition, and the soil in consequence behaves as if it was more coarsely grained, drying more easily and into a friable condition; whereas if the clay be knocked about or tempered when it is wet, the groups are broken up and the clay becomes deflocculated. The value of lime in improving the texture of a soil, in rendering it dryer and more workable, is due to the flocculating power of the lime salts which begin to wash through the soil.

Returning to the experiment, it was pretty clear that there

must be some substance in the soils from the nitrated plots which had brought them into a deflocculated condition, and this substance could not well be anything else than a trace of alkali. On testing, the soils from the nitrated plots were found to be slightly alkaline, probably with carbonate of soda, whereupon a quantity of soil from the nitrate plot on the grass land was washed with hot water to see how much alkali could be extracted from it, this particular plot being selected because the soil contained no carbonate of lime, which itself might give rise to a soluble alkali. Table C. shows the quantities of carbonate of soda that were found in the successive 9-inch layers down to a depth of 3 feet, the results being calculated as lb. of carbonate of soda per acre.

TABLE C.—*Carbonate of Soda (lb. per acre) in Soil of Plot 14, Park Grass Field, Rothamsted.*

1st Depth, 0 to 9 inches.	2nd Depth, 9 to 18 inches.	3rd Depth, 18 to 27 inches.	4th Depth, 27 to 36 inches.
66	37	33	39

It will be seen that the total amounts to no less than 175 lb. of carbonate of soda, which is the chemical equivalent of 280 lb. of nitrate of soda, or about one-half of the yearly application (550 lb. per acre) of nitrate of soda to this plot. We cannot base our calculations on more than the year's application, because neither nitrate nor carbonate of soda are in the least retained by the soil, and both must wash out pretty completely during a wet winter. The problem then was thus far cleared—it had been shown that the soils which receive nitrate of soda afterwards contain carbonate of soda equivalent to as much as one-half of the nitrate applied, and this carbonate of soda was in itself enough to account for the bad texture of the soils, a bad texture which is due not to any special defect of composition but to the deflocculation of the clay particles in the soil. The next question was to account for the formation of the carbonate of soda, and here certain well-established facts

suggested an explanation—facts to which the late Mr Warington had drawn particular attention in a paper contributed to the *Journal of the Royal Agricultural College at Cirencester* in 1899. Warington had pointed out that when the composition of any plant is examined, the acids and bases do not balance one another, but the acids are in excess. Taking the ash of a plant and summing the acids—phosphoric and sulphuric acid, chlorine—against the bases—potash, soda, lime, magnesia, iron—there is generally an excess of bases; but this excess is turned into a deficit as soon as we bring into account the nitrogen in the plant, which being burnt off is not found in the ash. Yet in this connection it must be counted as an acid because it entered the plant as nitrate of lime or soda—one of the neutral salts originally present in the soil, which pass into solution in the soil water and then diffuse through into the plant's roots. If then the nitrogen is calculated as nitric acid and added to the acids in the plant, it is evident that the ordinary crop must have taken from the soil a greater amount of the acids than of the bases contained in the salts presented to it as food. Table CI. shows this relation for four different crops at Rothamsted, the figures given for acids and bases being equivalents, *i.e.*, reductions to a common measure in which one of any acid will combine with one of any alkali, while in the last two lines the excess of base left in the soil is recalculated as lb. per acre of carbonate of soda and carbonate of lime respectively (see Hall and Miller, *Proc. Roy. Soc.*, B. 77 (1905), 1).

From these results it is apparent that if the plant contains such an excess of acid it must leave behind in the soil a corresponding excess of base, because the food salts in the soil are in the main neutral compounds. At this rate the plant ought to make a medium in which it is growing progressively more basic, or alkaline if the bases set free happen to be soluble; and some of the earlier observers like Knop and Stohmann show that a culture solution containing growing plants will become alkaline in course of time if the solution is not

changed. To verify these observations various water cultures were started in which vigorous growth was maintained for some months, at the end of which time analyses were made both of the plants and of the liquid. The results all confirmed the older observations and the deductions that can be made from the composition of the crops from the field: the culture solution, which represents the soil, become more alkaline as growth proceeds (or in the majority of cases less acid, because for the success of the water culture it is desirable to start with

TABLE CI.—*Acids and Bases in Crops reduced to Equivalents.*

	Wheat.	Barley.	Swedes.	Hay.
<i>Bases—</i>				
Ferric Oxide . . . . .	0·03	0·04	0·09	0·17
Lime . . . . .	0·36	0·46	1·24	1·03
Magnesia . . . . .	0·33	0·34	0·35	0·60
Potash . . . . .	0·78	0·68	1·99	2·64
Soda . . . . .	0·03	0·09	0·36	0·44
Total . . . . .	1·53	1·61	4·03	4·88
<i>Acids—</i>				
Phosphoric . . . . .	0·87	0·90	1·02	1·18
Sulphuric . . . . .	0·14	0·15	0·80	0·50
Chlorine . . . . .	0·09	0·15	0·30	1·47
Nitrogen . . . . .	3·00	2·97	6·74	5·35
Total . . . . .	4·10	4·17	8·86	8·50
Excess of Acid . . . . .	2·57	2·56	4·83	3·62
Equivalent to Carbonate of Lime . . . . .	129	128	242	181
Equivalent to Carbonate of Soda . . . . .	136	135	256	192

the solution somewhat acid), and the greater the growth the greater the amount of base left in the solution. In one example, details of which are quoted in the original paper (*loc. cit.*), wheat was grown in the same jar of solution from 3rd March until 11th June, until grain was fully formed and the plants had reached the weight of 93·7 grams; by this time the solution had acquired an excess of bases equal to about 25 per cent. of the total present, while the plant contained a corresponding excess of acids. Thus two distinct lines of evidence agreed in assigning the production of alkali in the

soil to the growth of the plant itself; whenever a plant is fed with nitrate of soda some of the base will be left behind in the soil in the form of carbonate of soda.

Collateral evidence is also forthcoming that nitrate of soda gives rise to a free base in the soil—evidence derived from the determinations of carbonate of lime in the Rothamsted soils, to which allusion has already been made. On looking back to Table XCVII., it will be seen that the plots receiving nitrate of soda have been losing their carbonate of lime less rapidly than the unmanured plots, 100-200 lb. per acre per annum less, though too much reliance cannot be placed on the weights calculated. This reduction in the amount of carbonate of lime annually removed from the soil is due to the fact that the carbonate of soda formed from the nitrate of soda has done part of the work for which carbonate of lime is usually required, and has thus indirectly afforded it some protection from waste. Both substances act alike in serving as bases for such processes as nitrification.

Though the selective action of the plant upon the nitrate of soda is the main agency in producing carbonate of soda in the soil, a similar action is brought about by bacteria, particularly when the nitrate of soda is present in a water-logged soil lacking aeration. Though no wholesale destruction of nitrates usually occurs under field conditions, even when they are applied in conjunction with an excess of farmyard manure, some losses of the soil do undoubtedly occur, as may be seen from the fact that in most experiments the whole of the nitrogen applied as nitrate is not recovered in the crop even though there has been no washing out of nitrates by drainage. The bearing of denitrification upon our problem comes from the fact that when the nitrogen of the nitrate of soda is thus lost the soda base is left behind as carbonate of soda, hence from some of the nitrate of soda that is not taken up by the crop there will be carbonate of soda produced by the organisms of denitrification. Moreover, there are other bacteria in the soil which will take the nitrogen from nitrate of soda; they

do not waste it by setting it free as gas, but they convert it into proteins and similar substances out of which their own bodies are constructed; in these cases also the soda part of the salt is left behind as carbonate. This process is strictly comparable with the production of acid by the action of micro-fungi upon sulphate of ammonia; in each case the living organism effects a splitting of the salt in order to obtain nitrogen, and it rejects and leaves behind in the soil in the one case the acid part of the salt, in the other the base.

We are now in a position to sum up the features of this secondary action of nitrate of soda applied to the soil, an action which causes so great an injury to its texture when the land is at all heavy. The bad texture is due to the deflocculation of the clay particles, which is brought about by the presence in the soil of a small quantity of dissolved carbonate of soda. The carbonate of soda is formed by the action of the crop plants and of certain soil bacteria upon the nitrate of soda; they take up the nitrogen-containing part of the salt, because nitrogen is an element indispensable to their development, and leave behind the soda base combined with the carbon dioxide which they excrete.

The next point of importance is to find both a remedy for the injured tilth of the heavy soil, where nitrate of soda has been too freely applied, and a means of preventing such action in the future. Lime is of no benefit to a soil which has been deflocculated by an alkali like carbonate of soda, because lime is an alkali itself, and would rather tend to make matters worse. The flocculating action of lime on ordinary clay soils only takes place when the lime gets washed into the soil as soluble bicarbonate; lime itself, when protected from carbon dioxide, has no flocculating action (see Hall and Morison, *J. Agric. Sci.*, 2 (1907), 244). In this particular case the flocculating action of lime would be largely masked by the carbonate of soda which would still remain in the soil. Gypsum has been used in America as a means of getting rid of carbonate of soda in those unfertile and unworkable soils known as

“black alkali”; the two substances interact to form sulphate of soda and carbonate of lime. It takes, however, a large and unprofitable amount of gypsum to effect this change, and a more practical plan is always to use superphosphate as the phosphatic manure on such land. The acid of the superphosphate will go to neutralise the alkaline carbonate of soda, and the gypsum which is also present will aid in the desired flocculation of the clay particles. Another remedial measure is a liberal dressing of soot; the particles of carbon have a beneficial mechanical effect in lightening the texture of the soil, and at the same time the ammonia salts that are present in the soot are helpful in flocculating the clay. As a preventive, undoubtedly the simplest and wisest plan to follow is to use on all strong soils, instead of nitrate of soda alone, a mixture in equal proportions of nitrate of soda and sulphate of ammonia, especially where considerable quantities of concentrated nitrogenous manure are required for market-gardening purposes. Since one of these compounds tends to produce an acid and the other an alkali in the soil, they neutralise the effects of each other, and as far as the conditions depend upon the manuring, such a mixture will not disturb the reaction of the soil in one direction or the other. Moreover, there is a good deal to be said for the use of such a mixture from the point of view of the nutrition of the plant; of course, the great value of nitrate of soda lies in its immediate availability, but when too much is put on it may easily form a solution that is injuriously strong in certain parts of the soil.

Now the ammonium sulphate mixed with the nitrate of soda would be to some extent temporarily withdrawn from solution by the soil, so that an application of a mixture of it with nitrate of soda would result in a less concentrated soil solution than would be set up by an equivalent amount of nitrate of soda alone. Yet the sulphate of ammonia would begin to nitrify very rapidly, and would thus provide food for the plant as the nitrate of soda was beginning to get exhausted. No inconveniences arise from making such a mixture; it is

just as effective and active as the nitrate alone, and it sets up no injurious action, either in the direction of acidity or alkalinity in the soil, so that large amounts can be used without detriment either to the tilth or the health of the soil. There can be little doubt but that the discredit which the practical farmer sometimes attaches to nitrate of soda as a stimulant exhausting the soil, even as a "scourge" as it has been called, is due to its effect upon the tilth. Although nitrate of soda, when used alone, is a one-sided manure that will greatly aid the plant to remove the available phosphoric acid and potash from the soil, it still supplies the most important element of fertility, and cannot exhaust the soil in any real sense. It gets described as an exhausting manure, not because it robs the land in any special way, but simply because it sets up the bad texture of the soil, which so easily leads to an inferior yield in the following crop.

The list, indeed, of these secondary interactions between fertiliser and soil, which may have a potent influence on the value of the fertiliser in practice, is not ended with the changes set up by nitrate of soda and sulphate of ammonia; there is plenty of practical evidence that the effect of applying potash salts such as kainit, muriate, or sulphate of potash, is not wholly comprised in the provision of a certain amount of potash for the nutriment of the crop. It has often been remarked by those concerned with field experiments that cases occur when the addition of potash salts to a mixture, so far from increasing the return, actually reduces it. As a rule, these results may be set down to the large experimental error which is inevitable in all field trials; but so convinced have been some experimenters of the reality of the effect, that they have begun to speak of the "depressing effect of potash" upon the crop. Now from the point of view of nutrition alone, such a depressing effect is impossible; in some way the effect must be special to the soil, and due to an unsuspected interaction between soil and potash fertiliser. A clue to the sort of action to be looked for may be found

in the observations which have been recorded in some of the cases where the use of potash had resulted in a lowered yield, that the ground remains a little wetter after the application of kainit or other potash salts. This apparent wetness has been set down to the water-absorbing properties of potash salts, which are chiefly due to the magnesium chloride always present in them; but as already indicated with regard to nitrate of soda, the small amount of water which is absorbable by any ordinary manurial dressing would be inappreciable when diffused through the soil. The wetness suggests deflocculation, and the appearance of many of the plots receiving potash at Rothamsted would bear out this view. On the mangold field in particular the characteristic deflocculation features shown by the plots receiving nitrate of soda, especially their way of drying with a tough glazed crust on top, are reproduced on the plots receiving sulphate of potash, and the worst plot of all is that which receives both of these fertilisers. Tested by the suspension of a small quantity of soil in a large bulk of pure water, the opinion is confirmed that the soil of these potash plots is completely deflocculated. Another practical case has fallen under the observation of the writer where the application of 8 cwt. per acre of kainit to a piece of heavy land, which had not long before been limed, so destroyed the texture of the soil that the ploughman knew at once when he entered upon the plot in question because of the heavier draught of the plough. Accepting, then, deflocculation as an explanation of the injurious effects of potash salts upon clay soils, the question that remains is the origin of the alkali, for alkali it must be that has brought about the deflocculation. The interaction with the zeolites of the soil, by which means potash is normally retained by the soil, would not give rise to any substance of an alkaline nature.

The carbonate of lime in the soil next suggested itself as a possible reacting substance, and a series of experiments have showed that when weak solutions of potash salts remain in

contact with carbonate of lime a small quantity of free carbonate of potash is produced. As the extent of the change that is set up depends upon the relative quantities of the reacting bodies in the soil, where the carbonate of lime would generally be in great excess, the proportion of the potash salts converted into carbonate would be comparatively large.

Moreover, common salt has exactly a similar action, and this at once provides us with an explanation of the many unintelligible and often contradictory reports of the action of salt as a fertiliser. It has variously been reported as enabling the soil to retain more moisture, as injuring the soil, especially when the land has been flooded with sea water, as sometimes increasing but occasionally as diminishing the crop. These reports coincide with those concerning the action of potash, and the effect in both cases may be set down to the deflocculation brought about by the small trace of carbonate of soda or potash that is formed by the action of the carbonate of lime in the soil upon the soluble potash or soda salt.

Deflocculation brought about by potash salts or by common salt is rarely a matter of much practical importance, but it may be obviated by using superphosphate as the phosphatic manure going with the potash salts, and again by applying the latter fertiliser in the winter. This will give time for the reactions between fertiliser and soil to be completed, and for some of the useless by-products like the carbonate of soda to be washed out. If on arable land, there will also be time for the spring frosts to restore the texture of the land before the preparation of the seed bed is taken in hand. No fear need be entertained that the valuable potash salts will be washed out of the soil. Way's and Voelcker's papers show that they are retained, and Dr B. Dyer, in his examination of the Rothamsted soils, found that of the potash annually applied and not utilised by the crop, very little had been washed away, even after fifty years of the treatment.

It will be noticed that all the effects of fertilisers upon soil which have been discussed are due to chemical changes of a

comparatively minor order, which were overlooked or not suspected when fertiliser actions first began to be studied, because in most cases the agent in the process is that part of the substance which possesses no value as a fertiliser. For example, sulphate of ammonia was considered as a source of nitrogen only, the sulphuric acid it contained was entirely ignored and regarded as of no account. Similarly with nitrate of soda, the nitrogen is the important part upon which its value as a fertiliser depends; the mistake came in supposing that the soda was entirely without effect. The same state of affairs has occurred over and over again in the history of science; the broad conclusions reached by early generations of investigators, which become the staple of the text-books and the dogma of the lecture rooms, and in the process always grow cruder and more hard and fast in statement than is justified by the original researches, prove eventually to be no more than first approximations to the truth. To complete the story, a second, sometimes even a third, term requires to be introduced, the course of events in nature being always much more complex than the nice water-tight statements which our minds like to evolve under the guise of laws. These second approximations, which may become large enough to override the main truth, often make themselves evident to the practical man, who delights in them as proofs that theory and practice do not square, though as theory can never be more than a method of explaining and, in its turn, predicting the practice, any want of agreement between the two must only mean that the practical man is dealing with an imperfect theory.

However, it is the duty of the scientific man to recognise that practical affairs will always be stretching the range of actions upon which he founded his general statements into regions where they will no longer fit the facts, and by picking up the hints of such discrepancies as the practical man can often supply, the theory may be founded on a more accurate basis.

## SUMMARY.

1. The long-continued use of sulphate of ammonia on soils poor in lime, results in the soils becoming acid.

2. The acidity is caused by certain micro-fungi in the soil, which split up the sulphate of ammonia in order to obtain the ammonia, and thereby set free sulphuric acid.

3. The infertility of such soils is due to the way all the regular bacterial changes in the soil are suspended by the acidity; instead fungi permeate the soil and seize upon the manure.

4. The remedy, as may be seen upon the Woburn plots, is the use of sufficient lime to keep the soil neutral.

5. From the Rothamsted soils carbonate of lime is being washed out at the rate of 800 to 1000 lb. per acre per annum, the losses being increased by the use of sulphate of ammonia, but lessened by dung or nitrate of soda.

6. Nitrate of soda, when applied to heavy soils in large quantities, destroys their texture.

7. Some of the nitrate of soda gets converted into carbonate of soda by the action of plants and bacteria, and carbonate of soda, by deflocculating the clay particles, destroys the tilth.

8. The best remedies are the use of soot or superphosphate; the best preventive is the use of a mixture of nitrate of soda and sulphate of ammonia instead of either separately.

9. Soluble potash manures and common salt may also injure the tilth of heavy soils through the production of a little soluble alkali by interaction with carbonate of lime in the soil. The remedy is to apply such manures in the winter or in conjunction with superphosphate.

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## APPENDIX

### LIST OF PUBLICATIONS ISSUED FROM THE ROTHAMSTED EXPERIMENTAL STATION, 1843-1905.

(The publications since 1905 are given in the Annual Reports.)

The Authors are indicated by initials as follows:—

J. B. L.	= the late Sir John Bennet Lawes.
J. H. G.	= the late Sir J. Henry Gilbert.
R. W.	= the late R. Warington.
A. D. H.	= A. D. Hall.
N. H. J. M.	= the late N. H. J. Miller.

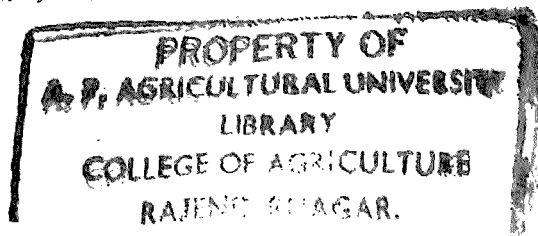
*R. Mem.* (Rothamsted Memoirs) refers to the bound volumes of reprints which were distributed, ten in 1890 and one in 1915, to the Chief Libraries, Agricultural Colleges, and Experiment Stations, both at home and abroad.

<i>J.R.A.S.</i>	= <i>Journal of the Royal Agricultural Society of England.</i>
<i>J.C.S.</i>	= <i>Journal of the Chemical Society.</i>
<i>T.C.S.</i>	= <i>Transactions of the Chemical Society.</i>
<i>P.C.S.</i>	= <i>Proceedings of the Chemical Society.</i>

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