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THE BOOK OF THE ROTHAMSTED EXPERIMENTS

The Book of the othamsted Experiment

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PREFACE

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 investigations 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.

A list is given of the men who have worked in the Rothamsted Laboratory, either as members of the staff, or as voluntary workers for a long or short period. Although by the terms of the trust deed no teaching may be done at the Station, accommodation may be provided for men capable of assisting in research; such men 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,
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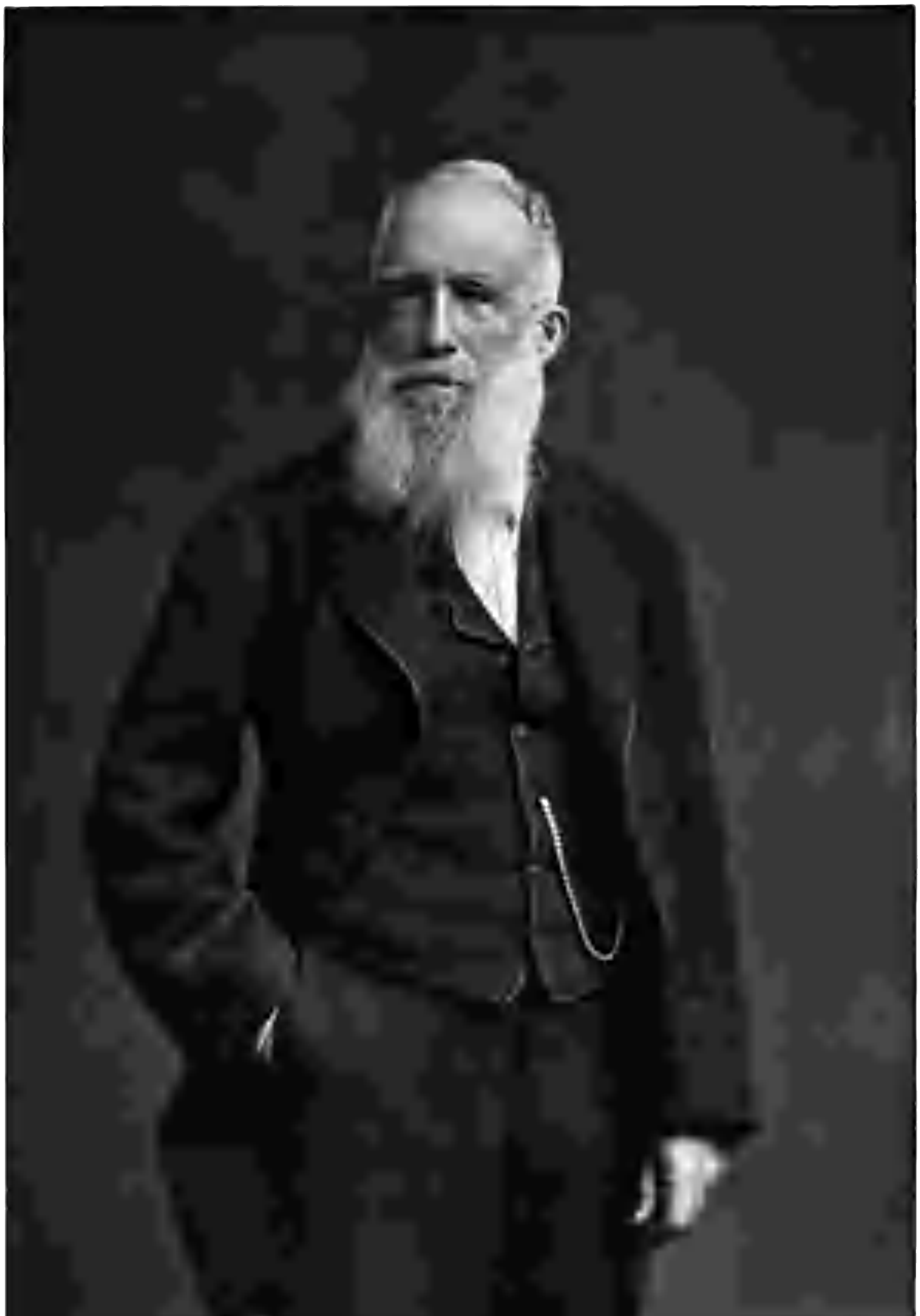

Sir John Bennet Lawes, Bart., D.C.L., LL.D., F.R.S.

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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 up. He seems to have led the life of a country boy, and his

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* Reprinted from the Obituary Notices of the Royal Society.

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

tion." 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. One provision of the trust deed directs the Committee to send a lecturer from time to time to the United States of America to lecture upon the results of the Rothamsted investigations.

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

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 unremitted 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 survives 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 Sibthorpian 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.

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.

R. Warington.

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 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 proteids, 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 only nitrogen 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 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 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 to always 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:—

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.*

		Nitrogen removed per acre.
		Lb.
Wheat . . .	24 years	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.

the following comparative figures were obtained after both had been under a 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, 30 years.		
	Wheat and Fallow alternately.	Trifolium repens.	Melilotus leucantha.	Medicago sativa.
	Lb.	Lb.	Lb.	Lb.
Average Annual Removal of Nitrogen, 8 years (1878–85)	12	83	71	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 contained 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.	
	Plot A.	Plot B.
1873	Barley, 37·3	Clover, 151·3
1874	Barley, 39·1	Barley, 69·4
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 Polygoneæ, 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 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.

Plant.	Pot No.	Duration of Experiment.	Nitrogen. At Beginning. In Soil, Soil-Extract, and Seeds.	Nitrogen. At Beginning. Total.	Nitrogen. At End. In Sand or Soil.	Nitrogen. At End. In Produce.	Nitrogen. At End. Total.	Gain or Loss of Nitrogen.	Nitrogen of Infected Plants to Uninfected = 1.
Annuals.									
		Wks.	Grams.	Grams.	Grams.	Grams.	Grams.	Grams.	
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, 0·6665 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 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.

Without doubt, Hellriegel and Wilfarth's discovery came as somewhat of a disappointment to the Rothamsted investigators; although the statistics they had accumulated form to this day the best demonstration of its truth on a field scale, still they had so long and so rightly upheld the necessity of combined nitrogen to the nutrition of the plant, that to have to concede the point in issue, as far even as the leguminous plants were concerned, could not have been welcome. Indeed, Liebig's idea having thus triumphed in the one special case, his most sweeping generalisation was justified—that it is the function of plants to manufacture the complex nitrogen compounds from elementary nitrogen, just as they do the carbon compounds from the carbon dioxide in the atmosphere. These complex nitrogen and carbon compounds are necessary to animals, which derive their vital heat and energy by breaking them down again into the simpler materials used by the plant. In this eternal cycle Liebig had placed nitrogen alongside of carbon, and though the statement may be true only of the particular leguminous plants, it is true, in a general sense, in that these plants (or rather the bacteria with which they are associated) are probably the original sources of the world's stock of combined nitrogen.

References

"Agricultural Chemistry, especially in relation to the Mineral Theory of Baron Liebig." *J.R.A.S.*, **12** (1851), 1. *R. Mem.*, Vol. I., No. 5.

"On the Sources of the Nitrogen of Vegetation." *Phil. Trans.*, **151** (1861), 431. *R. Mem.*, Vol. I. (4to), No. 1.

"On the Sources of the Nitrogen of Vegetation." *Jour. Chem. Soc.*, **16** (1863), 100. *R. Mem.*, Vol. III., No. 1.

"Sketch of the Progress of Agricultural Chemistry." Rep. Brit. Assn. for 1880. *R. Mem.*, Vol. V., No. 13.

"On the Present Position of the Question of the Sources of Nitrogen of Vegetation." *Phil. Trans.*, **180**, B (1889), 1. *R. Mem.*, Vol. I. (4to), No. 2.

"Results of Experiments at Rothamsted on the Question of the Fixation of Free Nitrogen." *Agricultural Students' Gazette*, New Series, **5**, 1890-91. *R. Mem.*, Vol. VII., No. 1.

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

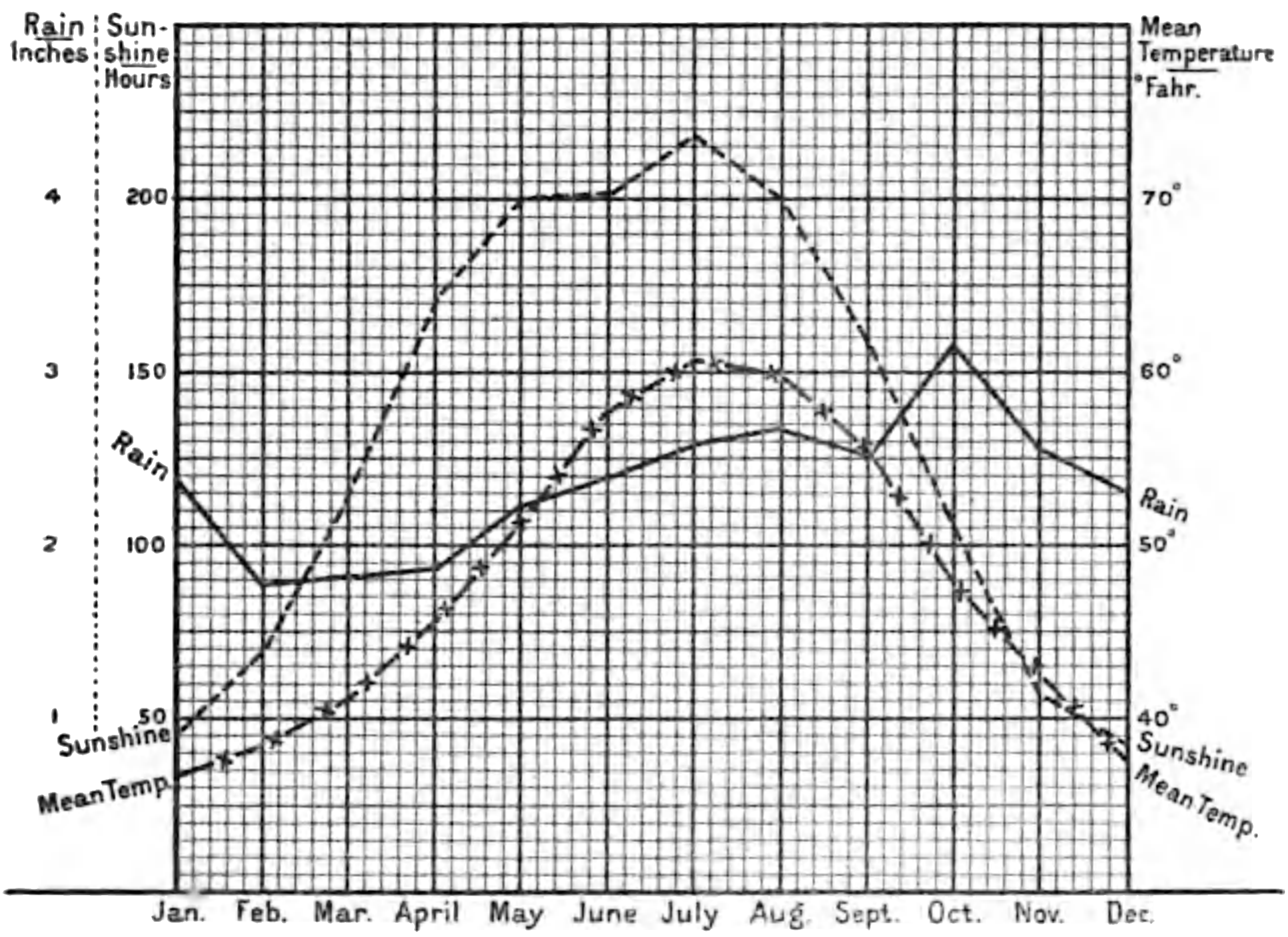

Fig. 1.—Rainfall: Average of 51 years (1853-1903).
Sunshine: Average of 11 years (1892, 1893, and 1895-1903).
Mean Temperature: Average of 26 years (1878-1903).

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

The greatest average rainfall (see Table VI.) is in October, 3·16 inches, followed by 2·57 in November, while in December and January the amounts decline to 2·31 and 2·35 inches respectively. From February to August inclusive there is a gradual rise from 1·78 to 2·67 inches, but it declines to 2·51 inches in September.

TABLE VI.—*Meteorological Summary.*

	Rainfall.			Bright Sunshine.				Temperature.		
	Average, 51 years (1858-1908).			Average, 11 years (1892, 1893, and 1895-1908).				Average, 26 years (1878-1908).		
	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 . .	2·35	16	52	46·4	19	16	51	31·5	41·6	36·6
February .	1·78	13	47	69·2	25	19	66	32·5	43·9	38·2
March . .	1·81	13	42	114·6	32	26	85	33·5	48·3	40·9
April . .	1·86	13	43	170·3	42	27	91	36·8	54·2	45·5
May . .	2·22	13	42	199·9	41	29	93	42·2	60·2	51·2
June . .	2·39	12	41	201·9	41	27	91	48·4	66·6	57·5
July . .	2·58	13	43	217·5	44	29	95	51·7	69·7	60·7
August . .	2·67	14	44	201·1	45	30	96	51·4	68·5	59·9
September .	2·51	13	44	158·3	43	27	92	47·6	64·1	55·9
October . .	3·16	18	57	106·1	32	25	79	41·1	54·8	48·0
November .	2·57	17	55	57·0	22	18	58	36·8	48·3	42·6
December .	2·31	16	52	43·2	18	16	51	32·4	42·9	37·7
Whole year	28·21	171	47	1585·5	36	289	79	40·5	55·3	47·9

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 (217·5 hours, or 44 per cent.). There is a slight decrease in August followed by a very rapid decrease until November. The minimum (43·2 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 August, which is closely followed by July, September, and April, with 44, 43, and 42 per cent. respectively, and May and June with 41 per cent. Of the remaining months, March and October (32 per cent.) have the highest, and January and December the lowest percentages (19 and 18) of possible sunshine. In the whole year we have an average amount of 1586 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 in December 1887 and February 1888, since which time ammonia has been regularly determined each month. Nitric acid has been determined uninterruptedly since September 1886 (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).	Nitrogen.							Chlorine.	
		Per million.		Per acre.			Per cent. of Total.			
		As Ammonia.	As Nitrates and Nitrites.	As Ammonia.	As Nitrates and Nitrites.	Total.	As Ammonia.	As Nitrates and Nitrites.	Per million.	Per acre.
	Inches.			Lb.	Lb.	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

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

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, 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

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

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.

No recent determinations of sulphuric acid in rain-water

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

1881-7.	Rainfall.	Per million.		Per acre.		SO_3 to 1 Cl.
		Cl.	SO_3.	Cl.	SO_3.	
	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

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 (as SO_3), 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 thirty-four years 1871-1904.

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,

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 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.	Agdell 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	15·5	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	5·3

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 Broadbaik 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.

References

"Determinations of Nitrogen in the Soils of some of the Experimental Fields at Rothamsted, and the bearing of the results on the question of the sources of the Nitrogen of our Crops." American Association for the Advancement of Science—Montreal, August, 1882. *R. Mem.*, Vol. V., No. 19.

"On Some Points in the Composition of Soils; with Results illustrating the Sources of the Fertility of Manitoba Prairie Soils." Full Paper, *Trans. Chem. Soc.*, **47** (1885), 380. *R. Mem.*, Vol. VI., No. 4.

"On the Present Position of the Question of the Sources of the Nitrogen of Vegetation, etc., etc." *Phil. Trans.*, **180**, B (1889), 1. *R. Mem.*, Vol. I. (4to), No. 2.

"On the Analytical Determination of Probably Available 'Mineral' Plant Food in Soils," by B. Dyer, D.Sc. *Trans. Chem. Soc.*, **65** (1894), 115.

"Results of Investigations on the Rothamsted Soils, etc., etc.," by B. Dyer, D.Sc. Bulletin No. 106, Office of Experiment Stations, U.S. Department of Agriculture, 1902.

"A Chemical Study of the Phosphoric Acid and Potash Contents of the Wheat Soils of Broadbalk Field, Rothamsted," by B. Dyer, D.Sc. *Phil. Trans.*, **194**, B (1901), 235.

"The Determinations of Available Plant Food in Soils by the use of weak Acid Solvents," by A. D. Hall, and F. J. Plymen. *Trans. Chem. Soc.*, **81** (1902), 117.

"The Geological Survey in Reference to Agriculture; with Report on the Soils and Subsoils of the Rothamsted Estate," by Horace Woodward, F.R.S. Summary of Progress of the Geological Survey for 1903, Appendix I. (1904), 143.

"The Mechanical Analysis of Soils and the Composition of the Fractions resulting therefrom," by A. D. Hall. *Trans. Chem. Soc.*, **85** (1904), 950.

"The Effect of the long-continued use of Sodium Nitrate on the Constitution of the Soil," by A. D. Hall. *Trans. Chem. Soc.*, **85** (1904), 964.

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 handhoeings, 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.	Superphosphate.	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 superphosphate 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 fifty-one years, for the last ten years, and for the single year 1902.

TABLE XV.—*Experiments on Wheat, Broadbalk Field. Produce of Grain and Straw per acre. Average over* 51 *years* (1852-1902); *and over* 10 *years* (1893-1902); *also Produce in* 1902.

Plot.	Abbreviated Description of Manuring.	Dressed Grain.			Straw.		
		Average, 51 years (1852-1902).	Average last 10 years (1893-1902).	Season 1902.	Average, 51 years (1852-1902).	Average last 10 years (1893-1902).	Season 1902.
		Bush.	Bush.	Bush.	Cwt.	Cwt.	Cwt.
2	Farmyard Manure	35·7	40·0	41·5	34·1	40·4	46·9
3	Unmanured	13·1	12·7	13·3	10·5	9·3	9·4
5	Minerals	14·9	15·4	15·5	12·2	11·8	11·4
6	Single Ammonium-salts and Minerals	24·0	23·5	26·2	21·5	20·2	20·8
7	Double do. do.	32·9	32·4	38·2	33·0	32·2	40·0
8	Treble do. do.	37·1	39·2	45·2	40·9	43·0	48·1
9	Single Nitrate and Minerals	...	27·3	33·1	...	25·5	28·6
10	Double Ammonium-salts alone	20·7	19·6	23·7	18·7	16·7	16·9
11	Do. and Superphosphate	24·0	20·2	23·0	22·7	19·2	19·8
12	Do. do. and Sulph. Soda	30·0	27·6	33·4	28·3	25·2	32·2
13	Do. do. and Sulph. Potash	31·5	30·6	39·3	31·3	29·8	37·6
14	Do. do. and Sulph. Mag.	30·1	25·9	32·4	28·8	24·0	27·3
15	Double Amm.-salts in autumn, and Minerals	30·6	28·2	39·6	29·8	27·5	37·2
16	Double Nitrate and Minerals	...	32·5	33·5	...	33·3	35·4
17	Minerals alone, or Double Ammonium-salts *	15·3	15·9	20·2	13·1	12·8	16·8
18	alone, in alternate years †	30·4	30·0	36·9	29·5	29·0	40·1
19	Rape Cake alone	...	28·0	34·1	...	26·7	34·8

* 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 five successive ten-year periods from 1852 to 1901. Although ten-year periods are not long enough to entirely 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.

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* (1852-1901) *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).	50 years (1852-1901).
	Dressed Grain.							
		Bush.	Bush.	Bush.	Bush.	Bush.	Bush.	Bush.
2	Farmyard Manure	28·0	34·2	37·5	28·7	38·2	39·2	35·6
3	Unmanured	17·2	15·9	14·5	10·4	12·6	12·3	13·1
5	Minerals	...	18·4	15·5	12·1	13·8	14·8	14·9
6	Single Ammonium-salts and Minerals	...	27·2	25·7	19·1	24·5	23·1	23·9
7	Double do. do.	...	34·7	35·9	26·9	35·0	31·8	32·9
8	Treble do. do.	...	36·1	40·5	31·2	38·4	38·5	36·9
10	Double Ammonium-salts alone	25·1	23·2	25·1	17·3	19·4	18·4	20·7
11	Do. and Superphosphate	...	28·4	27·9	21·7	22·7	19·5	24·0
12	Do. do. and Sulph. Soda	...	33·4	34·3	25·1	30·1	26·7	29·9
13	Do. do. and Sulph. Potash	...	32·9	34·8	26·8	32·5	29·6	31·3
14	Do. do. and Sulph. Mag.	...	33·5	34 4	26·4	31·1	25·0	30·1
	Straw.							
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
2	Farmyard Manure	26·6	33·9	34·0	28·0	34·8	38·7	33·9
3	Unmanured	15·5	15·2	11·5	8·5	8·5	9·1	10·6
5	Minerals	...	17·1	12·8	9·7	9·9	11·5	12·2
6	Single Ammonium-salts and Minerals	...	26·3	22·8	17·7	20·5	20·0	21·5
7	Double do. do.	...	36·4	34·3	28·7	34·1	31·1	32·9
8	Treble do. do.	...	40·5	43·2	36·6	42·5	41·7	40·9
10	Double Ammonium-salts alone	23·7	24·5	21·9	15·2	15·8	16·2	18·7
11	Do. and Superphosphate	...	28·2	24·5	21·3	20·8	18·8	22·7
12	Do. do. and Sulph. Soda	...	34·2	30·5	25·0	27·3	24·0	28·2
13	Do. do. and Sulph. Potash	...	34·4	33·4	27·6	31·9	28·6	31·2
14	Do. do. and Sulph. Mag.	...	35·0	30·7	26·3	28·6	23·4	28·8

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 five 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

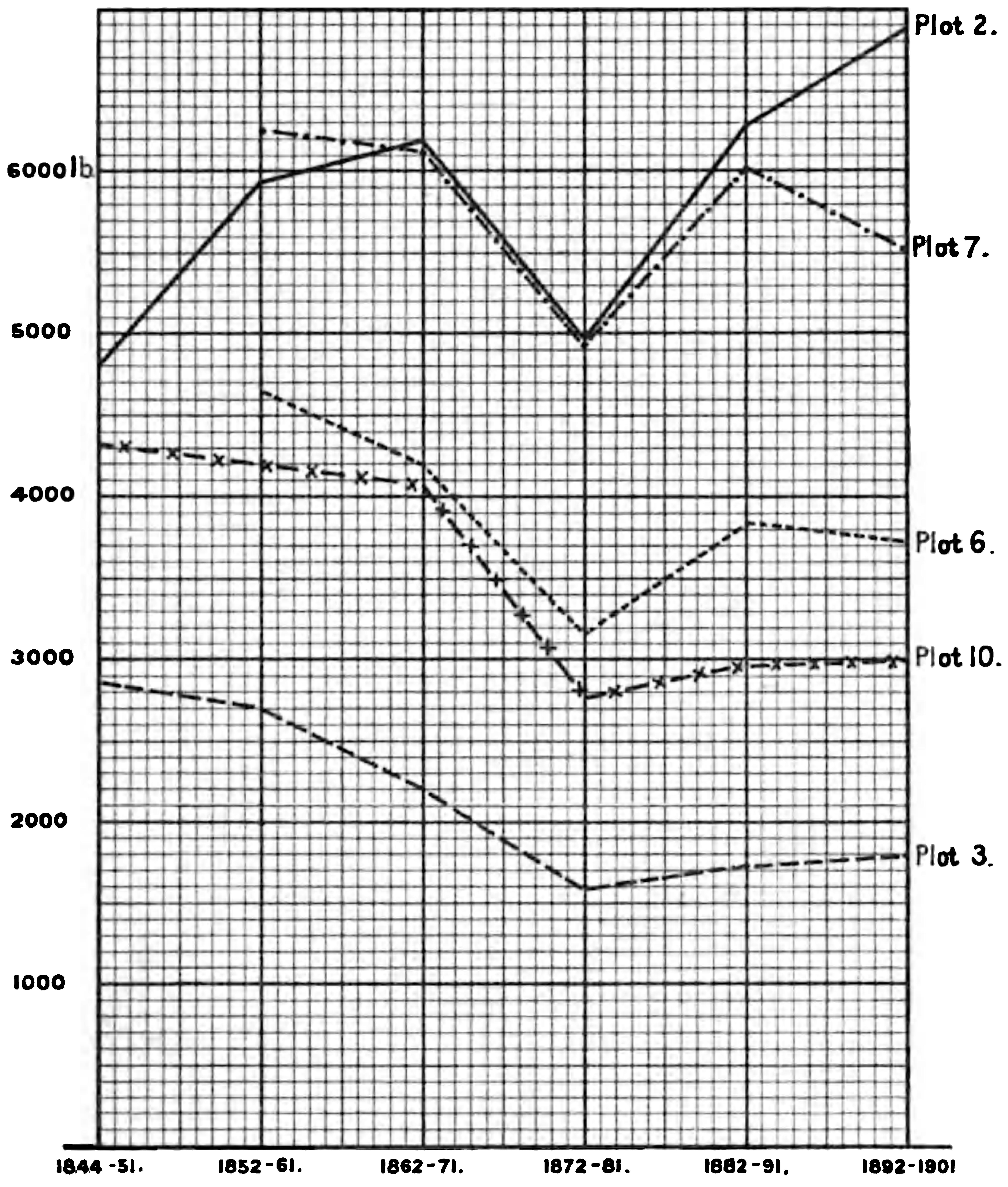

FIG. 2.—Broadbalk Wheat. Total Produce.

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

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 ten years, and a comparatively constant position for the last forty 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 1·8 bushels, the nitrogen alone has produced an average increase of 7·6 bushels, the unmanured plot being taken as the standard in either case. The curve, however, shows that the production on this Plot 10 is declining, notwithstanding the great reserves of mineral plant food with which the soil started. At the present time also 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 whole period since 1852.

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

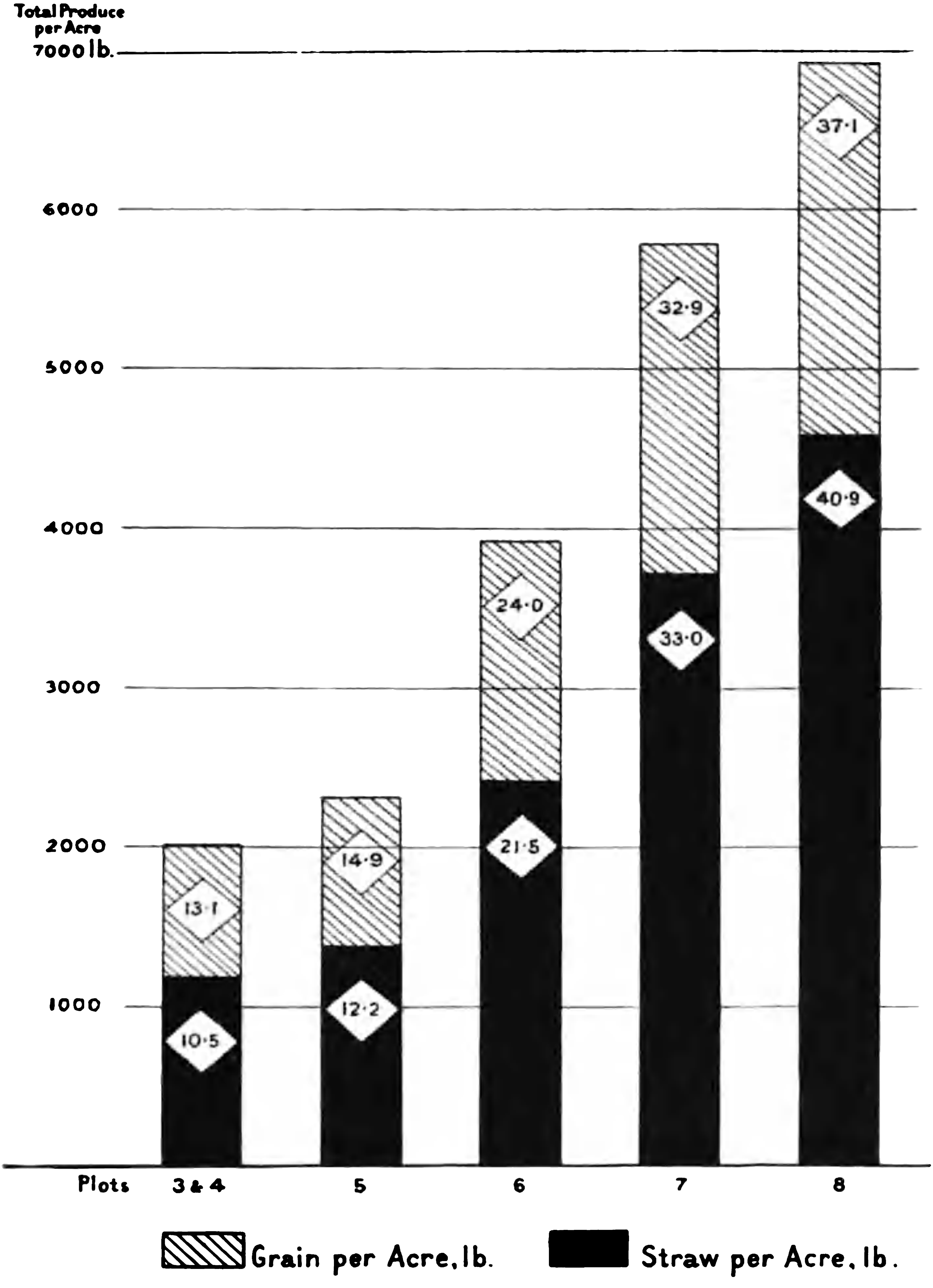

FIG. 3.—Broadbalk Wheat. Effect of increasing amounts of Nitrogen on the production of Wheat (Grain and Straw). Average, 51 years (1852-1902).
The figures in the labels indicate bushels of grain and cwt. of straw.

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 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 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 of the last ten years, 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 2½ per cent. of carbonate of lime.

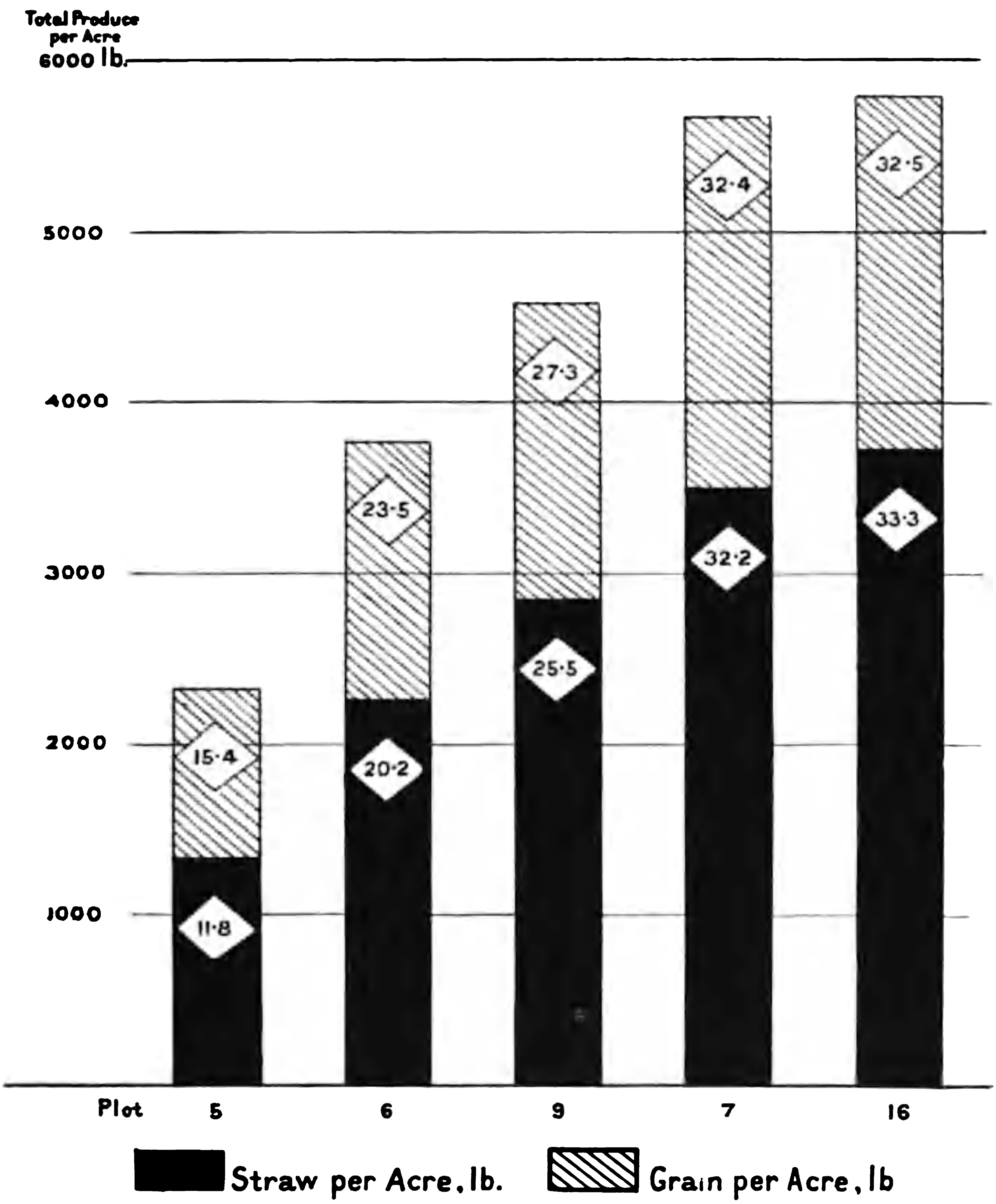

FIG. 4.—Comparison of Nitrate of Soda and Ammonium-salts on Wheat. 10 years (1893-1902). All Plots receive Minerals alike.

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

9·1 bushels more than Plot 5 with no nitrogen, another 43 lb. of nitrogen on Plot 7 produce a further increase of 8·9 bushels, 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.	
		Produce per acre.	Increase for each additional 43 lb. N. in Manure.	Produce per acre.	Increase for each additional 43 lb. N. in Manure.
		Bush.	Bush.	Cwt.	Cwt.
5	Minerals alone	18·3	...	16·6	...
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.

third addition of manure only returns 14s. for an expenditure 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 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

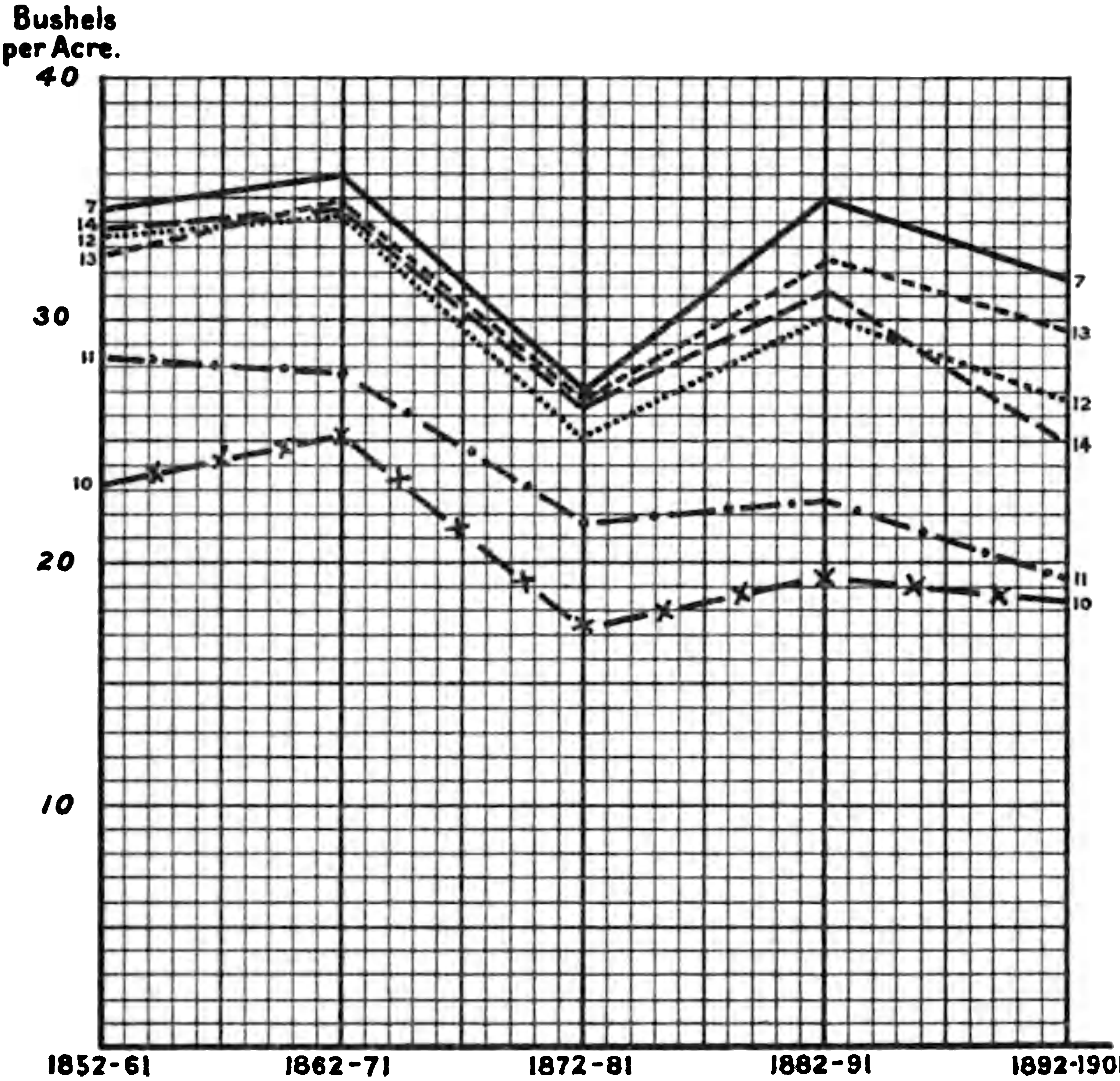

FIG. 6.—Production of Wheat with varying Mineral Manures. All Plots receive equally 86 lb. N. as Ammonium-salts. Averages over 10-year periods (1852-1901).

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 exhausted, and there is a manifest decline on the plots receiving magnesia or soda only. 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, gives throughout 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 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.

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

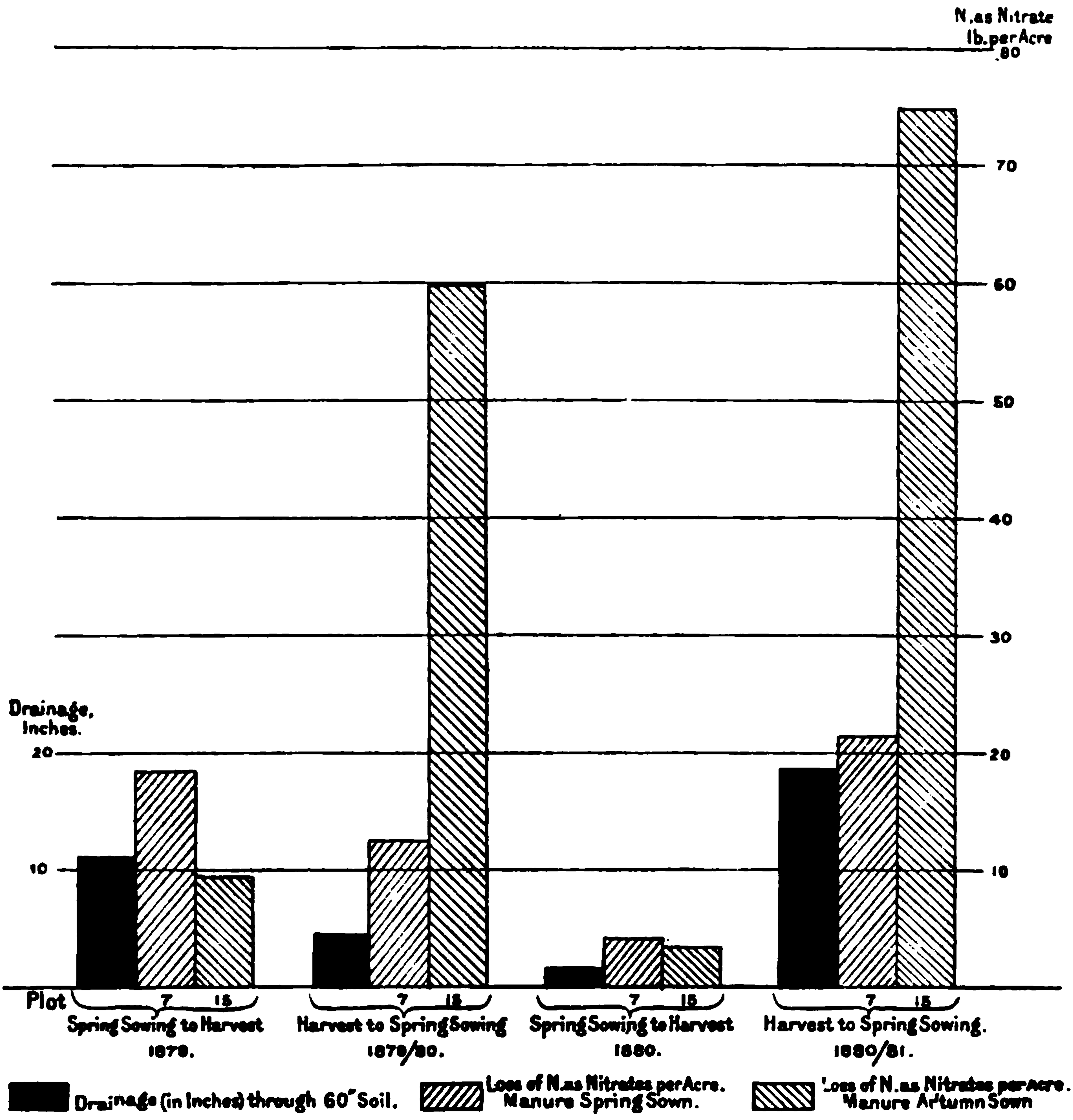

FIG. 7.—Loss of Nitrogen as Nitrates in the Drainage Water, lb. per acre. Comparison of Plot 7 manured with Ammonium-salts in the spring, and Plot 15 in the autumn.

salts and the minerals are applied in alternate years to the two plots. Thus in 1903 Plot 17 received ammonium-salts but no minerals, and Plot 18 the minerals without the ammonium-salts, and the treatment was reversed in 1902 and again in 1904. It will be seen from Table XV., or 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 19, where organic compounds of nitrogen are used, the accumulation of nitrogen is far less than the difference between the nitrogen applied and that removed would indicate.

Table XVIII. gives 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

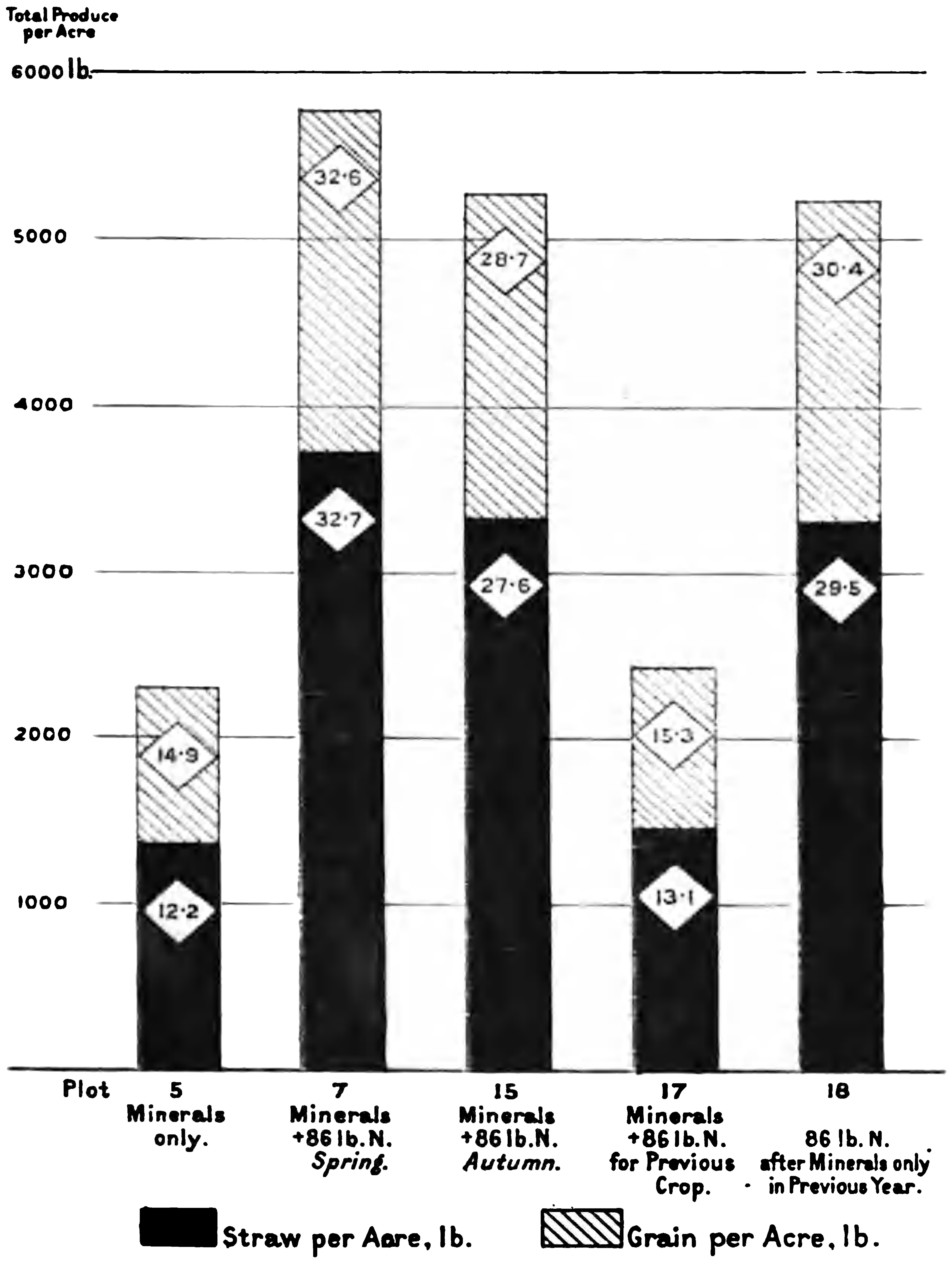

FIG. 8.—Comparative Effects on Wheat of Ammonium-salts applied at different times. Averages for 51 years (1852-1902). Plots 7 and 15, 25 years only (1878-1902).

that any appreciable amount of organic matter has found its way into the subsoil.

It will be seen 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

TABLE XVIII.

Plot.	Manuring.	Nitrogen in Soil, 9 inches deep, 1898.		Approximate Supply of Nitrogen in Manure in 50 Years.	Approximate Removal of Nitrogen in Crops, 50 years (1844-1898).	Surplus of Nitrogen over Plot 3, unaccounted for in Crop or Soil.
		Per cent.	Pounds per acre.			
				Lb.	Lb.	Lb.
3	Unmanured . .	0·0992	2,570	...	850	...
2	Farmyard Manure .	0·2207	5,150	10,000	2,600	5,670

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. 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.

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

Table XIX. gives certain particulars regarding the quality of crops grown during the last fourteen years, covering the years

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 the potash in the soil of this plot. The plot receiving farmyard 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

TABLE XX.—*Wheat, Broadbalk Field, Rothamsted. Comparison of the yield in a* wet *year* (1879), *and in a* dry *year* (1893), *with the average over* 51 *years* (1852-1902).

Plot.	Abbreviated Description of Manures.	Dressed Grain.			Straw.			Weight per Bushel of Dressed Grain.			Grain to 100 Straw.		
		1879. wet	1893. dry	Average, 51 years (1852-1902).	1879. wet	1893. dry	Average, 51 years (1852-1902).	1879. wet	1893. dry	Average, 51 years (1852-1902).	1879. wet	1893. dry	Average, 51 years (1852-1902).
		Bush.	Bush.	Bush.	Cwt.	Cwt.	Cwt.	Lb.	Lb.	Lb.			
2	Farmyard Manure	16·0	34·2	35·7	20·0	20·1	34·1	56·8	63·4	60·6	47·5	99·5	59·1
3	Unmanured	4·5	10·7	13·1	6·7	5·6	10·5	51·8	62·5	58·9	42·8	110·3	69·8
5	Minerals	5·6	14·2	14·9	7·6	7·0	12·2	53·5	62·3	59·4	44·9	116·0	68·9
6	Single Ammonium-salts and Minerals .	10·5	19·4	24·0	14·2	10·2	21·5	56·5	63·1	60·1	43·5	110·4	63·0
7	Double do. do. .	16·2	20·2	32·9	26·9	11·7	33·0	56·7	62·5	60·1	34·9	100·4	56·4
8	Treble do. do. .	20·5	21·7	37·1	37·3	13·9	40·9	56·5	62·4	59·9	32·4	90·6	51·5
9*a*†	Nitrate ‡ and Minerals	21·9	17·9	33·8†	38·8	10·6	36·6†	56·5	61·7	59·5†	33·6	96·2	52·0†
9*b*	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	20·7	8·5	5·6	18·7	50·8	59·1	58·0	33·6	84·4	62·7
11	Do. and Superphos. . . .	11·1	7·7	24·0	18·0	6·2	22·7	54·6	56·4	58·0	36·2	67·3	59·9
12	Do. do. and Sulph. Soda .	14·0	11·4	30·0	22·0	7·6	28·3	55·9	59·2	59·4	37·8	85·5	59·8
13	Do. do. and Sulph. Potash	16·0	16·4	31·5	27·2	9·7	31·3	57·8	62·6	60·3	35·2	98·0	57·0
14	Do. do. and Sulph. Mag. .	16·1	12·8	30·1	25·9	8·1	28·8	57·2	60·3	59·5	37·9	90·8	59·1

* Average of 40 years (1852-1891).
‡ 550 lb. per annum to 1884 inclusive; 275 lb. only since.
† 9*a* to 1893 inclusive; whole plot (*a* and *b*), 1894 to 1902.

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 fifty-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* 50 *years* (1852-3 *to* 1901-2).

	1878-9.	1892-3.	Average, 50 years (1852-3 to 1901-2).
	Inches.	Inches.	Inches.
September . .	1·46	2·46	2·56
October . . .	2·99	3·99	3·15
November . .	4·55	2·06	2·68
December . .	1·60	1·63	2·33
January . . .	2·85	2·05	2·35
February . . .	3·80	3·62	1·79
March . . .	1·18	0·42	1·78
April . . .	2·79	0·25	1·86
May . . .	3·48	1·22	2·23
June . . .	5·55	1·00	2·31
July . . .	4·24	3·00	2·55
August . . .	6·56	2·38	2·65
Total .	41·05	24·08	28·24

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 higher in the dry than in the wet year, averaging 61·2 lb. against 55·0 lb. In the dry years the manures have comparatively little effect, the crops on all the plots being brought nearer to a uniform level; in the wet year, on the contrary, the difference due to manuring are very much accentuated. The

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 last thirty years 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 9a. Nitrate Soda.	Plots 6 and 7. Ammonium-salts.	
	Inches.	Bushels.	Bushels.	
14 Seasons *below* average Rainfall .	24·23	30·6	26·5	86·6
16 Seasons *above* 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 *above* average Percolation.	15 Seasons *below* 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

TABLE XXIV.—*Wheat without Manure.—Grown continuously (Broadbalk Field), and in alternation with Fallow (Hoos Field). Average Produce per acre,* 47 *years* (1856-1902).

Wheat every Year. (Broadbalk Field, Plot 3.)		Wheat after Fallow. (Hoos Field, Plot 0.)	
Dressed Grain.	Straw.	Dressed Grain.	Straw.
Bushels. 12·7	Cwt. 10·0	Bushels. 17·1	Cwt. 14·2

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

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

		16 Seasons *less* than average Rainfall.	16 Seasons *more* than average Rainfall.
Rainfall (Sept. to Dec. inclusive)	In.	8·88	13·66
Percolation through 60 in. of Soil (Sept. to Dec. inclusive)	In.	4·03	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

For the wet autumns, however, with an average rainfall of 13·66 inches and a percolation of 8·92 inches, the wheat after

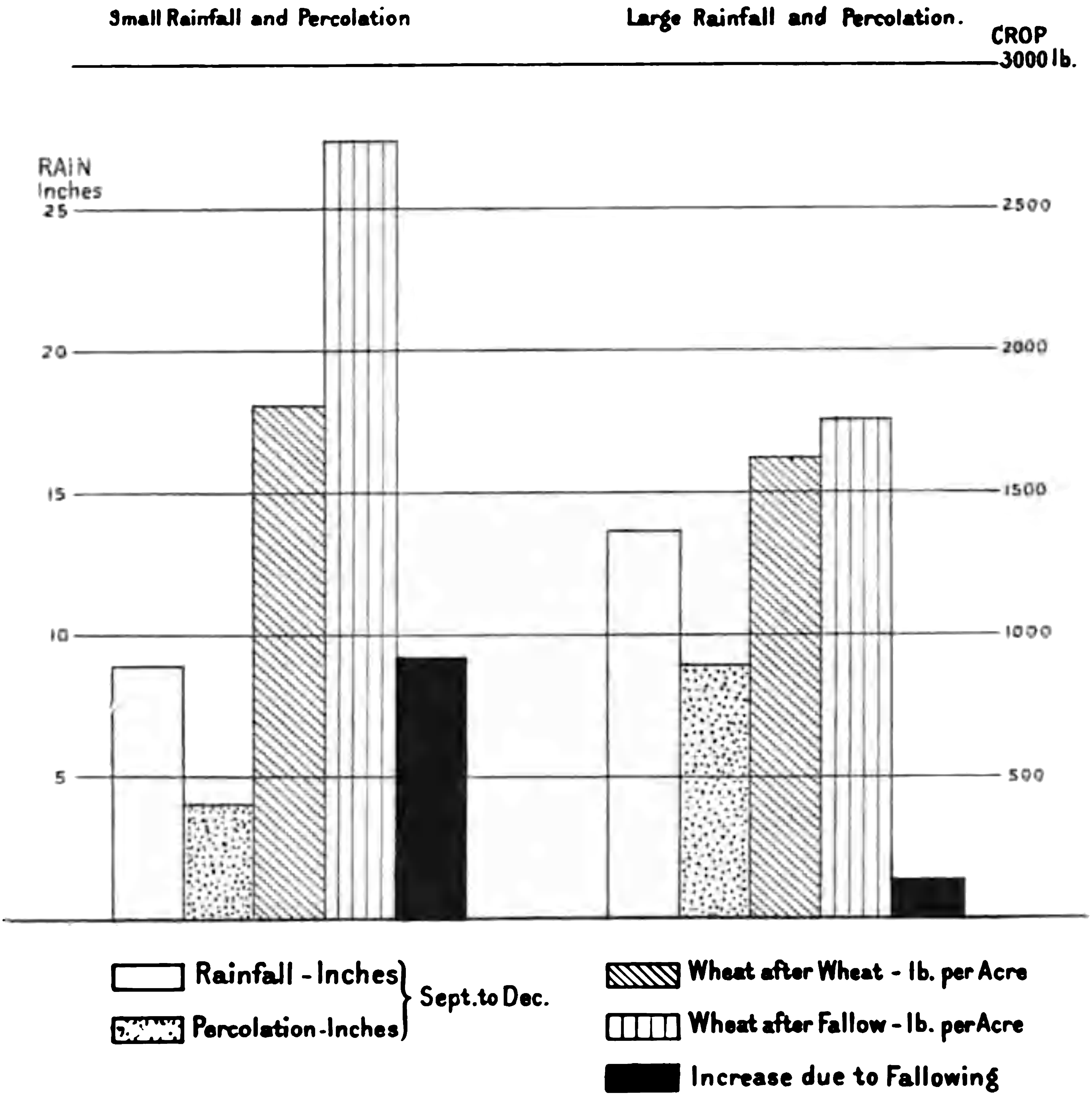

FIG. 9.—Effect of Wet or Dry Autumns on continuous Wheat, and Wheat alternated with Fallow.

fallow yielded 1757 lb. against 1627 lb. on the continuous wheat plot, or a gain of 130 lbs. 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* 12 *years* (1855, '59, '63, '67, '71, '75, '79, '83, '87, '91, '95 *and* 1899).

Dressed Grain per acre.		
Continuous Wheat. (Broadbalk, Plot 3.)	Wheat after Fallow. (Hoos Field, Plot 0.)	Rotation Wheat. (Agdell Field, Plots 21-22.)
Bushels. 12·4	Bushels. 18·1	Bushels. 28·6

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 twelve years during which comparison is possible the average crop of wheat grown thus in rotation on continuously unmanured land has been 28·6 bushels per acre, as against 18·1 bushels for wheat after fallow and 12·4 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	54·5	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 (Hallett's)	30·0	35·3	36·4	43·6	26·0	40·1	44·4	....	...	...	...	36·5
Victoria White (Hallett'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 (Hallett'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

(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 1½ 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.

References

"Report of Experiments on the Growth of Wheat for Twenty Years in succession on the same Land." *Jour. Roy. Ag. Soc.*, **25** (1864), 93 and 449. *Rothamsted Memoirs*, Vol. III., No. 4.

"Our Climate and our Wheat Crops." *Jour. Roy. Ag. Soc.*, **41** (1880), 173. *Rothamsted Memoirs*, Vol V., No. 11.

"On the Composition of the Ash of Wheat Grain and Wheat Straw, grown at Rothamsted, in different Seasons, and by different Manures." *Trans. Chem. Soc.*, **45** (1884), 305. *Rothamsted Memoirs*, Vol. VI., No. 2.

"Report of Experiments on the Growth of Wheat for the Second Period of Twenty Years in succession on the same Land." *Jour. Roy. Ag. Soc.*, **45** (1884), 391. *Rothamsted Memoirs*, Vol. VI., No. 3.

"On Agricultural Investigation; illustrated by Results of Experiments at Rothamsted, on the Growth of Wheat, for Forty Years in succession on the same Land." Being a Lecture delivered at the Michigan State Agricultural College, Lansing, Michigan, October 14, 1884; and at Rutgers' College, New Brunswick, N.J., October 27, 1884. *Rothamsted Memoirs*, Vol. VI., No. 5.

CHAPTER V

EXPERIMENTS UPON BARLEY

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 fifty 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

TABLE XXIX.—*Experiments on Barley, Hoos Field. Produce of Grain and Straw per acre. Averages over* 51 *years* (1852-1902), *and over* 10 *years* (1893-1902). *Also Produce in* 1902.

Plot.	Abbreviated Description of Manures.	Dressed Grain.			Straw.		
		Average, 51 years (1852-1902).	Average, 10 years (1893-1902).	Season 1902.	Average, 51 years (1852-1902).	Average, 10 years (1893-1902).	Season 1902.
		Bush.	Bush.	Bush.	Cwt.	Cwt.	Cwt.
1 O	No Minerals, and no Nitrogen	15·3	10·1	14·3	8·8	6·4	5·6
2 O	Superphosphate only. do.	20·1	13·6	21·7	10·2	7·8	9·9
3 O	Alkali Salts only, do.	16·1	8·9	13·3	8·9	5·9	6·3
4 O	Complete Minerals do.	20·4	12·4	18·2	10·8	8·0	10·9
1 A	Ammonium-salts alone	26·5	16·2	21·7	14·9	10·5	9·7
2 A	Superphosphate and Ammonium-salts	39·9	26·8	39·8	22·5	16·5	20·8
3 A	Alkali Salts and do.	29·4	20·8	20·0	17·0	12·9	10·4
4 A	Complete Minerals and do.	42·1	35·1	40·3	24·9	20·5	23·1
1 N	Nitrate of Soda alone	30·4	20·5	25·1	18·1	14·4	14·1
2 N	Superphosphate and Nitrate of Soda	44·0	35·9	45·9	26·2	23·0	26·1
3 N	Alkali Salts and do.	31·5	23·4	22·0	19·7	15·3	10·0
4 N	Complete Minerals and do.	43·5	34·9	36·5	27·4	22·6	23·4
1 C	Rape Cake alone	39·2	31·0	38·7	22·4	18·4	20·5
2 C	Superphosphate and Rape Cake	41·5	33·2	41·4	23·9	19·6	24·2
3 C	Alkali Salts and do.	37·7	29·6	39·7	22·4	18·1	22·7
4 C	Complete Minerals and do.	41·0	32·5	40·7	24·5	20·1	25·4
7-1	Unmanured (after dung 20 yrs., 1852-71)	27·0*	19·9	27·5	15·4*	12·8	14·3
7-2	Farmyard Manure	47·6	42·6	42·4	29·1	28·8	27·4

* Average, 31 years (1872-1902).

Table XXX. shows the average production during each of the successive ten year periods from 1852.

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

One of the plots, 1-0, 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 10 bushels for the last ten years, against an average of more than 15 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 wheat plot. The more

TABLE XXX.—*Experiments on Barley, Hoos Field. Average Produce per acre of Dressed Grain and Straw over successive* 10-*year periods, from* 1852-1901 *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).	50 years (1852-1901).
	Dressed Grain.						
		Bush.	Bush.	Bush.	Bush.	Bush.	Bush.
1 O	No Minerals, and no Nitrogen . .	22·4	17·5	13·7	12·7	10·0	15·3
2 O	Superphosphate only, do. . .	27·9	23·2	17·9	17·7	13·5	20·0
3 O	Alkali Salts only, do. . .	24·7	20·1	14·5	12·4	9·1	16·2
4 O	Complete Minerals, do. . .	30·5	24·4	17·7	16·9	12·8	20·5
1 A	Ammonium-salts alone	33·6	31·2	26·2	25·0	16·6	26·5
2 A	Superphosphate, and Ammonium-salts	45·6	48·4	40·5	36·7	28·0	39·8
3 A	Alkali Salts, do. .	35·0	35·0	30·1	25·5	22·1	29·5
4 A	Complete Minerals, do. .	46·1	46·4	41·0	40·7	36·3	42·1
1 N	Nitrate of Soda alone	39·7	34·2	28·2	28·5	21·9	30·5
2 N	Superphosphate, and Nitrate of Soda .	48·9	49·6	42·0	42·7	36·5	43·9
3 N	Alkali Salts, do. .	38·6	36·1	29·9	29·1	24·8	31·7
4 N	Complete Minerals, do. .	49·9	49·5	42·2	40·4	36·0	43·6
1 C	Rape Cake alone	47·0	43·6	39·0	35·4	31·3	39·3
2 C	Superphosphate, and Rape Cake . .	47·8	45·7	41·5	38·4	33·7	41·4
3 C	Alkali Salts do. . .	44·0	43·2	37·4	33·8	29·7	37·7
4 C	Complete Minerals, do. . .	47·4	47·2	41·9	36·0	32·4	41·0
7-1	Unmanured (after dung 20 yrs., 1852-71)	} 45·0	51·5 {	34·2	26·4	20·3	35·5
7-2	Farmyard Manure			50·2	47·6	44·3	47·7
	Straw.						
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
1 O	No Minerals, and no Nitrogen . .	13·4	10·2	6·9	6·8	6·6	8·8
2 O	Superphosphate only, do. . .	14·9	11·8	8·4	8·1	7·8	10·2
3 O	Alkali Salts only, do. . .	13·9	10·7	7·1	6·8	6·3	9·0
4 O	Complete Minerals, do. . .	16·1	12·6	8·5	8·4	8·0	10·7
1 A	Ammonium-salts alone	19·8	17·4	13·6	13·4	11·0	15·0
2 A	Superphosphate, and Ammonium-salts	27·9	27·5	20·5	19·7	17·0	22·5
3 A	Alkali Salts, do. .	21·9	19·7	15·6	14·6	13·9	17·1
4 A	Complete Minerals, do. .	28·9	28·0	23·5	23·4	21·1	25·0
1 N	Nitrate of Soda alone	24·0	20·1	15·4	16·5	14·8	18·2
2 N	Superphosphate, and Nitrate of Soda .	31·9	29·2	22·8	23·9	23·3	26·2
3 N	Alkali Salts, do. .	25·8	22·1	17·5	17·6	16·4	19·9
4 N	Complete Minerals, do. .	34·6	30·1	24·4	24·5	23·5	27·4
1 C	Rape Cake alone, ...	29·4	24·3	21·1	18·9	18·6	22·5
2 C	Superphosphate, and Rape Cake . .	30·8	26·0	22·3	20·7	19·8	23·9
3 C	Alkali Salts, do. . .	28·9	25·3	20·8	18·9	18·4	22·5
4 C	Complete Minerals, do. . .	31·3	27·8	23·1	20·5	19·9	24·5
7-1	Unmanured (after dung 20 yrs., 1852-71)	} 26·6	29·9 {	18·5	14·5	13·3	20·6
7-2	Farmyard Manure			30·1	29·3	29·9	29·2

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 due to a run of less

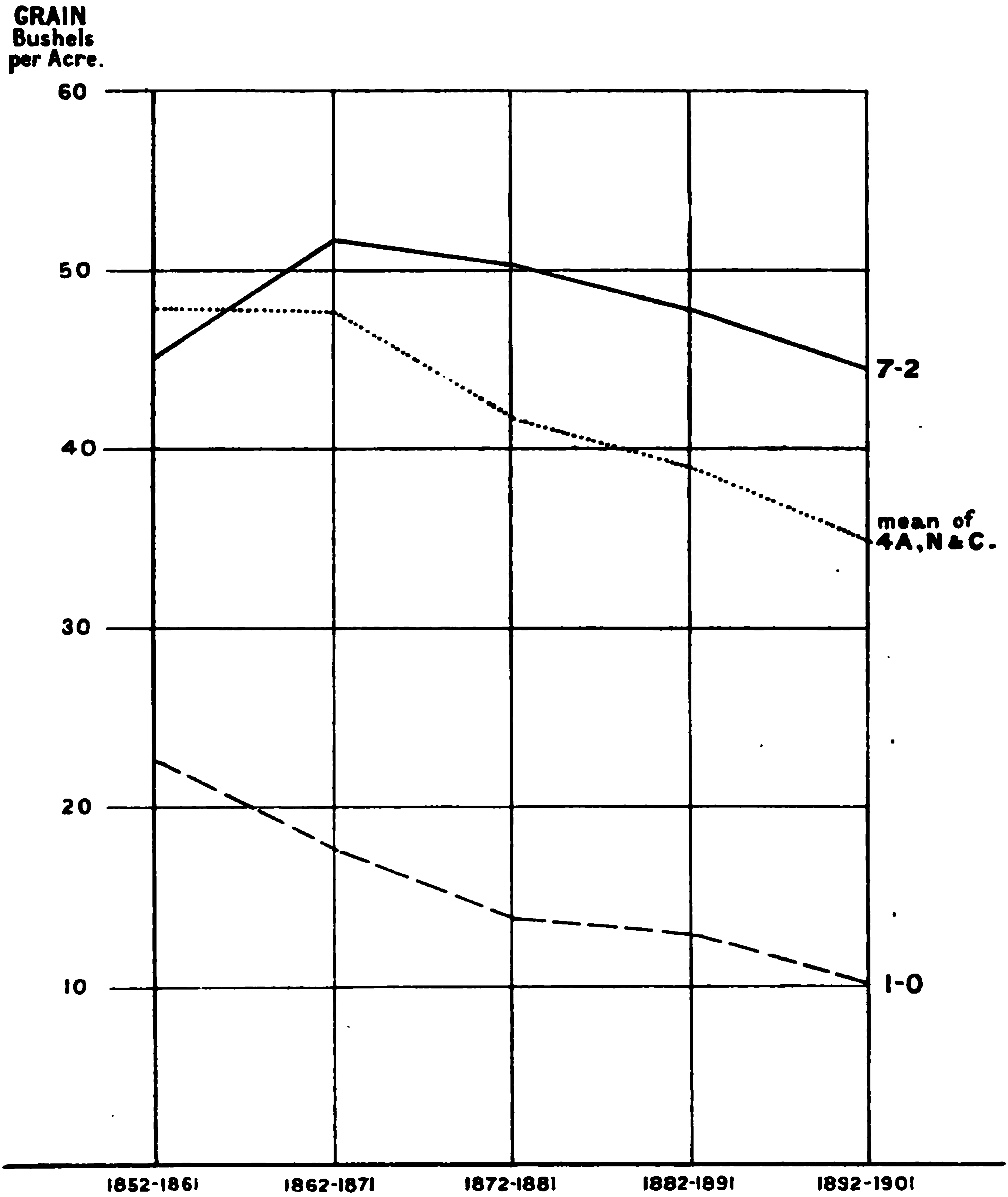

Fig. 10.—Yield of Barley during successive 10-year periods (1852-1901). Plot 7-2.—Farmyard Manure. Plots 4 A, N, and C.—Each receive Complete Minerals, + N. as Amm.-salts, Nitrate Soda, or Rape Cake. Plot 1-0.—Unmanured.

favourable seasons. Both the continuously dunged plot, which must be gaining fertility, and the plots which receive heavy complete dressings of artificial manures show a similar decline in the average production for the last four decades, as may be seen

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 shows a much greater progressive decline than the corresponding unmanured plot growing barley in rotation, where the land is practically fallowed in alternate seasons. On the whole, the results 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 4-0, 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 two 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 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 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

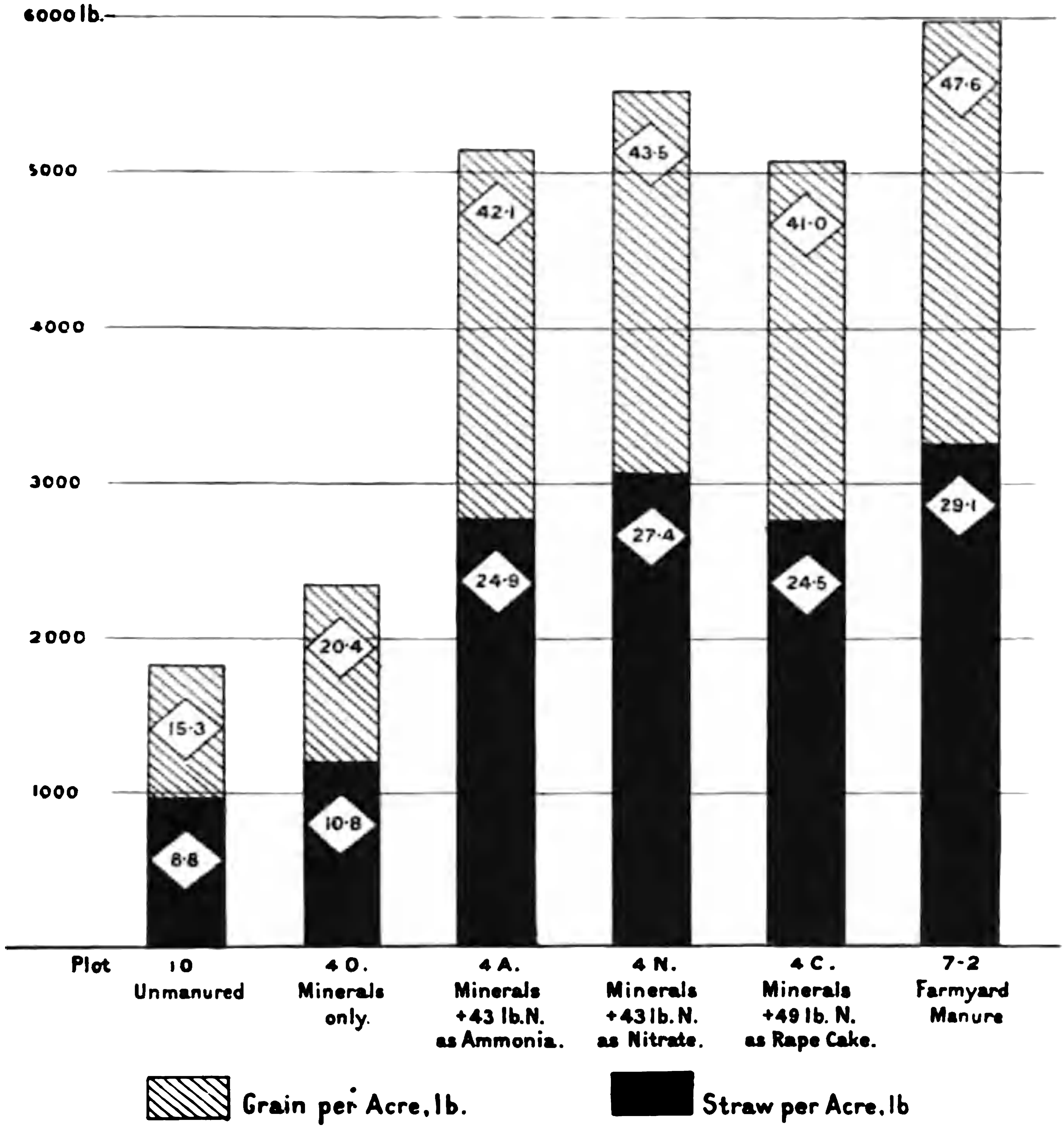

Fig. 11.—Yield of Barley (Grain and Straw) with different sources of Nitrogen. Averages for 51 years, 1852–1902.
The figures in the labels indicate bushels of grain and cwt. of straw.

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 thirty 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 1-0.	Plot 7-2.	Plot 7-1.	Plot 1-0.
	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

obtained from the three plots in question for the thirty years which have elapsed since the dung on Plot 7-1 was discontinued, the first five years are given singly, after that five years are grouped into one period and the mean result given. In order

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 32·9 bushels per acre against 32, taking the average of the three series A, N, and C—but that a very marked increase to 42·2 bushels per acre is found on Plots 4 for the addition of phosphoric acid. The straw shows just as marked an increase of crop brought about by phosphoric acid as does the grain, rising from 19·7 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)

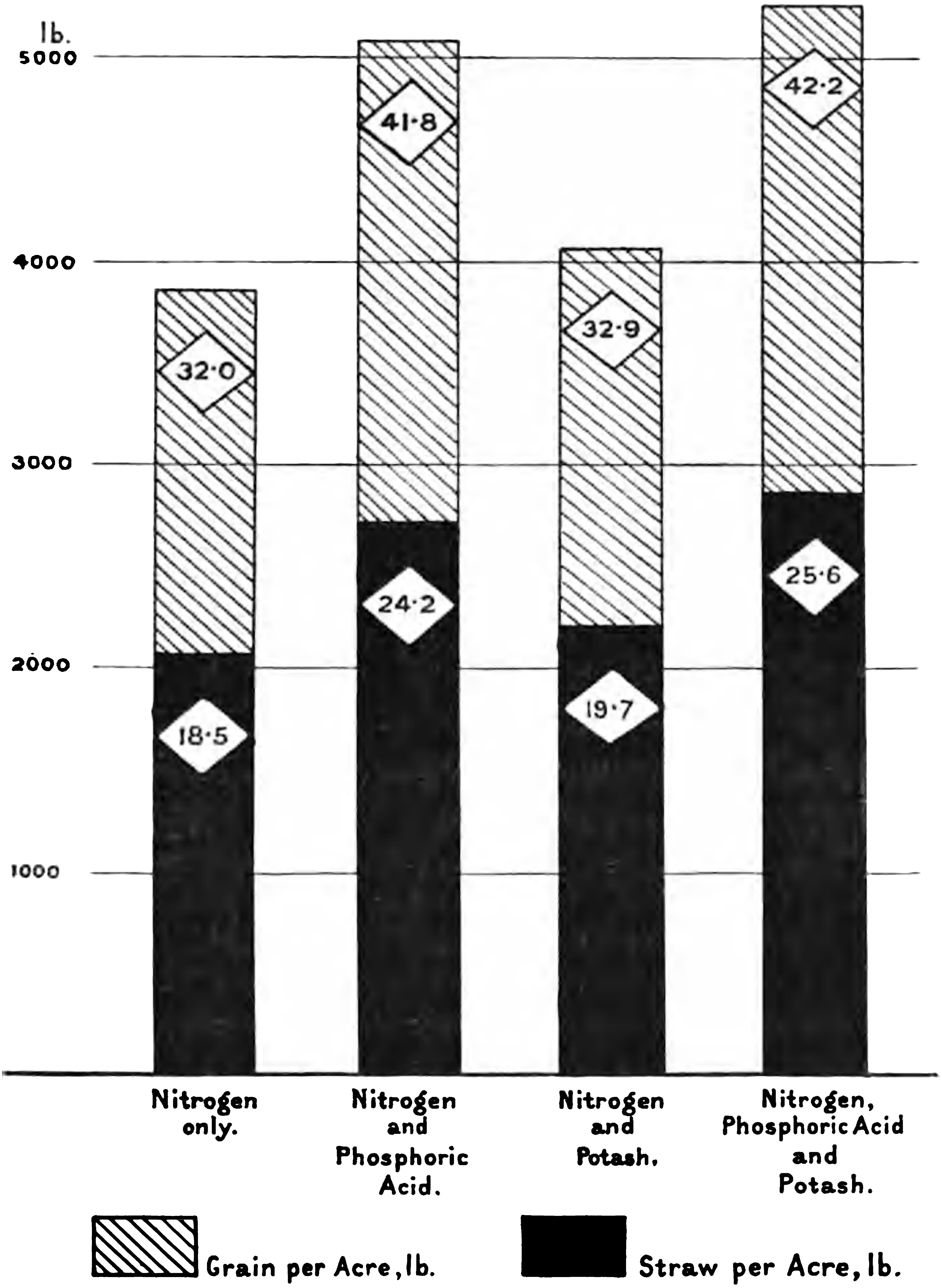

FIG. 13.—Effect of Mineral Manures on the yield of Barley (Grain and Straw). Mean of Series A. N. and C. 51 years (1852-1902).

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 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,

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.
Ratio of 2 A to 4 A, Ammonium-salts .	98·9	104·3	98·8	90·2	77·1
Ratio of 2 N to 4 N, Nitrate of Soda .	98·0	100·2	99·5	105·7	101·4

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 next decade. 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 A, receiving nitrate of soda and superphosphate, the omission of potash has made no difference to the yield up to the end of the fifty-year period. The figures

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

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*. (Std. each year as 100.)	Offal Grain to 100 of Head.	Weight of 100 Grains.*	N. per cent. in Grain (Dry), (20-year average, 1852-71).
		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	104·1	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 N	Nitrate of Soda alone	52·6	82·2	91·3	8·9	4·05	...
2 N	Superphosphate, and Nitrate of Soda .	53·6	84·6	100·0	7·5	4·04	...
3 N	Alkali Salts, and do. .	53·4	80·9	93·6	6·1	4·12	...
4 N	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.

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 N 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 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 N 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-

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.
		Bush.	Bush.	Cwt.	Cwt.	Lb.	Lb.	Per cent.	Per cent.	Per cent.	Per cent.
1 O	No Minerals, and no Nitrogen	8·3	10·0	6·0	7·8	55·6	51·1	71·9	70·3	1·899	1·409
2 O	Superphosphate only, no Nitrogen	11·7	16·7	6·9	10·1	56·1	52·1	89·1	85·6	1·890	1·380
3 O	Alkali Salts only, do.	7·8	9·5	5·9	6·9	55·5	51·6	70·0	73·4	1·995	1·441
4 O	Complete Minerals, do.	9·9	13·1	7·0	8·4	56·1	52·1	74·3	79·2	2·011	1·467
1 A	Ammonium-salts alone	11·6	10·4	7·3	9·5	55·1	50·4	85·3	67·5	2·188	1·646
2 A	Superphosphate, and Ammonium-salts	18·1	34·9	9·8	24·0	54·0	51·9	101·0	77·0	2·129	1·600
3 A	Alkali Salts, do.	16·8	17·8	10·3	12·3	55·8	51·5	85·9	788	2·171	1·614
4 A	Complete Minerals, do.	30·8	41·4	16·0	26·8	56·3	54·1	102·2	77·7	2·081	1·440
1 N	Nitrate of Soda alone	14·5	14·8	9·5	12·3	55·1	50·3	81·3	63·5	2·243	1·741
2 N	Superphosphate, and Nitrate of Soda	31·3	40·9	17·1	30·5	55·8	53·1	99·8	74·1	1·984	1·476
3 N	Alkali Salts, do.	17·9	19·0	11·6	14·4	56·3	51·0	81·9	68·4	2·198	1·688
4 N	Complete Minerals, do.	29·6	45·0	15·8	33·4	55·1	54·2	100·4	69·2	2·132	1·561
1 C	Rape Cake alone	28·2	35·9	15·5	23·2	55·1	53·9	90·5	78·5	2·046	1·549
2 C	Superphosphate, and Rape Cake	30·8	36·8	16·0	26·6	55·4	53·4	100·8	70·5	1·963	1·543
3 C	Alkali Salts, do.	28·4	32·0	16·9	23·9	55·1	54·1	87·8	720	2·108	1·587
4 C	Complete Minerals, do.	31·6	37·4	17·6	28·1	56·5	54·2	95·2	68·3	2·025	1·601
7-1	Unmanured, after Dung	20·2	23·8	13·5	15·4	56·0	53·4	78·5	78·2	2·109	1·505
7-2	Farmyard Manure	43·4	44·6	24·8	41·3	57·3	52·4	95·7	577	2·229	2·000

The Table (XXXVI.) shows the fifty-three barley crops since 1852, 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.						
Grain.	Straw.	March.	April.	May.	June.	July.	Total. March, April, May.	Total. 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 latter 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, but that the decline must on the whole be set down to unfavourable seasons.

For selected plots on the rotation field, Table XXXVII. gives the production of grain and straw and certain particulars as to quality, taking an average of the last five courses only. 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, they take away a certain quantity of nitrogen, and therefore exhaust the soil

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

Manuring for Roots before Barley.	Treatment 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.						
			Bush.	Cwt.	Lb.		Grams.	Per cent.	s.	D.
1. Unmanured	Carted	Fallow	15·6	10·8	53·8	76·6	42·4	1·562	27	10
2. Minerals .	Carted	Fallow	13·6	9·3	54·0	77·3	39·7	1·484	28	7
3. Do. . .	Carted	Clover	19·9	12·8	54·4	80·0	43·0	1·559	29	0
4. Do. . .	Fed	Clover	28·9	17·5	55·3	85·9	44·3	1·576	29	11
5. Complete .	Fed	Clover	34·1	23·4	55·3	74·9	46·2	1·693	29	6

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 are 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.

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.		
	Sulphate of Potash.	Sulphate of Soda.	Sulphate of Magnesia.	Superphosphate of Lime.	Ammonium-salts.*	Nitrate of Soda.	Quantity.	Weight per Bushel.	Straw.
	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	28·5
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 Mangels, Barn Field, 1876-1904:
   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 Mangel Crop as affected by Manuring.
   General Conclusions.
II. Experiments upon Turnips, Barn Field, 1847-70.
   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

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 mangel 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 Mangels, Barn Field, 1876-1904.

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 8, 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 Mangel Wurzel, Barn Field, beginning 1876. Quantities of Manures per acre per annum.*

Strip.	Strip Manures: Farmyard Manure.	Strip Manures: Superphosphate.	Strip Manures: Sulphate of Potash.	Strip Manures: Sulphate of Magnesia.	Strip Manures: Chloride of Soda. (Salt.)	Strip Manures: Ammonium-salts.*	Nitrogenous Manures running across all the Strips: Series O. None.	N. Nitrate of Soda.	A. Ammonium-salts.*	AC. Rape Cake.	AC. Ammonium-salts.*	C. 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 twenty-seven years, 1876-1902; (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 mangels, 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 the plots receiving dung and those which are manured exclusively with "artificials."

TABLE XL.—*Barn Field Mangel Wurzel. Average Produce of Roots per acre over* 27 *years* (1876 *to* 1902).

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	17·44	24·74	21·73	24·05	23·96
2	Dung, Super., Potash* .	17·95	25·19	22·35	24·91	24·43
4	Complete Minerals .	5·36	18·01	14·86	25·49	21·33
5	Superphosphate only .	5·21	15·40	7·66	10·38	11·13
6	Super. and Potash .	4·55	15·38	14·03	22·48	18·63
7	Super., Potash, and 7·8 lb. N. as Amm.-salts .	5·93	15·63	14·60	22·30	19·19
8	None	3·91	10·24	5·89	9·84	10·00

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

TABLE XLI.—*Barn Field Mangel Wurzel. 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.	28·05	41·35	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	48·20	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.	10·30	28·70	28·70	38·95	29·20
		L.	1·35	4·85	5·10	7·20	4·20
8	None	R.	7·75	22·55	12·35	15·65	15·40
		L.	1·15	4·85	3·65	3·35	3·40

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

form of rape cake to 10·0 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 9·8 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 10·2 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 show 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, 5·4 tons per acre, which is increased to 14·9 tons per acre by the addition of 86 lb. nitrogen in ammonium-salts, or to 18·0 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 21·3 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 25·5 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 of crop is somewhat dependent on the source of nitrogen employed: thus 1 lb. of nitrogen as ammonium-salts gives an increase of 0·110 ton, as nitrate of soda the increase is 0·147 ton for each lb. of nitrogen, while with rape cake the increase

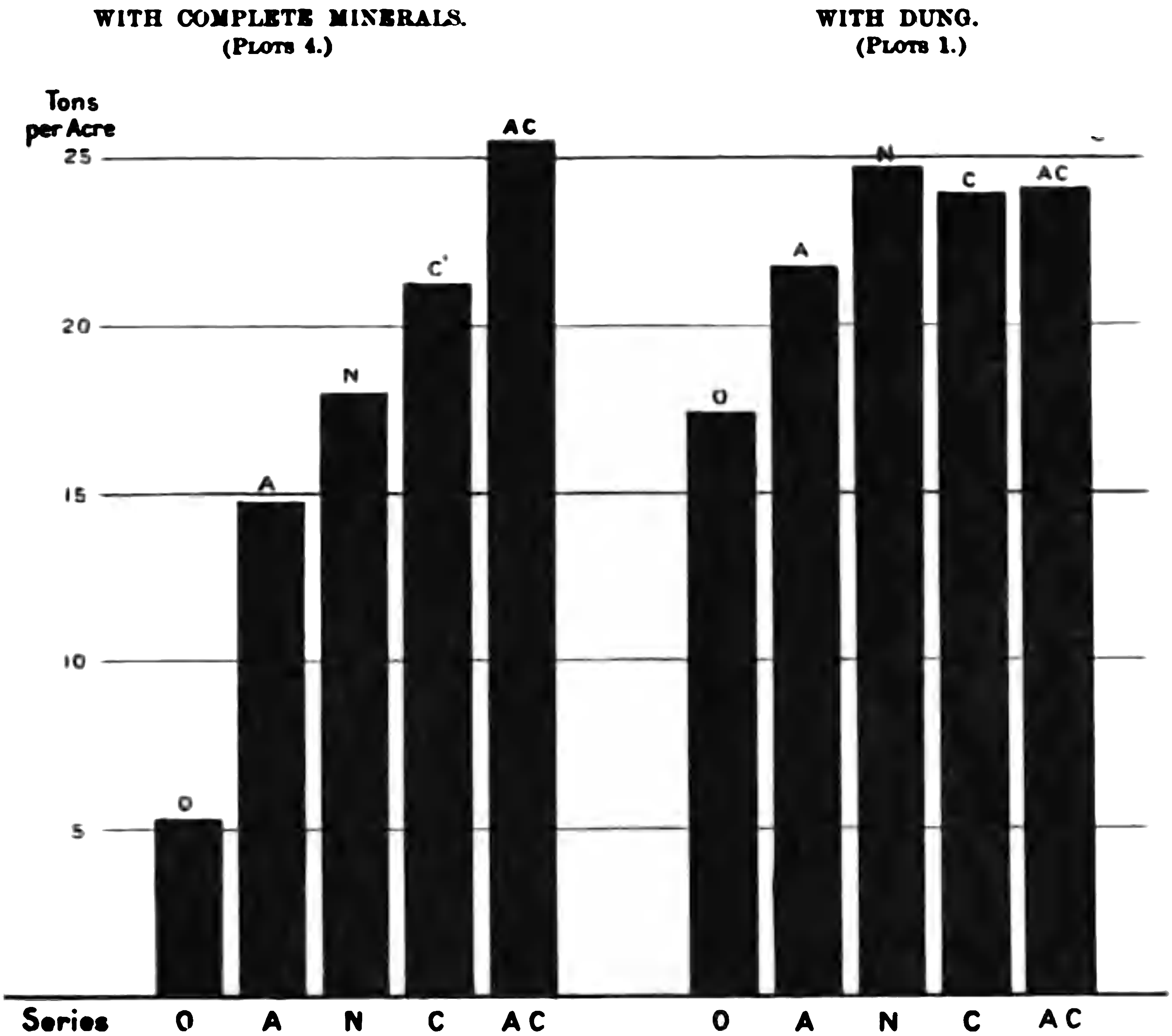

FIG. 14.—Mangel Wurzel. Effect of increasing amounts of Nitrogen. Average Produce of Roots per acre, 1876-1902.

O = No Nitrogenous Manure.
A = 86 lb. Nitrogen as Ammonium-salts.
N = 86 lb. Nitrogen as Nitrate of Soda.
C = 98 lb. Nitrogen as Rape Cake.
AC = 98 lb. Nitrogen as Rape Cake, and 86 lb. Nitrogen as Ammonium-salts.

is 0·163 ton for each lb. of nitrogen applied. Rape cake, in fact, is not strictly comparable with the other two sources of nitrogen, for not only does it contribute a considerable amount of organic matter to the soil, thus improving its texture and water-retaining power, but it is also a more slowly-acting manure. Some of its residues accumulate from season to season, and little by little become available for the later crops, while we have plenty of evidence that, on the Rothamsted soil, 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 mangel 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,

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 Plot 6, with potash in

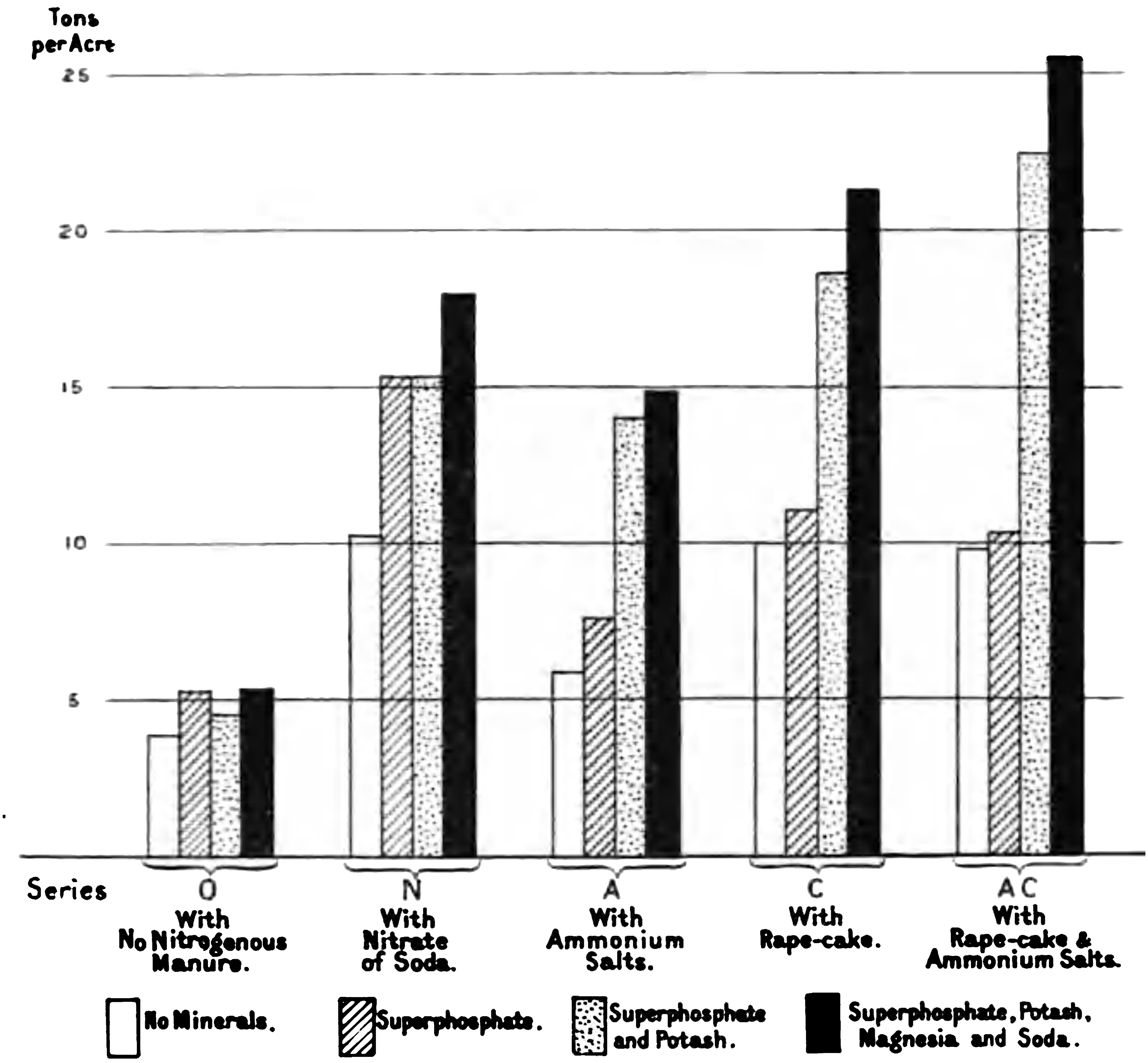

FIG. 15.—Mangel Wurzel. Effect of various Mineral Manures. Average Produce of Roots per acre, 1876-1902.

addition to the superphosphate; and the last column represents the crop of Plot 4, which receives superphosphate and all the alkalies—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 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 1·2 tons per acre, whereas the average increase it causes where nitrate of soda is used amounts to 5·2 tons per acre. This latter result demonstrates that phosphoric acid is necessary for the proper development of the mangel 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 7·7 to 14·0 tons per acre; with rape cake the rise is from 11·1 to 18·6 tons per acre; with rape cake and ammonium-salts the increase is from 10·4 to 22·5 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 mangel 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 mangel crop is very striking, and is to be correlated with the fact that the mangel 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 mangel 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

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 mangels 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 mangels 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 1-0 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 mangel, 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.

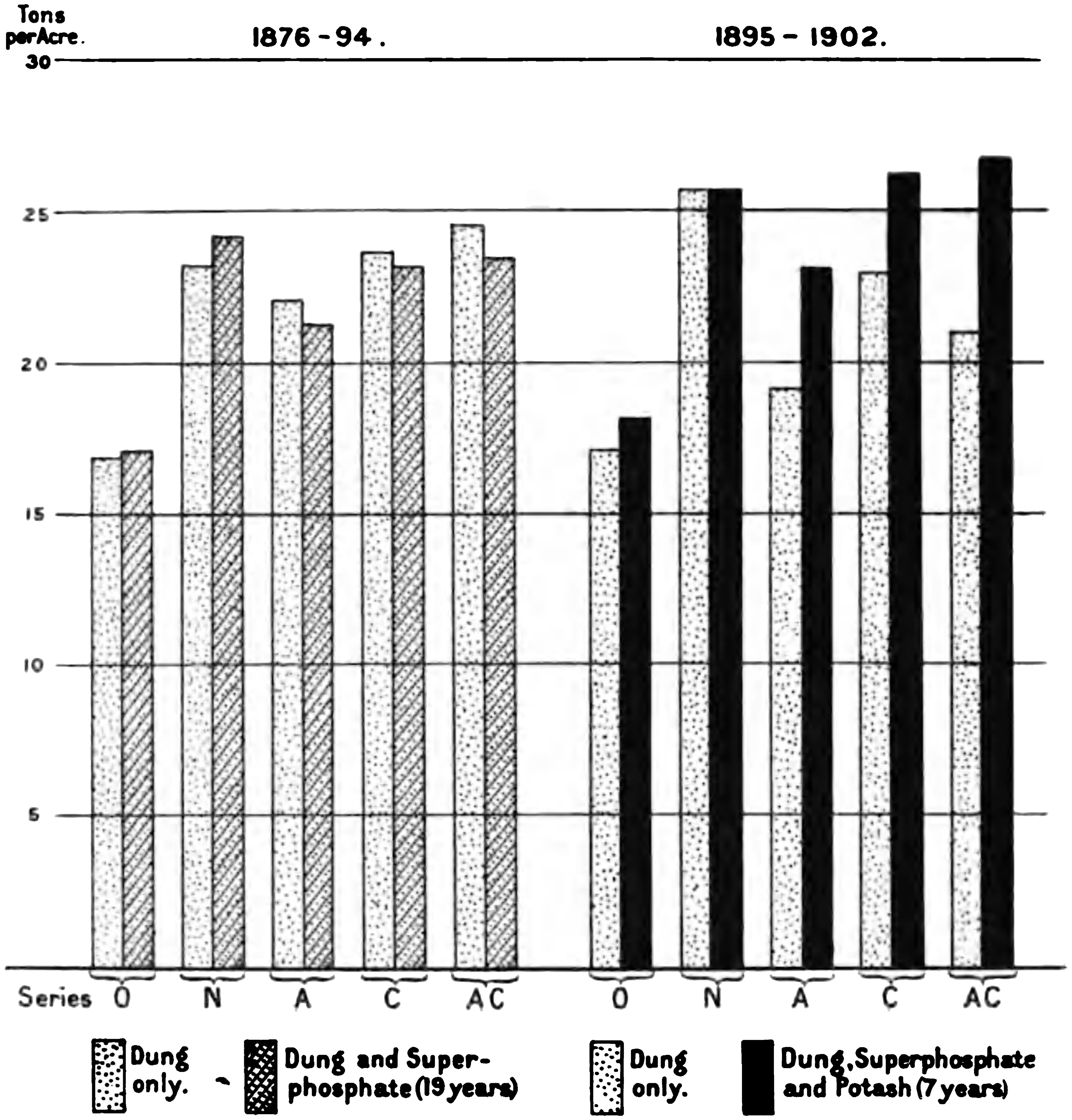

FIG. 16.—Mangel Wurzel. Effect of addition of Mineral Manure to Dung, with various Nitrogenous Cross-dressings. Average Produce of Roots per acre.

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

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 riper, 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 mangel 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.—*Mangel Wurzel. 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 following table 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

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 Mangel 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	13·03	0·29	8·32	63·9	3·5	7247	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	6099
	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	3828
	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	3268
	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	4522
	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	8·26	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 mangel is not visible in the dunged plots.

Although the analyses which have been made of the nitrogenous constituents of mangels 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 proteid 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 mangels 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.

on practically the same lines as have been maintained for the mangel 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

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

Strip.	Strip Manures.	Cross-Dressings. O. None.	N. Nitrate of Soda.*	A. Ammonium-salts.	AC. Amm.-salts and Rape Cake.	C. Rape Cake.
	Norfolk White Turnips, 4 seasons (1845-48).					
	Nitrogen per acre in Cross-Dressings . . .	Lb. ...	Lb. ...	Lb. 45	Lb. 135	Lb. 90
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
3	Gypsum, 1845; afterwards Unmanured (av. 1846-47-48)	24	...	27	110	131
4	Superphos. each year; Pot., Sod., and Mag., 1847-48	161	...	195	205	222
5	Superphosphate	176	...	198	201	218
6, 7	Superphos. each year; and Potash in 1847-48 . .	160	...	196	207	217
	Swedes, 4 seasons (1849-52).†					
	Nitrogen per acre in Cross-Dressings . . .	Lb. ...	Lb. ...	Lb. 43	Lb. 141	Lb. 98
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
3	No Standard Manure, 1846 and since . . .	46	...	77	140	154
4	Superphos., Sulphates Pot. and Mag., and Soda-ash	157	...	189	261	247
5	Superphosphate	149	...	174	224	210
6, 7	Superphosphate and Sulphate Potash . . .	136	...	174	248	234
	Swedes, 5 years (1856-60).‡					
	Nitrogen per acre in Cross-Dressings . . .	Lb. ...	Lb. 43	Lb. 43	Lb. 51	Lb. 98
		Cwt.	Cwt.	Cwt	Cwt.	Cwt.
1	14 tons Farmyard Dung	145	156	190	181	127
2	Do. and Superphosphate . .	155	152	191	171	119
3	No Standard Manure, 1846 and since . . .	17	24	21	30	24
4	Complete Mineral Manure	106	124	130	134	95
5	Superphosphate	96	123	108	119	86
6	Superphosphate and Sulphate Potash . . .	82	103	129	128	91
7	Superphos., Sulph. Pot., and 36½ lb. Amm.-salts .	100	116	143	152	111
8	No Standard Manure, 1853 and since . . .	39	48	34	46	59
	Swedes, 10 years (1861-70).					
	Nitrogen per acre in Cross-Dressings . . .	Lb. ...	Lb. 86	Lb. 86	Lb. 184	Lb. 98
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
1	14 tons Farmyard Dung	143	177	194	210	202
2	Do. and Superphosphate . .	143	183	190	210	198
3	No Standard Manure, 1846 and since . . .	11	21	13	89	95
4	Superphos. only; previously Complete Minerals .	52	115	100	158	134
5	Superphosphate	49	103	81	138	124
6	Do. ; previously Sulph. Potash also .	45	105	88	150	126
7	Do.; previously Sulph. Pot., and 36½ lb. Amm.-salts also	49	104	95	156	130
8	No Standard Manure, 1853 and since . . .	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 1851 or 1852.
‡ Average produce of 3 years only (1856-58), 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

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 ¾ 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

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.	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, 2000 lb. = 98 lb. N.
			Standard Manures and Cross-Dressings each year as under.			
	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 1-0, 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 versâ*.

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 mangel field which had previously been receiving dung. It was subsoiled and well

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 mangels.

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 mangels.

References

"Agricultural Chemistry, Turnip Culture." *Jour. Roy. Ag. Soc.*, **8** (1847), 494. *Rothamsted Memoirs*, Vol. I., No. 2.

"Results of Experiments at Rothamsted on the Growth of Root-crops for many years in succession on the same land." *Agricultural Students' Gazette*, New Series, Vol. III., Part V., 1887. *Rothamsted Memoirs*, Vol. VI., No. 12.

"Results of Experiments at Rothamsted on the Growth of Potatoes for twelve years in succession on the same land." *Agricultural Students' Gazette*, New Series, Vol. IV., Part II., 1888. *Rothamsted Memoirs*, Vol. VI., No. 13.

"The Rothamsted Experiments: being an account of some of the Results of the Agricultural Investigations conducted at Rothamsted, *Trans. Highland and Agricultural Society of Scotland*, Fifth Series, **7** (1895), 19-67.

"The Growth of Sugar-Beet, and the Manufacture of Sugar in the United Kingdom." *Jour. Roy. Ag. Soc.*, **59** (1898), 344-370. *Rothamsted Memoirs*, Vol. VII., No. 11.

"Experiments at Rothamsted on the Changes in the Composition of Mangels during Storage," by N. H. J. Miller. *Jour. Roy. Ag. Soc.*, **61** (1900), 57; and **63** (1902), 135.

"The Continuous Growth of Mangels for twenty-seven years on the same land, Barn Field, Rothamsted," by A. D. Hall. *Jour. Roy. Ag. Soc.*, **63** (1902), 27-59.

CHAPTER VIII

EXPERIMENTS UPON THE CONTINUOUS GROWTH OF LEGUMINOUS CROPS

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 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.

TABLE XLVIII.—*Continued.*

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.*
Average per acre per annum, over each period of 8 years, and the total period of 32 years.									
	Lb.	Lb.	Lb.	Lb	Lb.	Lb.	Lb.	Lb.	Lb.
8 years (1847-1854) .	1205	1573†	1763	1216	1635†	1792	2421	3208†	3555
8 years (1855-1862) .	676	960	1013	988	1506	1616	1664	2466	2629
8 years (1863-1870) .	150	580	881	456	1042	1317	606	1622	2198
8 years (1871-1878) .	409	713	749	455	793	897	864	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	1158	1129	1721	1847	1902	2818	3005
3rd 8 years, 7 crops	171	663	1007	521	1191	1506	692	1854	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

* 5 years (1847-1851), 46 lb. Nitrogen as Ammonium-salts; 11 years (1862, 1864-1870, 1875, 1876, and 1878) 86 lb. Nitrogen as Sodium Nitrate.

† 7 years, excluding 1849.

‡ 31 years, excluding 1849.

§ 7 crops, excluding 1849.

‖ 25 crops, excluding 1849.

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, 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 have 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* constitutes a considerable proportion of the herbage. The conclusion seems inevitable that the preliminary long-continued growth of leguminous plants (beans and clover) has in some way unfitted the soil for

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.	
Gramineous Herbage.			
Number of Species.	11	10	
Botanical Names:—	Per cent.	Per cent.	*Ordinary English Names:—*
1. *Phleum pratense* . .	4·89	0·08	1. Meadow Cat's Tail.
2. *Agrostis alba* . . .	11·02	0·20	2. Marsh Bent Grass.
3. *Aira cæspitosa* . .	...	86·19	3. Tufted Hair-grass.
4. *Avena elatior* . .	3·50	2·34	4. False Oat.
5. *Dactylis glomerata* . .	35·12	4·53	5. Cock's Foot.
6. *Lolium perenne* . .	3·22	0·05	6. Perennial Rye.
Other Species amounting to	1·89	1·87	
Total . .	59·64	95·26	
Leguminous Herbage.			
Number of Species.	5	2	
1. *Trifolium repens* . .	3·08	0·05	1. White or Dutch Clover.
2. *Trifolium pratense* . .	0·55	...	2. Common Red Clover.
3. *Lathyrus pratensis* . .	18·36	...	3. Meadow Vetchling.
4. *Vicia sepium* . . .	0·40	0·38	4. Bush Vetch.
5. *Medicago lupulina* . .	2·92	...	5. Black Medick or Nonsuch.
Total . .	25·31	0·43	
Miscellaneous Herbage.			
Number of Species.	24	14	
1. *Heracleum sphondylium* .	4·28	1·71	1. Cow Parsnip or Hogweed.
2. *Scabiosa arvensis* . .	2·87	...	2. Field Scabious.
3. *Centaurea nigra* . .	1·05	...	3. Black Knapweed.
4. *Carduus arvensis* . .	0·81	0·30	4. Creeping Plume Thistle.
5. *Plantago lanceolata* .	2·46	0·26	5. Ribwort Plantain.
6. *Rumex obtusifolius* . .	...	0·94	6. Broad-leaved Sorrel Dock.
Other Species amounting to	3·58	1·10	
Total . .	15·05	4·31	
Summary.			
Total Number of Species.	40	26	
Total Gramineæ . .	59·64	95·26	
,, Leguminosæ . .	25·31	0·43	
,, Miscellaneæ . .	15·05	4·31	
Total . .	100·00	100·00	

score, it is still difficult to account for the magnitude of the accumulation, especially for Geescroft, where, as the botanical analysis shows, there are 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 *Aira cæspitosa* 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, 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

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. Mineral Manure alone.	2. Mineral and Nitrogenous Manures.
		Lb.	Lb.
1849	Clover	10,214	10,326
1850	Wheat	(6,261)	(6,345)
1851	Clover	2,309	2,368
1852	Clover	5,895	4,914
1853	Clover	No crop	No crop
1854	Fallow	...	...
1855	Clover	1,281	2,606
1856	Fallow	...	...
1857	Fallow	...	...
1858	Barley	(6,598)	(7,578)
1859	Clover	2,752	3,087
1860	Clover	No crop	No crop
1861	Fallow	...	...
1862	Barley	(5,745)	(6,730)
1863	Fallow	...	...
1864	Clover	No crop	No crop
1865	Clover	2,467	4,500
1866	S. 1 Clover, S. 2 Barley .	No crop	(2,974)
1867	Fallow	...	...
1868	Clover	No crop	No crop
1869	Clover	No crop	No crop
1870	Barley	(3,328)	(3,312)
1871	Clover	No crop	4,085
1872	Fallow	...	...
1873	Fallow	...	...
1874	Clover	No crop	Fallow
1875	Clover	4,277	Fallow
1876	Fallow	...	...
1877	Barley	(1,864)	(1,864)
SUMMARY. Produce.			
29 years (1849-1877)	Total . . .	52,991	60,689
	Average . .	1,827	2,093
Years of Crop only	Average . .	4,416	4,668
Years of Clover only (7)	Total . . .	29,195	31,886
	Average . .	4,171	4,555
SUMMARY. Nitrogen (Estimated).			
29 years (1849-1877)	Total . . .	929·4	1043·1
	Average . .	32·0	36·0
Years of Crop only	Average . .	77·5	80·2
Years of Clover only (7)	Total . . .	700·7	765·3
	Average . .	100·1	109·3

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	3187	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—1903 being the fiftieth 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 fifty 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 the two periods of twenty-five years each, and over the total period of fifty years, 1854-1903. 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 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,* 1854-1903.

Year.	Number of Cuttings.	As Hay.	Dry Matter.	Nitrogen.*	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		...
1864	2	5,500	4,583	1,123 (1861–1866)	...
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 (1867–1872)	...
1871	1	4,513	3,761		1871, April.
1872	2	10,142	8,452		...
1873	2	9,287	7,740		...
1874	3	5,899	4,916		1874, May and July.
1875	1	2,731	2,276	607 (1873–1877)	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 (1878–1882)	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 (1883–1887)	...
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.
SUMMARY. Averages.					
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	

* 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.

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.

References

"Report of Experiments on the Growth of Red Clover by different Manures." *Jour. Roy. Ag. Soc.*, **21** (1860), 178. *Rothamsted Memoirs*, Vol. I., No. 13.

"Notes on Clover Sickness." *Jour. Roy. Hort. Soc.*, **3** (1871), 86. *Rothamsted Memoirs*, Vol. III., No 12.

"Results of Experiments at Rothamsted on the Growth of Leguminous Crops for many years in succession on the same land." *Agricultural Students' Gazette*, New Series, **4** (1889), 137, and **4** (1890), 179. *Rothamsted Memoirs*, Vol. VI., No 15

"The Rothamsted Experiments: being an account of some of the Results of the Agricultural Investigations conducted at Rothamsted." *Trans. Highland and Agricultural Society of Scotland*, Fifth Series, **7** (1895), 100-136.

"The Accumulation of Fertility by Land allowed to Run Wild." A. D. Hall. *Jour. Agric. Science*, I. (1905), 241.

CHAPTER IX

EXPERIMENTS UPON GRASS LAND MOWN FOR HAY EVERY YEAR

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

TABLE LVII.—*Produce of Hay per acre. Average over the period of* 47 *years* (1856-1902), *the* 10 *years* (1893-1902), *and the individual year* 1902. *Rothamsted. Total of first, and second crops* (*if any*).

Plot.	Abbreviated Description of Manures.	Averages over 47 years (1856-1902).	Averages over 10 years (1893-1902).	Season 1902.
		Cwt.	Cwt.	Cwt.
3	Unmanured every year	21·9	15·9	11·4
12	Unmanured every year	24·5	18·5	13·8
2	Unmanured; following Farmyard Dung for first 8 years	27·9*	17·4	12·4
1	Ammonium-salts alone (=43 lb. N.); with Farmyard Dung for first 8 years	35·4†	24·9	21·8
4-1	Superphosphate of Lime	23·3§	17·8	19·0
8	Mineral Manure without Potash	28·1	21·6	25·8
7	Complete Mineral Manure	38·8	36·5	53·6
6	Complete Mineral Manure as Plot 7; following Ammonium-salts alone first 13 years	37·4‡	36·0	52·5
15	Complete Mineral Manure as Plot 7; following Nitrate of Soda alone first 18 years	37·0‖	40·8	54·0
5	Ammonium-salts alone=86 lb. Nitrogen	(26·1)**	...	...
17	Nitrate of Soda alone=43 lb. Nitrogen	35·3¶	30·6	26·4
4-2	Superphosphate and Ammonium-salts=86 lb. N.	35·5§	28·3	27·1
10	Mineral Manure (without Potash), and Ammonium-salts=86 lb. N.	49·3	38·1	40·4
9	Complete Mineral Manure and Ammonium-salts =86 lb. N.	54·1	46·8	55·5
13	As Plot 9, and Chaffed Wheat Straw also to 1897 inclusive	61·3	50·8	54·3
11-1	Complete Mineral Manure, and Ammonium-salts =129 lb. N.	65·5	64·6	86·3
11-2	As Plot 11-1, and Silicate of Soda	72·0	68·0	84·8
16	Complete Mineral Manure and Nitrate Soda =43 lb. N.	48·0¶	42·4	46·8
14	Complete Mineral Manure and Nitrate Soda =86 lb. N.	59·3¶	53·4	60·8

* After the change. Before the change 42·9 cwt.
† " " 49·5 cwt.
‡ " " 30·6 cwt.
‖ " " 35·4 cwt.

§ 44 years only (1859-1902).
¶ 45 years only (1858-1902).
** 42 years (1856-1897).

Table LVIII. shows the first crops only for four successive ten-year periods, and one eight-year period, 1856-1903.

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 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

TABLE LVIII.—*Average produce of Hay per acre over the four successive 10-year periods, and the subsequent* 8 *years, from* 1856 - 1903. *Rothamsted. First crops only.*

Plot.	Abbreviated Description of Manuring.	Averages over				
		10 years (18[illegible]5).	10 years (1866-1875).	10 years ([illegible]).	10 years (1886-1895).	8 years (1896-1903).
		Cwt.	Cwt.	Cwt.	Cwt.	Cwt.
3	Unmanured every year	[illegible]·6	2[illegible]	17·[illegible]	16·8	11·7
12	Unmanured every year	[illegible]·1	22·0	18·6	17·1	14·2
1	Ammonium-salts alone; with Dung also first 8 years	48·4	37·8	30·1	23·8	19·2
4-1	Superphosphate of Lime alone	24·4†	21·3	19·1	16·5	15·2
8	Mineral Manure without Potash *	33·6	26·6	21·8	16·5	18·6
7	Complete Mineral Manure	33·9	36·8	32·3	27·1	31·9
17	Nitrate of Soda alone = 43 lb. N.	34·3‡	33·5	30·1	27·0	26·8
4-2	Superphosphate and Ammonium-salts = 86 lb. N.	39·6†	30·5	30·4	29·0	25·0
10	Mineral Manure (without Potash),* and Ammonium-salts = 86 lb. N.	52·8	39·6	38·6	35·5	34·0
9	Complete Mineral Manure and Ammonium-salts = 86 lb. N.	53·6	48·4	50·5	39·3	42·6
11-1	Complete Mineral Manure and Ammonium-salts = 129 lb. N.	61·7	53·6	48·5	47·6	58·6
16	Complete Mineral Manure and Nitrate Soda = 43 lb. N.	48·1‡	47·6	41·5	37·4	38·6
14	Complete Mineral Manure and Nitrate Soda = 86 lb. N.	53·1‡	60·5	53·8	45·6	48·5

* Including Potash, first 6 years. † Seven years only (1859-65). ‡ Eight years only (1858-65).

represented; the dominant species are those most suited to their environment, *i.e.*, to the amount and nature of the plant 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 forty-seven years, and for the single year 1902. Summaries of the five complete separations made in 1862, 1867, 1872, 1877, and 1903 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 Quaking Grass, so generally taken as a sign of poor land, which constituted 20 per cent. of the whole herbage in 1903, and Sheep's Fescue;

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 forty 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).	Average of 10 years (1876-1885).	Average of 10 years (1886-1895).	Average of 5 years (1896-1900).	Season 1901.
		Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb
2	Farmyard Manure, 8 yrs. (1856-63); Unmanured since	4804	5392	2848	3726	3748	2791	1747	581
3	Unmanured continuously	2665	2688	1296	2374	3025	2621	1568	516
	Relation to Produce of Plot 3 reckoned as 100.								
2	Farmyard Manure, 8 yrs. (1856-63); Unmanured since	180	201	220	157	124	106	111	113
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, for three ten-year and one five-year periods afterwards, and for the season 1901. 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 the same proportion of

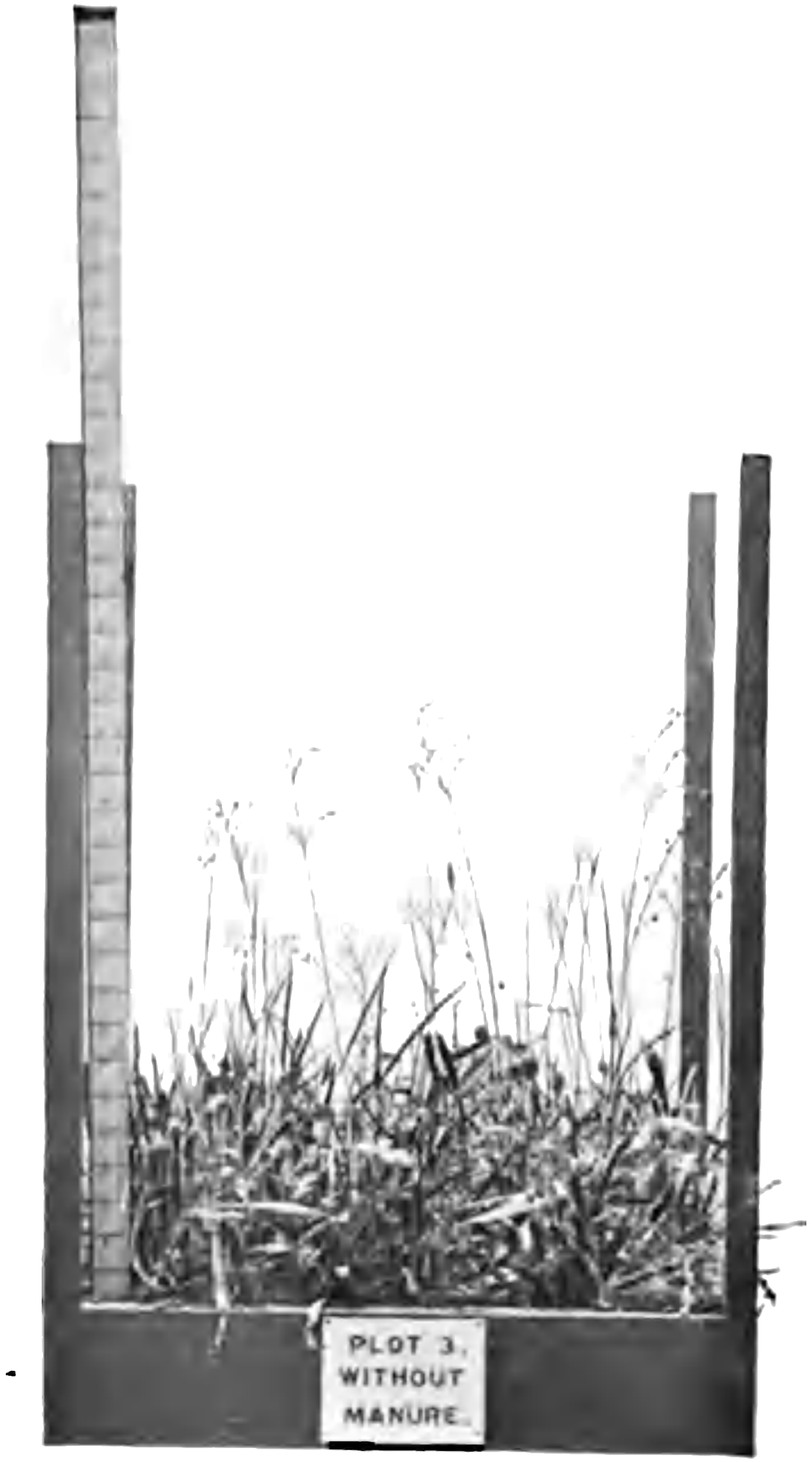

FIG. 17.

FIG. 18.

[Face page 156.

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 83 per cent. of the whole, the nitrate of soda plot possesses a much more varied herbage, of which weeds form 40 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 application, but without potash, since 1861, while Plot 4-1

Fig. 19.

Fig. 20.

[Face page 158.

which has an opportunity to develop because it is not crushed out by the competition of taller-growing herbage, such as is found with the bigger crop on Plot 7. The characteristic weeds of this plot are the Buttercup, 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 the most abundant grass is Quaking Grass, and where weeds, chiefly Hawkbit, Burnet, and Plantain, 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

FIG 22.

FIG. 23.

[Face page 160.

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, Smooth-stalked Meadow Grass, Sweet Vernal, and Sheep's Fescue; Meadow Foxtail, Cocksfoot, Yorkshire Fog, and Bent 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; 97 per cent. of the herbage is made up of three species alone—False Oat Grass, Meadow Foxtail, and Yorkshire Fog, the latter representing 45 per cent. of the whole herbage. In the earlier years of the experiment this latter grass 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 72 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. 24.

FIG. 25.

[Face page 162.

Plot 16, which receives the smaller quantity of nitrate of soda, still grows a very large crop, averaging 48 cwt. over the whole period. The vegetation resembles that of Plot 14, but is even 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 35 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 Smooth-stalked Meadow Grass, as much as 85 per cent. of the whole herbage.

The characteristic appearance of the herbage is well seen in

FIG. 26.

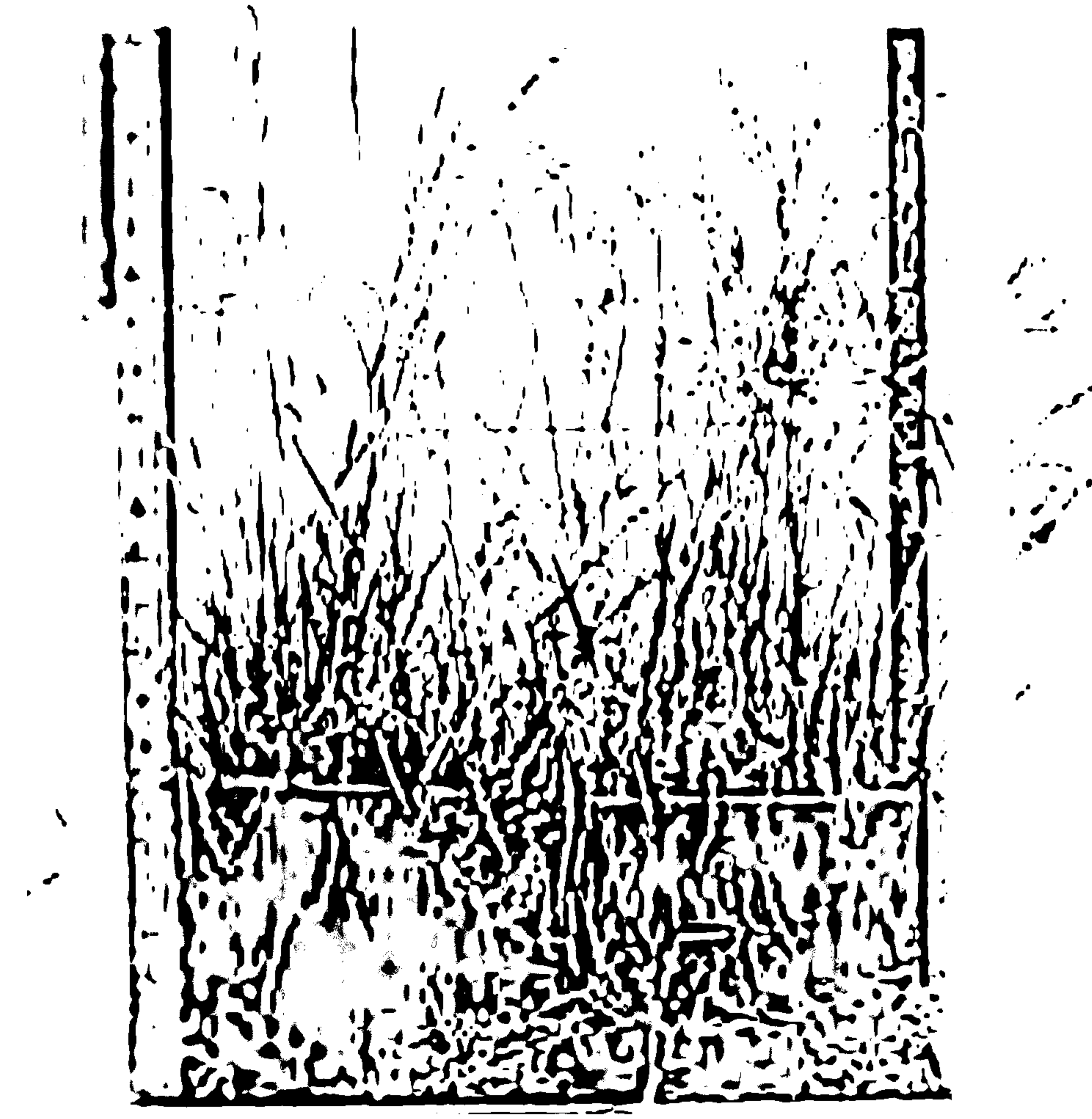

FIG. 27.

[Face page 164.

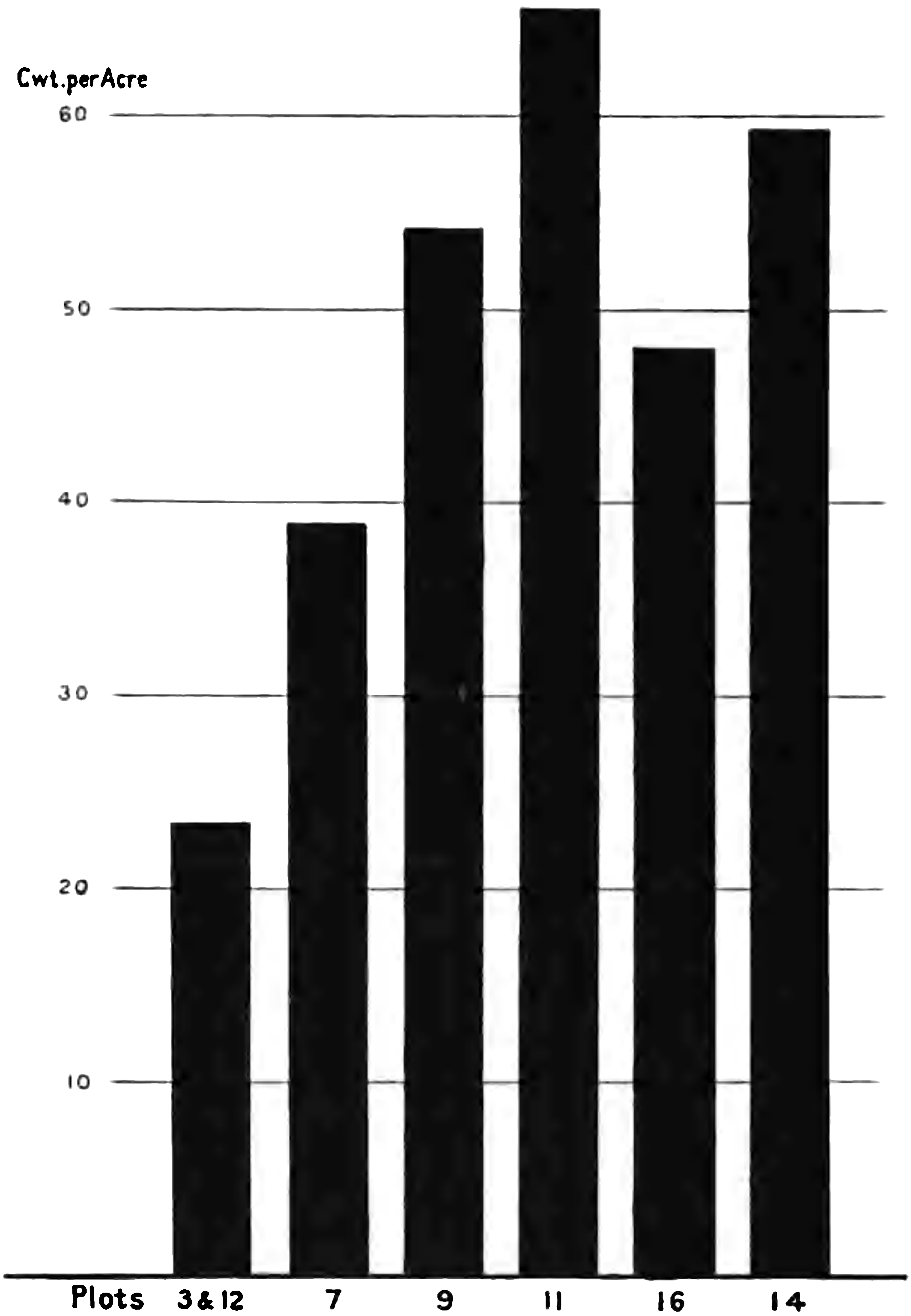

FIG. 28.—Effect of Nitrogenous Manures on the produce of Hay per acre. Average over 47 years (1856-1902).

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 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.

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.	
		Unlimed.	Limed.	Unlimed.	Limed.	Unlimed.	Limed.	Unlimed.	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).

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

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. 80.

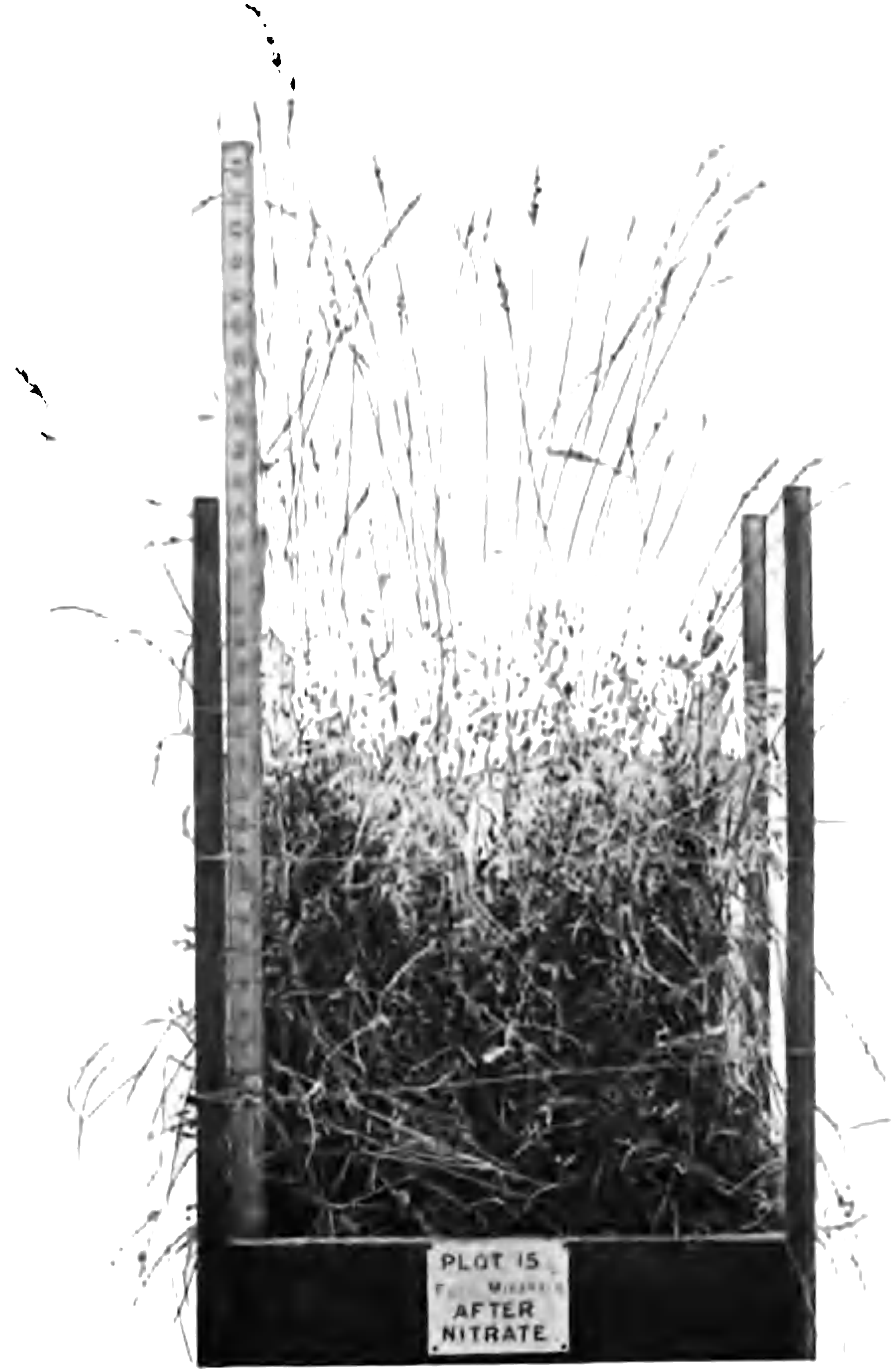

FIG. 81.

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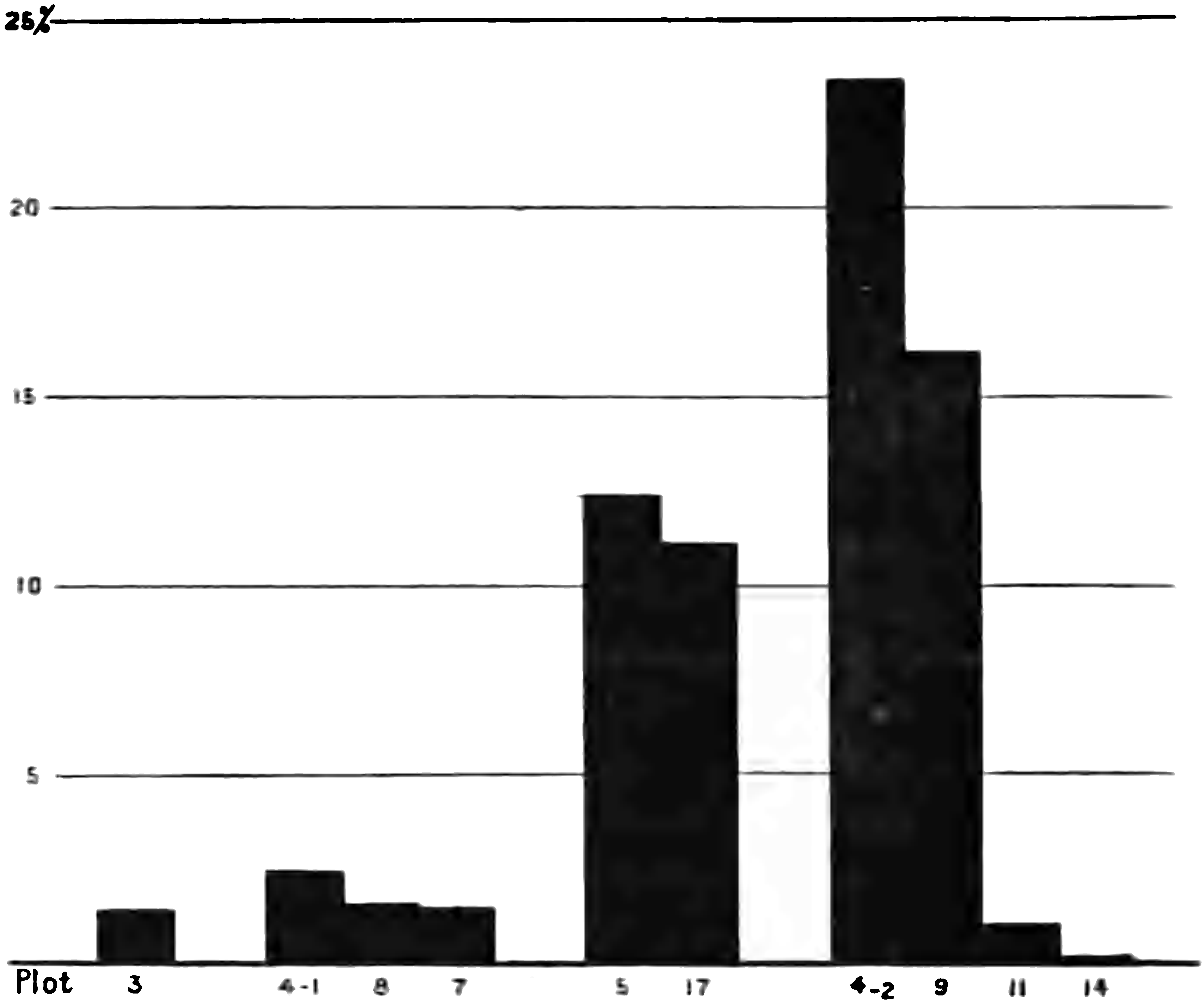

FIG. 32.—Percentage of *Anthoxanthum odoratum* in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts.
	8. No Nitrate.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. } Amm.-salts.
			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). Five separations,* 1862, '67, '72, '77, *and* 1903.

(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
						Anthoxanthum odoratum (Sweet-scented Vernal Grass).						
1862	4·28	3·66	3·72	3·06	3·92	1·82	**5·77**	2·06	2·24	1·24	0·09	0·35
1867	**8·66**	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	**7·94**	2·72	6·22	4·49	3·04	4·50	1·47	2·25	0·78	0·02
1877	5·12	5·11	**7·55**	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	**23·44**	16·19	0·98	0·13
						Alopecurus pratensis (Meadow Foxtail).						
1862	4·49	1·32	0·39	0·34	1·70	6·90	0·65	**23·94**	0·66	0·27	2·80	0·22
1867	5·82	1·84	0·88	0·88	0·02	5·95	0·47	**21·71**	14·75	0·07	13·11	3·54
1872	0·52	0·86	0·52	1·17	0·03	2·46	0·83	**16·25**	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	**20·18**
1903	0·59	0·31	0·55	4·51	0·59	10·24	0·27	9·74	4·56	4·08	28·51	**28·72**
						Agrostis vulgaris (Common Bent).						
1862	11·36	7·21	10·01	7·14	21·43	7·65	**24·30**	11·01	19·38	12·81	13·17	0·42
1867	8·63	6·08	4·32	5·69	14·41	6·86	**20·97**	7·05	14·00	13·43	19·27	0·61
1872	16·14	13·88	9·32	11·72	23·27	7·66	**26·62**	10·60	20·59	15·46	13·56	0·24
1877	13·28	9·87	12·40	12·02	8·58	12·90	**29·46**	17·92	24·39	12·23	29·20	1·55
1903	0·19	0·03	0·72	3·34	2·51	2·99	**11·65**	1·76	2·04	3·81	1·42	0·14
						Holcus lanatus (Woolly Soft Grass, or Yorkshire Fog).						
1862	5·04	11·82	4·51	5·06	8·17	7·61	10·08	8·23	**16·21**	12·14	9·92	6·60
1867	7·97	9·16	10·25	**11·81**	3·07	**11·81**	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	**10·38**	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	2·87	2·35	0·03	4·84	1·05	3·94	**45·57**	0·02
						Arrhenatherum avenaceum (False Oat Grass).						
1862	0·07	0·13	**4·52**	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	**6·50**	...	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	**11·40**	10·41	...
1877	0·05	0·05	3·17	1·29	2·77	...	0·23	0·01	1·02	13·23	**14·86**	0·32
1903	0·10	0·03	4·20	1·16	1·94	0·16	0·19	...	0·95	**48·30**	23·00	17·28
						Avena pubescens (Downy Oat Grass).						
1862	9·65	9·42	12·68	13·81	**14·54**	3·53	7·31	4·24	7·38	10·22	1·66	0·90
1867	3·07	**4·97**	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	1·83	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	**9·77**	8·04	4·28	7·50	4·18	0·01	8·69	...	0·06	...	2·32

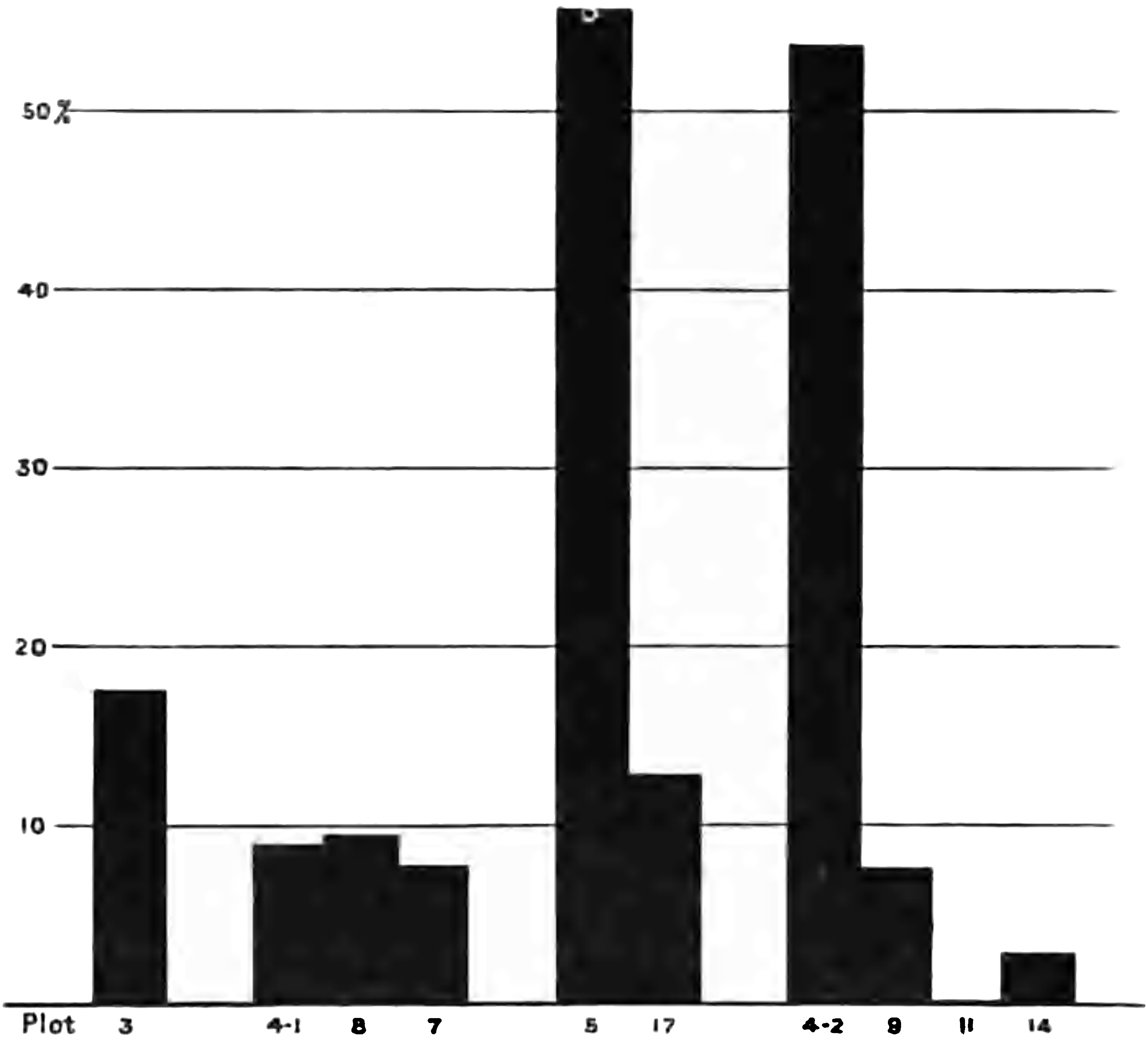

FIG. 33.—Percentage of *Festuca ovina* in the Herbage of the Grass Plots.
First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate. 8. No Potash. 7. Complete.	5. Amm.-salts. 17. Nitrate Soda.	4-2. No Potash } Amm.-salts. 9. Complete } Amm.-salts. 11. Excess N. } Amm.-salts. 14. Complete; Nit. Soda.

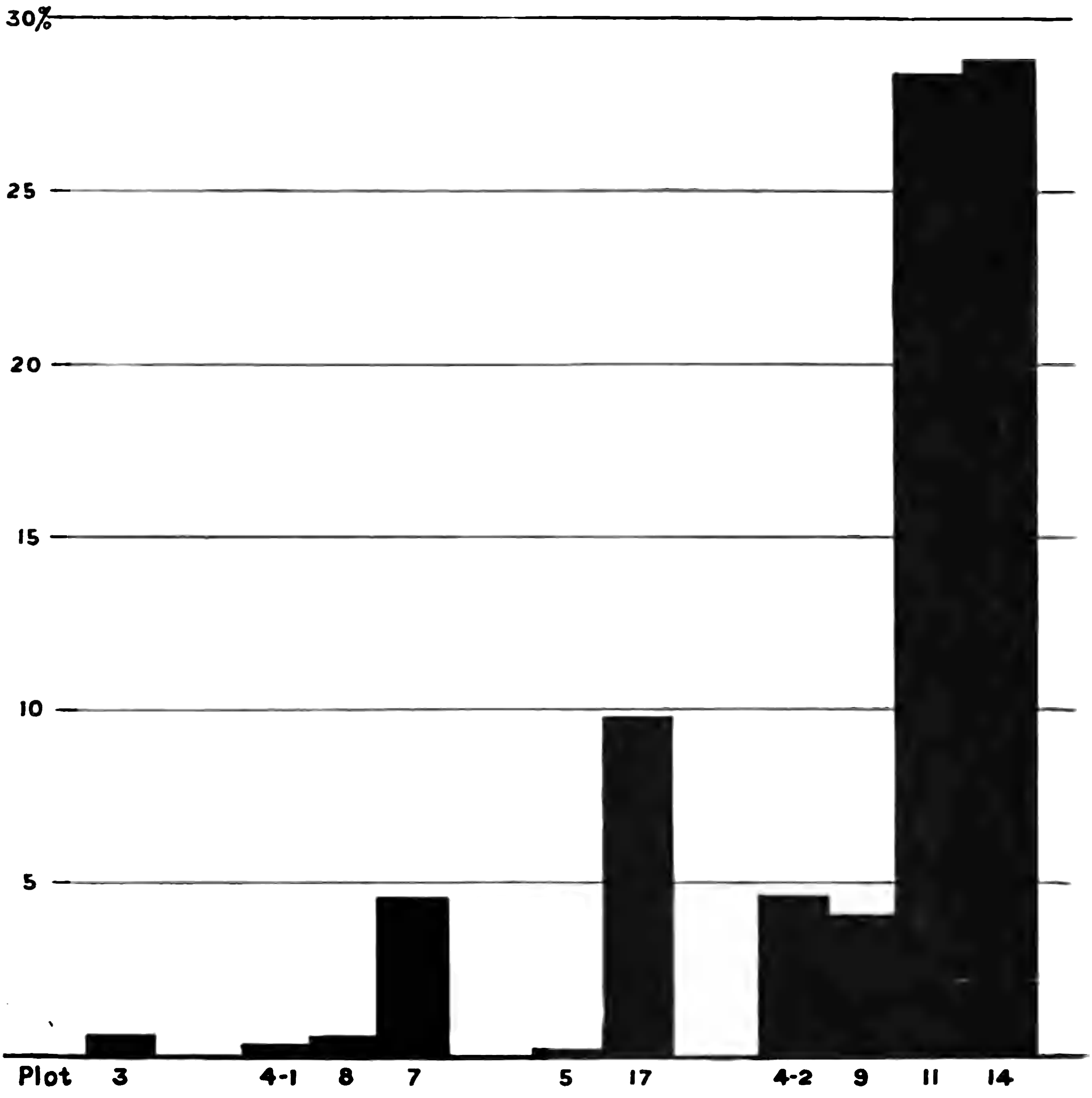

FIG. 34.—Percentage of *Alopecurus pratensis* in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
3.	4-1. Superphosphate. 8. No Potash. 7. Complete.	5. Amm.-salts. 17. Nitrate Soda.	4-2. No Potash } 9. Complete } Amm.-salts. 11. Excess N. } 14. Complete; Nit. Soda.

TABLE LXII.—*Continued.*

Years.	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
GRAMINEÆ—*Continued.*												
***Bromus mollis* (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
***Lolium perenne* (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	18·80
1867	4·03	5·24	2·61	2·40	1·39	3·24	1·21	3·23	1·36	1·01	0·08	9·38
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	7·68	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
Total of other Species under 5 per cent. (*Phleum pratense*, *Aira cæspitosa*, *Cynosurus cristatus*, *Festuca pratensis*, *elatior*, and *loliaceæ*).												
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	0·34	0·67	0·86	0·04	0·48	0·15	0·50	0·01	0·07	...	0·20
1872	1·13	1·11	1·38	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	...	...	...	...
LEGUMINOSÆ.												
***Trifolium repens* (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	...	0·13	0·01	...	...	0·01
***Trifolium pratense* (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	...	...	...	...
***Lotus corniculatus* (Bird's Foot Trefoil).**												
1862	1·88	0·41	0·15	1·27	0·01	0·02	0·05	0·05	...	...	...	...
1867	2·35	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	...	...	...	...

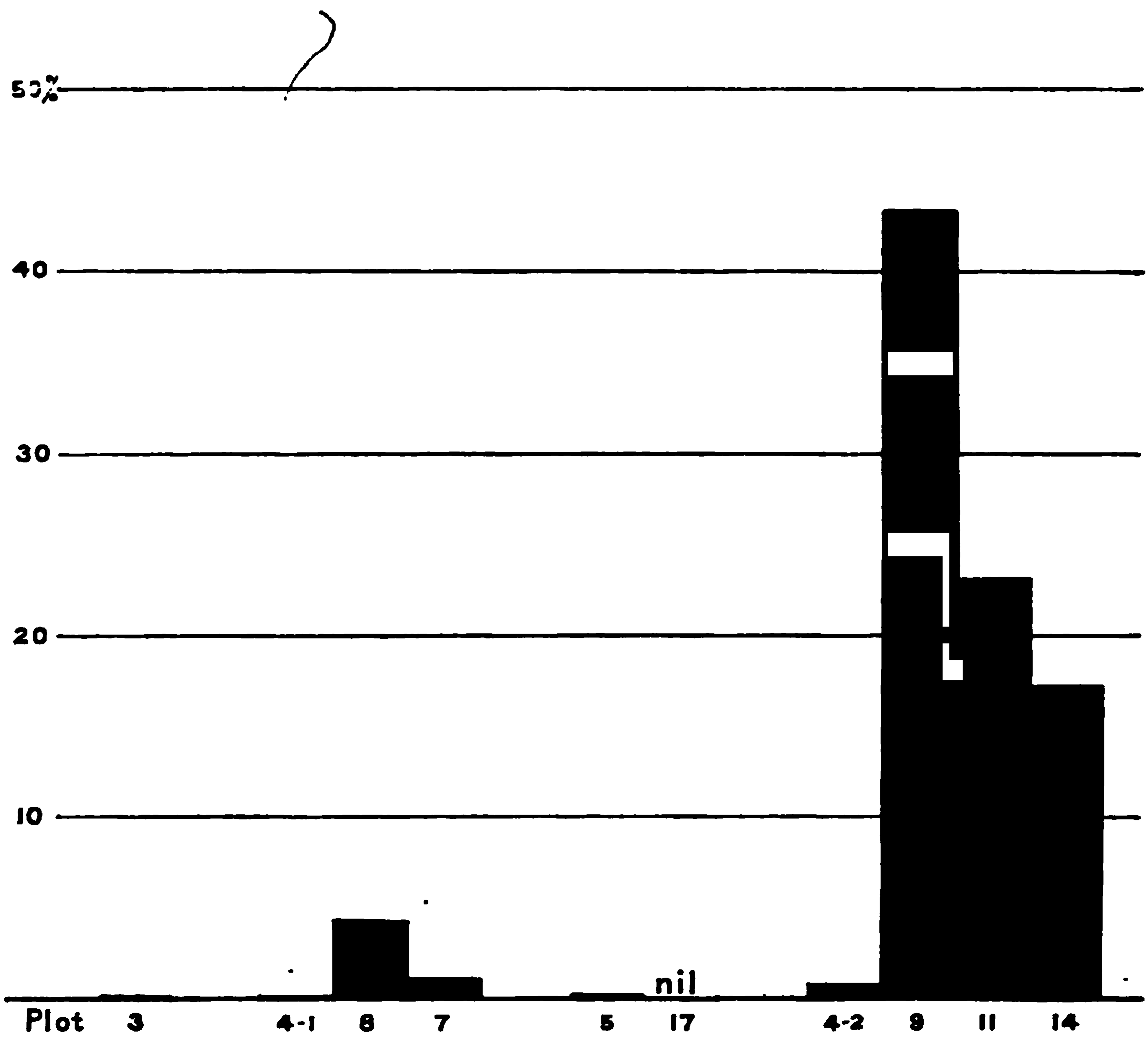

FIG. 35.—Percentage of *Arrhenatherum avenaceum* in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts.
	8. No Potash.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. } Amm.-salts.
			14. Complete; Nit. Soda.

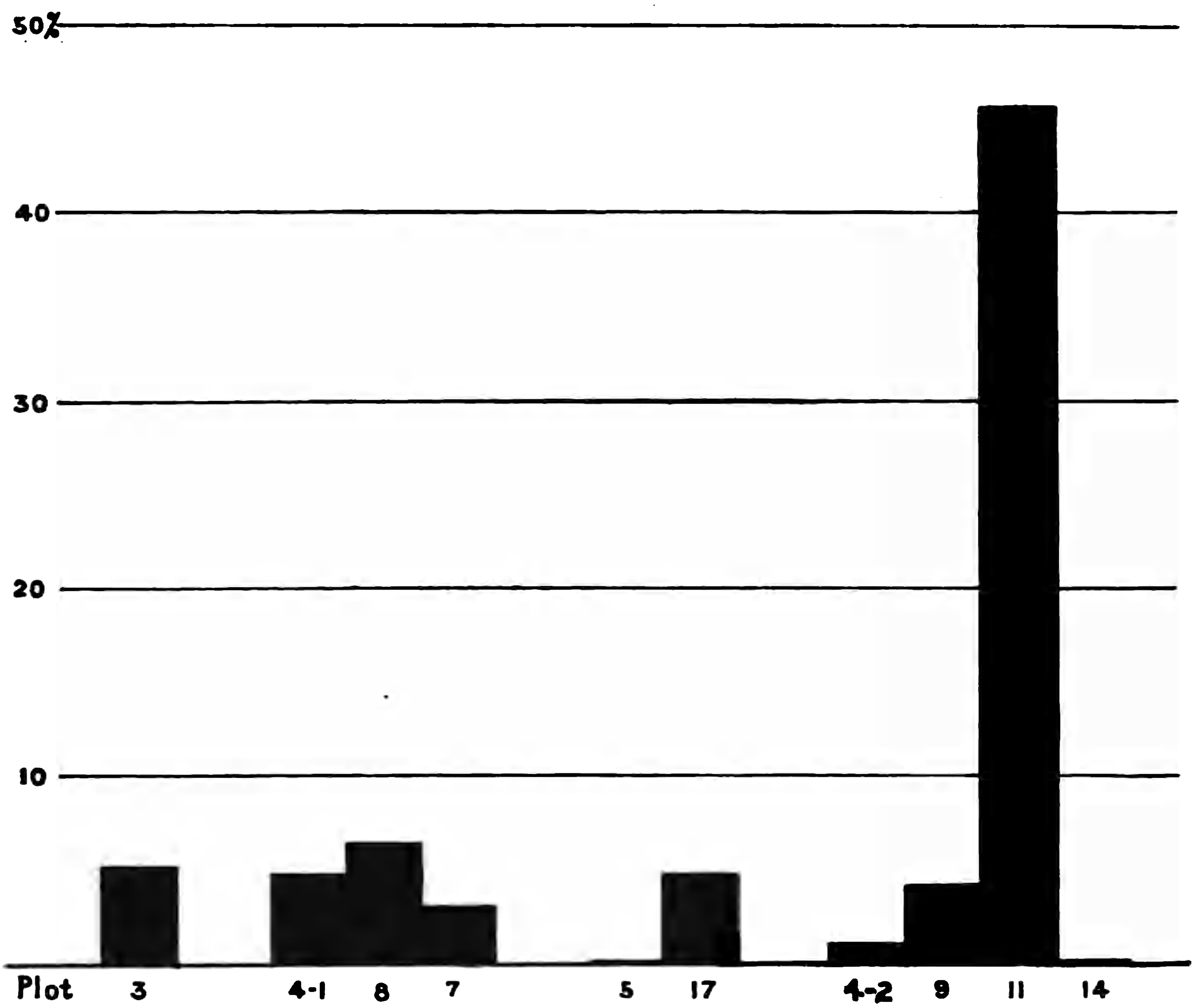

FIG. 36.—Percentage of *Holcus lanatus* in the Herbage of the Grass Plots.
First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only*	*Nitrogen and Minerals.*
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts.
	8. No Potash.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. } Amm.-salts.
			14. Complete; Nit. Soda.

TABLE LXII.—*Continued.*

MISCELLANEOUS SPECIES—*Continued.*

Years.	Plot 3	4-1	8	7	6	15	5	17	4-2	9	11-1	14
					***Centaurea nigra* (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	**10·28**	1·25	0·02	...	...
1877	1·06	0·66	0·76	0·10	0·44	0·90	0·53	**2·82**	0·85	...	...	...
1903	4·05	4·77	7·21	1·03	1·35	0·81	0·71	**11·20**	1·43	...	...	0·03
					***Achillea millefolium* (Yarrow or Milfoil).**							
1862	1·53	1·42	0·93	1·69	**3·84**	2·53	1·33	2·14	1·77	1·95	1·45	0·24
1867	1·16	1·88	**4·39**	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	0·16	1·39	0·27	0·04	0·01	0·65
1903	2·67	1·80	3·50	8·95	7·62	**9·95**	0·04	2·82	0·01	0·37	...	0·12
					***Leontodon hispidus* (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	**1·82**	0·92	...	...	...	0·01	...	0·25	...	...	...	...
1903	5·98	**14·68**	0·85	...	...	...	...	3·68	...	...	...	...
					***Plantago lanceolata* (Ribwort Plantain).**							
1862	**7·34**	5·63	0·71	0·23	0·06	6·92	0·10	3·85	0·04	0·01	...	0·18
1867	**10·78**	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	...	0·28	...	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**	...	...	...	...
					***Rumex acetosa* (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	**14·34**	1·80	0·54	2·79	0·13	0·57
					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**	3·82	2·37	2·14	2·08	1·91	2·12	2·58	1·00	0·51	0·20	0·35
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

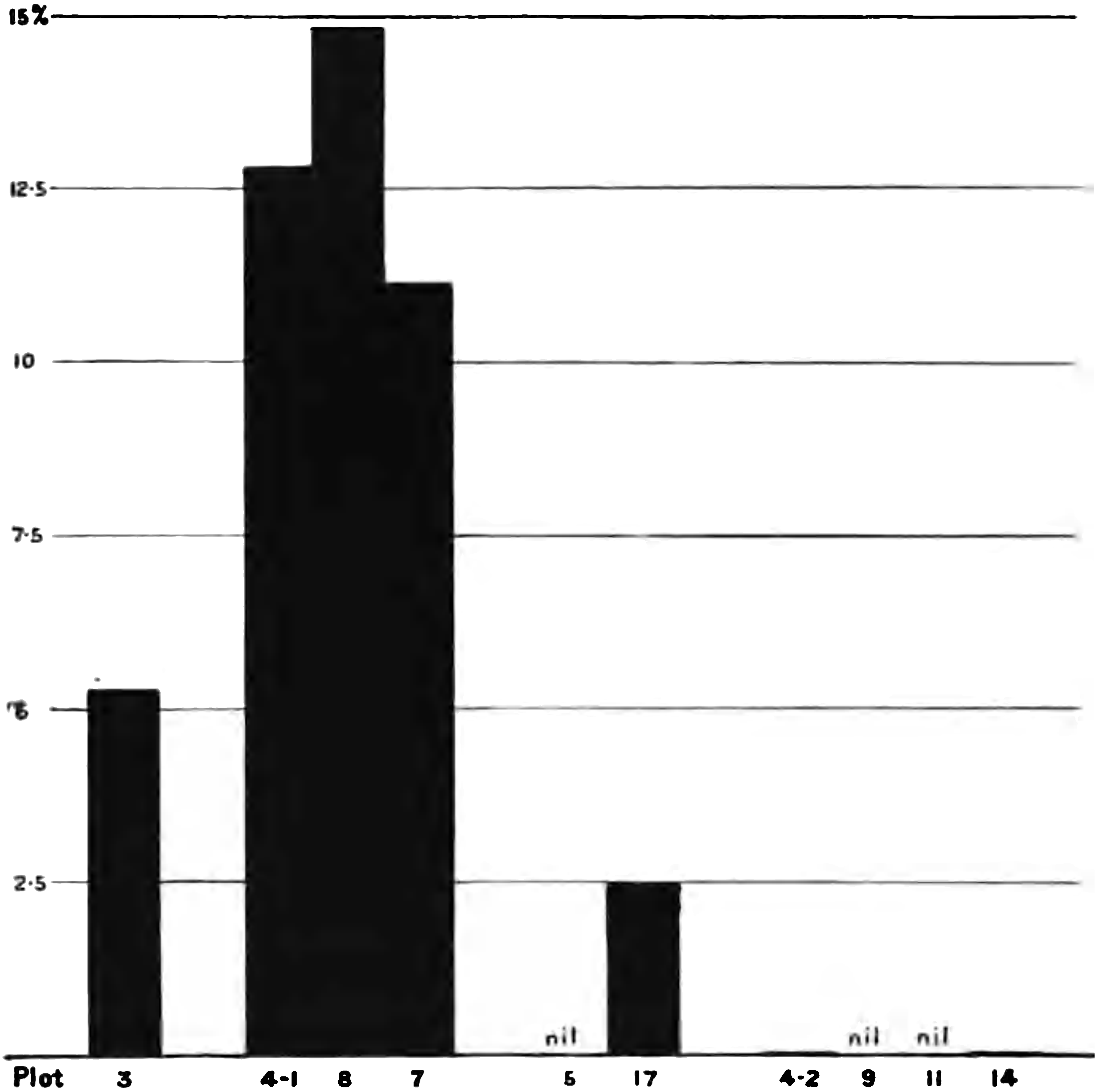

FIG. 37.—Percentage of *Trifolium repens*, *Trifolium pratense*, and *Lotus corniculatus* (together) in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate. 8. No Potash. 7. Complete.	5. Amm.-salts. 17. Nitrate Soda.	4-2. No Potash } Amm.- 9. Complete } salts. 11. Excess N. } 14. Complete; Nit. Soda.

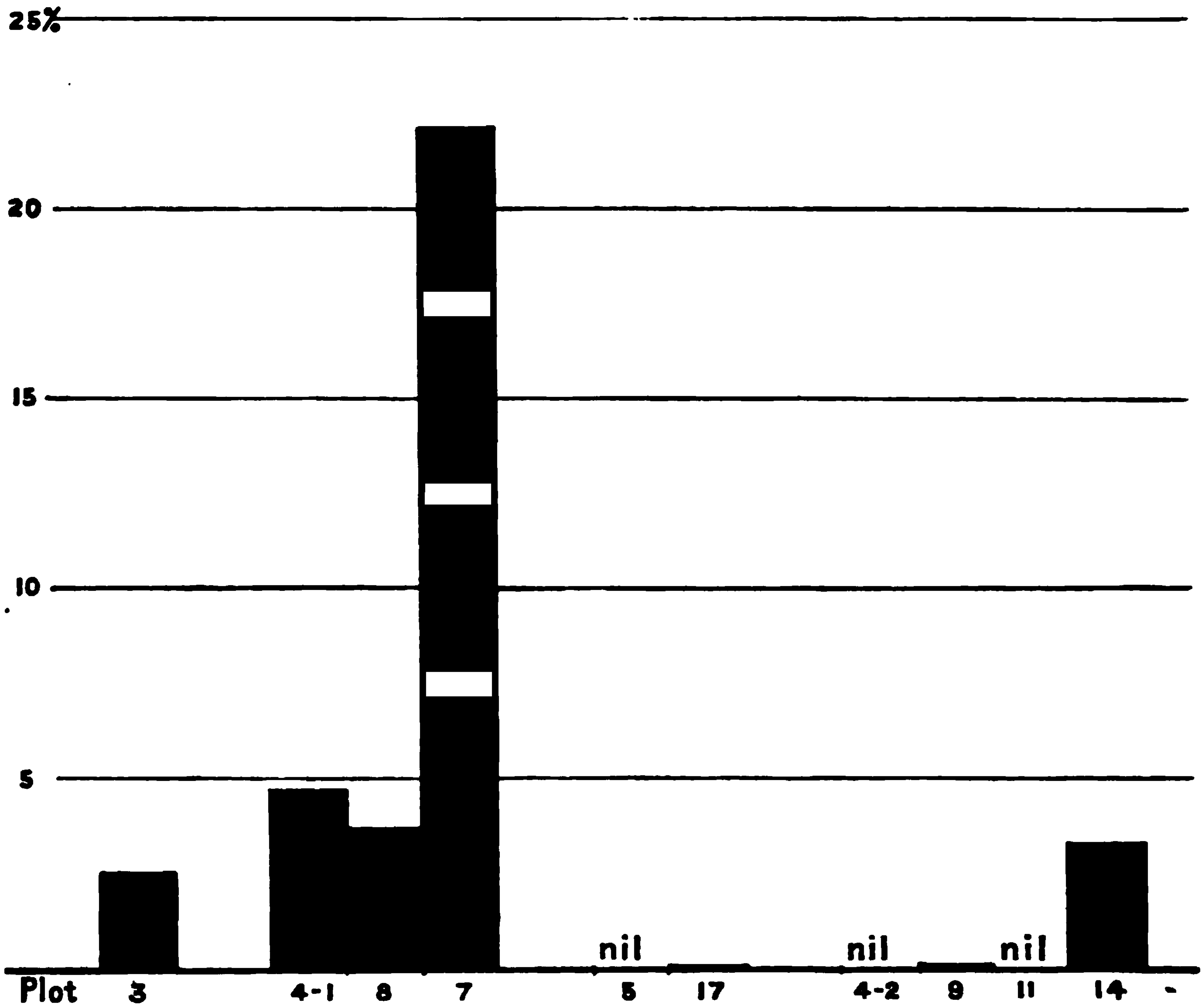

Fig. 38.—Percentage of *Lathyrus pratensis* in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts.
	8. No Potash.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. } Amm.-salts.
			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.				
			March.	April.	May.	June.	Total, March to 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	1·188	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.							
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	0·962	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

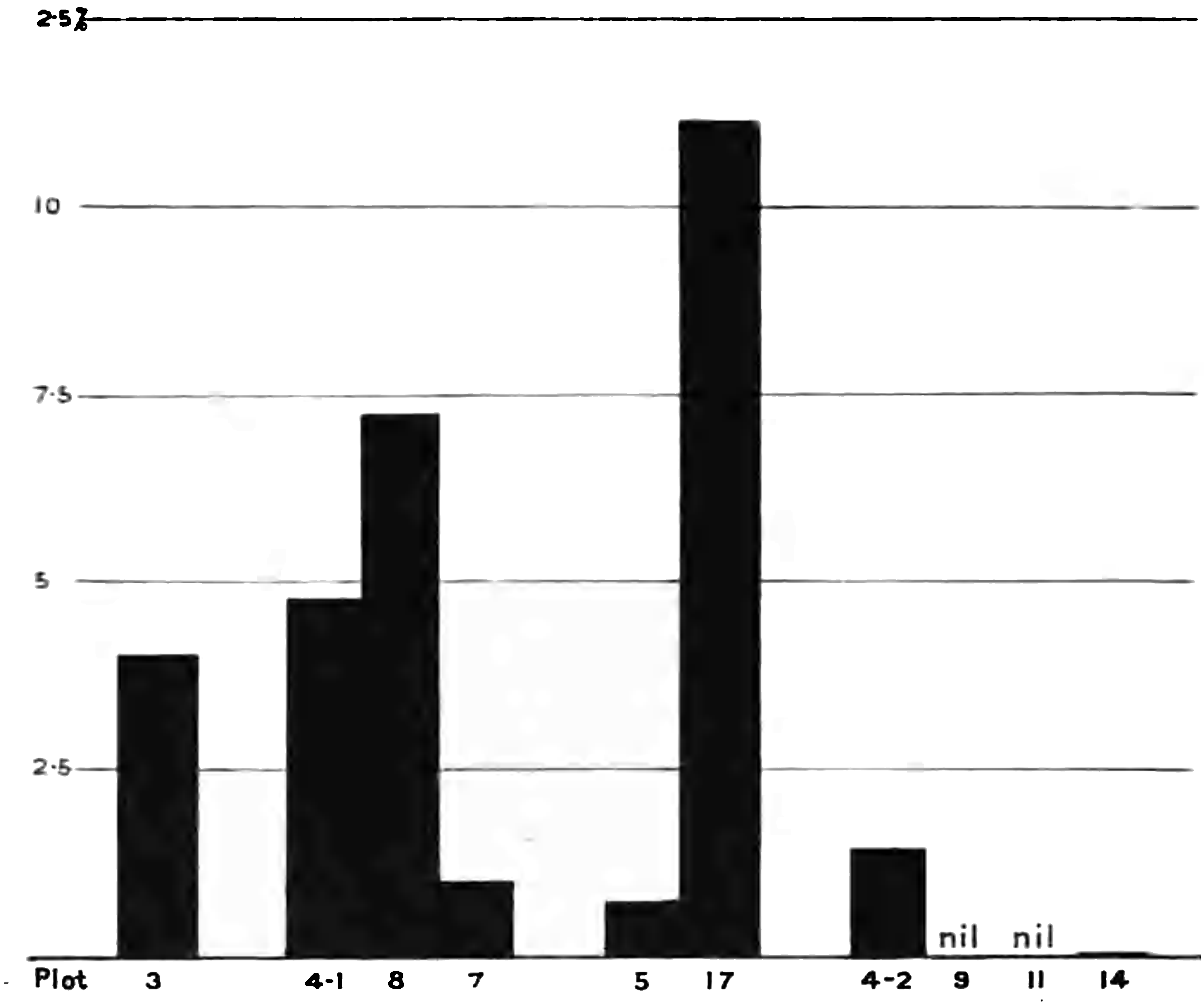

Fig. 39.—Percentage of *Centaurea nigra* in the Herbage of the Grass Plots. First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts.
	8. No Potash.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. } Amm.-salts.
			14. Complete; Nit. Soda.

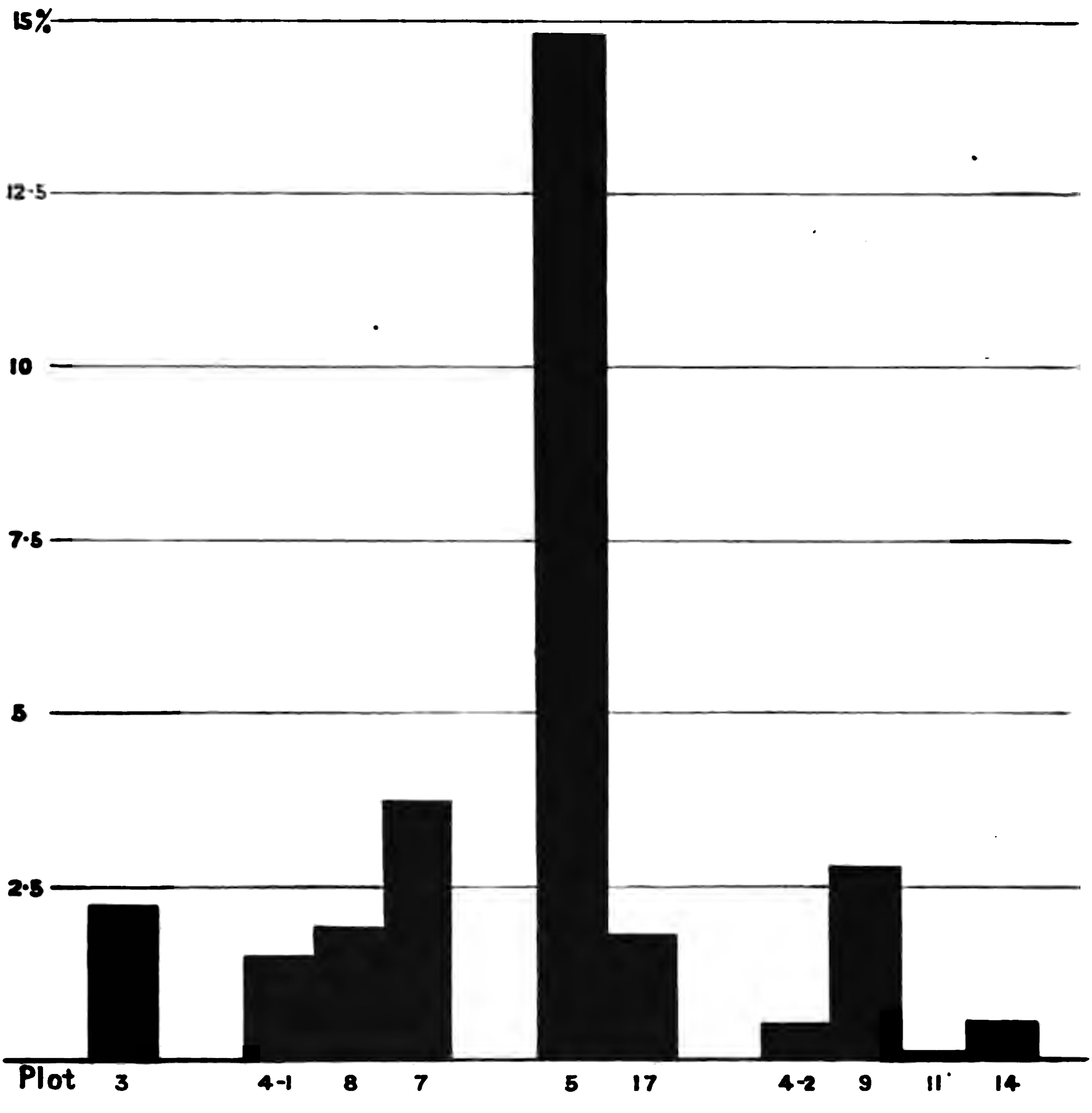

FIG. 40.—Percentage of *Rumex acetosa* in the Herbage of the Grass Plots.
First Crop, Season 1903.

Unmanured.	*Minerals only.*	*Nitrogen only.*	*Nitrogen and Minerals.*
	4-1. Superphosphate.	5. Amm.-salts.	4-2. No Potash } Amm.-salts.
	8. No Potash.	17. Nitrate Soda.	9. Complete } Amm.-salts.
	7. Complete.		11. Excess N. } Amm.-salts.
			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.

References

"Report of Experiments with Different Manures on Permanent Meadow Land, with Tabular Appendix." *Jour. Roy. Ag. Soc.*, **19** (1858), 552, and **20** (1859), 228 and 398. *Rothamsted Memoirs*, Vol. I., No. 12.

"The Effects of Different Manures on the Mixed Herbage of Grass Land." *Jour. Roy. Ag. Soc.*, **24** (1863), 131. *Rothamsted Memoirs*, Vol. I., No. 18.

"Further Report of Experiments with Different Manures on Permanent Meadow Land." *Jour. Roy. Ag. Soc.*, **24** (1863), 504. *Rothamsted Memoirs*, Vol. III., No. 3.

"Effects of the Drought of 1870 on some of the Experimental Crops at Rothamsted." *Jour. Roy. Ag. Soc.*, **32** (1871), 91. *Rothamsted Memoirs*, Vol. III., No. 11.

"Agricultural, Botanical, and Chemical Results of Experiments on the Mixed Herbage of Permanent Meadow, conducted for more than twenty years in succession on the same land." Part I., The Agricultural Results. Full Paper. *Phil. Trans.*, **171** (1880), 289. *Rothamsted Memoirs*, Vol. II., 4to, No. 1.

"Agricultural, Botanical, and Chemical Results of Experiments on the Mixed Herbage of Permanent Meadow, conducted for more than twenty years in succession on the same land." Part II., The Botanical Results. Full Paper. *Phil. Trans.*, **173** (1882), 1181. *Rothamsted Memoirs*, Vol. II., 4to, No. 2.

"The History of a Field newly laid down to Permanent Grass." *Jour. Roy. Ag. Soc.*, **50** (1889), 1. *Rothamsted Memoirs*, Vol. VI., No. 14.

"Agricultural, Botanical, and Chemical Results of Experiments on the Mixed Herbage of Permanent Grass Land, conducted for many years in succession on the same land." Part III., The Chemical Results. Section I., Full Paper. *Phil. Trans.*, Series B., **192** (1900), 139. *Rothamsted Memoirs*, Vol. II., 4to, No. 3.

"The Manuring of Grass Lands," by A. D. Hall. *Jour. Roy. Ag. Soc.*, **64** (1903), 76.

CHAPTER X

EXPERIMENTS UPON CROPS GROWN IN ROTATION, AGDELL FIELD

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 is further subdivided into four, so as to obtain the following comparisons:—(1) Half the plots carry clover or beans as the third crop of the course, and half the plots are bare fallow. This shows 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 are carted; on the other half the roots are eaten on the land by sheep; or rather, since the land is unsuited to winter folding, the roots are chopped up and ploughed in. This shows the effect on the succeeding crops of barley, etc., of the return of a root crop to the land by folding.

The Table LXIV. shows the mean results for the last five courses, 1884-1903.

1.—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 Hoos field, 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 *and* 1884-1903). *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

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 a comparison between the crops on the unmanured and the completely manured plot for the first four (or rather the second to the fifth) and the last five courses of the rotation, from which an idea can be obtained of how far each crop

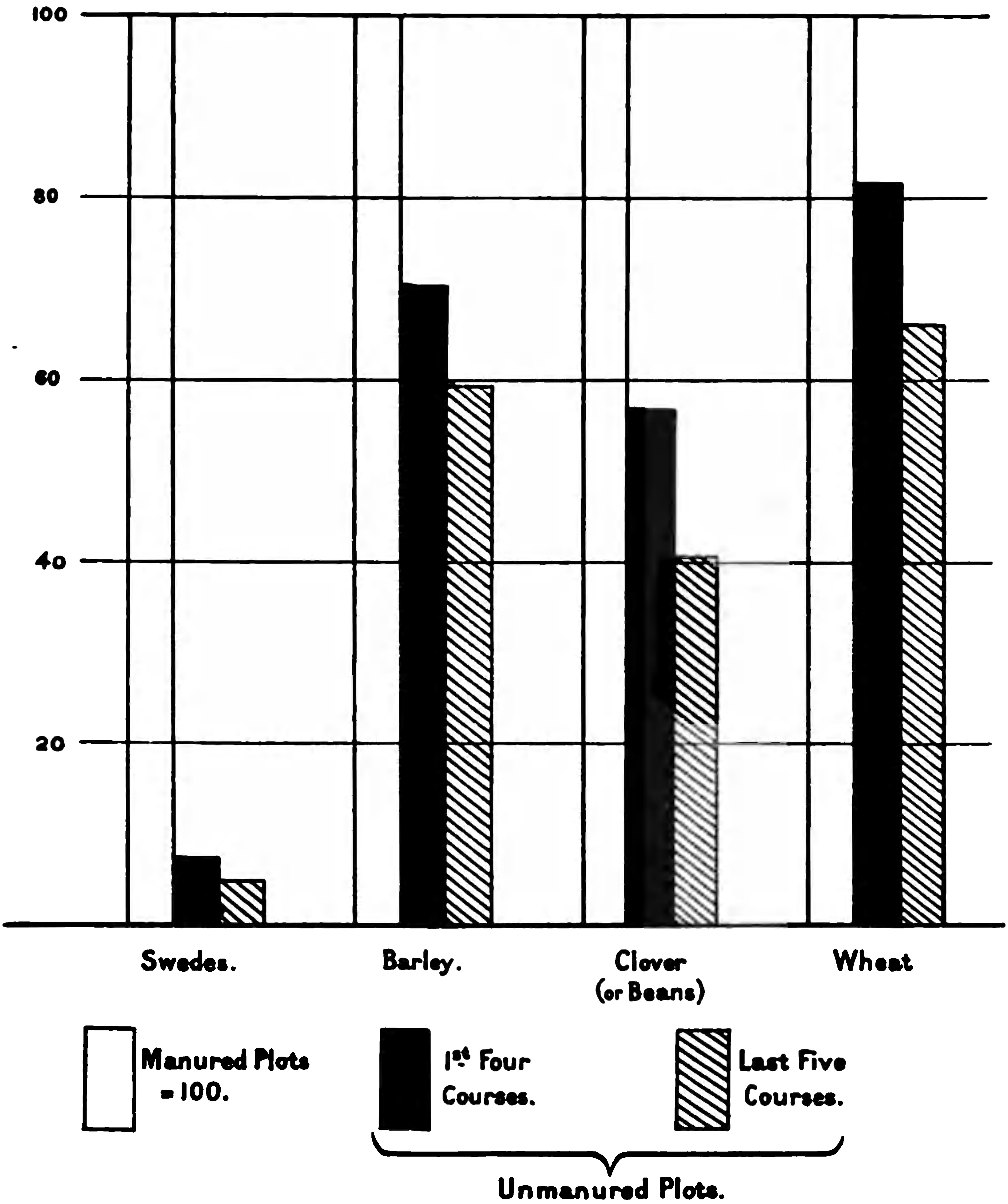

FIG. 41.—Crops Grown in Rotation. Relative Yield on Manured and Unmanured Plots in the earlier and later years of the Experiment.

has been affected during the fifty-six years of the experiment by the continued absence of manure. The same results are shown graphically in Fig. 41.

During the last five courses the crop of Swedes on the unmanured plots has averaged only 16 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 last 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 16 bushels of grain and 11 cwt. of straw per acre during the last five courses. This amounts to about 59 per cent. of the yield on the manured plots in the same years, 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 27 per cent. of that of the manured plots, while the rotation barley on the unmanured had only fallen to 59 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 less than 41 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 26·2 bushels per acre on the unmanured plots, as compared with 11·6 bushels per acre on the unmanured plot in Broadbalk

It should be remembered that each of these three plots is further subdivided into four quarter plots, in the first place the third crop may be clover or a bare fallow, and again the roots are carted off or fed on the land.

The effect of the mineral manures without nitrogen is very marked on the roots; during the last five courses the crop averaged 208 cwt. per acre, as against 16 cwt. per acre only on the unmanured plot. Even on the most impoverished of the quarter plots, that from which the roots are always carted and where a bare fallow is taken after the barley, the production amounted to 178 cwt. (see Table LXIV.), 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 is much less marked on the barley than on the roots, it only increases the average crop from 15·8 to 20 bushels per acre. This increase again is wholly found on the plots growing clover and beans and so receiving nitrogen collected from the air; the two quarter plots which are fallowed after the barley actually grow 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 to 33 cwt. of clover hay, and in the case of beans, from 15·7 bushels of corn and 8·7 cwt. of straw to 28·0 bushels of corn and 17 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 averaged about 32·4 bushels per acre, as against 27·1 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 40 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 five courses having been 20 tons, as against less than 10·5 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 slightly better, but 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.

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 six 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—Mean of "Fed" and "Carted" portions.*

	Clover Crops.*	Wheat.†			Bean Crops.‡	Wheat.§		
		After Fallow.	After Clover.	Increase due to Clover.		After Fallow.	After Beans.	Increase due to Beans.
	Cwt.	Lb.	Lb.	Per cent.	Lb.	Lb.	Lb.	Per cent.
O. Unmanured	15·2	4173	3475	−16·7	1888	4907	4373	−10·9
M. Mineral Manure	44·4	5245	5613	+ 7·0	2615	5528	5447	− 1·5
C. Complete Manure	52·9	5479	6130	+11·9	3177	6092	5929	− 2·7

* 5 years (1874, 1882, 1886, 1894, and 1902).
† 5 years (1875, 1883, 1887, 1895, and 1903).
‡ 8 years (1854, 1858, 1862, 1866, 1870, 1878, 1890, and 1898).
§ 8 years (1855, 1859, 1863, 1867, 1871, 1879, 1891, and 1899).

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 44·4 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 5245 lb. to 5613 lb., or by 7 per cent. On the completely manured plot a still greater crop of clover is obtained, averaging 53 cwt., and this still further increases the wheat crop from 5479 lb. to 6130 lb., or by 12 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—Mean of "Fed" and "Carted" portions.*

	Clover, 1894.	Wheat, 1895.			Beans, 1862.	Wheat, 1863.		
		After Fallow.	After Clover.	Increase due to Clover.		After Fallow.	After Beans.	Increase due to Beans.
	Cwt.	Lb.	Lb.	Per cent.	Lb.	Lb.	Lb.	Per cent.
O. Unmanured .	16·5	3131	3193	+ 2·0	3603	7222	5281	– 26·9
M. Mineral Manure .	59·7	4220	5180	+ 22·7	4033	7910	6090	– 23·0
C. Complete Manure	76·7	4547	5209	+ 14·6	5755	8792	7674	– 12·7

In 1894 the clover on the unmanured plot produced only 16·5 cwt. of hay and caused a barely perceptible increase in the total produce of the wheat, amounting to only 2 per cent. On the plot receiving a complete mineral manure, however, a very large crop of clover was obtained, 59·7 cwt. per acre, and this increased the total produce of the wheat crop from 4220 lb. to 5180 lb., or by 22·7 per cent., the extra grain amounting to

8 bushels per acre. On the completely manured plot a still greater clover crop was obtained, 76·7 cwt. of hay; this in its turn increased the total produce of the wheat crop from 4547 lb. to 5209 lb., or by 14·6 per cent. The increase of grain in this case was 7 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 cent. on the plot receiving superphosphate only, and 12·7 per cent. on the completely manured plot. These results can only

TABLE LXIX.—*Crops grown in rotation, Agdell Field. Effect of Clover (or Beans) on the succeeding Swede and Barley Crops. Mean of four Courses—Produce per acre.*

	10th-13th Courses (1884-99).	11th to 14th Courses (1888-1908).					
		Root Crops.			Barley.		
	Clover (or Beans).	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 . .	1809	28·1	11·5	−59·1	2086	2115	+ 1·4
M. Mineral Manure .	4777	201·4	251·9	+25·1	2037	3007	+47·6
C. Complete Manure .	4320	465·5	446·5	− 4·1	3170	3780	+19·2

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 four courses which have been completed, showing a comparison of the roots and the barley after fallow and after clover (or beans) re-

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.

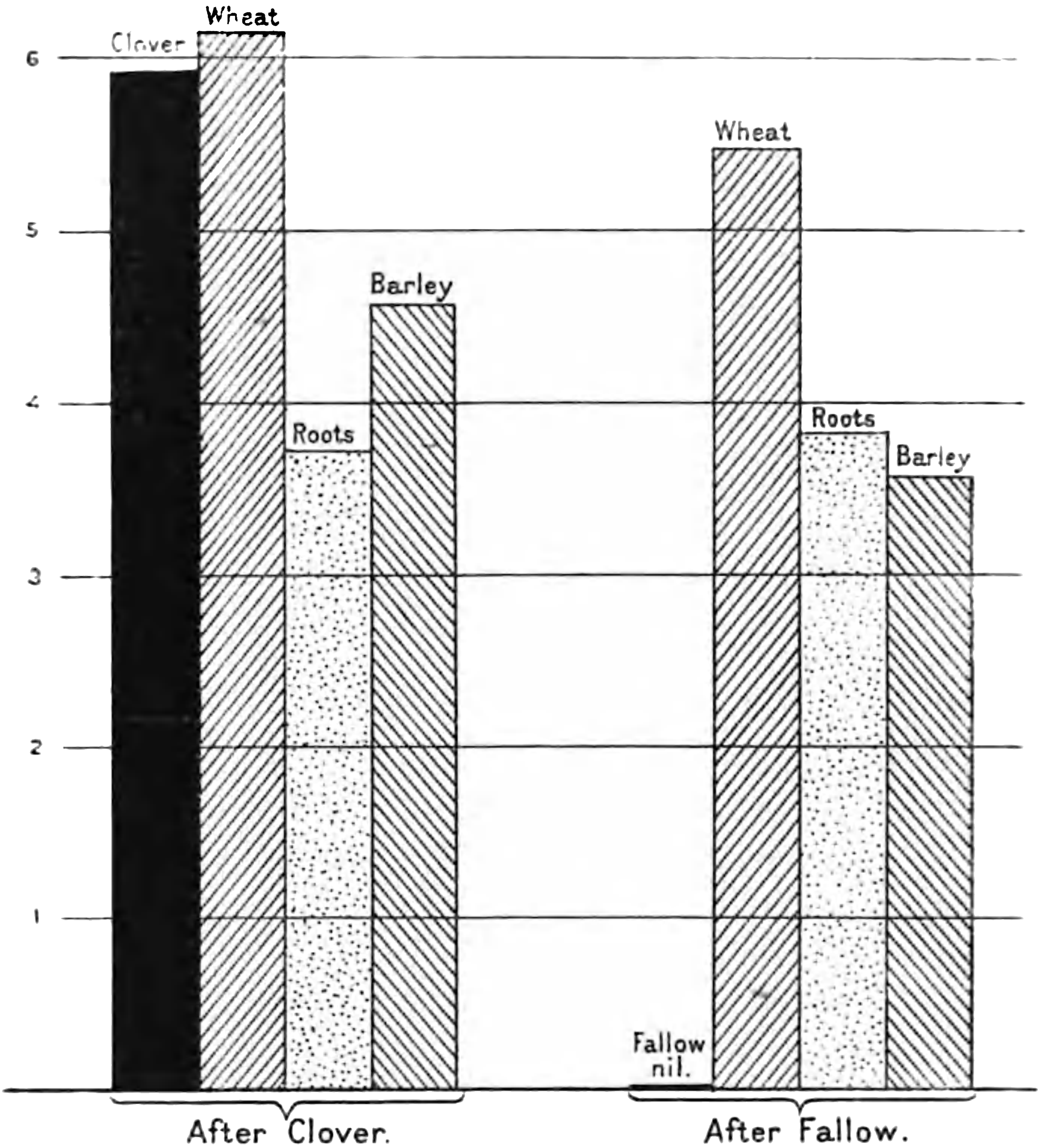

FIG. 43.—Comparative Effect of Clover or Bare Fallow on the succeeding Crops in the Rotation. Total Produce—In 1000 lb. for Clover, Wheat, and Barley, and in 100 cwt. for Roots.

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 188 to 448 cwt. per acre, or of 138 per cent. This crop of roots is entirely removed, but the succeeding barley crop shows a total produce of 2575 lb. on the plot where nitrogen was applied to the roots, against 1825 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 five Courses,* 1884-1903. *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.				
	Cwt.	Lb.	Lb.	Lb.
Minerals only	188·1	1825	Fallow	5180
Minerals + Nitrogen	448	2575	Fallow	5521
Increase Actual	259·9	750	...	341
Increase Per cent.	138·1	41·1	...	6·6
Roots carted, Beans or Clover.				
Minerals only	227	2548	3751	5995
Minerals + Nitrogen	445·4	3543	3317	6140
Increase Actual	218·4	995	- 434	145
Increase Per cent.	96·2	39·1	- 11·6	2·4

for the last five 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 nearly 7 per cent. A very similar increase in the barley crop, of 39 per cent. instead of 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 11·6 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 are removed with those to which the roots are 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.

	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 . . .	...	...	...	...
Wheat . . .	5521 lb.	6224 lb.	100	113

(grain and straw) for the last 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 diagram, Fig. 44, shows graphically the effect that feeding off the root crop on the land has on the succeeding

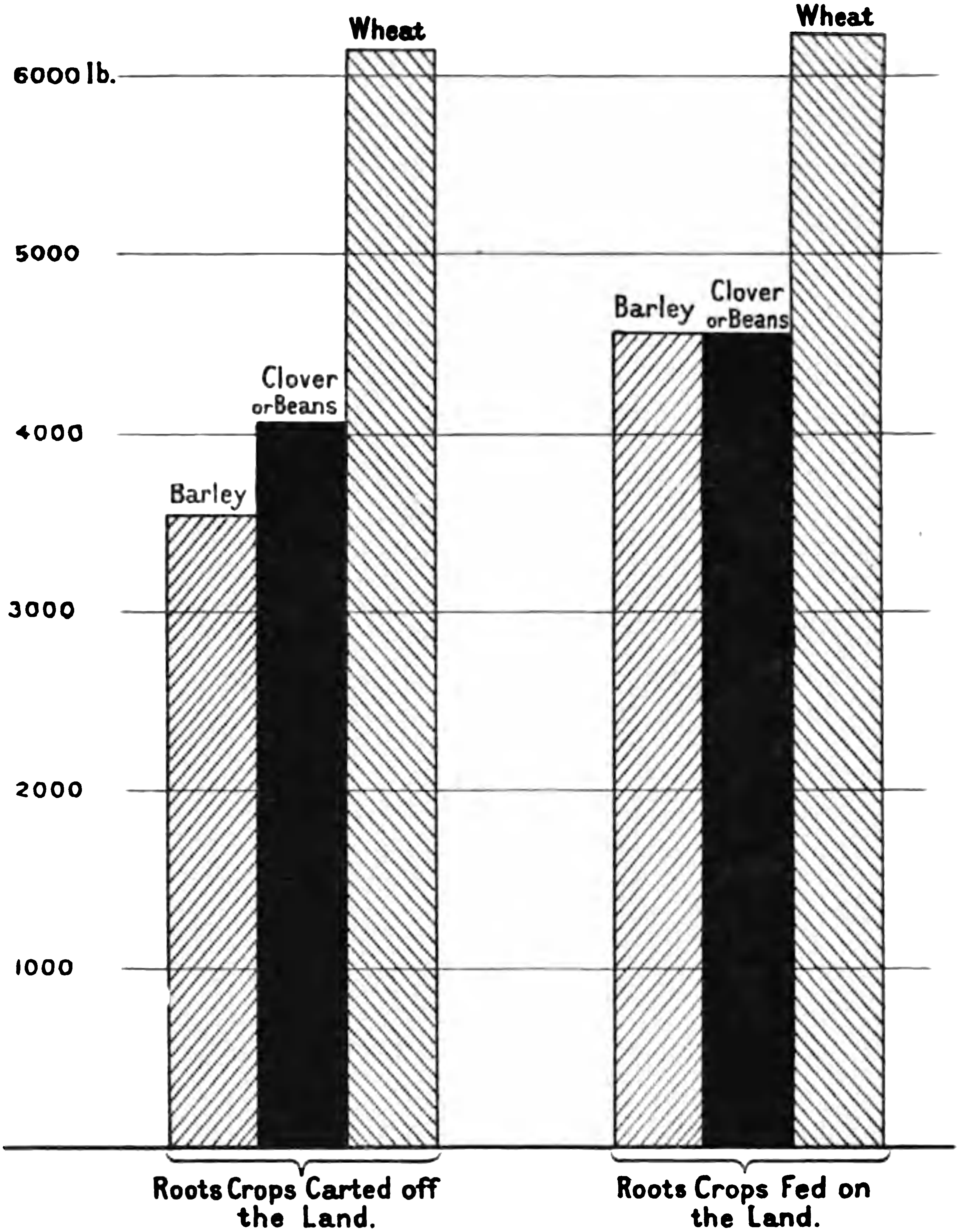

FIG. 44.—Effect of Feeding or Carting the Root Crop on the succeeding Crops in the Rotation. Total Produce—Averages over five courses (1884-1903). Roots completely Manured.

crops under the ordinary conditions of farming when clover forms parts of the 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	159·8
Per acre per annum	19·1	24·3	40·0

It will be seen that on the unmanured plots the removal of nitrogen is chiefly effected by the two cereal crops, so small has the crop of roots become. The average loss of nitrogen over the whole four years of the rotation amounts to just over 19 lb. per acre per annum, which agrees very closely with the average annual removal of nitrogen from the unmanured plot in Broadbalk where wheat is grown year after year. When mineral manures are used for the Swedes 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 losses due to the decomposition of nitrogenous materials in the soil with the evolution of their nitrogen as gas, "denitrification" so called. 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 latter years less than half the crop of the earlier ones. The seasons in the latter 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

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 denitrification 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.

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.

	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

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.

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.

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, Mr 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. Although Warington was not able at that time to demonstrate in a pure

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 mangel 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. 113-4). 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.

Latterly the term denitrification has been used in a wider sense for all bacterial decomposition of organic bodies containing nitrogen, which result in the loss of nitrogen as free gas. Such actions must be always going 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 aërated by the action of the plough.

It will now be realised that the most favourable conditions 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.	
							Super. only.	Complete Manure.
	Fallow Portion.				After Crop.		Fallow Portion.	
	Oct. 1878.	March 1881.	July 1883.	July 1884.	Oct. 1881.	Oct. 1893.	Oct. 1878.	Oct. 1878.
First 9 inches .	28·5	7·05	19·48	17·12	9·9	9·64	22·3	30·0
Second " .	5·2	3·35	8·05	3·67	5·2	9·22	14·0	18·8
Third " .	...	3·13	2·47	2·76	2·8	2·74	...	...

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.

It has already been pointed out in dealing with the wheat

TABLE LXXVIII.—*Nitrogen as Nitrates in Broadbalk Wheat Soils, October* 1893. *Lb. per acre.*

Plot	3.	2B.	19.	5.	6.	7.*	8.	16.
	Un-manured.	Dunged.	Rape Cake.	Minerals only.	Minerals +43 lb. N. as Amm.-salts.	Minerals +86 lb. N. as Amm.-salts.	Minerals +129 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	5·81	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. 51), 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 there can be no doubt that the nitrates in the subsoil water will 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 mangels 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

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.*

Depth of Soil.	Unmanured.	Dunged.	Ammonium-salts only.	Nitrate of Soda only.
	Plot 1.	Plot 8.	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 ,, . .	0·56	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 large 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.

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

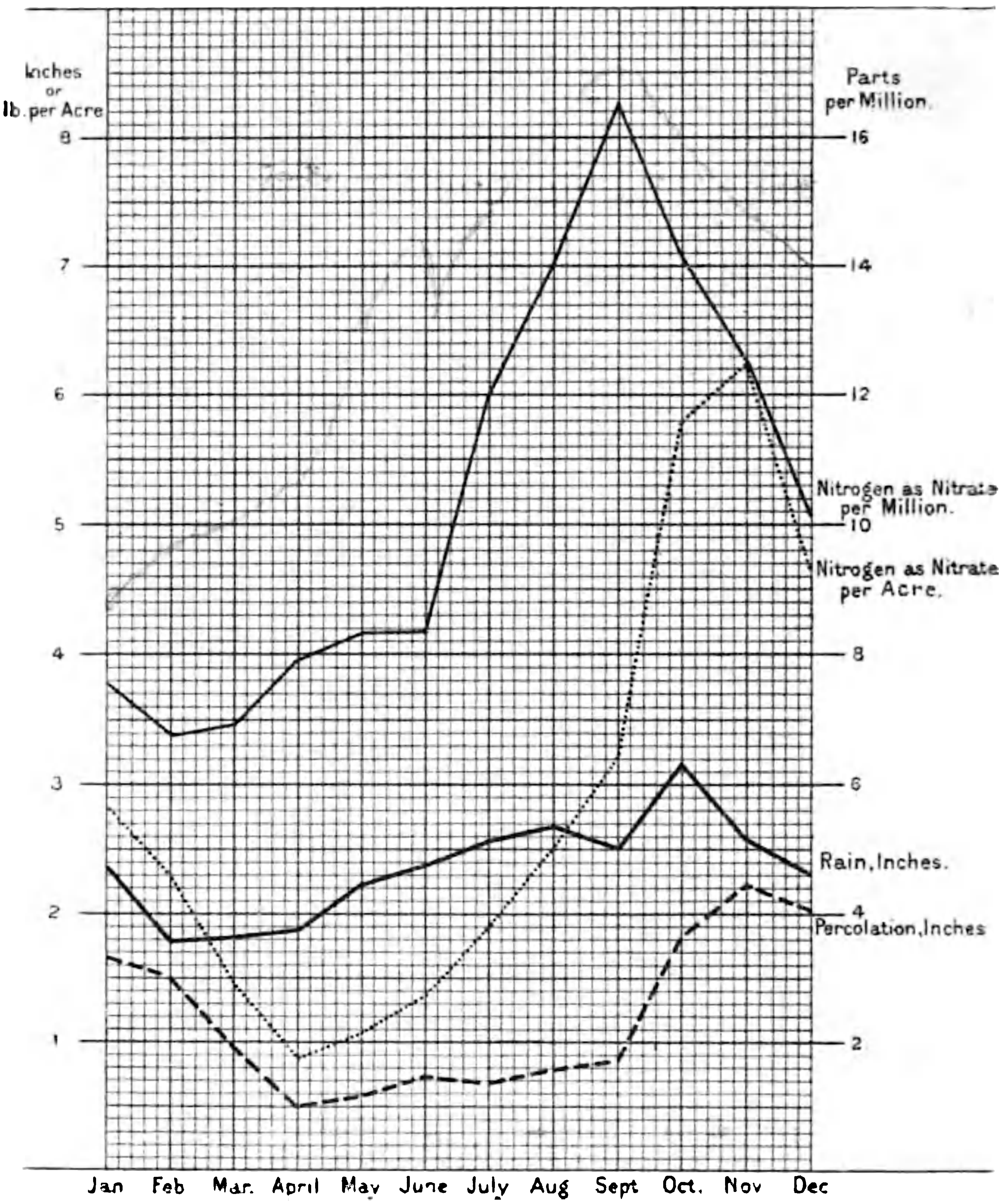

Fig. 45.—Rainfall, Percolation, and Nitrogen as Nitrate in Drainage through 20 inches of Soil. Rothamsted. 26 years (1878-1903).

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

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 3.	Plot 7.	Plot 9.	Plot 15.
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 3.	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 28	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

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 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_2, 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	13·7	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	28·3	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

CHAPTER XII

THE FEEDING EXPERIMENTS

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, Thaer'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. Thaer's hay values were based parlty 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,

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

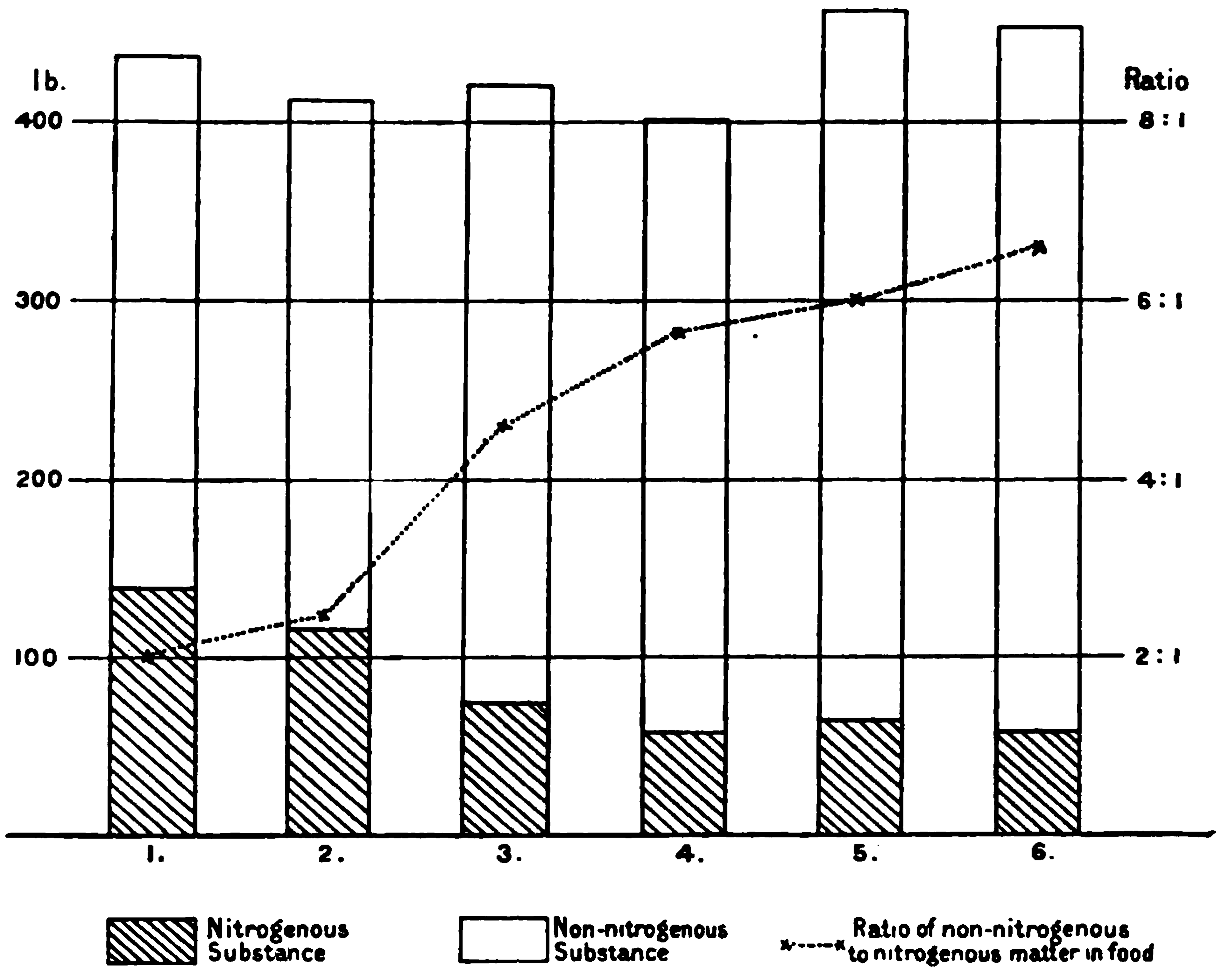

FIG. 47.—Nitrogenous and Non-nitrogenous Matter in Food required to produce 100 lb. Live-weight Increase. Pigs.

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.*

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 overtaxed."

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-

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.		
			Days.	Lb.	Lb.	Lb.	Lb.	Lb.
Oxen	27	112	87	146¼	121	13·0	9·4	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 experimenters, 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	389
Second Fortnight	67·5	36·7	17·4	9·4	389
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.

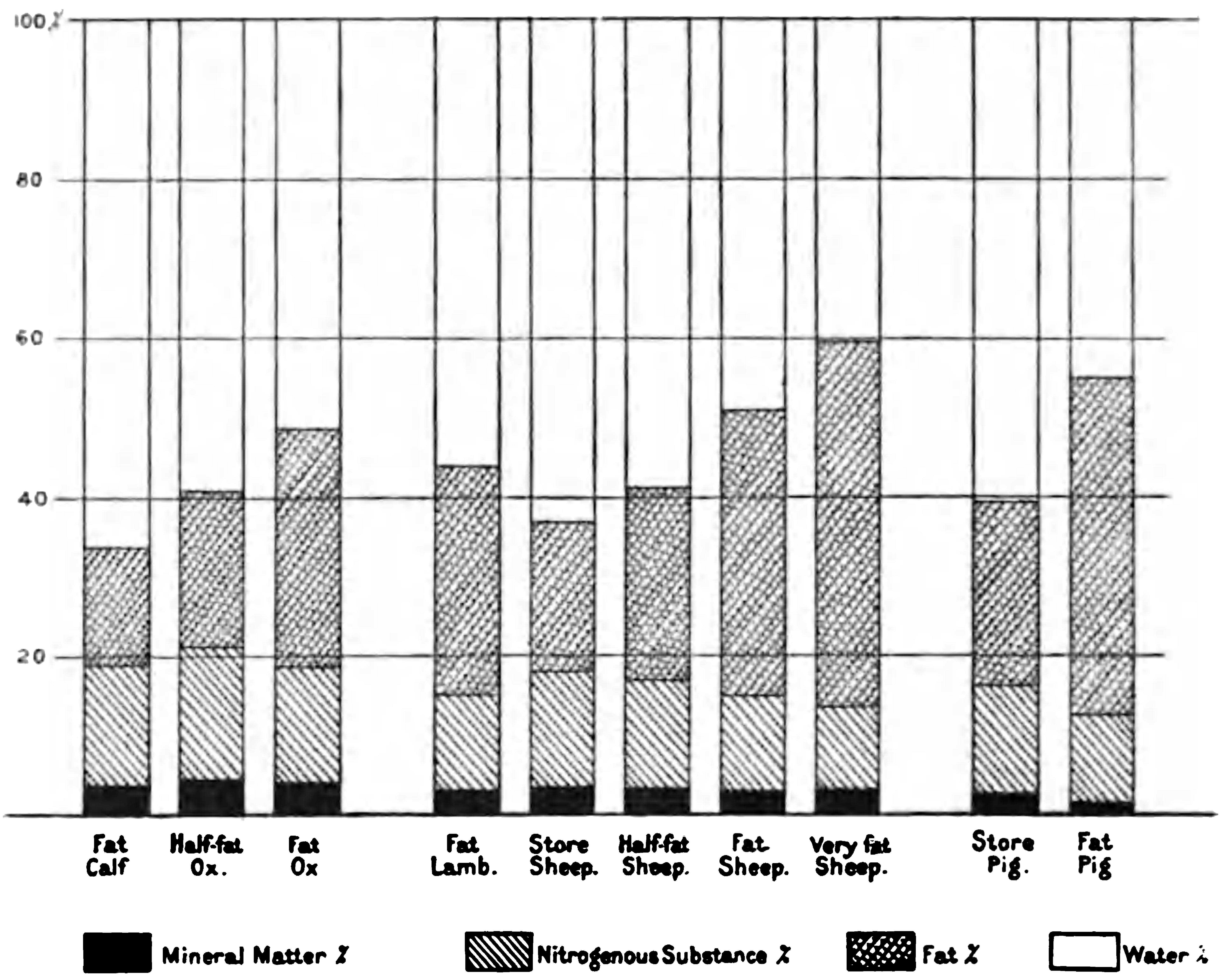

Fig. 48.—Percentage Composition of the Whole Bodies of Oxen, Sheep, and Pigs.

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.

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

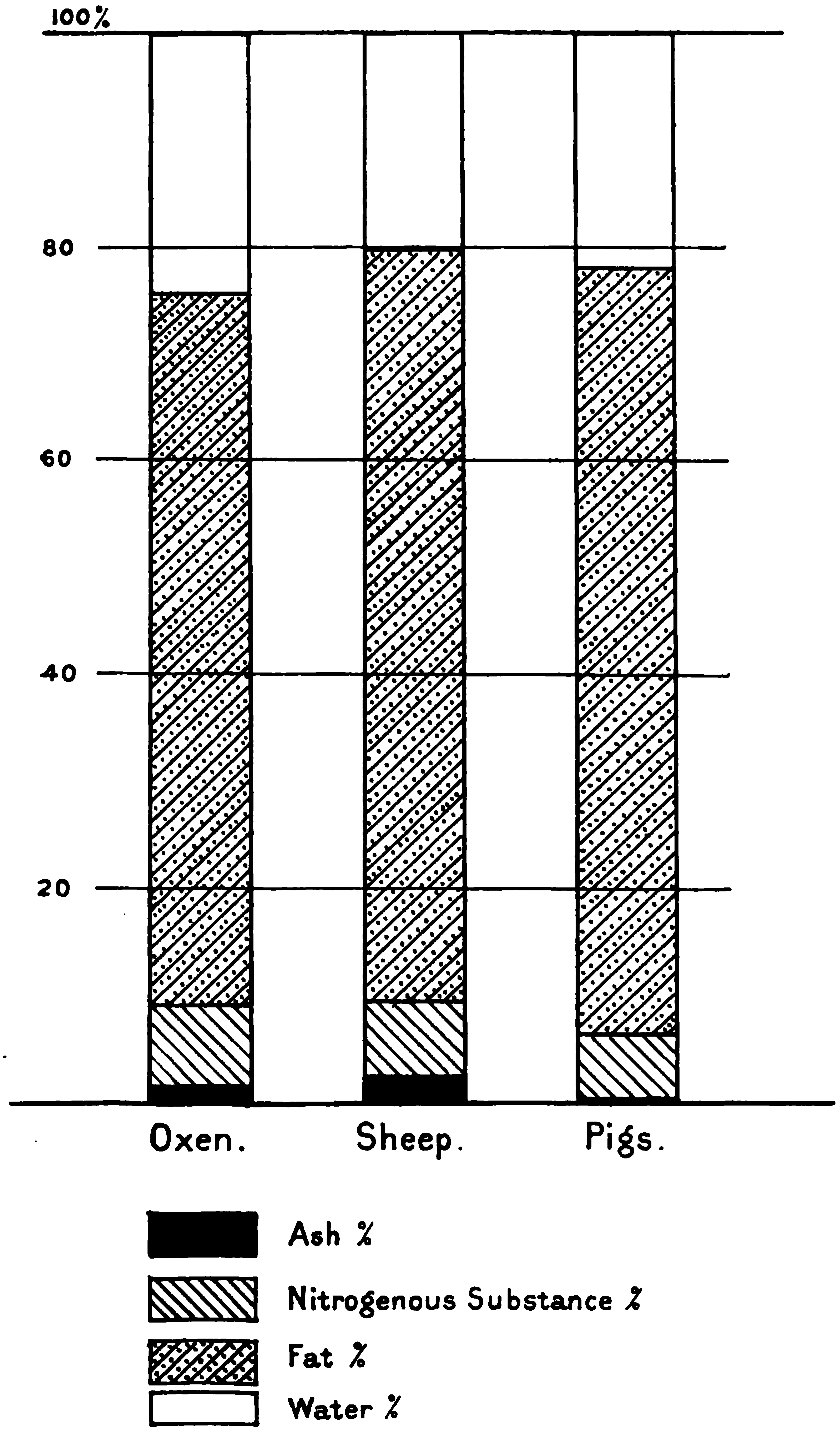

FIG. 49.—Oxen, Sheep, and Pigs. Composition of increase in Fattening.

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

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 purchased 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

CHAPTER XIII

MISCELLANEOUS ENQUIRIES

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

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 ¾ 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 ¾ 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

90 lb. of mangels, 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 results seemed to show that the cows on the clover silage tended to fatten rather more than those on the mangels; though giving slightly less milk they gained in live weight, while the mangel-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 mangel-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

composition between English and foreign-grown wheat, is again at the present time being made the subject of investigation at Rothamsted.

References

"On some Points in the Composition of Wheat Grain, its Products in the Mill, and Bread." *Jour. Chem. Soc.*, **10** (1857), 1. *Rothamsted Memoirs*, Vol. I., No. 10.

"Bread Reform." *Jour. Soc. Arts*, January 21, 1881. *Rothamsted Memoirs*, Vol. V., No. 16.

"On the Sewage of Towns (Third Report and Appendices 1, 2, and 3, of the Royal Commission, presented to Parliament), 1865." *Rothamsted Memoirs*, Vol. IV., No. 2.

"Report (presented to Parliament) of Experiments undertaken by Order of the Board of Trade to determine the Relative Values of Unmalted and Malted Barley as Food for Stock, 1866." *Rothamsted Memoirs*, Vol. IV., No. 3.

"Experiments on Ensilage conducted at Rothamsted, Season 1884-5." *Agric. Gazette*, April 27 to Aug. 10, 1885. *Rothamsted Memoirs*, Vol. IV., No. 12.

APPENDIX I

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.	=	R. Warington.
A. D. H.	=	A. D. Hall.
N. H. J. M.	=	N. H. J. Miller.

R. Mem. (Rothamsted Memoirs) refers to the ten bound volumes of reprints which were distributed in 1890 and since to the chief Libraries, Agricultural Colleges, and Experiment Stations, both at home and abroad.

J.R.A.S.	=	*Journal of the Royal Agricultural Society of England.*
J.C.S.	=	*Journal of the Chemical Society.*
T.C.S.	=	*Transactions of the Chemical Society.*
P.C.S.	=	*Proceedings of the Chemical Society.*

I.—LIST OF PUBLICATIONS ISSUED FROM THE ROTHAMSTED EXPERIMENTAL STATION, 1843-1905.

1. "Experiments at Rothamsted Farm, Herts, in 1843 and 1844, on the Growth of Turnips" (by J. B. L., *Gard. Chron.*, June 1845).
2. "Agricultural Chemistry" (by J. B. L., *J.R.A.S.*, **8**, 1847, 226), *R. Mem.*, Vol. I., No. 1.
3. "Agricultural Chemistry, Turnip Culture" (by J. B. L., *J.R.A.S.*, **8**, 1847, 494), *R. Mem.*, Vol. I., No. 2.
4. "On the Sources of the Alkalies in Agriculture" (by J. B. L., *The Farmers' Magazine*, **29**, 1848, 178).
5. "Agricultural Chemistry, Sheep Feeding, and Manure," Part I. (by J. B. L., *J.R.A.S.*, **10**, 1849, 276), *R. Mem.*, Vol. II., No 1.
6. "Experimental Investigation into the Amount of Water given off by Plants during their Growth" (by J. B. L., *Jour. Hort. Soc. Lond.*, **5**, 1850, 38), *R. Mem.*, Vol. I., No. 3.
7. "Report of some Experiments undertaken to ascertain the Comparative Evaporating Properties of Evergreen and Deciduous Trees" (by J. B. L., *Jour. Hort. Soc. Lond.*, **6**, 1851, 227), *R. Mem.*, Vol. I., No. 4.

8. "Agricultural Chemistry, especially in relation to the Mineral Theory of Baron Liebig" (by J. B. L. and J. H. G., *J.R.A.S.*, **12**, 1851, 1), *R. Mem.*, Vol. I., No. 5.
9. "Report of Experiments on the Comparative Fattening Qualities of Different Breeds of Sheep" (by J. B. L., *J.R.A.S.*, **12**, 1851, 414), *R. Mem.*, Vol. II., No. 2.
10. "Report of Experiments on the Comparative Fattening Qualities of Different Breeds of Sheep" (by J. B. L., *J.R.A.S.*, **13**, 1852, 179), *R. Mem.*, Vol. II., No. 3.
11. "On the Composition of Foods" (by J. B. L. and J. H. G., *Rep. Brit. Assn.*, 1852), *R. Mem.*, Vol. II., No. 4.
12. "Agricultural Chemistry; Pig Feeding" (by J. B. L., *J.R.A.S.*, **14**, 1853, 459), *R. Mem.*, Vol. II., No. 5.
13. "On the Amounts of, and Methods of Estimating, Ammonia and Nitric Acid in Rain-water" (by J. B. L. and J. H. G., *Rep. Brit. Assn.*, 1854), *R. Mem.*, Vol. I., No. 6.
14. "On the Equivalency of Starch and Sugar in Food" (by J. B. L. and J. H. G., *Rep. Brit. Assn.*, 1854), *R. Mem.*, Vol. II., No. 6.
15. "Experiments on the Comparative Fattening Qualities of Different Breeds of Sheep" (by J. B. L., *J.R.A.S.*, **16**, 1855, 45), *R. Mem.*, Vol. II., No. 7.
16. "On the Sewage of London" (by J. B. L., *Jour. Soc. Arts*, 1855), *R. Mem.*, Vol. II., No. 8.
17. "Report on the Experiments on the Growth of Wheat at Holkham Park Farm" (by J. B. L., *J.R.A.S.*, **16**, 1855, 207), *R. Mem.*, Vol. I., No. 7.
18. "On some Points connected with Agricultural Chemistry; being a reply to Baron Liebig's Principles of Agricultural Chemistry" (by J. B. L. and J. H. G., *J.R.A.S.*, **16**, 1855, 411), *R. Mem.*, Vol. I., No. 8.
19. "On the Growth of Wheat by the Lois-Weedon System" (by J. B. L. and J. H. G., *J.R.A.S.*, **17**, 1856, 582), *R. Mem.*, Vol. I., No. 9.
20. "On some Points in the Composition of Wheat Grain, its products in the Mill, and Bread" (by J. B. L. and J. H. G., *J.C.S.*, **10**, 1857, 1), *R. Mem.*, Vol. I., No. 10.
21. "On the Growth of Barley by Different Manures continuously on the same Land" (by J. B. L. and J. H. G., *J.R.A.S.*, **18**, 1857, 454), *R. Mem.*, Vol. I., No. 11.
22. "Letter on the Utilisation of Town Sewage" (by J. H. G., Report ordered by House of Commons, 1857, Appendix, **12**, 1857, 477), *R. Mem.*, Vol. II., No. 9.
23. "Experimental Inquiry into the Composition of some of the Animals Fed and Slaughtered as Human Food" (by J. B. L. and J. H. G., Abstract, *Proc. Roy. Soc.*, **9**, 1858, 348), *R. Mem.*, Vol. II., No. 10.
24. "Observations on the recently introduced Manufactured Foods for Agricultural Stock" (by J. B. L., *J.R.A.S.*, **19**, 1858, 199), *R. Mem.*, Vol. II., No. 11.
25. "On the Annual Yield of Nitrogen per acre in Different Crops" (by J. B. L. and J. H. G., *Chemical Gazette*, Nov. 1, 1858, 413).

42. "Report of Experiments on the Growth of Wheat for Twenty Years in Succession on the same Land" (by J. B. L. and J. H. G., *J.R.A.S.*, **25**, 1864, 93 and 449), *R. Mem.*, Vol. III., No. 4.
43. "On the Selection of Artificial Manures for the Sugar-Cane" (by J. B. L., 1864), *R. Mem.*, Vol. III., No. 5.
44. "On the Chemistry of the Feeding of Animals for the Production of Meat and Manure" (by J. B. L., *Jour. Roy. Dublin Soc.*, 1864, 256), *R. Mem.*, Vol. IV., No. 1.
45. "On the Sewage of Towns" (by J. B. L. and J. T. Way, Royal Commission, Third Report, and Appendices 1, 2, and 3, 1865), *R. Mem.*, Vol. IV., No. 2.
46. "On the Accumulation of the Nitrogen of Manure in the Soil" (by J. B. L. and J. H. G., *Rep. Brit. Assn.*, 1866), *R. Mem.*, Vol. III., No. 6.
47. "Report (presented to Parliament) of Experiments undertaken by Order of the Board of Trade to Determine the relative Values of Unmalted and Malted Barley as Food for Stock" (by J. B. L., 1866), *R. Mem.*, Vol. IV., No. 3.
48. "On the Composition, Value, and Utilisation of Town Sewage" (by J. B. L. and J. H. G., *J.C.S.*, **19**, 1866, 80), *R. Mem.*, Vol. IV., No. 4.
49. "Food in its Relations to the various Exigencies of the Animal Body" (by J. B. L. and J. H. G., *Phil. Mag.*, Fourth Series, **32**, 1866, 55), *R. Mem.*, Vol. IV., No. 5.
50. "On the Sources of Fat of the Animal Body" (by J. B. L. and J. H. G., *Rep. Brit. Assn.*, 1866; *Phil. Mag.*, Fourth Series, **32**, 1866, 439), *R. Mem.*, Vol. IV., No. 7.
51. "On the Home Produce, Imports, and Consumption of Wheat" (by J. B. L. and J. H. G., *J.R.A.S.*, **29**, 1868, 359), *R. Mem.*, Vol. III., No. 8.
52. "Exhaustion of the Soil in relation to Landlords' Covenants, and the Valuation of Unexhausted Improvements" (by J. B. L., London Farmers' Club, 1870), *R. Mem.*, Vol. III., No. 9.
53. "Scientific Agriculture with a view to Profit" (by J. B. L., Maidstone Farmers' Club, 1870), *R. Mem.*, Vol. III., No. 10.
54. "Effects of the Drought of 1870 on some of the Experimental Crops at Rothamsted" (by J. B. L. and J. H. G., *J.R.A.S.*, **32**, 1871, 91), *R. Mem.*, Vol. III., No. 11.
55. "Notes on Clover Sickness" (by J. H. G., *Jour. Roy. Hort. Soc.*, **3**, 1871, 86), *R. Mem.*, Vol. III., No. 12.
56. "Report of Experiments on the Growth of Barley for Twenty Years in Succession on the same Land" (by J. B. L. and J. H. G., *J.R.A.S.*, **34**, 1873, 89 and 275), *R. Mem.*, Vol. III., No. 13.
57. "Unexhausted Tillages and Manures, with reference to the Landlord and Tenant (Ireland) Act, 1870" (by J. B. L.), *R. Mem.*, Vol. III., No. 14.
58. "On the more frequent Growth of Barley on Heavy Land" (read before the London Farmers' Club, 1875, by J. B. L.), *R. Mem.*, Vol. V., No. 1.
59. "On the Valuation of Unexhausted Manures" (by J. B. L., *J.R.A.S.*, **36**, 1875, 1), *R. Mem.*, Vol. V., No. 2.

60. "Note on the Occurrence of Fairy Rings" (by J. H. G., *Jour. Linn. Soc.*, Botany, **15**, 1875, 17), *R. Mem.*, Vol. V., No. 3.

61. "On some Points in connection with Vegetation" (Address delivered at South Kensington Science Conferences, 1876, by J. H. G.), *R. Mem.*, Vol. V., No. 4.

62. "On some Points in connection with Animal Nutrition" (by J. H. G., Address delivered at South Kensington Science Conferences, 1876), *R. Mem.*, Vol. IV., No. 9.

63. "On Rainfall, Evaporation, and Percolation" (by J. H. G., *Proc. Inst. C.E.*, **45**, 1876), *R. Mem.*, Vol. V., No. 5.

64. "On the Use of Germinated Barley for Feeding" (by J. B. L., *Agric. Gazette*, May 1876).

65. "On the Quantitative Determination of Nitric Acid by Indigo" (by R. W., *Chem. News*, **35**, 1877, 45, 57).

66. "The Rothamsted Allotment Club" (by J. B. L., *J.R.A.S.*, **38**, 1877, 387).

67. "Freedom in the Growth and Sale of the Crops of the Farm" (by J. B. L., *Jour. Soc. Arts*, Dec. 12, 1877), *R. Mem.*, Vol. V., No. 6.

68. "On the Formation of Fat in the Animal Body" (by J. B. L. and J. H. G., *Jour. Anat. and Phys.*, **11**, 1877), *R. Mem.*, Vol. IV., No. 10.

69. "Composition of Potatoes" (by J. H. G., Note, *Jour. Roy. Hort. Soc.*, **5**, 1878), *R. Mem.*, Vol. V., No. 7.

70. "On Nitrification" (by R. W., *T.C.S.*, **33**, 1878, 44).

71. "Is Higher Farming a Remedy for Lower Prices" (by J. B. L., Lecture delivered before the East Berwickshire Agricultural Association, May 3, 1879; Berwick, 1879), *R. Mem.*, Vol. V., No. 8.

72. "On Nitrification," Part II. (by R. W., *T.C.S.*, **35**, 1879, 429).

73. "On the Determination of Nitric Acid, as Nitric Oxide, by means of its action on Mercury" (by R. W., *T.C.S.*, **35**, 1879, 375).

74. "On the Determination of Nitric Acid by means of Indigo, with special reference to Water Analysis" (by R. W., *T.C.S.*, **35**, 1879, 578).

75. "On some Points in connection with Agricultural Chemistry" (by J. H. G., Abstract, *Rep. Brit. Assn.*, 1879), *R. Mem.*, Vol. V., No. 10).

76. "Our Climate and our Wheat Crops" (by J. B. L. and J. H. G., *J.R.A.S.*, **41**, 1880, 173), *R. Mem.*, Vol. V., No. 11.

77. "Agricultural, Botanical, and Chemical Results of Experiments on the Mixed Herbage of Permanent Meadow—Part I., The Agricultural Results" (by J. B. L. and J. H. G., *Phil. Trans.*, **171**, 1880, 289), *R. Mem.*, Vol. II. (4to), No. 1.

78. "Sketch of the Progress of Agricultural Chemistry" (by J. H. G., *Rep. Brit. Assn.*, 1880), *R. Mem.*, Vol. V., No. 13.

79. "On the Determination of Nitric Acid as Nitric Oxide, by means of its reaction with Ferrous Salts" (by R. W., Part I., *T.C.S.*, **37**, 1880, 468; Part II., *T.C.S.*, 41, 1882, 345).

80. "On the Determination of Carbon in Soils" (by R. W. and W. A. Peake, *T.C.S.*, **37**, 1880, 617).

81. "On the Home Produce, Imports, Consumption, and Price of Wheat, over 27 (or 28) Harvest-years, 1852-3 to 1879-80" (by J. B. L. and J. H. G., *J.R.A.S.*, **41**, 1880, 337), *R. Mem.*, Vol. V., No. 14; see also *Jour. Stat. Soc.*, **43**, 1880, 313.
82. "Letter on Bread Reform" (by J. H. G., *Jour. Soc. Arts*, 1881), *R. Mem.*, Vol. V., No. 16.
83. "On the Amount and Composition of the Rain and Drainage Waters collected at Rothamsted" (by J. B. L., J. H. G., and R. W., Parts I., II., and III., and Appendix Tables (*J.R.A.S.*, **42**, 1881, pp. 241 and 311; **43**, 1882, 1), *R. Mem.*, Vol. V., No. 18.
84. "Letters on Fertility" (by J. B. L., *Agric. Gazette*, Feb. 21 to May 9, 1881), *R. Mem.*, Vol. V., No. 17.
85. "On the Formation and Decomposition of Carbonic Acid" (by J. B. L., *Phil. Mag.*, 1881, 206).
86. "On Increasing the Fertility of Pastures" (by J. B. L., *Jour. Amer. Agric. Assn.*, **1**, 1881, 67).
87. "On Alterations in the Properties of the Nitric Ferment by Cultivation" (by R. W., *Rep. Brit. Assn.*, 1881, 593).
88. "Note on the Appearance of Nitrous Acid during the Evaporation of Water" (by R. W., *T.C.S.*, **39**, 1881, 229).
89. "Some Practical Aspects of recent investigations on Nitrification" (by R. W., *Jour. Soc. Arts*, April 7, 1882).
90. "Determinations of Nitrogen in the Soils of some of the Experimental Fields at Rothamsted, and the bearing of the results on the Question of the Sources of the Nitrogen of our Crops" (by J. B. L. and J. H. G., American Assn. for the Advancement of Science, Montreal, August 1882), *R. Mem.*, Vol. V., No. 19.
91. "Agricultural, Botanical, and Chemical Results of Experiments on the Mixed Herbage of Permanent Meadow. Part II., The Botanical Results" (by J. B. L., J. H. G., and M. T. Masters, *Phil. Trans.*, **173**, 1882, 1181), *R. Mem.*, Vol. II. (4to), No. 2.
92. "On the Determination of Nitric Acid in Soils" (by R. W., *T.C.S.*, **41**, 1882, 351).
93. "The Future of Agricultural Field Experiments" (by J. B. L., *Agric. Students' Gazette*, **4**, 1882, 33).
94. "On some of the Changes which Nitrogenous Matter undergoes within the Soil" (by R. W., Lecture delivered at South Kensington, April 16, 1883).
95. "Contribution to the Chemistry of Fairy Rings" (by J. B. L., J. H. G., and R. W., *T.C.S.*, **43**, 1883, 208), *R. Mem.*, Vol. V., No. 20.
96. "New Determinations of Ammonia, Chlorine, and Sulphuric Acid, in the Rain-water collected at Rothamsted" (by J. B. L., J. H. G., and R. W., *J.R.A.S.*, **44**, 1883, 313), *R. Mem.*, Vol. V., No. 21.
97. "The Nitrogen as Nitric Acid, in the Soils and Subsoils of some of the Fields at Rothamsted" (by J. B. L., J. H. G., and R. W., *J.R.A.S.*, **44**, 1883, 331), *R. Mem.*, Vol. V., No. 22.

116. "Remarks on the Products of the Cow" (by J. B. L., *Agric. Students' Gazette*, **2**, 1885, 129).

117. "Mangels as a Milk-producing Food" (by J. B. L., *Agric. Students' Gazette*, **2**, 1885, 147).

118. "On the Necessity for some Change in the Law in regard to the Adulteration of Milk" (by J. B. L., British Dairy Farmers' Assn., Oct. 7, 1885, Vol. II., 1886, 197).

119 "Results of Experiments at Rothamsted on the Growth of Barley for more than Thirty Years in succession on the same Land" (by J. H. G., *Agric. Students' Gazette*, New Series, **3**, 1886, 1), *R. Mem.*, Vol. VI., No. 8.

120. "Remarques sur la relation qui existe entre les sommes de température et la production agricole" (by J. H. G., *Archives des Sciences Physiques et Naturelles*, 3[e] *période*, **16**, 1886, 421), *R. Mem.*, Vol. VI., No. 9.

121. "Shall we Import, or Breed?" (by J. B. L., *Live Stock Journal Almanac*, 1886).

122. "Selling Live Stock by Weight" (by J. B. L., *Jour. Newcastle Farmers' Club*, 1886, 3).

123. "On the Distribution of the Nitrifying Organism in the Soil" (by R. W., *T.C.S.*, **51**, 1887, 118).

124. "Succulent Food" (by J. B. L., *Jour. Bath and W. of Eng. Soc.*, Series III., **18**, 1886-7, 299).

125. "What is an Average Turnip Crop?" (by J. B. L., *Jour. Bath and W. of Eng. Soc.*, Series III., **18**, 1886-7, 301).

126. "The Home Produce, Imports, Consumption, and Price of Wheat in the United Kingdom, 34 Harvest-years, 1852-3 to 1885-6" (by J. B. L. and J. H. G., *The Field*, Feb. 12, 1887), *R. Mem.*, Vol. VI., No. 10.

127. "A Contribution to the Study of Well Waters" (by R. W., *T.C.S.*, **51**, 1887, 500).

128. "On the present position of the Question of the Sources of the Nitrogen of Vegetation—Preliminary Notice" (by J. B. L. and J. H. G., *Proc. Roy. Soc.*, **43**, 1887, 108), *R. Mem.*, Vol. VI., No. 11.

129. "Results of Experiments at Rothamsted on the Growth of Root-crops for many years in succession on the same Land" (by J. H. G., *Agric. Students' Gazette*, New Series, **3**, 1887), *R. Mem.*, Vol. VI., No. 12.

130. "Nature of Nitrogenous Organic Matter in Soils" (by R. W., *Chem. News*, **55**, 1887, 27).

131. "Some Remarks upon Foods" (by J. B. L., *Agric. Science*, **1**, 1887, 99).

132. "Food in Relation to Milk" (By J. B. L., *Jour. Brit. Dairy Farmers' Assn.*, **3**, 1887, 7).

133. "The Relative Value of Store and Fat Stock" (by J. B. L., *Scottish Agric. Gazette Almanac*, 1887).

134. "Tables for Estimating Dead Weight and Value of Cattle from Live Weight" (by J. B. L., 1888. Published by *Roy. Agric. Soc.*).

135. "Results of Experiments at Rothamsted on the Growth of Potatoes for Twelve Years in succession on the same Land" (by J. H. G., *Agric. Students' Gazette*, New Series, **4**, 1888), *R. Mem.*, Vol. VI., No. 13.

136. "The Permanent Wheat and Barley Experiments in Stackyard Field, Woburn" (J. B. L., *J.R.A.S.*, **49**, 1888, 1).

137. "The Chemical Actions of some Micro-organisms" (by R. W., *Proc. Chem. Soc.*, **4**, 1888, 69; *T.C.S.*, **53**, 1888, 727).

138. "On the Present Position of the Question of the Sources of Nitrogen of Vegetation" (by J. B. L. and J. H. G., *Phil. Trans.*, **180**, B, 1889, 1), *R. Mem.*, Vol. I. (4to), No. 2.

139. "The History of a Field newly laid down to Permanent Grass" (by J. B. L., *J.R.A.S.*, **50**, 1889, 1), *R. Mem.*, Vol. VI., No. 14.

140. "The Amount of Nitric Acid in the Rain-water at Rothamsted, with notes on the Analysis of Rain-water" (by R. W., *T.C.S.*, **55**, 1889, 537).

141. "Results of Experiments at Rothamsted on the Growth of Leguminous Crops for many years in succession on the same Land" (by J. H. G., *Agric. Students' Gazette*, New Series, **4**, 1889, 137; and **4**, 1890, 179), *R. Mem.*, Vol. VI., No. 15.

142. "The Food of our Agricultural Crops" (by J. B. L., *J.R.A.S.*, **51**, 1890, 69), *R. Mem.*, Vol. VI., No. 17.

143. "Results of Experiments at Rothamsted on the Question of the Fixation of Free Nitrogen" (by J. H. G., *Agric. Students' Gazette*, New Series, **5**, 1890, 33; and **5**, 1891, 62), *R. Mem.*, Vol. VII., No. 1.

144. "Condiments" (by J. B. L., *The Farmer and Stockbreeder's Year-book*, 1890, 25).

145. "The Market Value of the Different Samples of Wheat and Barley grown in 1889 on the Experimental Plots at Rothamsted" (by Lawes Agric. Trust Committee, *J.R.A.S.*, **51**, 1890, 432).

146. "Observations on Rainfall, Percolation, and Evaporation, at Rothamsted; with Tabular Results for Twenty Harvest-years, 1870-1 to 1889-90 inclusive" (by J. H. G., *Proc. Inst. Civil Engineers*, **105**, 1891, Part III.), *R. Mem.*, Vol. VII., No. 2.

147. "Results of Experiments at Rothamsted on the Question of the Fixation of Free Nitrogen" (by J. H. G., *Nature*, Nov. 12, 1891), *R. Mem.*, Vol. VII., No. 3.

148. "The Sources of the Nitrogen of our Leguminous Crops" (by J. B. L. and J. H. G., *J.R.A.S.*, **52**, 1891, 657), *R. Mem.*, Vol. VII., No. 4.

149. "On Nitrification," Part IV. (by R. W., *P.C.S.*, **7**, 1891, 927; *T.C.S.*, **59**, 1891, 484).

150. "Six Lectures on the Investigations at Rothamsted Experimental Station, delivered under the provisions of the Lawes Agricultural Trust before the Assoc. of American Agric. Colleges and Expt. Stations, at Washington, D.C., Aug. 12-18, 1891" (by R. W., U.S. Dept. of Agric., Office of Expt. Stations, Bul. No. 8, Washington, 1892).

151. "Allotments and Small Holdings" (by J. B. L. and J. H. G., *J.R.A.S.*, **53**, 1892, 439), *R. Mem.*, Vol. VII., No. 5.

152. "Nutritive Ratios" (by J. B. L., *Agric. Students' Gazette*, New Series, **6**, 1892, 1).

153. "Small Holdings" (by J. B. L., *Farming World Year-book*, 1893).

154. "Home Produce, Imports, Consumption, and Price of Wheat, over 40 Harvest-years, 1852-3 to 1891-2" (by J. B. L. and J. H. G., *J.R.A.S.*, **54**, 1893, 77), *R. Mem.*, Vol. VII., No. 6.

155. "Rotation of Crops" (by J. B. L. and J. H. G., *J.R.A.S.*, **55**, 1894, 585), *R. Mem.*, Vol. VII., No. 7.

156. "Upon some Properties of Soils, which have Grown a Cereal Crop and a Leguminous Crop for many years in Succession" (by J. B. L., *Agric. Students' Gazette*, New Series, **7**, 1895).

157. "The Agricultural Investigations at Rothamsted, England, during a period of Fifty Years" (by J. H. G., United States Dept. of Agric., Office of Expt. Stations, Bul. No. 22, Washington, 1895).

158. "The Rothamsted Experiments; being an account of some of the Results of the Agricultural Investigations conducted at Rothamsted, in the Field, the Feeding-shed, and the Laboratory, over a period of Fifty Years" (by J. B. L. and J. H. G., *Trans. Highland and Agric. Soc. of Scotland*, Fifth Series, **7**, 1895, 1).

159. "The Feeding of Animals, for the Production of Meat, Milk, and Manure, and for the Exercise of Force" (by J. B. L. and J. H. G., *J.R.A.S.*, **56**, 1895, 47), Vol. VII., No. 13.

160. "The Depression of Corn Prices; and the Production of Wheat in some of the chief exporting Countries of the World" (by J. B. L. and J. H. G., *J.R.A.S.*, **57**, 1896, 723), *R. Mem.*, Vol. VII., No. 8.

161. "The Lawes Agricultural Trust Committee. Brief Summary of Proceedings during its first Five Years of Office" (*J.R.A.S.*, **57**, 1896, 324).

162. "Soil Inoculation" (by N. H. J. M., *J.R.A.S.*, **57**, 1896, 236).

163. "The Royal Commission on Agricultural Depression and the Valuation of Unexhausted Manures" (by J. B. L. and J. H. G., *J.R.A.S.*, **58**, 1897, 674), *R. Mem.*, Vol. VII., No. 9.

164. "Production of Milk Rich in Fat" (by N. H. J. M., *J.R.A.S.*, **58**, 1897, 655).

165. "The Valuation of the Manures obtained by the Consumption of Foods for the Production of Milk" (by J. B. L. and J. H. G., *J.R.A.S.*, **59**, 1898, 103), *R. Mem*,, Vol. VII., No. 10.

166. "The Growth of Sugar-beet, and the Manufacture of Sugar, in the United Kingdom" (by J. B. L. and J. H. G., *J.R.A.S.*, **59**, 1898, 344), *R. Mem.*, Vol. VII., No. 11.

167. "The World's Wheat Supply" (by J. B. L. and J. H. G., *The Times*, Dec. 2, 1898), *R. Mem.*, Vol. VII., No. 12.

168. "Agricultural, Botanical, and Chemical Results of Experiments on the Mixed Herbage of Permanent Grass Land, conducted for many years in succession on the same Land. Part III. The Chemical Results—Section I." (by J. B. L. and J. H. G., *Phil. Trans.*, **192**, B, 1900, 139), *R. Mem.*, Vol. II. (4to), No. 3.

3. "On the Productive Powers of Soils in Relation to the Loss of Plant Food by Drainage" (by A. Voelcker, *J.C.S.*, **24**, 1871, 276).

4. "Bodenstatik und Bodenanalysen" (by H. von Liebig, Zeits. landw. Vereines, Bayern, 1872).

5 "On the Composition of Waters of Land Drainage" (by A. Voelcker, *J.R.A.S.*, **35**, 1874, 132).

6. "Sixth Report of the Rivers Pollution Commission, London, 1874" (see results by Dr E. Frankland, pp. 58-68).

7. "The Analytical Determinations of probably available Mineral Plant Food in Soils" (by B. Dyer, *Proc. C.S.*, **10**, 1894, 36; and *Trans. C.S.*, **65**, 1894, 115).

8. "Manurial Conditions affecting the Malting Quality of English Barley" (by J. M. H. Munro and E. S. Beaven, *J.R.A.S.*, **58**, 1897, 65).

9. "Denitrification and Farmyard Manure" (by R. W., *J.R.A.S.*, **58**, 1897, 577).

10. "On the Analysis of Soil as a Guide to its Fertility" (by B. Dyer, *Trans. Highland and Agric. Soc. of Scotland*, Fifth Series, **10**, 1898, 26).

11 ["Analyses of Rothamsted Soils"] (by A. Goss and H. Snyder, U.S. Dept. of Agric., Division of Chem., Bul. No. 51, 1898, 73).

12. "Some of the Principles which should Determine Compensation for the Use of Foods and Manures" (by R. W., Lecture to Newcastle Farmers' Club, Vinton, London, 1898).

13. "Various Conditions affecting the Malting Quality of Barley" (by J. M. H. Munro and E. S. Beaven, *J.R.A.S.*, **61**, 1900, 185).

14. "Results of Percolation Experiments at Rothamsted, Sept. 1870 to Aug. 1899" (by R. H. Scott, *Quart. Jour. Roy. Met. Soc.*, **26**, 1900, 139).

15. "The Comparative Value of Nitrate of Sodium and Sulphate of Ammonium as Manures" (by R. W., *J.R.A.S.*, **61**, 1900, 300).

16. "A Chemical Study of the Phosphoric Acid and Potash Contents of the Wheat Soils of Broadbalk Field, Rothamsted" (by B. Dyer, *Proc. R.S.*, **68**, 11; *Phil. Trans.*, **194**, B, 1901, 235).

17. "The Determination of Available Plant Food in Soils by the use of Weak Acid Solvents" (by A. D. Hall and F. J. Plymen, *Proc. C.S.*, 1901; and *Trans. C.S.*, **81**, 1902, 117).

18. "Sur les phosphates du sol solubles à l'eau" (by Th. Schloesing, jun., *Compt. rend.*, **134**, 1902, 1383).

19. "Lost Fertility: The Production and Loss of Nitrates in the Soil" (by R. W., *Trans. Highland and Agric. Soc. of Scotland*, Fifth Series, **17**, 1905, 148).

III.—OTHER PUBLICATIONS DEALING WITH THE ROTHAMSTED EXPERIMENTS.

1. "The Rothamsted Agricultural Experimental Station" (*Gard. Chron.*, Sept. 22, 1877).

2. "Rothamsted—Trente Années d'Experiences Agricoles de MM. Lawes et Gilbert" (par A. Ronna, Paris, 1887).

3. "Notes sur Rothamsted" (par H. Grosjean, *Ann. Inst. Nat. Agron.*, **3**, 1878-9).
4. "Die Resultate der hauptsächlichsten Felddüngungs-versuche, von Lawes und Gilbert in England und ihre Bedeutung für die deutsche Landwirthschaft" (von Dr Paul Behrend, Berlin, 1881).
5. "The Rothamsted Experiments on the Growth of Wheat, Barley, and the Mixed Herbage of Grass Land" (by W. Fream, London, 1888).
6. "Le Blé à Rothamsted" (par Eugène Marchand, *Jour. d'Agriculture Pratique*, Paris, 1888-90).
7. "Le Blé l'Avoine et l'Orge à Rothamsted" (par Eugène Marchand, *Jour. d'Agriculture Pratique*, Paris, 1889-90).
8. "L'Azote dans la Culture du Blé" (par Eugène Marchand, *Jour. d'Agriculture Pratique*, Paris, 1890?).
9. "Lessons afforded by the Rothamsted Experiments" (U.S. Dept. of Agriculture, Expt. Station Record, **7**, 1896, 343; also *J.R.A.S.*, **57**, 1896, 140).
10. "Die Rothamsteder Versuche nach dem Stande des Jahres, 1894" (von K. Bieler, Berlin, 1896).
11. "Concise Review of Principal Data on Rothamsted Experiments as carried out by Sir J. B. Lawes and Prof. J. H. Gilbert, based mainly on Prof. W. Fream's Book" (by Gustav Kottmann, Ph.D., Sydney, 1897).
12. "The Rothamsted Experiments and their Practical Lessons for Farmers" (by C. J. R. Tipper, London, 1897).
13. "Försöksverksamheten vid Rothamsted i England" (H. von Feilitzen, Jönköping, 1900).
14. "Rothamsted—Un Demi-siècle d'Expériences Agronomiques de MM. Lawes et Gilbert" (par A. Ronna, *Annales de la Science Agronomique française et étrangère, 2e série, 6e année*, Paris, 1900).
15. "Du Role des Éléments de Cendres dans la Végétation" (par A. Ronna, *Jour. d'Agriculture Pratique, 25 avril et 2 mai*, Paris, 1901).
16. "The Geological Survey in Reference to Agriculture, with Report on the Soils and Subsoils of the Rothamsted Estate" (by Horace B. Woodward. Summary of Progress of the Geological Survey for 1903, Appendix I., 1904, 143).

Note.—It should be mentioned that Nos. 54, 56 (Sec. 4), 65, 71, 77 (part), 83 (part), 90, 97, 102, and 162, of Series I., were translated into French by M. P. P. Dehérain, and published in the *Annales Agronomiques*.

APPENDIX II

Trustees.

The Rt. Hon. Lord Avebury, D.C.L.
The Rt. Hon. Lord Walsingham.
Sir J. Evans, K.C.B., D.C.L.

Committee.

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Sir J. H. Thorold, Bart.
J. A. Voelcker, M.A., Ph.D.

Former Members.

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The Rt. Hon. the Earl Cawdor (*Member of Committee*).
Sir W. T. Thiselton Dyer, K.C.M.G. (*Member of Committee*).
C. Whitehead (*Member of Committee*).

Secretary.

H. Rix, B.A.

2. *Former Members of the Staff*—continued.

Name.	Date.	Position.
H. King	1843-1879	General Assistant and Laboratory Man.
G. Knott	1858-1891	Chemical and General Assistant.
F. Bassill	1857-1858	General Assistant.
T. Plummer	1859-1864	Laboratory Man.
W. Grubb	1860-1861	Laboratory Assistant.
W. Freeman	1868-1872	General Assistant.
A. Sears	1872-1874	General Assistant.
H. W. Lawrence . .	1891-1901	Chemical Assistant.
H. Bracey	1877-1901	General Assistant.
W. Luck	1884-1887	Keeper of Dairy Records.
G. Newson	1887-1890	Keeper of Dairy Records.

3. *Other Workers in connection with the Experiments.*

E. Pugh, Ph.D., of Pennsylvania, U.S.A.

At Rothamsted Dr Pugh worked at the Question of the Assimilation of Atmospheric Nitrogen by Plants, in the years 1857-59. See joint paper, No. 34. He also introduced many new methods into the routine of the laboratory. Dr Pugh returned to America in 1859, and became President of the Agricultural College, Pennsylvania, which position he occupied until his death in 1864. (See *Jour. Chem. Soc.*, 18, 1865, 346.)

R. Warington, F.R.S.

Mr Warington, who had worked in the Rothamsted Laboratory for some time in 1859, came to Rothamsted in 1876 and remained until 1890, working chiefly at questions connected with Nitrification. See papers Nos. 65, 70, 72, 73, 74, 79, etc.

M. T. Masters, Ph.D., F.R.S.

Worked on the Grasses from the botanical side. He was joint-author of paper No. 91.

W. E. G. Atkinson.

Worked on the Composition of Wheat and Flour, 1902-4.

4. *Botanists Working in connection with the Separation of Grasses.*

Name.	Date.	Name.	Date.
W. Sutherland . .	1862	W. Davis	1877
A. Keenan . . .	1867	H. G. Mundy . .	1903
W. B. Hemsley, F.R.S. .	1872		

5. *Voluntary Workers.*

Name.	Date.	Name.	Date.
Prof. Th. Segelcke .	1858-1859	C. J. T. Morison, B.A. .	1904-1905
J. Moulin	about 1877	A. Amos, B.A. . .	1904-1905
T. S. Dymond . . .	1892	C. Carter, B.Sc. . .	1904
C. M. Luxmoore, D.Sc.	1893	R. Aladjem	1904
S. F. Ashby, B.Sc. .	1903-1905	N. Marmu	1905

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