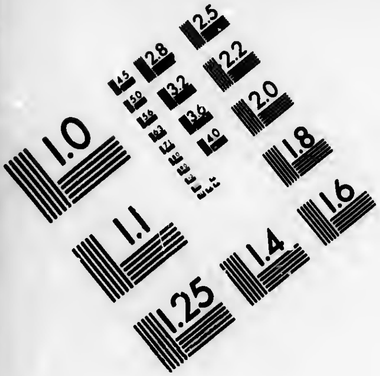

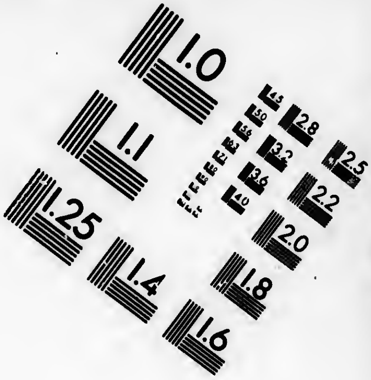

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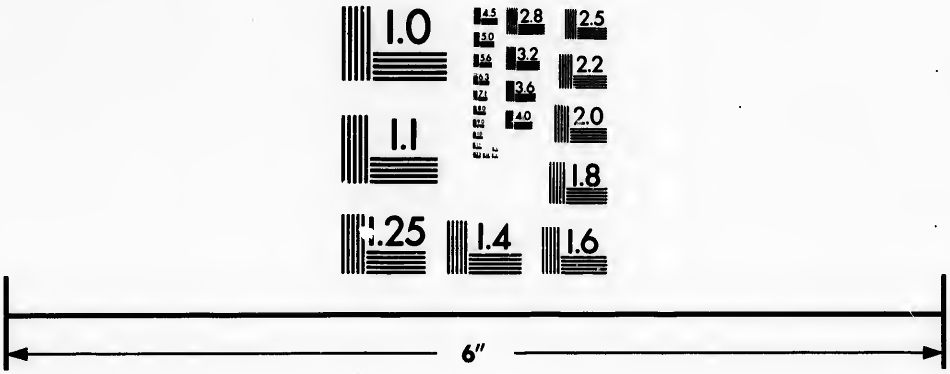

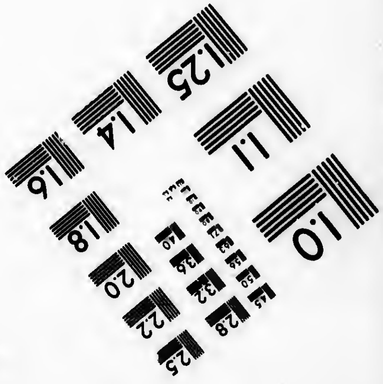

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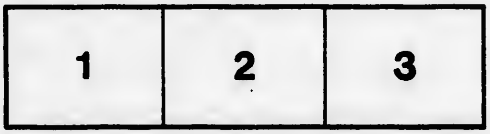
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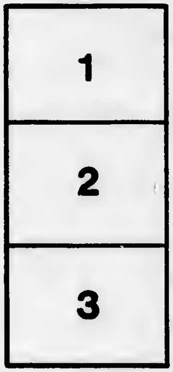
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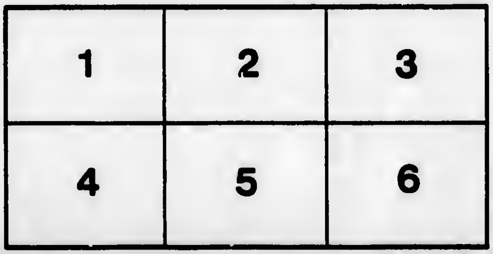
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1906. Lawes

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

SIR JOHN BENNET LAWES, BART., LL.D., F.R.S., F.C.S.,
AND
JOSEPH HENRY GILBERT, PH.D., F.R.S., F.C.S., F.L.S.

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By Sir John Bennet Lawes, Bart., LL.D., F.R.S., F.C.S., and Joseph Henry Gilbert, Ph.D., F.R.S., F.C.S., F.L.S.

Introduction.

It is just about a century since the question of the sources of the nitrogen of vegetation became a subject of experimental inquiry, and also of conflicting opinion. It is nearly half a century since Boussingault was led by a study of the chemistry of agricultural production to see the importance of determining the sources of the nitrogen periodically available to vegetation over a given area of land. Somewhat later the Rothamsted experiments, now in their fortieth year, were commenced, and in their progress many facts have been elicited bearing upon the same subject. Still, almost from the date of Boussingault's first investigations, the question has been one of controversy, and at the present time very conflicting views are entertained respecting it.

For ourselves, we have pointed out how entirely inadequate is the amount of combined nitrogen coming down in the measureable aqueous deposits from the atmosphere to supply the nitrogen of the vegetation of a given area. Other possible supplies of combined nitrogen from the atmosphere have also been considered, and pronounced inadequate. Again, the question whether or not plants assimilate the free or uncombined nitrogen of the atmosphere has been the subject of laborious experimental inquiry, and also of critical discussion, at Rothamsted. Finally, the question whether the stores of the soil itself are an important source of the nitrogen of our crops has frequently been considered.

It may at the outset be frankly admitted that so long as the facts of production alone are studied, without knowledge of, or reference to, the changes in the stock of the nitrogen in the soil, it would seem essential to assume that a large proportion of the nitrogen of crops growing without any direct supply of it by manure, must be derived, in some way or other, from atmospheric sources.

The assumption which is most in favour with some prominent writers is, that whilst some plants derive most or all of their nitrogen from the stores of the soil itself, or from manure applied to it, others derive a large proportion from the free nitrogen of the atmosphere. We, on the other hand, whilst freely admitting that the facts of production are not conclusively explained thereby, have maintained that such collateral evidence as the determinations of nitrogen in our soils afford, is in favour of the supposition that the soil may be the source of the otherwise unexplained supply of nitrogen. This latter conclusion we have frequently stated in general terms; but we have not hitherto published the numerical results upon which it is based. Fairly enough, it has been objected that such an important conclusion cannot be accepted without the numerical evidence to support it. Further, erroneously interpreting our statements, calculations have been made to show that it is quite beyond the reach of present methods of determination of nitrogen in soils to afford results justifying the conclusions we have drawn.

Since this subject of the sources of the nitrogen of our crops has been much discussed in America, it has been thought that it would not be inappropriate to answer the challenge by bringing forward some of the numerical evidence we have accumulated before this meeting of the American Association for the Advancement of Science, and to do this is the object of the present communication.

Before calling attention to the special results in question, it will be necessary, in order to convey a clear idea of the problem to be solved, to recapitulate some of the important facts which have been established as to the amount of nitrogen yielded over a given area by different crops.

In his original inquiries, Boussingault estimated the amounts of nitrogen supplied by manure, and removed in the crops, in ordinary agricultural practice. This mode of estimate is also the one generally adopted by others, and we have ourselves not neglected it. But it is obvious that the results of experiments in which different crops have been grown for very many years in succession on the same land, both separately and in an actual course of rotation, and both without nitrogenous manure and with known quantities of such manure, must afford very important data as to the amounts of nitrogen available to vegetation, from soil and atmosphere, over a given area. The Rothamsted field experiments are pre-eminently adapted to provide such data. Thus, wheat has now been grown for thirty-nine years in succession on the same land; barley for thirty-one years; wheat in alternation with fallow thirty-one years; beans for nearly thirty years; clover for many years; turnips, sugar-beet, or mangels, nearly forty years; whilst experiments on the mixed herbage of grass land have been continued for twenty-seven years, and on an actual course of rotation for thirty-five years. We have, from time to time, published what we may call the nitrogen statistics of the crops so grown; and we have compared these facts of production with what is known of the sources of nitrogen available to the crops.

YIELD OF NITROGEN IN DIFFERENT CROPS.

The following table (I) shows the yield of nitrogen per acre per annum, in wheat, barley, root-crops, beans, clover, and in ordinary rotation, in each case without any nitrogenous manure. It will be observed that only in the case of the root-crops is the record brought down to a later date than 1875. Independently of the fact that the requisite nitrogen determinations are not yet completed for the subsequent period, it has been decided that, owing to the number of very exceptionally unfavourable seasons for corn crops which have occurred since 1875, it would be fallacious to bring the results for those crops in the later seasons as illustrating the falling off of yield due to soil exhaustion.

TABLE I.

Yield of Nitrogen per acre per annum in various Crops grown at Rothamsted, without Nitrogenous Manure.

Crops, &c.	Condition of Manuring, &c.		Duration of Experiment.	Average Nitrogen per Acre per annum.
				lbs.
Wheat....	Unmanured		8 years, 1844–'51	25·2
			12 years, 1852–'63	22·6
			12 years, 1864–'75	15·9
			24 years, 1852–'75	19·3
			32 years, 1844–'75	20·7
	Complex mineral manure......		12 years, 1852–'63	27·0
			12 years, 1864–'75	17·2
			24 years, 1852–'75	22·1
Barley....	Unmanured		12 years, 1852–'63	22·0
			12 years, 1864–'75	14·6
			24 years, 1852–'75	18·3
	Complex mineral manure......		12 years, 1852–'63	26·0
			12 years, 1864–'75	18·8
			24 years, 1852–'75	22·4
Root-crops	Complex mineral manure......	Turnips......	8 years, 1845–'52	42·0
		(Barley).....	3 years, 1853–'55	(24·3)
		Turnips......	15 years, 1856–'70*	18·5
		Sugar beet...	5 years, 1871–'75	13·1
		Mangels.....	5 years, 1876–'80	15·5
		Total........	36 years, 1845–'80	25·2
Beans	Unmanured		12 years, 1847–'58	48·1
			12 years, 1859–'70†	14·6
			24 years, 1847–'70	31·3
	Complex mineral manure......		12 years, 1847–'58	61·5
			12 years, 1859–'70†	29·5
			24 years, 1847–'70	45·5
Clover....	Unmanured		22 years, 1849–'70‡	30·5
	Complex mineral manure........		22 years, 1849–'70‡	39·8
Barley....	Unmanured		1 year, 1873	37·3
Clover....			1 year, 1873	151·3
Barley......	Unmanured	After barley..	1 year, 1874	39·1
		After clover ..	1 year, 1874	69·4
	Barley after clover more than after barley...............		—	30·3
Rotation.. 7 courses..	1. Turnips...... 2. Barley ...... 3. Clover or beans 4. Wheat.......	Unmanured .	28 years, 1848–'75	36·8
		Superphosphate ..	28 years, 1847–'75	45·2

* Thirteen years' crop, two years failed.

† Nine years' beans, one year wheat, two years' fallow.

‡ Six years' clover, one year wheat, three years' barley, twelve years' fallow.

Yield of Nitrogen in Wheat and Barley.

The first series of results relates to the yield of nitrogen in wheat grown thirty-two years in succession on the same land without manure. It is seen that, over the first eight years, the yield was 25·2 pounds of nitrogen per acre per annum, over the next twelve years 22·6 pounds, and over the last twelve of the thirty-two years only 15·9. There has thus been a considerable reduction in the annual yield of nitrogen over each succeeding period; and for the third period of twelve years the average is less than two-thirds as much as for the first period of eight years.

Excluding the first eight years of the growth of wheat, the average annual yield of nitrogen over the next twenty-four years was 19·3 pounds per acre per annum; and the table shows that over the same twenty-four years, barley without manure yielded 18·3 pounds; and whilst with the wheat the decline in yield was from 22·6 pounds over the first twelve of the twenty-four years to 15·9 over the second twelve, it was with the barley from 22·0 to 14·6 pounds, or almost in the same proportion.

It might be objected that here the evidence is not conclusive that the falling off is due to the gradual reduction in the amount of nitrogen annually available from the soil. But the results with the two crops, where there is a liberal supply of mineral constituents every year, exclude the supposition that the decline is due to the exhaustion of mineral constituents. Thus, over the same twenty-four years, with a complex mineral manure, such as is very effective in conjunction with artificial supply of nitrogen to the soil, the yield of nitrogen in the wheat falls off from 27·0 pounds per acre per annum over the first twelve years, to 17·2 pounds over the second twelve years; and in the barley, over the same two periods, it declines from 26·0 to 18·8 pounds.

The similarity in the actual yield, and in the rate of decline of yield, of nitrogen over the same periods in these two closely allied crops, though growing in different fields, and with somewhat different previous manurial history, is very striking. The slightly higher yield in both cases with than without the mineral manure is doubtless due to more complete utilisation of the previous accumulations within the soil, and not to increased assimilation from atmospheric sources.

Yield of Nitrogen in Root-crops.

We now come to the yield of nitrogen by plants of other natural families, and the first of such results relate to the so-called "root-crops"—turnips of the natural order Cruciferæ, and sugar-beet, and mangel-wurzel of the order Chenopodiaceæ. The table records the results for thirty-six years in succession, 1845–1880; but it should be stated that during three of those years barley was interposed without any manure, in order, as far as possible, to equalise the condition of the land before re-arranging the manuring; and during two other years the turnips failed, and there was no crop. It should be further explained that, without manure of any kind, root-crops, after a few years, give scarcely any produce at all, and hence the results selected, and recorded in the table, are those obtained by the use of mineral manures, but without any supply of nitrogen.

During the first eight years (four years Norfolk whites and four years Swedes), the turnips gave an average of 42 pounds of nitrogen per acre per annum, or very much more than either of the cereal crops. During the next three years barley (without manure) yielded 24·3 pounds, or even somewhat less than the yield in wheat or barley with mineral manures in the earlier years of their continuous growth. During the next fifteen years (thirteen with Swedish turnips and two without any crop), the yield was reduced to 18·5 pounds; during the next five years, with sugar-beet, to 13·1 pounds; and during the last five years, to 1880 inclusive (with mangel-wurzel), to 15·4 pounds. Lastly, over the whole thirty-six years, the average annual yield of nitrogen was 25·2 pounds.

Here, then, compared with wheat or barley, we have with the root-crops, the growth of which extends much further into the autumn months, a much higher annual yield of nitrogen in the earlier years, and with this a much more rapid rate of decline subsequently, the annual yield over the last ten years being only about one-third as much as over the first eight years; whilst the yield in the later years is actually less than in either wheat or barley with the same complex mineral manure. Here, again, the marked decline in the yield of nitrogen, with liberal mineral manuring, points to a deficiency in the available supply of nitrogen itself as the cause of the deficient assimilation of it by the crop.

It may here be observed, that those who maintain that the atmosphere is an important source of the nitrogen of our crops assume that the root-crops, if provided with a small quantity of nitrogenous manure to favour the early development of the plant, will obtain the remainder from the atmosphere. How far this is the case may be illustrated by the following results, which are the average of five years' successive growth of mangel-wurzel on the same plots, and in each case with the same manure year after year.

TABLE II.

Average produce of Mangel-wurzel five years, 1876—1880.

	Roots.		Leaves.	
	Tons.	Cwt.	Tons.	Cwt.
1. Superphosphate of lime, and sulphate potassium .	4	10	1	0
2. As 1, and 36½ lbs. ammonium salts (= 7·8 lbs. N) .	6	0	1	6
3. As 1, and 400 lbs. ammonium salts (= 86 lbs. N) .	14	0	2	16

Thus, the annual application of about 7·8 pounds of nitrogen, as ammonium salts, has increased the crop of roots by only 30 cwts. per acre per annum; and the increased yield of nitrogen in the crop was even somewhat less than the amount supplied in the manure. An application of 86 pounds of nitrogen has, however, increased the crop by 160 cwts. more. It is obvious from these facts, that the small application of nitrogen did not enable the plant to take up any from atmospheric sources, and that it required further direct supply of nitrogen to obtain further increase of crop. These results obviously afford confirmation of the view that it was a reduction of the available supply of nitrogen within the soil that was the cause of the decline in the annual yield of the crop, and of the amount of nitrogen contained in it.

Yield of Nitrogen in Leguminous Crops.

We next come to the consideration of the yield of nitrogen in crops of the leguminous family, when these are grown separately, year after year, on the same land. Plants of this family are said to rely almost exclusively on atmospheric sources for their nitrogen.

Table I shows that, without manure, beans gave over the first twelve years an annual yield of 48·1 pounds of nitrogen, but over the second twelve only 14·6 pounds. Over the first period, therefore, the yield was about twice as much as in either wheat or barley, and more even than with the roots. But with this greater yield in the earlier years, the reduction is proportionally much greater over the second period; the yield then coming down to less than one-third, and to much the same as in the later periods with the other crops. Over the whole period of twenty-four years, however, there was an annual yield of 31·3 pounds of nitrogen, or more than one and a half time as much as in either wheat or barley, and more than in the roots.

It was seen that in the case of the cereal crops the mixed mineral manure increased the yield of nitrogen but little. Not so in the case of the leguminous crop, beans. During the first twelve years, the complex mineral manure (containing a large amount of potash) yielded 61·5 pounds of nitrogen per acre per annum, against 48·1 pounds without manure. During the next twelve years, the mineral manure gave 29·5 pounds, against only 14·6 pounds without manure. During the whole period of twenty-four years, the potash manure yielded 45·5 pounds of nitrogen per acre per annum, against 31·3 pounds without manure. Lastly, with the mixed mineral manure beans have yielded over a period of twenty-four years more than twice as much nitrogen per acre as either wheat or barley.

But notwithstanding that the beans have for a long series of years yielded so very much more nitrogen over a given area than either of the gramineous crops, and much more also than the root-crops, the significant fact cannot fail to be observed that this crop of the leguminous family, which is supposed to rely almost exclusively on the atmosphere for its nitrogen, has declined in yield as strikingly as the other crops, even when grown by a complex mineral manure, containing a large amount of potash. Why should this be so if the supply of nitrogen is from the atmosphere and not from the soil?

The results next recorded relate to red clover, and the period of experiment was twenty-two years. It is well known that on most soils a good crop of clover cannot be relied upon oftener than once in about eight years, and on many soils not so frequently. It will not excite surprise, therefore, that in the course of the twenty-two years of experiment, in only six was any crop of clover obtained, and in some of those only poor ones. Indeed, the plant failed nine times out of ten during the winter and spring succeeding the sowing of the seed. In one year a crop of wheat, and in three years barley, was taken instead; whilst in the remaining twelve years the land was left fallow after the failure of the clover. Still the annual yield of nitrogen over the twenty-two years was 30·5 pounds without any manure, and 39·8 pounds by a complex mineral manure containing potash. Unfavourable as is this result in an agricultural point of view, it is still seen that the interpolation of this leguminous crop has greatly increased the yield of nitrogen compared with that in either wheat or barley grown continuously; and here again, as with beans, a potash manure has considerably increased the yield.

The next experiment affords a still more striking illustration of the large amount of nitrogen that may be taken up in a clover crop; and it further illustrates the fact, well known in agriculture, that the removal of this highly nitrogenous leguminous crop is one of the best possible preparations for the growth of a cereal crop, which characteristically requires nitrogenous manuring. A field which had grown six corn crops in succession, by artificial manures alone, was then divided, and (in 1873) on one half barley, and on the other half clover, was grown. The barley yielded 37·3 pounds of nitrogen per acre; but the three cuttings of clover yielded 151·3 pounds. In the next year (1874) barley was grown on both portions of the field. Where barley had previously been grown, and had yielded 37·3 pounds of nitrogen per acre, it now yielded 39·1 pounds; but where the clover had previously been grown, and had yielded 151·3 pounds of nitrogen, the barley succeeding it gave 69·4 pounds, or 30·3 pounds more nitrogen after the removal of 151·3 pounds in clover than after the removal of only 37·3 pounds in barley. It will be seen further on that this result was not in any way accidental.

Yield of Nitrogen by a Rotation of Crops.

The last results recorded in the table relate to the yield of nitrogen in an ordinary four-course rotation of—turnips, barley, clover or beans, and wheat. The average yield per annum is given for seven courses, or for a period of twenty-eight years; in one case without any manure during the whole of that time, and in the other with superphosphate of lime alone, applied once every four years, that is, for the turnips commencing each course.

Here, with a turnip crop, and a leguminous crop, interpolated with two cereal crops, we have, without manure of any kind, an average of 36·8 pounds of nitrogen per acre per annum, or very much more than was obtained in either of the cereal crops grown consecutively. With superphosphate of lime alone, which much increased the yield of nitrogen in the turnips, reduced it in the succeeding barley, increased it greatly in the leguminous crops, and slightly in the wheat succeeding them, the average annual yield of nitrogen is increased to 45·2 pounds, or to about double that obtained in either wheat or barley grown consecutively by a complete mineral manure. On this point it may be further remarked that in adjoining experiments, in which, instead of a leguminous crop, the land was fallowed in the third year of each course, the total yield of nitrogen in the rotation was very much less. In other words, the removal of the most highly nitrogenous crops of the rotation—clover or beans—was succeeded by a growth of wheat, and an assimilation of nitrogen by it, almost as great as when it succeeded a year of fallow; that is, a period of some accumulation by rain, &c., and of no removal by crops.

Yield of Nitrogen in the Mixed Herbage of Grass Land.

Another illustration of the amounts of nitrogen removed from a given area of land by different descriptions of crop will be found in Table III, which shows the results obtained when plants of the gramineous, the leguminous, and other families, are grown together, in the mixed herbage of grass land.

TABLE III.

Yield of Nitrogen on the Mixed Herbage of Permanent Grass Land at Rothamsted.

Plots.	Conditions of Manuring.	Average Produce per acre per annum, 20 years, 1856–1875, according to mean per cent., at six periods, 1862, '67, '71, '72, '74, '75.			Average Nitrogen per Acre per annum.		
		Gramineæ.	Leguminosæ.	Other Orders.	Ten years 1856–1865.	Ten years 1866–1875.	Twenty years 1856–1875.
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
3	Unmanured........	1635	219	529	35·1	30·9	33·0
4–1	Superphosphate*....	1671	149	673	35·7	31·5	33·6
8	Complex Min. Man.†	2442	296	639	54·4	38·1	46·3
7	Complex Min. Man.‡	2579	806	573	55·2	56·0	55·6

Before referring to the figures, attention should be called to the fact that gramineous crops grown separately on arable land, such as wheat, barley, or oats, contain a comparatively low percentage of nitrogen, and assimilate a comparatively small amount of it over a given area. Yet nitrogenous manures have generally a very striking effect in increasing the growth of such crops. The highly nitrogenous leguminous crops, on the other hand, such as beans and clover, yield, as has been seen, very much more nitrogen over a given area: yet they are by no means characteristically benefited by nitrogenous manuring, but their growth is considerably increased, and they yield considerably more nitrogen over a given area, under the influence of purely mineral manures, and especially of potash

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* Mean of four separations only, namely, 1862, 1867, 1872, and 1875.

† Including potash, six years, 1856–1861; without potash, 14 years, 1862–1875.

‡ Including potash, 20 years, 1856–1875.

manures. Bearing these facts in mind, the results given in the table will be seen to be quite consistent.

The first three columns in the table show, approximately, how the mixed herbage was made up under the four different conditions of manuring. It will be observed that, without manure, and with superphosphate of lime alone, both the proportion and the amount of the different descriptions of herbage are much the same. Plot 8, with a complex mineral manure, including potash the first six years, but excluding it the next fourteen years, gave a considerable increase of both gramineous and leguminous herbage; whilst plot 7, with a complex mineral manure, including potash every year of the twenty, there is a still further increase of gramineous herbage, but a very much greater proportional increase of leguminous herbage.

It will be observed how much greater is the increase of gramineous produce by the application of purely mineral manures to this mixed herbage than in the case of gramineous crops grown separately. It is a question how far this is due to the mineral manures enabling the grasses to form much more stem and seed, that is, the better to mature, which in fact they do; how far to their favouring more active nitrification in the more highly nitrogenous permanent mixed herbage soil; or how far to an increased amount of combined nitrogen in a condition available for the grasses in the upper layers of the soil, as the result of the increased growth of the Leguminosæ in the first instance, induced by the potash manure, as in the case of the alternation of clover and barley, and as in the actual course of rotation?

To turn to the yield of nitrogen on the different plots of the mixed herbage, it will be seen that the amounts are almost identical without manure, and with superphosphate of lime alone, about 33 pounds per acre per annum. On plot 8, where a complex mineral manure, including potash six years, but excluding potash fourteen years, was employed, the amount is raised to 46·3 pounds; and on plot 7, which received the mixed mineral manure, including potash every year of the twenty, the yield is 55·6 pounds per acre per annum. Further, without manure, and with superphosphate of lime alone, there was a decline in the yield of nitrogen in the later, compared with the earlier years. With the mineral manure, including potash in the first six years only, there was a much more marked decline. With the mineral manure, including potash every year, there was, on the other hand, even a slight tendency to an increased yield of nitrogen in the later years.

Yield of Nitrogen in Melilotus Leucantha.

One more striking illustration of high yield of nitrogen by a plant of the leguminous family, this time on soil which had not received any nitrogenous manure for nearly thirty years, must be given. In 1878, the land upon which attempts had been made to grow red clover in frequent succession since 1849, was devoted to experiments with fourteen different descriptions of leguminous plants; so that the present season, 1882, is the fifth year of the experiments. The object was to ascertain whether, among a selection of plants, all of the leguminous family, but of different habits of growth, and especially of different character and range of roots, some could be grown successfully for a longer time, and would yield more produce, containing more nitrogen as well as other constituents, than others; all being supplied with the same descriptions and quantities of manuring substances, applied to the surface soil. Further, whether the success in some cases and the failure in others, would afford additional evidence as to the source of the nitrogen of the Leguminosæ generally, and as to the causes of the failure of red clover in particular, when it is grown too frequently on the same land. Fourteen different descriptions of plants were selected, and, after two or three immaterial changes, the list at the present time includes eight species or varieties of *Trifolium*, two of *Medicago*, *Melilotus leucantha*, *Lotus corniculatus*, *Vicia sativa*, and *Onobrychis sativa.*

Of the numerous species or varieties of *Trifolium*, all gave but meagre produce, excepting *T. incarnatum.* The *Lotus corniculatus* also gave very small produce. The two species of *Medicago*, the black *Medick*, and the purple *Medick* or Lucerne, and the *Onobrychis*, or common Sainfoin, gave much more; the *Vicia sativa* or common vetch, more still. But of all, the *Melilotus leucantha*, or Bokhara clover, has yielded the most. It is estimated that, taking the average of four years, 1878–81, it yielded about 70 pounds of nitrogen per acre per annum, on plots which have received no nitrogenous manure for more than thirty years; whilst the produce of the fifth season, 1882, is heavier than in either of the preceding years; and it is estimated to contain about 150 pounds of nitrogen. In fact, in the second, as well as in the fifth year, the *melilotus* yielded considerably more than 100 pounds of nitrogen per acre; and on the average of the five years it has yielded between 80 and 90 pounds per acre on this nitrogen-exhausted soil.

How long this very luxuriant growth, and this very high yield of nitrogen per acre, will continue, is a question of very great interest.

On this point it may be observed that, in parts of the continent of Europe where some of the very free-growing and deep-rooted Leguminosæ are cultivated, it is usual to let them grow for several years, after which they cannot be repeated for twenty years or more. We shall recur to the results above quoted further on.

SUMMARY OF YIELD OF NITROGEN IN CROPS.

The foregoing facts of production, showing the yield of nitrogen in different crops grown without nitrogenous manure, generally for very many years in succession on the same land, may be briefly summed up as follows:

The average yield of nitrogen per acre per annum, was, with wheat, thirty-two years without manure, 20·7 pounds, and twenty-four years with a complex mineral manure, 22·1 pounds; with barley, twenty-four years without manure, 18·3 pounds, and twenty-four years with a complex mineral manure, 22·4 pounds; with root-crops, thirty-six years (including three of barley), with a complex mineral manure, 25·2 pounds; with beans, twenty-four years without manure, 31·3 pounds, and twenty-four years with a complex mineral manure, 45·5; with clover, six crops in twenty-two years, with one crop of wheat, three crops barley, and twelve years fallow, without manure, 30·5 pounds; with complex mineral manure, 39·8 pounds; with clover, on land which had not grown the crop for very many years, one year, 151·3 pounds; with a rotation of crops, seven courses, twenty-eight years, without manure, 36·8 pounds, and with superphosphate of lime, 45·2 pounds; with the mixed herbage of grass land, twenty years without manure, 33 pounds, and with complex mineral manure, including potash, 55·6; lastly, with Bokhara clover, five years, with mineral manure, between 80 and 90 pounds of nitrogen per acre per annum.

The root-crops yielded more nitrogen than the cereal crops, and the leguminous crops very much more still.

In all the cases of the experiments on ordinary arable land—whether with cereal crops, root-crops, leguminous crops, or a rotation of crops (excepting as yet the Bokhara clover)—*the decline in the annual yield of nitrogen, none being supplied by manure, was very great.*

SOURCES OF THE NITROGEN OF CROPS.

We must next consider whence comes the nitrogen of the crops, and especially whence comes the much larger amount taken up by plants of the leguminous, and some other families, than by the

Gramineæ. Lastly, what is the significance of the great decline in the yield of nitrogen in all the crops grown on arable land when none is supplied in the manure?

Combined Nitrogen in Rain, &c.

It has been assumed by some that the amount of combined nitrogen annually coming down in the measured aqueous deposits from the atmosphere is sufficient for all the requirements of annual growth. In Liebig's earlier writings he assumed the probability of a very much larger quantity of ammonia coming down in rain than he did subsequently; but even in his more recent work, "The Natural Laws of Husbandry," published in 1863, he supposes that as much as 24 pounds of nitrogen per acre may be annually available to vegetation from that source. Such an amount would, it is obvious, do much towards meeting the requirements of many of the crops the nitrogen statistics of which have been given.

The earliest considerable series of determinations of the amount of ammonia coming down in rain in the open country were by Boussingault, in Alsace. He gives the amount of ammonia per million of rain-water in each fall for a period of between five and six months, May–October, 1852; but he does not calculate the amount so coming down over a given area of land. His average amount per million was, however, somewhat less than that found at Rothamsted in 1853 and 1854, and found by Mr. Way in Rothamsted rain-water collected in 1855 and 1856; which, calculated according to the rain-fall of the periods, give the following amounts of nitrogen so coming down per acre. The amounts of nitrogen as nitric acid, as determined by Mr. Way, and the amount of total combined nitrogen as ammonia and nitric acid together, are also given.

TABLE IV.

Nitrogen, as Ammonia and Nitric Acid, in the Rainfall of Three Years, at Rothamsted, in Pounds per Acre.

Years.	Rainfall.	Nitrogen per Acre, as—		
		Ammonia.	Nitric Acid.	Total Nitrogen.
	Inches.	lbs.	lbs.	lbs.
1853–'54	29·014	5·20	(0·74)	5·94
1855..................	29·166	5·82	0·72	6·58
1856..................	27·215	7·28	0·76	8·00
Mean	28·465	6·10	0·74	6·84

It will be seen that, according to these results, an average of 6·84 pounds was contributed per acre per annum in the rain in the form of ammonia and nitric acid. More recently, however, Dr. Frankland has determined the amount of ammonia and nitric acid in numerous samples of rain and snow water, dew, hoar-frost, &c., collected at Rothamsted from April, 1869, to May, 1870, inclusive: and the average amount of ammonia per million of water found by him is considerably lower than the earlier determinations show. More recently still the ammonia has been determined in the Rothamsted laboratory, in the rain of each day separately (if any), for a period of six months, July–December, 1881; also in the proportionally mixed rain for each month, for a period of thirteen months, June, 1881, to June, 1882. The average proportion of ammonia in these most recent determinations accords with the results of Dr. Frankland, and points to a smaller amount of total combined nitrogen supplied per acre in the average annual rainfall at Rothamsted than that recorded in the table; probably, indeed, to not more than four or five pounds of total combined nitrogen per acre per annum.

Dr. R. Angus Smith, in his work entitled "Air and Rain, the Beginnings of a Chemical Climatology," 1872, gives the results of numerous analyses of rain-water collected both in country and town districts in the United Kingdom. The amounts of ammonia and nitric acid in the rain vary exceedingly, according to locality; but the amounts in the rain of country places accord generally with those found in the Rothamsted rainfall.

The following table summarises the results of numerous determinations made at various stations on the continent of Europe, in each case extending over a whole year:—

TABLE V.

Nitrogen as Ammonia and Nitric Acid in the Rain of various Localities in Europe.

[Quantities in Pounds per Acre per Annum.]

Localities.	Years.	Rainfall.	Nitrogen as—		
			Ammonia.	Nitric Acid.	Total.
		Inches.	lbs.	lbs.	lbs.
Kuschen	1864–'65	11·85	1·44	0·42	1·86
Kuschen	1865–'66	17·70	1·83	0·67	2·50
Insterburg	1864–'65	27·55	3·55	1·94	5·49
Insterburg	1865–'66	23·79	4·14	2·67	6·81
Dahme	1865	17·09	5·50	1·16	6·66
Regenwalde	1864–'65	23·48	10·82	4·27	15·09
Regenwalde	1865–'66	19·31	8·27	2·11	10·38
Regenwalde	1866–'67	25·37	13·20	3·24	16·44
Ida-Marienhütte; mean six years	1865–'70	22·65	..	..	9·92
Proskaw	1864–'65	17·81	13·58	7·33	20·91
Florence	1870	36·55	9·71	3·65	13·36
Florence	1871	42·48	7·78	2·11	9·89
Florence	1872	50·82	9·50	3·01	12·51
Vallombrosa	1872	79·83	7·65	2·73	10·38
Montsouris, Paris	1877–'78	23·62	10·25	1·29	11·54
Montsouris, Paris	1878–'79	25·79	7·05	4·11	11·16
Montsouris, Paris	1879–'80	15·70	4·83	5·69	10·52
Mean, 22 years	..	27·03	..	..	10·23

It is seen that the numerous very widely varying determinations, some made in the vicinity of towns and some in the open country, give a mean of 10·23 pounds of combined nitrogen annually supplied per acre by rain with a mean rainfall of 27·03 inches. Making all allowance for far inland open country positions on the one hand, and for proximity to towns on the other, the very small amounts of combined nitrogen so supplied per acre in some of the cases, and the comparatively large quantities in others, seem difficult to explain, or to reconcile, either with one another or with the results of Boussingault and of Rothamsted. When, however, the comparatively limited and uniform total amounts recorded for Montsouris, within the walls of Paris, are considered, 11·54 pounds, 11·16 pounds, and 10·52 pounds per acre per annum, it will not excite surprise that we should estimate the amount of combined nitrogen coming down in the measured aqueous deposits from the atmosphere at probably not more than, if as much as, 5 pounds per acre per annum in the open country at Rothamsted.

With records of the amounts of combined nitrogen contributed to a given area in rain, we come to an end of all quantitative evidence as to the amount of combined nitrogen available to the vegetation of a given area from atmospheric sources. It will be seen how entirely inadequate is the amount probably so available to supply the quantities yielded in different crops grown without nitrogenous manure, as recorded in Tables I and III (pp. 8 and 14).

It is true that the minor aqueous deposits from the atmosphere are much richer in combined nitrogen than rain, and there can be no doubt that there would be more deposited within the pores of a given area of soil than on an equal area of the non-porous even surface of a rain-gauge. How much, however, of this might be available beyond that determined in the collected aqueous deposits, existing evidence does not afford the means of estimating with certainty.

Other Supposed Sources of Combined Nitrogen.

Further, it has been argued that, in the last stages of the decomposition of organic matter in the soil, hydrogen is evolved, and that this nascent hydrogen combines with the free nitrogen of the atmosphere, and so forms ammonia. Again, it has been suggested that ozone may be evolved in the oxidation of organic matter in the soil, and that, uniting with free nitrogen, nitric acid would be produced.

We have discussed these various possible supplies of combined nitrogen to the soil from atmospheric sources on more than one occasion; and we have given our reasons for concluding that none of them can be taken as accounting for the facts of growth. Incidentally, some evidence will be given further on, confirming the conclusion that any such supplies are limited and inadequate.

But, if the supplies from the atmosphere to the soil itself are inadequate, how about the direct supplies from the atmosphere to the plant?

One view which has been advocated is, that broad-leaved plants have the power of taking up combined nitrogen from the atmosphere, in a manner, or in a degree, not possessed by the narrow-leaved gramineous plants. The only experiments that we are aware of, made to determine whether plants can take up nitrogen by their leaves from ammonia supplied to them in the ambient atmosphere, are those of Adolph Mayer in Germany, and of Schlösing in France. Both found that very small quantities of nitrogen were so taken up; but both concluded that the action takes place in very immaterial degree in natural vegetation.

We have elsewhere shown that a consideration of the chemistry and the physics of the subject would lead to the conclusion that the plants which assimilate more nitrogen over a given area than others do not do so by virtue of a greater power of absorbing already combined nitrogen from the atmosphere by their leaves. But, apart from such considerations, our statistics of nitrogen production seem to preclude the idea that the broad-leaved root-crops, turnips and the like, to which the function has with the most confidence been attributed, take up any material proportion of their nitrogen by their leaves from combined nitrogen in the atmosphere. We need only here recall attention to the fact that the yield of nitrogen in these crops, even with the aid of a complex mineral manure, was in the later years reduced to as low a point as in the case of the narrow-leaved cereals.

Do Plants Assimilate Free Nitrogen?

The question still remains to consider—whether plants assimilate the free nitrogen of the atmosphere, and whether some descriptions do so in a much greater degree than others? It is freely admitted that if this were established many of our difficulties would vanish.

This question has been the subject of a great deal of experimental inquiry, since the time that Boussingault entered upon it about the year 1837; and more than twenty years ago it was elaborately investigated at Rothamsted.

We will here give a summary of the very conflicting results which have been published in reference to this subject of the assimilation of the free nitrogen of the atmosphere by plants, confining attention, for want of space, to the three most comprehensive series of experiments which have been undertaken relating to it.

Though not the first in point of date, we will first refer to the experiments of M. G. Ville, the results of which led him to conclude that plants do assimilate the free nitrogen of the air—a view of which he has been the arch-apostle for many years, and upon which he may be said to have founded a system, in his work on "Artificial Manures."

From 1849 to 1856, M. G. Ville made numerous experiments on this subject. The following table (VI) gives a summary of his results, and shows the special conditions of each separate series of experiments:—

TABLE VI.

Results of M. G. VILLE'S *Experiments, to determine whether Plants assimilate free Nitrogen.*

Plants.	Nitrogen, grams.			Nitrogen in Products to 1 Supplied.
	In Seed, and Air; and Manure, if any.	In Products.	Gain or Loss.	
1849: *Current of unwashed air supplying* 0·001 *gram N. as Ammonia.**				
Cress	0·0260	0·1470	0·1210	5·6
Large Lupins	0·0640	0·0640	0·0000	1·0
Small Lupins	0·0640	0·0470	– 0·0170	0·7
	0·1550	0·2580	0·1030	1·7
1850: *Current of unwashed air supplying* 0·0017 *gram N. as Ammonia.**				
Colza (plants)	0·0260	1·0700	1·0440	41·1
Wheat	0·0160	0·0310	0·0150	1·9
Rye	0·0130	0·0370	0·0240	2·8
Maize	0·0290	0·1280	0·0990	4·4
	0·0857	1·2660	1·1803	14·8
1851: *Current of washed air.**				
Sunflower	0·0050	0·1570	0·1520	31·4
Tobacco	0·0040	0·1750	0·1710	43·7
Tobacco	0·0040	0·1620	0·1580	40·5
1852: *Current of washed air.**				
Autumn Colza	0·0480	0·2260	0·1780	4·7
Spring Wheat	0·0290	0·0650	0·0360	2·2
Sunflower	0·0160	0·4080	0·3920	25·5
Summer Colza	0·1730	0·5950	0·4220	3·4
Summer Colza	0·1050	0·7010	0·5960	6·7
1854: *Current of washed air (under superintendence of a Commission).*				
Cress	0·0099	0·0097	–0·0002	1·0
Cress	0·0038	0·0530	0·0492	13·9
Cress	0·0039	0·0110	0·0071	2·8

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* Recherches Expérimentales sur la Végétation, par M. Georges Ville, Paris, 1853.

TABLE VI.—*continued.*

Plants.	Nitrogen, grams.			Nitrogen in Products to 1 Supplied.
	In Seed, and Air; and Manure, if any.	In Products.	Gain or Loss.	
1854: *Current of washed air (closed, superintended by a Commission).**				
Cress..................	0·0063	0·0350	0·0287	5·6
1855 *and* 1856: *In pure air, with* 0·5 *gram Nitre* = 0·069 *Nitrogen.*†				
Colza..................	0·0700	0·0700‡	0·0000	1·0
Colza..................	0·0700	0·0660‡	−0·0040	0·9
Colza..................	0·0700	0·0680‡	−0·0020	1·0
1855 *and* 1856: *In free air, with* 1 *gram Nitre* = 0·138 *Nitrogen.*†				
Colza..................	0·1400	0·1970‡	0·0570	1·41
Colza..................	0·1400	0·3740‡	0·2340	2·67
Colza..................	0·1400	0·2160‡	0·0760	1·54
Colza..................	0·1400	0·2500‡	0·1100	1·79
1856: *In free air, with* 0·792 *gram Nitre* = 0·110 *Nitrogen.*†				
Wheat	0·1260	0·2180‡	0·0920	1·7
Wheat	0·1260	0·2240‡	0·0980	1·8
1855: *In free air, with* 1·72 *grams Nitre* = 0·238 *Nitrogen.*†				
Wheat	0·2590	0·3080‡	0·0490	1·2
1856: *In free air, with* 1·765 *grams Nitre* = 0·244 *Nitrogen.*†				
Wheat	0·2650	0·2170‡	−0·0480	0·8
Wheat	0·2650	0·3500‡	+0·0850	1·3

These results, as well as those of others, we have fully discussed elsewhere (*Phil. Trans.*, 1859, and *Jour. Chem. Soc.*, vol. xvi, 1863), and we can only very briefly refer to them in this place.

The column of actual gain or loss shows in one case, with colza, a gain of more than 1 gram nitrogen; and the amount in the products is more than forty-one times as much as that supplied as combined

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* Compt. rend., 1855.

† Recherches Expérimentales sur la Végétation, 1857.

‡ In plants only.

nitrogen in the seed and air. The results with wheat, rye, or maize, showed very much less of both actual and proportional gain. Experiments with sunflower showed in one case thirty-fold, and with tobacco in two cases more than forty-fold, as much in the products as was supplied. It will be observed, however, that upon the whole M. G. Ville's later experiments showed considerably less both actual and proportional gain than his earlier ones.

M. G. Ville in some cases attributed the gain to the large leaf surface. In explanation of the assimilation of free nitrogen by plants, he calls attention to the fact that nascent hydrogen is said to give ammonia, and nascent oxygen nitric acid, with free nitrogen, and he asks: Why should not the nitrogen in the juices of the plant combine with the nascent carbon and oxygen in the leaves? He refers to the supposition of M. De Luca, that the nitrogen of the air combines with the nascent oxygen given off by the leaves of plants, and to the fact that the juice of some plants (mushrooms) has been observed to ozonise the oxygen of the air, and he asks: Is it not probable, then, that the nitrogen dissolved in the juices will submit to the action of the ozonised oxygen with which it is mixed, when we bear in mind that the juices contain alkalies, and penetrate tissues, the porosity of which exceeds that of spongy platinum?

The following table (VII) summarises the results of M. Boussingault. His experiments on the subject commenced in 1837, and were continued at intervals up to 1858. The conditions of each set of experiments as to soil, air, or application of manurial substances, are given in the table.

TABLE VII.

Results of M. BOUSSINGAULT'S *Experiments to determine whether Plants assimilate free Nitrogen.*

Plants.	Nitrogen, grams.			Nitrogen in Products to 1 Supplied.
	In Seed, or Plants; and Manure, if any.	In Products.	Gain or Loss.	
1837: *Burnt soil, distilled water, free air, in closed summer-house.**				
Trefoil	0·1100	0·1200	+0·0100	1·09
Trefoil	0·1140	0·1560	+0·0420	1·37
Wheat	0·0430	0·0400	−0·0030	0·93
Wheat	0·0570	0·0600	+0·0030	1·05

* Ann. Ch. Phys. [2], lxvii. (1838).

TABLE VII.—*continued.*

Plants.	Nitrogen, grams.			Nitrogen in Products to 1 Supplied.
	In Seed, or Plants; and Manure, if any.	In Products.	Gain or Loss.	
1838: *Conditions as in* 1837.[*]				
Peas	0·0460	0·1010	+0·0550	2·20
Trefoil (Plants)	0·0330	0·0560	+0·0230	1·70
Oats (Plants)	0·0590	0·0530	−0·0060	0·90
1851 *and* '52: *Washed and ignited pumice with ashes, distilled water, limited air, under glass shade, with Carbonic Acid.*[†]				
Haricot, 1851	0·0349	0·0340	−0·0009	0·97
Oats, 1851	0·0078	0·0067	−0·0011	0·86
Haricot, 1852	0·0210	0·0189	−0·0021	0·90
Haricot, 1852	0·0245	0·0226	−0·0019	0·92
Oats, 1852	0·0031	0·0030	−0·0001	0·97
1853: *Prepared pumice, or burnt brick, with ashes, distilled water, limited air, in glass globe, with Carbonic Acid.*[†]				
White Lupin	0·0480	0·0483	+0·0003	1·01
White Lupin	0·1282	0·1246	−0·0036	0·97
White Lupin	0·0349	0·0339	−0·0010	0·97
White Lupin	0·0200	0·0204	+0·0004	1·02
White Lupin	0·0399	0·0397	−0·0002	1·00
Dwarf Haricot	0·0354	0·0360	+0·0006	1·02
Dwarf Haricot	0·0298	0·0277	−0·0021	0·93
Garden Cress	0·0013	0·0013	0·0000	1·00
White Lupin	0·1827	0·1697	−0·0130	0·93
1854: *Prepared pumice with ashes, distilled water, current of washed air, and Carbonic Acid, in glazed case.*[‡]				
Lupin	0·0196	0·0187	−0·0009	0·95
Dwarf Haricot	0·0322	0·0325	+0·0003	1·01
Dwarf Haricot	0·0335	0·0341	+0·0006	1·02
Dwarf Haricot	0·0339	0·0329	−0·0010	0·97
Dwarf Haricot	0·0676	0·0666	−0·0010	0·99
Lupin	0·0180	0·0334	−0·0021	0·94
Lupin	0·0175			
Cress	0·0046	0·0052	+0·0006	1·13

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[*] Ann. Ch. Phys. [2], lxix. (1838).

[†] Ann. Ch. Phys. [3], xli. (1854).

[‡] Ann. Ch. Phys., Sér. [3], xliii. (1855).

TABLE VII.—*continued.*

Plants.	Nitrogen, grams.			Nitrogen in Products to 1 Supplied.
	In Seed, or Plants; and Manure, if any.	In Products.	Gain or Loss.	
1851, '52, '53, *and* '54: *Prepared soil, or pumice with ashes; distilled water, free air, under glazed case.**				
Haricot (dwarf), 1851....	0·0349	0·0380	+0·0031	1·09
Haricot, 1852	0·0213	0·0238	+0·0025	1·12
Haricot, 1853	0·0293	0·0270	−0·0023	0·92
Haricot (dwarf), 1854....	0·0318	0·0350	+0·0032	1·10
Lupin (white), 1853	0·0214	0·0256	+0·0042	1·20
Lupin, 185[illegible]	0·0199	0·0229	+0·0030	1·15
Lupin, 1854	0·0367	0·0387	+0·0020	1·05
Oats, 1852	0·0031	0·0041	+0·0010	1·32
Wheat, 1853............	0·0064	0·0075	+0·0011	1·17
Garden Cress, 1854......	0·0259	0·0272	+0.0013	1·05
1858: *Nitrate of Potassium as Manure.†*				
Helianthus	0·0144‡	0·0130	−0·0014	0·90
	0·0255‡	0·0245	−0·0010	0·96

The last two columns of the table (VII) show the actual and proportional gain or loss of nitrogen in M. Boussingault's experiments. It will be seen that in his earlier experiments, those in free air in a summer house, the leguminous plants, trefoil and peas, did indicate a notable gain of nitrogen: but, in all his subsequent experiments, there was generally either a slight loss, or, if a gain, it was represented in only fractions, or low units, of milligrams. After 20 years of varied and laborious investigation of the subject, M. Boussingault concluded that plants have not the power of assimilating the free nitrogen of the atmosphere. And in a letter received from him as recently as 1876, after discussing several aspects of the question, he says:—

"If there is one fact perfectly demonstrated in physiology, it is this of the non-assimilation of free nitrogen by plants; and I may add by plants of an inferior order, such as mycoderms and mushrooms."—(Translation.)

Our own experiments on this subject were commenced in 1857, and a young American chemist, the late Dr. Pugh, of the Pennsylvania

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* Ann. Ch. Phys., Sér. [3], xliii. (1855).

† Compt. rend., xlvii. (1858).

‡ Nitrogen in Seed and Nitrate.

TABLE VIII.

Results of Experiments made at Rothamsted to determine whether Plants assimilate free Nitrogen.

			Nitrogen, grams.			Nitrogen in Products to 1 Supplied.
			In Seed, and Manure, if any.	In Plants, Pot, and Soil.	Gain or Loss.	
With NO *combined Nitrogen supplied beyond that in the seed sown.*						
Gramineæ	1857	Wheat....	0·0080	0·0072	−0·0008	0·90
		Barley....	0·0056	0·0072	+0·0016	1·11
		Barley....	0·0056	0·0082	+0·0026	1·46
	1858	Wheat....	0·0078	0·0081	+0·0003	1·04
		Barley....	0·0057	0·0058	+0·0001	1·02
		Oats......	0·0063	0·0056	−0·0007	0·89
	1858 A*	Wheat....	0·0078	0·0078	0·0000	1·00
		Oats......	0·0064	0·0063	−0·0001	0·98
Leguminosæ ..	1857	Beans	0·0796	0·0791	−0·0005	0·99
	1858	Beans	0·0750	0·0757	+0·0007	1·01
		Peas......	0·0188	0·0167	−0·0021	0·89
Other Plants ..	1858	Buck-wheat ..	0·0200	0·0182	−0·0018	0·91
With combined Nitrogen supplied beyond that in the seed sown.						
Gramineæ	1857	Wheat....	0·0329	0·0383	+0·0054	1·16
		Wheat....	0·0329	0·0331	+0·0002	1·01
		Barley....	0·0326	0·0328	+0·0002	1·01
		Barley....	0·0268	0·0337	+0·0069	1·25
	1858	Wheat....	0·0548	0·0536	−0·0012	0·98
		Barley....	0·0496	0·0464	−0·0032	0·94
		Oats......	0·0312	0·0216	−0·0096	0·69
	1858 A*	Wheat....	0·0268	0·0274	+0·0006	1·02
		Barley....	0·0257	0·0242	−0·0015	0·94
		Oats	0·0260	0·0198	−0·0062	0·76
Leguminosæ ..	1858	Peas......	0·0227	0·0211	−0·0016	0·93
		Clover....	0·0712	0·0665	−0·0047	0·93
	1858 A*	Beans	0·0711	0·0655	−0·0056	0·92
Other Plants ..	1858	Buck-wheat ..	0·0308	0·0292	−0·0016	0·95

* These experiments were conducted in the apparatus of M. G. Ville.

State Agricultural College, devoted between two and three years to the investigation at Rothamsted. The conditions of the experiments, and the results obtained up to that date, are fully described in the papers in the *Philosophical Transactions* for 1859, and in the *Journal of the Chemical Society* in 1863, already referred to. Table VIII (p. 28) summarises the results obtained.

The upper part of the table shows the results obtained in the experiments in which no combined nitrogen was supplied beyond that contained in the seed sown. The growth was in all cases extremely restricted; and the figures show that there was in no case, whether of Gramineæ, Leguminosæ, or buckwheat, a gain indicated by as much as 3 milligrams of nitrogen. There was in most cases much less gain, or a slight loss.

The lower part of the table shows the results obtained when the plants were supplied with known quantities of combined nitrogen, in the form of a solution of ammonium sulphate applied to the soil. The actual gains or losses range a little higher in these experiments, with larger quantities of nitrogen involved; but they are always represented by units of milligrams only, and the losses are higher than the gains. Further, the gains, such as they are, are all in the experiments with the Gramineæ, whilst there is in each case a loss with the Leguminosæ and the buckwheat.

It should be stated that the growth was far more healthy with the Gramineæ than with the Leguminosæ, which are even in the open field very susceptible to vicissitudes of heat and moisture, and were especially so when inclosed under glass shades. It might be objected, therefore, that the negative results with the Leguminosæ are not so conclusive as those with the Gramineæ. Nevertheless, we do not hesitate to conclude from our own experiments, as Boussingault did from his, that the evidence is strongly against the supposition that either the Gramineæ or the Leguminosæ assimilate the free nitrogen of the atmosphere.

RECAPITULATION.

In the foregoing *résumé* of mostly previously recorded facts, we have shown the amount of nitrogen assimilated by various crops over a given area, when grown for many years in succession on the same land without any nitrogenous manure; that is, under conditions in which the source of the nitrogen is as little as possible obscured by the influence of indefinite amounts available from manure.

It has been shown that the determined amounts of combined nitrogen annually coming down in the measured aqueous deposits from the atmosphere in the open country are entirely insufficient to do more than supply a small proportion of the nitrogen assimilated by crops so grown.

With regard to other possible supplies of already combined nitrogen from the atmosphere to the soil, it has been pointed out that there is no direct quantitative evidence at command, and that such evidence as does exist leads to the conclusion that such supplies are very limited and inadequate.

The same may be said, even in a greater degree, of the supposed combination of the free nitrogen of the air within the soil; also of the supposition that plants take up any material proportion of their nitrogen from combined nitrogen in the atmosphere by their leaves.

Finally, it has been concluded that the balance of direct experimental evidence is decidedly against the supposition that plants assimilate the free nitrogen of the atmosphere. Indeed, the strongest argument that we know of in favour of such a supposition is that, in defect of other conclusive evidence, some such explanation of the facts of production would seem to be needed.

The Nitrogen of the Soil as a Source of the Nitrogen of Crops.

We now turn to that part of the subject which it is the special object of this communication to bring forward, namely, the determinations of nitrogen in the soils of some of the experimental fields at Rothamsted, the yield of nitrogen in which has been given, and to show the bearing of the results on the question of the sources of the nitrogen of the crops.

We have no wish or intention to ignore the difficulties inherent in the treatment of the subject from this point of view. The difficulty of the problem will at once be recognised when it is borne in mind that a difference of 0·001 in the percentage of nitrogen in the dry soil may represent a difference of from 20 to 25 pounds of nitrogen per acre in a layer of 9 inches in depth. Again, it is further to be borne in mind that, in the case of the Rothamsted arable soils with which we have to deal, the percentage of nitrogen in the first 9 inches of depth is sometimes only about 0·1, and seldom exceeds 0·14 or 0·15; that in the second 9 inches it ranges from under 0·07 to little over 0·08; in the third 9 inches from under 0·06 to about 0·07; and that in the lower depths is rather lower still.

It will be seen, therefore, that if any quantitative estimates are to be based on the percentage amounts of nitrogen determined in samples of soil from different depths, the greatest care must be taken to insure that the samples truly represent the exact depth supposed. The mode usually adopted of taking samples of an indefinite area, perhaps not to a definite depth, and almost certainly not of uniform breadth or width to the depth taken, is obviously quite inapplicable for the purposes of any such inquiry as that here supposed.

Another difficulty is that, in the case of subsoils, with a low actual percentage of nitrogen, the variations in the amount in different samples are often proportionally great, and obviously unconnected with the special history of the plot.

Unfortunately, the few samples of soil that were collected in the early years of the Rothamsted field experiments were not taken in such a manner as to afford results applicable to our purpose. Commencing in 1856, however, the mode adopted has been, after carefully levelling the soil, to drive down a square frame, made of strong sheet-iron, open at top and bottom, and of an exact area, and of an exact depth, to the level of the surface. The inclosed soil is then carefully taken out, and its weight determined. The soil around the frame is then removed to the level of its lower edge, and it is again driven down, and the inclosed soil removed; and this process is repeated until the desired depth of sampling is reached.

Of surface soils, samples are taken from three, four, or as many as eight places on the same plot. A portion of each such sample is kept separate, as a means of testing the range of variation, and, if need be, of correction in case of any abnormal results due to accidental animal droppings, or other causes. Another portion of each separate sample of the surface soil is used to make a mixture of all. In the case of the subsoils, the separate samples of corresponding depth from the same plot are, as a rule, at once mixed. Surface soils are sometimes taken of an area of 12 by 12 inches, but frequently of only 6 by 6 inches, and subsoils almost invariably of the smaller area. The depth of each sample is generally 9 inches; but in some special cases it has been only 3 inches, and in some 6 inches. It is perhaps to be regretted that the depth originally fixed upon did not more nearly represent that to which the soil is more directly affected by the mechanical operations, and by the application of manure, say 6 inches. But having originally adopted 9 inches, it has been necessary to adhere to this depth subsequently, in order, as far as possible, to obtain comparable results at different dates.

The soils when brought to the laboratory are first broken up, and then partially dried in a stove-room at a temperature of about 130° F., to arrest nitrification, which would be liable to take place if the soils were moist. Next, the stones are removed; first those retained by a sieve of 1-inch mesh, next by a sieve of one-half-inch mesh, and then by a one-fourth-inch sieve. All that passes the one-fourth-inch sieve is termed the *mould.* Portions of this are very finely powdered and sifted for analysis; and the weights being recorded at each stage of preparation, and the water lost on drying at 100° C. being determined on the finely-powdered mould, all results of analysis are calculated into percentage on the so-determined *dry mould.* From the same data the amount of *dry mould* per acre is calculated, and upon this the amount of nitrogen per acre. It will be seen further on, that notwithstanding the means adopted to secure uniformity, the amounts of dry mould per acre calculated for a given depth, from the samples taken, vary considerably for the same field at different times, according to the dryness or wetness of the season, the condition of the land as affected by the crop, the mechanical operations, and other circumstances. The amounts also vary very considerably for the soils of adjoining fields.

Nitrogen in the Soils of the Experimental Wheat Plots.

The first series of determinations of nitrogen to which attention will be called relates to those made in the soils of some of the plots of Broadbalk field, which has now grown wheat for thirty-nine years in succession, and the yield of nitrogen in which, on the plots receiving no nitrogen in manure, has been given in Table I. It will be remembered that, under those conditions, there was a very marked decline in the annual yield of nitrogen in the crop, both without any manure, and with a mixed mineral manure used alone.

The first wheat crop of the series was harvested in 1844, and although isolated samples of the soil were taken in the early years, it was not until 1856 that any were collected on the plan now followed. At that date only four plots were sampled, and only to the depth of the first 9 inches. Eight samples were, however, taken from each plot, each 12 by 12 inches area, and the eight were mixed together. In 1865, samples were taken from eleven plots, from eight places on each plot, each sample 12 by 12 inches area, and this time to a depth three times 9 inches, or to a total depth of 27 inches. Lastly, in 1881, twenty plots were sampled; six samples, each 6 by 6 inches area, were taken from each plot, and in each case to three depths of 9 inches each, or in all to 27 inches.

Thus, it is only in 1865 and 1881 that we have any considerable series of samples, and the nitrogen determined in them; that is, in 1865 after the twenty-second, and in 1881 after the thirty-eighth crop had been removed. It is obvious that, if the results at these two periods are to be compared, we must first determine whether the samples taken represent layers of equal depth and weight in the two cases. Confining attention on the present occasion to the results relating to the first 9 inches of depth, the following figures show the average weight of dry mould per acre; that is, of soil excluding stones and moisture, calculated from the weight of the samples taken, and from the results of the mechanical separation, and of the determination of moisture in the soils. For 1865, the calculations are based on the results afforded by 80 samples, eight from each of ten of the eleven plots, the eleventh being the one annually receiving farmyard manure; and for 1881 they are based on the results relating to 114 samples, that is, six samples each from 19 plots, again excluding the one with farmyard manure.

Number of Samples.	Calculated dry Mould per Acre.
	lbs.
1865, 10 plots, 8 samples from each	2,299,038
1881, 19 plots, 6 samples from each	2,552,202

The importance of taking samples of definite area and depth, and of determining the weights, is here strikingly illustrated. Thus, it is obvious that the samples analysed in 1881 represented, on the average, almost exactly one-ninth more soil per acre than those analysed in 1865. In other words, if the samples of 1865 fairly represented 9 inches of depth in the average condition of consolidation of the soil, those of 1881 represented 10 inches of soil in the same condition: that is, they included 1 inch more of subsoil, with its much lower percentage of nitrogen than the 9 inches above it. It may, of course, be a question whether the condition of consolidation of the soil was the more normal at the one period or at the other. It would, however, make scarcely any difference in the relation of the results to one another at the two periods, whether the actually determined percentages of nitrogen in the 1865 samples were lowered, on the assumption that they should have included 1 inch more of subsoil, or whether the determined percentages in the 1881 samples are raised, on the assumption that they contained 1 inch too much of subsoil. We have concluded, from a consideration of all the facts at command, that the latter alternative is upon the whole the best. We adopt, therefore, the percentages of nitrogen as actually determined in the 1865 samples, and we assume the weight of dry mould (9 inches deep) represented by the samples to be 2,300,000 pounds per acre. But, in the case of the 1881 samples, we assume that one-tenth of the heavier weight had the composition determined in the second 9 inches (it would be very slightly higher), and the percentage in the remaining nine-tenths, representing 2,300,000 pounds of surface soil, is raised by calculation accordingly.

The following table (IX, p. 35) gives for the surface soils (9 inches deep), of the unmanured plot, and the nine artificially manured plots, sampled in 1865, the actually determined percentages of nitrogen in the dry mould; and for the 1881 samples from the same plots, it gives both the actually determined percentages, and the corrected percentages calculated as above described. The table also shows the amount of nitrogen per acre, reckoning 2,300,000 pounds of dry mould, calculated for 1865 according to the actually determined percentages, and for 1881 according to the corrected percentages. The quantities per acre more (+), or less (—), in 1881 than in 1865 are also given. Lastly, for each period, there are given the quantities more or less on each of the other plots than on plot 5*a*, which received the mineral manure alone.

As already said, in 1865 the land had grown twenty-two crops of wheat in succession, and in 1881 thirty-eight crops. Plot 3 had been unmanured from the commencement. Plot 10*a* received mineral manure in the first year, but the ammonium salts alone each year since. The remaining plots were somewhat variously manured during the first eight of the thirty-eight years; but (excepting plot 16) each has been manured every year for the last thirty of the thirty-eight years, as described in the table.

It will be observed that, for every plot, the actual determinations show a lower percentage of nitrogen in 1881 than in 1865. The corrected percentages for 1881 are, of course, all rather higher than the actual determinations; and they, in some cases, show a higher, and in others a lower, percentage than in 1865. Nevertheless, it cannot fail to be noted that the relation of plot to plot is essentially accordant at the two periods.

The significance of the results will, however, be rendered the more apparent on an examination of the calculated quantities per acre. It is obvious that absolute accuracy cannot be claimed for such figures, but the general accordance of the indications at the two periods is such as to leave no doubt of their import.

Keeping in view the special object of this communication, which

TABLE IX.—BROADBALK FIELD SOILS.

Nitrogen, per cent. in the dry Mould, and per Acre.

[Wheat thirty-nine years in succession, 1843–1844 to 1881–1882, inclusive.]

Plots.	Manures, per acre, per annum (as in 1851–52 and since).	Nitrogen.								
		Per cent. in dry Mould.			Per Acre, 2,300,000 pounds dry Mould.					
		1865.	1881.		1865.	1881.	1881 + or − 1865.	+ or − plot 5*a*.		
		Actual.	Actual.	Corrected.				1865.	1881.	1881 + or − 1865.
		Per cent.	Per cent.	Per cent.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
3	Unmanured (1843–44 and since)	0·1090	0·1009	0·1045	2507	2404	−103	—	—	—
5*a*	Mixed mineral manure	0·1119	0·0981	0·1012	2574	2328	−246	—	—	—
7*a*	Mixed mineral manure, and ammonia salts = 86 lbs. nitrogen	0·1230	0·1207	0·1264	2829	2908	+ 79	+255	+580	+325
9*a*	Mixed mineral manure, and nitrate of soda = 86 lbs. nitrogen	0·1232	0·1200	0·1253	2834	2883	+ 49	+260	+555	+295
10*a*	Ammonia salts = 86 lbs. nitrogen (1845 & since)	0·1108	0·1034	0·1074	2548	2471	− 77	− 26	+143	+169
11*a*	Ammonia salts = 86 lbs. nitrogen, and superphosphate	0·1171	0·1121	0·1164	2693	2676	− 17	+119	+348	+229
12*a*	Ammonia salts = 86 lbs. nitrogen, superphosphate, and sodium sulphate	0·1208	0·1155	0·1202	2778	2765	− 13	+204	+437	+233
13*a*	Ammonia salts = 86 lbs. nitrogen, superphosphate, and potassium sulphate	0·1206	0·1191	0·1245	2774	2863	+ 89	+200	+535	+335
14*a*	Ammonia salts = 86 lbs. nitrogen, superphosphate, and magnesium sulphate	0·1197	0·1163	0·1215	2753	2794	+ 41	+179	+466	+287
16*a*	Ammonia salts = 172 lbs. nitrogen, and mixed mineral manure*	0·1264	0·1066	0·1112	2907	2557	−350	+333	+229	−104

* 13 years to 1864; unmanured since.

is to show the bearing of what may be called the nitrogen statistics of the soils, on the question of the sources of the nitrogen in the crops, it will be seen that, during the sixteen years from 1865 to 1881, both the unmanured plot (3), and the mineral manured plot (5*a*), the yield of nitrogen in the crops of which declined so strikingly, show a great reduction in the stock of nitrogen in the surface soil. The reduction in these later years is considerably greater in the surface soil of the mineral manured than in that of the entirely unmanured plot, the previous accumulation in which had been many more years subject to exhaustion. Taking the results, however, for the first, second, and third 9 inches, the calculated loss to the depth of 27 inches is approximately the same for the two plots. The figures recorded for the first 9 inches only are, however, sufficient to show that the decline in the yield of nitrogen in the crop, where none has been supplied in manure, is accompanied by a decline in the stock of nitrogen in the soil.

A further illustration on this point is afforded by the results for plot 16*a*. For the thirteen years, 1852—1864, plot 16 received, besides the mixed mineral manure, twice as much ammonium salts as any of the other plots, the results for which are given in the table; and it gave on the average of those years 39½ bushels of grain per acre per annum. Since 1864, however, the plot has been left unmanured, and during the seventeen years, 1865—1881, it has yielded an average of only 14¾ bushels of grain; and in recent years the produce has been very little more than without manure, or with purely mineral manure. The table shows that in 1865, that is, after one crop had been removed since the application of the excess of ammonium salts, the surface soil still contained considerably more nitrogen than any other plot in the series. In 1881, however, after sixteen years more of cropping without manure, the stock of nitrogen on the plot was reduced by a greater amount than on any other plot, and to a lower point than on any other of the ammonium plots, excepting plot 10 with the ammonium salts alone.

Let us now refer to the last three columns in the table, which show, for each of the plots receiving ammonium salts, the amount of nitrogen per acre in the surface soil, *more* or *less* than in that of plot 5*a*, with mineral manure alone. All the plots, 7 to 14 inclusive, received the same quantity of nitrogen, namely 86 pounds per acre per annum. But it will be seen that the excess of nitrogen in the surface soils compared with the mineral manured plot 5, varies exceedingly. In fact, it is obvious that the amounts have no direct relation to the amount of nitrogen supplied in the manure.

The following table (X) will afford some explanation of the differences. The plots under consideration, all of which received the same amount of nitrogen in manure, are there given in the order of their average annual increased yield of nitrogen in the crops over plot 5. The first column shows the estimated average annual increased yield of nitrogen per acre in the crops; the second, the estimated annual loss of nitrogen as nitric acid by drainage; the third, the estimated annual excess of nitrogen in the surface soil over that on plot 5 with the mineral manure alone; and the last column shows the relation which that excess in the soil bears to 100 increased yield of nitrogen in the crops.

Table X.

Estimated Nitrogen per Acre per Annum.

Plots.		In Crops over Plot 5.	Loss by Drainage over Plot 5.	In Surface Soil 9 inches deep, over Plot 5.	Excess in Surface Soil to 100 increase in Crop.
		lbs.	lbs.	lbs.	lbs.
10	Ammonia salts = 86 lbs. nitrogen (1845 and since)	12·4	31·2	4·8	38·7
11	Ammonia salts = 86 lbs. nitrogen and superphosphate...........	17·7	28·5	11·6	65·5
12	Ammonia salts = 86 lbs. nitrogen superphosphate and soda	22·2	24·5	14·6	65·8
13	Ammonia salts = 86 lbs. nitrogen superphosphate and potash	23·4	25·6	17·8	76·1
14	Ammonia salts = 86 lbs. nitrogen superphosphate and magnesia ..	24·1	27·5	15·5	64·3
7	Ammonia salts = 86 lbs. nitrogen and mixed mineral manure	25·9	19·0	19·3	74·5
9	Nitrate soda = 86 lbs. nitrogen and mixed mineral manure	26·5	23·7	18·5	71·2

It is seen that the increased yield of nitrogen in the crops also varied exceedingly with the same amount supplied in manure, according to the condition as to supply of mineral constituents. Plot 10, with the ammonium salts alone, gives the smallest increased yield of nitrogen in the crop; and plots 7 and 9, with the most complete mineral manure, each more than twice as much; the other plots giving intermediate amounts.

The order of the estimated loss of nitrogen by drainage is almost the converse of that of the increased yield in the crops. Plot 10, which gives the least increased yield in the crop, shows the greatest loss by drainage; and plots 7 and 9, which yield the greatest increase in the crop, show the least loss by drainage.

The excess in the soils (over plot 5) is obviously much more in the order of the increased yield in the crops. Plot 10, with the least in the increase of crop and the most in the drainage, shows the least excess in the soil; whilst plots 7 and 9, with the greatest increased yield in the crop, and the least loss by drainage, show the greatest excess in the soil.

It is clear, therefore, that whilst the excess in the soil has no direct relation to the amount supplied in the manure, it has a very obvious relation to the increased yield in the crop; in other words, to the amount of growth. The last column of the table brings this out more clearly. Excepting in the case of plot 10, with the ammonium salts alone, there is a general uniformity in the proportion of the excess in the soil over plot 5 to the increased yield in the crop over plot 5; and the variations, such as they are, have an obvious connection with the conditions of growth. Thus, plots 11, 12, and 14, all with a deficient supply of potash, show approximately equal proportions retained in the soil for 100 of increase in the crop. Plots 13, 7, and 9, again, all with liberal supplies of potash, show higher, but approximately equal, proportions retained in the surface soil for 100 of increased yield in the crop.

Upon the whole, it is obvious that the relative excess of nitrogen in the soils of the different plots is little, if at all, due to the direct retention by the soil of the nitrogen of the manure, but is almost exclusively dependent on the difference in amount of the residue of the crops—of the stubble and roots, and perhaps of weeds.

Recurring to the main point which it is our object to elucidate, there can be no doubt that the determinations of nitrogen in the surface soils of the plots of the experimental wheat field, at different dates, establish the fact that the decline in the yield of nitrogen in the crops, when none is supplied in manure, is accompanied by a decline in the stock of nitrogen in the soil.

It will be well to consider, as far as the data at command will allow, what relation the yield of the nitrogen in the crops bears to the loss of nitrogen by the soil?

On this point it may be stated that, taking the average of thirty years, 1852—1881, it is estimated that the unmanured plot yielded 18·6 pounds of nitrogen in the crops, and lost 10·3 pounds in the drainage, or in all 28·9 pounds per acre per annum over that period. In like manner, it is estimated that plot 5, which received nitrogenous as well as mineral manure during the preceding eight years, but mineral manure alone during the thirty years, yielded an average of 20·3 pounds of nitrogen in the crops, and 12 pounds in the drainage, or in all 32·3 pounds per acre per annum. It would thus appear that, without nitrogenous manure, about 30 pounds of nitrogen has been contributed per acre per annum, from some source, to crop and drainage together. The determinations of nitrogen in the soils of the two plots indicate that they have lost an average of about two-thirds of this amount annually to the depth of 27 inches. There would, therefore, according to this reckoning, remain about one-third —say 10 pounds more or less—to be contributed by seed, by rain and condensation from the atmosphere, and by all the other supplies of combined nitrogen which have been supposed to be available, whether by the combination of free nitrogen within the soil, or its assimilation by the plant. Of this amount about 2 pounds will be due to seed, and if we suppose, say, only 5 pounds to be annually supplied by rain and the minor aqueous deposits from the atmosphere, there is but little left to be provided by all the other sources assumed.

Nitrogen in the Soils of the Experimental Barley Plots.

Unfortunately we have not so complete a series of determinations of nitrogen in the soils of the experimental barley plots as of those in the experimental wheat field. In 1868 four of the barley plots were sampled. Four samples, each 6 by 6 inches area, by 9 inches deep, were taken from each plot, and the four mixed together. In March, 1882, 26 plots were sampled, four samples being taken from each plot, each 6 by 6 inches area, and to the depth of three times 9, or 27 inches. Of the plots sampled in 1868 only one had received no nitrogenous manure, but we are able to give the percentage of nitrogen in the surface soil of this plot at the two dates.

TABLE XI.—HOOSFIELD BARLEY LAND.

Nitrogen, per cent. in the dry Mould, first 9 inches.

[Barley, 31 years in succession, 1852–1882 inclusive.]

Description of Manure.	1868.	1882.
	Per cent.	Per cent.
Mixed mineral manure alone	0·1202	0·1124

The calculated average weights of dry mould per acre, to the depth of 9 inches, were not very different at the two dates. The 1882 samples were, however, slightly the heavier, which would indicate that, for comparison, the percentage of nitrogen given for the latter date is perhaps somewhat too low. Still, it is obvious that, as in the case of the wheat land, so also in that of the barley land, there is, with the decline in the yield of nitrogen in the crop at the same time a decline in the stock of the nitrogen in the soil.

Nitrogen in the Soils of the Experimental Root-crop Plots.

The next results relate to the land upon which root-crops—common turnips, swedes, sugar-beet, and mangel-wurzel (with the exception of the interpolation of three years of barley without manure) have been grown for forty years in succession, 1843–1882 inclusive. Samples of the soil have only been taken once, namely, in April, 1870; that is, after the experiment had been continued twenty-seven years. At that time 35 plots were sampled, and four samples were taken from each plot, each 6 by 6 inches area, and to a depth of 3 times 9, or 27 inches.

The following table shows the percentage of nitrogen in the surface soil of the continuously unmanured plot, and of three plots with mineral manure alone:—

TABLE XII.—BARNFIELD ROOT-CROP LAND.

Nitrogen, per cent. in dry Mould, first 9 inches.

[Root-crops (except barley three years) 40 years in succession, 1843–1882 inclusive.]

Description of Manure.	1870.
	Per cent.
Plot 3.—Unmanured	0·0852
Plot 4.—Mixed mineral manure	0·0934
Plot 5.—Superphosphate alone	0·0888
Plot 6.—Superphosphate and potash	0·0867
Mean of plots 4, 5, 6	0·0896

Having only taken samples once, we have, of course, no means of comparing the condition of the land as to its percentage of nitrogen at different periods. The point to be observed in the results given in the table is, that each of these four plots, which have received no nitrogenous manure, shows, after twenty-seven years of experiment (twenty-four years roots and three years barley), a lower percentage of nitrogen in the surface soil than has been found in any of the other experimental fields; though determinations made in samples from other parts of the same field, and also in an adjoining field, show considerably higher results. The nearest approach to so low an amount in any other field is where the land had been under alternate wheat and fallow, without manure, for more than thirty years.

It will be remembered that the root-crops gave, with mineral manure alone, a very much higher yield of nitrogen than the cereals in the earlier years, and as low a yield in the later years. That they did not give less still is probably owing to the fact that their growth extends later in the season than that of the cereals, by virtue of which they are probably enabled to arrest the nitric acid formed within the soil during the early autumn months, which in the case of the cereals would be more subject to loss by drainage.

Both the mechanical conditions of surface soil known to be favourable for the growth of the root-crops, and the large amount of fibrous root they throw out near the surface, are indications of an active demand on the resources of the upper layers of the soil, and are perfectly consistent with the supposition that their growth has led to a greater reduction in the stores of nitrogen of the superficial layers than in the case of any of the other crops.

The evidence afforded, both by the facts of production, and by the determinations of nitrogen in the soil, is indeed strongly in favour of the view that the source of the nitrogen of the root-crops, as of the cereals, is, when grown without nitrogenous manure, the soil itself, and the small quantity of combined nitrogen annually contributed by rain, and the minor aqueous deposits from the atmosphere. It is said, however, that these crops require a certain amount of nitrogen to be supplied by manure, and that they are able to take up the remainder from atmospheric sources. The facts of production recorded at page 11 afford no countenance to such a view. We conclude, indeed, that the dependence of these crops for their nitrogen, on the stores of the soil itself, or on supplies by manure, is as clearly established as in the case of the cereals.

Is the Soil a Source of the Nitrogen of the Leguminosæ?

We have now to consider the bearing of the evidence on the question of the sources of the nitrogen of the Leguminosæ; and here we approach not only the most important but the most difficult part of our subject.

The first of the leguminous crops, the yield of nitrogen in which is recorded in Table I, is beans. Without manure the yield of nitrogen was in the earlier years very much higher than with the cereals; but the decline was very great, and in the later years it was as low as with the cereals. With mixed mineral manure, including potash, the yield throughout was much higher, but the decline was, as without manure, very great. We have not a sufficiently comparative series of determinations of nitrogen in the soils of the bean plots, but such results as are at command lead to the conclusion that there has been a gradual decline in the percentage of nitrogen in the surface soils; but, considering the little tendency of the plant to throw out feeding root in the superficial layers, it may be a question how far the reduction is due to exhaustion by the direct action of growth, or how far to nitrification and passage of the nitrates downwards.

Nitrogen in the Soils of the Experimental Clover Plots.

The most important of the leguminous crops to which reference has been made is red clover. In Table I is recorded the yield of nitrogen over twenty-two years, 1849-70, in only six of which, however, was any crop obtained. The experiment has ' een continued, with some modifications; and in 1877, that is after twenty-nine years, in nine of the last ten trials the plant had died off during the winter and spring succeeding the sowing of the seed. Several small crops have since been obtained, and in March, 1881, samples of soil were taken from five places where no nitrogenous manure has been applied from the commencement, and at each place to three depths of 9 inches each. Exactly corresponding samples were also taken from an immediately adjoining plot, which had been thirty years under alternate wheat and fallow, without manure of any kind. The nitrogen was determined in each of the five separate samples, and also in the mixture of the five. Table XIII summarises the results.

TABLE XIII.—HOOSFIELD CLOVER, AND WHEAT AND FALLOW, LAND.

Nitrogen per cent. in dry Mould, first 9 inches.

[Experiments more than 30 years.]

Mean.	1881.	
	Clover Land.	Fallow Land.
	Per cent.	Per cent.
Mean of determinations on five separate samples......	0·1067	0 0925
Mean on the mixture of the five samples	0·1055	0·0984
Mean	0·1061	0·0955

It is true that the tendency of the evidence on the point is to show that red clover derives, at any rate much of its nitrogen, from the lower layers of the soil; but it is surely significant that, after the growth of heavy crops in 1849, when the land was in ordinary condition as to manuring and cropping, and the constant failure since, there is, coincidently with this, nearly as low a percentage of nitrogen in the surface soil as with alternate wheat and fallow without manure. It is obvious that any accumulation near the surface, due to residue from the small crops, has been more than compensated by exhaustion. The evidence afforded by the figures may be said to be of a somewhat negative character; but it is at any rate clear that failure of growth of the clover has been associated with a declining, and a very low, percentage of nitrogen in the surface soil.

The next results are of a very much more definite character. They relate to the two portions of the field which had grown six corn crops in succession by artificial manures alone, was then divided (in 1873), and on one half clover (sown in the previous year), and on the other half barley, was grown. Table I shows that in the clover crops 151·3 pounds, and in the barley only 37·3 pounds of nitrogen were removed. Yet, in the next year (1874), barley being grown over both portions, the one which had yielded 151·3 pounds in clover now yielded 69·4 pounds in barley; and the other, which had yielded only 37·3 in barley, now yielded only 39·1 pounds in barley.

In October, 1873, after the clover and barley had been removed, and before the land was ploughed up, samples of the soil were taken as follows: From each portion four separate samples, each 12 by 12 inches area and 9 inches deep, and the nitrogen was determined in each separate sample, and also in an equal mixture of the four. Six other samples, each 6 by 6 by 9 inches, were also taken from each of the two portions, and the six samples representing each portion were mixed, and the nitrogen determined in the mixture. At each place corresponding separate samples were taken, and mixtures made, representing respectively the second and the third 9 inches of depth. In all cases three and in many four determinations of nitrogen were made on each sample. The following table gives the mean results on each of the four separate samples, the mean of these, the mean on the mixture of the four, the mean on the mixture of the six, and the mean of all:—

TABLE XIV.

Experimental Clover and Barley Land.

[Nitrogen per cent. in dry Mould, first 9 inches.]

Description of Samples.	1873.	
	Clover Land.	Barley Land.
	Per cent.	Per cent.
Sample No. 1 (12 × 12 × 9 inches)	0·1574	0·1468
Sample No. 2 (12 × 12 × 9 inches)	0·1529	0·1341
Sample No. 3 (12 × 12 × 9 inches)	0·1484	0·1431
Sample No. 4 (12 × 12 × 9 inches)	0·1631	0·1405
Mean on the four separate samples (12 × 12 × 9 inches)	0·1554	0·1411
Mean on a mixture of the four samples (12 × 12 × 9 ins.)	0·1566	0·1387
Mean on a mixture of six samples (6 × 6 × 9 inches)	0·1578	0·1450
General means	0·1566	0·1416

The determinations on the individual samples given in the upper portion of the table (XIV), forcibly illustrate the inapplicability of results obtained on single samples of soil. But the accordance of the mean results of the three sets of determinations for the clover land, and again of the three for the barley land, can leave no doubt whatever that there was a considerably higher percentage of nitrogen in the first 9 inches of the clover ground than to the same depth of the barley ground.

The results must, indeed, be accepted as indicating a marked distinction, which, in direction, is entirely consistent with what is known of the influence of a clover crop as a preparation for a succeeding cereal one, and entirely consistent with the results actually obtained with the barley succeeding the clover. It is, however, difficult to suppose that the figures correctly represent, in degree, the average difference in the composition of the first 9 inches of the two plots; for, calculated per acre, the excess of nitrogen in the surface soil of the clover plot would represent an accumulation equal to about twice as much as was removed in the three cuttings of the clover, notwithstanding all visible vegetable *débris* was removed before the soils were submitted to analysis;* nor have the subsequent crops benefited as much as might have been expected from such an amount of accumulation. On the other hand, samples taken in 1877 still show a higher percentage of nitrogen in the surface soil of the clover than of the barley land.

It is, at any rate, obvious that the surface soil of the clover ground has gained nitrogen, either from above or from below—from the atmosphere or from the subsoil. And, so far as the determinations of nitrogen in the subsoils go, the indication is that, if from below, it is at least mainly from a lower depth than 27 inches.

It is freely admitted that, in the facts of this experiment as they stand, there is no evidence as to the source of the large amount of nitrogen of the clover crop, and of the increased amount of it in the surface soil. In the absence of such evidence, it is natural enough to assume that the atmosphere has been the source. But whilst there is absolutely nothing in favour of this view excepting the fact that an explanation is needed, and that if that source were established the difficulty would be solved, there is, to say the least, much more evidence in favour of the supposition that the subsoil has been the source of at any rate much of the nitrogen.

The Soils of the Melilotus leucantha and White Clover Plots.

Reference has already been made to the enormous growth of *Melilotus leucantha*, and the enormous amount of nitrogen it yielded, for several years in succession, on the land where no nitrogen had been applied for more than thirty years, and where red clover had so frequently failed (p. 12). The crop of 1882, the fifth in succession, was the highest, and the yield of nitrogen in it was not far short of 150 pounds per acre; whilst, under exactly similar conditions, ordinary red and white clover gave very small produce. Accordingly, as soon as the crops were removed, samples of soil were taken from one of the *melilotus* plots, and from the corresponding white clover plot. Samples were taken from two places on each plot, and in each case to

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* This was more completely done in the case of the four 12 × 12 × 9 inch samples, than in that of the six 6 × 6 × 9 inch ones, and the latter are seen to give slightly higher percentages of nitrogen.

the depth of six times 9 inches, or in all 54 inches. The examination of these samples of soil is as yet very incomplete, but the following interesting facts have been ascertained :—

Whilst the strong roots of the *melilotus* were found to penetrate to the lowest depths of the sampling, there was very little development of white clover roots beyond the surface soil. Whilst to the eye, and to the hand, the subsoil where the *melilotus* had grown was obviously pumped dry, and was somewhat disintegrated, to the full depth sampled, that of the clover plot had no such characters. Determinations of moisture in the soils and subsoils show, at each of the six depths, much less water in the *melilotus* than in the white clover soils; and the difference is by far the greater in the lower depths. Calculated per acre, it would appear that, to the depth of 54 inches, the *melilotus* soil had lost approximately 540 tons more water per acre than the white clover soil; and there can be no doubt that the pumping action had extended deeper still.

There is here, then, clear evidence that the plant, whose habit of growth, and especially whose range, and feeding capacity, of root, suited it to the conditions, was enabled to take up much more water, and doubtless with it much more food, than, under exactly similar conditions of soil, were at the command of the plant of the much weaker and more restricted development.

Nitrogen as Nitric Acid in the Melilotus and White Clover Soils.

That the deep-rooting *melilotus* did derive more nitrogen from the subsoil than the shallow-rooting white clover is obvious from the following facts:—Watery exhausts were made of each soil, at each depth, and the nitrogen as nitric acid determined in them, by Schlösing's method, as nitric oxide, by its reaction with ferrous salts.

The following table summarises the results :—

Table XV.

Nitrogen as Nitric Acid.

	Per million, dry Soil.		Per Acre.		
	Melilotus Soil.	White Clover Soil.	Melilotus Soil.	White Clover Soil.	Difference.
			lbs.	lbs.	lbs.
First 9 inches........	1·28	3·24	3·39	8·59	5·20
Second 9 inches......	0·36	1·10	0·97	2·97	2·00
Third 9 inches.......	0·21	0·66	0·61	1·91	1·30
Fourth 9 inches......	0·33	1·03	0·99	3·09	2·10
Fifth 9 inches.......	0·28	1·46	0·84	4·38	3·54
Sixth 9 inches.......	0·55	1·77	1·65	5·31	3·66
Total...........	..	..	8·45	26·25	17·80

Thus the *melilotus* had not only exhausted the water, but the nitric acid of the soil, at each depth very much more than the white clover had done; and the difference is very marked, and increases, at the lower depths. It is seen that in the case of the white clover soil there is a diminishing amount of nitric acid from the first to the third depth, and then an increasing quantity to the sixth depth. There was, in fact, about the same total amount found in the three lower as in the three upper layers. It may fairly be supposed that there is greater concentration lower still, and that the exhausting action of the *melilotus* extended beyond the depth examined.

There is here direct evidence that the soil is the source of at any rate some of the excess of nitrogen of the *melilotus* over that in the white clover. The quantity, and the distribution, of nitric acid in the soil at any one time are so dependent on temporary conditions, that it would be fallacious to attempt to estimate from the figures as they stand the exact amount which the *melilotus* has taken up more than the white clover. Then it is obvious that the action extended below the depth examined; and it is a question whether, with the greater disintegration, and greater aëration, nitrification would not be favoured in the lower depths, and if so the supply would be in a sense cumulative. Lastly, it may be that the deeply and widely distributed *melilotus* roots have the capacity of taking up nitrogen from the soil in other forms than as nitric acid.

Nitrogen as Nitric Acid in other Soils and Subsoils.

It will be some further aid in judging of the possibility or probability that the nitric acid in the soil and subsoil may be an adequate source of the nitrogen of the Leguminosæ, if we quote a few results indicating the amount of nitric acid found in some other soils under known conditions.

In the first place, three soil drain-gauges, one with 20, one with 40, and one with 60 inches depth of soil, in its natural state of consolidation, and each of one-thousandth of an acre area, have been under experiment for between eleven and twelve years. No manure has been applied to these soils, nor have they grown any crop, from the commencement. The drainage has been regularly collected and measured; and for nearly the whole of the last five years the nitric acid has been determined in monthly average samples of the drainage waters. Taking the result of the three gauges, for four harvest-years (September 1, 1877, to August 31, 1881), these soils, which had been about six years without any manure at the commencement of the period under consideration, have lost by drainage an average of nearly 43 pounds of nitrogen as nitric acid per acre per annum, of which perhaps not much more than 5 pounds would be due to rain and condensation of combined nitrogen from the atmosphere. In fact, about 35 pounds, or perhaps more, would appear to have been annually due to the nitrification of the nitrogenous matter of these unmanured soils. It has to be borne in mind, however, that the blocks of soil having access of air from below as well as from above, the nitrification may have been freer than it would be in soil in its ordinary condition.

Again, in some of the samples of soil taken from the plots in the experimental wheat field, in October 1865, and in many of those taken in October 1881, that is in each case about two months after the removal of the crop, the nitric acid has been determined.

In the case of one plot sampled in 1865, which had received annually mixed mineral manure and ammonium salts, determinations made in 1866 (by Dr. Pugh's method), showed nearly 76 pounds of nitrogen as nitric acid per acre to the depth of 27 inches. As, however, these soils had been stored in a rather moist condition, it is possible that nitrification may have taken place after the collection, and that the results are so far somewhat too high.

The following table (XVI) gives an abstract of the results of the determinations of nitrogen as nitric acid in the 1881 samples of the experimental wheat field soils:—

TABLE XVI.

Nitrogen as Nitric Acid.

	Complex Mineral Manure		Sodium Nitrate alone.	Unmanured continuously.
	and Ammonium Salts.	and Sodium Nitrate.		
		Per Million Dry Soil.		
First 9 inches	8·95	7·73	6·38	3·80
Second 9 inches	4·17	3·69	7·43	1·94
Third 9 inches	2·07	2·98	6·44	1·00
		Per Acre.		
	lbs.	lbs.	lbs.	lbs.
First 9 inches	22·8	19·7	16·3	9·7
Second 9 inches	11·3	10·0	20·1	5·2
Third 9 inches	5·8	8·3	18·0	2·8
Total	39·9	38·0	54·4	17·7

Thus, in these 1881 samples, collected, like those in 1865, about two months after the removal of the crops, the amounts of nitric acid found to the depth of 27 inches only, represented—in the soil of the plot receiving mixed mineral manure and ammonium salts, 39·9 pounds of nitrogen per acre to that depth; in that of the plot receiving the same mineral manure and sodium nitrate, 38 pounds; in that of the plot to which nitrate of soda alone is annually applied, 54·4 pounds; and in the soil of the continuously unmanured plot, 17·7 pounds.

As in the case of the white clover land, in all cases (except with the nitrate alone), the amount decreased from the first to the third 9 inches of depth from the surface; and if, as in that case, it increased in the lower depths, and in anything like the same degree, we have evidence of a considerable store of nitric acid available for such plants as, by virtue of their habit of growth, are able to gather up the residue accumulated within the subsoil.

Determinations made in samples collected in the experimental rotation field, in September 1878, showed the following amounts of nitrogen as nitric acid per acre to the depth of 18 inches :—

	With Superphosphate only.*	With Complex Mineral and Nitrogenous Manure.*
	lbs.	lbs.
After fallow	36 ·3	48 ·8
After beans	10 ·6	20 ·5
Difference	25 ·7	28 ·3

Samples collected at the same date from the unmanured alternate wheat and fallow plots showed to the same depth:—

	lbs.
After fallow	33 ·7
After wheat	2 ·6
Difference	31 ·1

Lastly, two fields which had been manured and cropped in the ordinary course of the farm, and had been fallowed since the previous autumn, showed, according to determinations in samples collected in October 1881, the following amounts of nitrogen as nitric acid per acre to the depth of 27 inches:—

	lbs.
Claycroft field	58 ·8
Foster's field	56 ·5

Thus there was very much less nitrogen as nitric acid found in the soils to the depths examined, after the growth of the leguminous crop beans, as well [illegible]er that of the gramineous crop wheat, than in the correspond[illegible]w soils; indicating, therefore, a like source of some, [illegible]e, of the nitrogen of both crops.

It [illegible]be seen, however, that even in the cases of the soils receiving nitrogenous manure, the amount of nitric acid found to the depths examined, is very far from sufficient to account for so large an accumulation in the crop, and in the surface soil, as the figures relating to the nitrogen in the produce of the clover, and in the clover and barley soils, would indicate had been accumulated.

The amounts of nitric acid formed, or remaining, within a limited depth from the surface, at any one time, is, it is true, as already intimated, dependent on so many temporary circumstances, that it is

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* The manures are applied every fourth year, for the root-crop commencing each course of—roots, barley, leguminous crop or fallow, and wheat.

not to be expected that the amount found within such limits at any given time would represent more than a fraction of that which would be available, even within that range, during the long period of growth of the clover crop. Then, the indications are that there is considerable accumulation beyond the depth to which most of our examinations apply. Still, it is difficult to suppose, with the evidence at command, that the whole of the nitrogen which has to be accounted for, either in the *Melilotus*, or in the clover and barley experiment, can be attributed to that source. There remains the question whether the roots of the plant do not take up nitrogen from the soil in other states than as nitric acid.

Finally in regard to the experiments with clover and barley, it is admitted that the various results of soil examinations which have been adduced do not conclusively show the source of the whole of the nitrogen to have been the soil. It will, we think, nevertheless be granted, that they do clearly point to the fact that at any rate much of it is derived from that source; whilst there is no evidence whatever of an atmospheric source of more than the small amount of combined nitrogen coming down in rain, and the minor aqueous deposits, and the probably still smaller amount absorbed from the atmosphere by the porous soil.

Nitrogen in some of the Soils of the Experimental Mixed Herbage Plots.

The results next to be referred to will afford additional evidence of the soil-source of the nitrogen of the Leguminosæ.

In Table III it was shown that in the mixed herbage of permanent grass land, without manure 33·0 pounds, and with a purely mineral manure (including potash) 55·6 pounds of nitrogen were yielded per acre per annum in the crop over a period of twenty years. Whence comes the 22·6 pounds more nitrogen per acre per annum taken up when the mineral manure was applied than without manure?

After twenty years of continuous experiment, samples of soil were taken from three places on each plot, and in each case to the depth of six times 9 inches, or 54 inches. The mean results of the determinations of nitrogen in the surface soils of the unmanured plot, and of the plot receiving a complex mineral manure (including potash), are given in Table XVII which follows:—

TABLE XVII.—EXPERIMENTS ON PERMANENT MEADOW LAND.

Nitrogen, per cent. in dry Mould, and per Acre.

		1870.	1876.	1878.
		Per cent.	Per cent.	
Plot 3.—Unmanured		0·2517	0·2466	..
Plot 7.—Mixed mineral manure, including potash		..	0·2236	0·2246
Difference		..	0·0230	..
			lbs.	
Difference per acre	Total 20 years	..	506·0	..
	Average per annum	..	25·3	..

Although we have not previously quoted the figures, we have on several occasions stated in general terms that determinations of nitrogen show a lower amount in the mineral-manured soil, approximately corresponding to the increased yield in the crop.

It is in reference to our statements on this point that M. Joulie has called in question the possibility of obtaining results of the kind applicable to our argument. He takes the fact of the increased yield of nitrogen under the influence of purely mineral manure as conclusive proof of the atmospheric source of the increased amount of nitrogen assimilated. He assumes that our calculations are based on determinations of nitrogen in a sample of the mixed soil to the total depth of 54 inches. He calculates that in the mass of soil to that depth the difference in the amount in the two cases would be far too small to furnish a justification for the important conclusion that the soil was the source of the nitrogen. He objects that the roots of such herbage would derive their nutriment chiefly in the superficial layers. He further objects that if the difference we assume were a fact, it is probably due to an accidental difference in the soil of the two plots, such a difference having been admitted by us in the case of another plot. Lastly, he suggests that if there really were the reduction we suppose, it might be due to other causes—such as increased activity of nitrification under the influence of the mineral manure and passage of the nitrates downwards.

In the first place, in the case of the irregularity in the condition of one of the plots referred to, the difference was readily seen in the section of the soil, and there was no such difference in the instance now under consideration.

Then it is the determination of nitrogen in the first 9 inches of soil alone, to which we have hitherto referred, and to which we confine attention on the present occasion.

In the next place, that the difference in the condition of the two plots is not merely local is shown by the fact that the determinations on a sample from the unmanured plot taken in 1870 entirely confirm the relative composition shown by the samples of 1876. Again, the lower percentage of nitrogen in the 1876 samples of the mineral manured plot is entirely confirmed by the results obtained on samples taken in 1878. Further, of the twenty experimental plots, there is only one other showing so low a percentage as the mineral-manured plot, and that is the one which had received the same mineral manure, but for a shorter series of years.

We have in fact no doubt whatever that the differences indicated by the figures are real, and dependent on the conditions of manuring and of growth. The reduction is, moreover, very great, amounting to nearly one-tenth of the total quantity of nitrogen, and far beyond the limits of accidental difference in the sampling or the analysis.

Calculated per acre, the surface soil of the mineral-manured plot contained, at the end of the twenty years, 506 pounds less nitrogen than the soil of the unmanured plot to the same depth, corresponding to an annual reduction of 25·3 pounds of nitrogen per acre per annum. It is, to say the least, a very remarkable coincidence that the increased yield of nitrogen in the crop on the mineral-manured plot which has to be accounted for is 22·6 pounds per acre per annum.

We do not pretend to claim absolute accuracy for such results, but we ourselves entertain no doubt whatever of their significance and their importance.

It will be asked—How is it that in the case of the red clover, and the *melilotus*, it was concluded that, so far as the plants had derived their nitrogen from the soil, it was at any rate mainly from the lower depths, and that here, in the case of the permanent mixed herbage plots, we assume the increased yield of nitrogen to be derived from the surface soil?

Under the influence of the mineral manure, a larger proportion and amount of leguminous herbage was developed than on any other plot; but the leguminous plant the most, indeed very prominently, favoured was the *Lathyrus pratensis*, which throws out an enormous quantity of root near the surface; and it is sufficiently established that the potash of artificial manures remains almost exclusively in the superficial layers. On the other hand, the perennial red clover, and the *Lotus corniculatus*, which have a much more deeply-rooting tendency, are comparatively little encouraged.

The actual amount of leguminous herbage produced, however, is not sufficient to account for nearly the whole of the increased yield of nitrogen in the produce of the plot. The fact is that, besides a porportionally very large increase in the growth of leguminous herbage, there has been a gradually increasing amount of gramineous produce developed; far beyond what would be anticipated from the extremely limited effect of such manures on gramineous crops grown separately on arable land. How far this result may be due to an increased tendency of the grasses to form stem, and to ripen, under such conditions;—how far to more active nitrification induced under the influence of the mineral manure in the much more highly nitrogenous grass-land than in the poorer arable soil, and so yielding a direct supply to the Gramineæ of the mixed herbage;—or how far to an increased supply in a condition available for the grasses as the result of a previously increased growth of the Leguminosæ, may be a question. But it is of interest to note that the gramineous species that are developed are among the most superficially rooting of the grasses found on the experimental plots.

Before leaving the subject of these experiments on the mixed herbage of grass land, it may be well to call attention to the fact that, on the assumption that the whole of the nitrogen of the herbage, beyond the small amount of already combined nitrogen contributed by rain and condensation from the atmosphere, is derived from the soil, we have to conclude that about 25 pounds per acre per annum have been yielded by the soil of the unmanured plot, and nearly an additional 25 pounds, or in all about 50 pounds, from the mineral-manured plot. It was estimated that, in the case of the continuous wheat experiments, about 20 pounds of nitrogen had been annually obtained in the crop, and a minimum of 12 pounds lost by drainage; in all 32 pounds. It cannot fail to be observed how closely this amount corresponds with the annual yield of nitrogen (33 pounds) in the unmanured mixed herbage. With the richer grass-land, though less aërated than arable land, it might be expected there would be some increased activity of nitrification, even in the unmanured soil; and there may be some loss by drainage. But, with a mixed herbage of some 50 species, of very varying habit of growth, and with the possession of the soil all the year round, it is only what would be expected that there would be more of the available nitrogen taken up by the crop, and less lost by drainage, than with the cereal grown separately on arable land, and occupying the soil for only a very limited period of the year.

We conclude, then, that the results relating to the two mixed herbage plots can leave little doubt that the increased yield of nitrogen in the more highly leguminous produce of the mineral-manured plot had its source in the stores of the soil itself.

Source of the Nitrogen of Clover Grown on Rich Garden Soil.

We have one more illustration to bring forward having an important bearing on the question of the sources of the nitrogen of the Leguminosæ.

In view of the signal failure in the attempts to grow red clover on a nitrogen exhausted arable soil, it is of much interest that large, though declining, crops have been grown for twenty-nine years in succession on a small plot of rich kitchen-garden soil.

The experiment was commenced in 1854, and the following table shows the percentage of nitrogen in samples of the first 9 inches of soil, taken in October 1857, and in May 1879; that is, with an interval of twenty-one seasons of growth. In 1857 only one sample was taken, and only to the depth of 9 inches; but in 1879 three samples were taken, in each case to the depth of twice 9, or 18 inches. The results given in the table relate to the first 9 inches of depth only:—

TABLE XVIII.—CLOVER GROWN ON KITCHEN GARDEN SOIL.

Nitrogen, per cent. in dry Mould, and per Acre.

	1857.	1879.	Difference.
	Per cent.	Per cent. 0·3635 0·3640 0·3626	Per cent.
	0·5095	0·3634	0·1461
	lbs.	lbs.	lbs.
Per acre, total*	9,528	6,796	2,732
Difference per acre per annum	..	..	130

The percentage of nitrogen given for the single sample collected in October 1857, is the mean of determinations made in 1857, 1866, and

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* In the original paper, too high an average weight of soil per acre was adopted, and hence the amounts of nitrogen per acre were estimated to be higher than now given; but the *difference* was only 9 pounds more (139) than according to the new calculation.

1880, and is almost identical with the mean of those made at the latest date.

The first point to observe is that the first 9 inches of the garden ground contained more than half a per cent. of nitrogen, nearly four times as much as the average of the arable soils, and nearly five times as much as the exhausted clover land soil. It is of course true that the soil would be correspondingly rich in all other constituents; but some portions of the arable soil where clover failed, had received much more of mineral constituents by manure than had been removed in the crops.

The means of the determinations made on the three separate samples taken in 1879 are seen to agree very well, and the results can leave no doubt that there has been a great reduction in the stock of nitrogen in the surface soil. The reduction amounts to nearly 29 per cent. of the total. Reckoned per acre, as shown at the foot of the table, it corresponds to a loss of 2,732 pounds during the twenty-one seasons of growth; and although really good crops are still grown in most years, there has been, with this great reduction of the stock of nitrogen in the soil, a very marked reduction in the clover-growing capability of the soil. Thus, during the first fourteen of the twenty-nine years of the experiment, seed was sown only three times; whilst during the last fifteen years it has been necessary to sow ten times. It is obvious, therefore, that the plant stood very much longer during the earlier than the later years. Then, again, the produce from the three sowings during the first fourteen years was nearly twice as much as has been obtained since.

The question obviously arises—what relation does the amount of nitrogen lost by the soil bear to the amount taken off in the crops? We quite admit the uncertainty of calculations of produce per acre from the results obtained on a few square yards. We are, however, disposed to estimate the average yield of nitrogen over the twenty-one years between the two periods of soil sampling at about 200 pounds per acre per annum. The table shows that against this we have an estimated loss of nitrogen by the first 9 inches of soil of 130 pounds per acre per annum, corresponding approximately to two-thirds of the amount estimated in the crop.

There is, however, evidence leading to the conclusion that, in the case of arable soils to which excessive amounts of farm-yard manure are applied, there may be a loss by evolution as free nitrogen; and, obviously, so far as this may have occurred in the garden soil, there will be the less of the loss determined in the surface soil to be credited to assimilation by the growing clover.

On the other hand, it is known that when growing on ordinary arable soil, the clover plant throws out a large amount of roots in the lower layers, and although in the case of so rich a surface soil, the plant may derive a larger proportion of its nutriment from that source, we must at the same time suppose that it has also availed itself of the resources of the subsoil. Unfortunately, we did not sample deeper than 9 inches in 1857, so that we can make no comparison of the condition of the subsoil at the two periods. It may, however, be observed that, in 1879, the second 9 inches showed about three times as high a percentage as the subsoils of the arable fields at the same depth; indeed, not far from twice as high a percentage as several of the exhausted arable surface soils. It cannot be doubted, therefore, that the subsoil of the garden plot has contributed to the yield of nitrogen in the crop.

If, then, we have not here absolute proof that the source of the whole of the nitrogen of the clover growing on the garden soil was the soil itself, we have surely very strong grounds for concluding that much, and perhaps the whole of it, has been so derived.

GENERAL CONCLUSIONS.

After this review of the evidence which the determinations of nitrogen in the soils of our experimental plots afford, we end, as we began, by saying that, although we admit the facts of production are not yet conclusively explained, we maintain that there is, to say the least, much more of direct experimental proof of the soil than of the atmospheric source of the nitrogen. Moreover, we submit that this may be said, not only of the source of the nitrogen of the cereals, but also of that of the root-crops, and of the Leguminosæ.

If, on the other hand, the atmosphere is the main, if not the exclusive, source of the nitrogen of the Leguminosæ, we would ask here, as we have asked elsewhere—why those leguminous crops which take up the most nitrogen can be less frequently grown on the same soil? Why we entirely failed to grow clover successively on ordinary arable land, which was nevertheless in a condition to yield fairly good cereal crops? Why the only condition under which we have been able to grow clover continuously was where the soil was very much richer in nitrogen (and of course in other constituents also) than the arable land? And lastly, why its growth under such circumstances has been accompanied by a rapid diminution in the amount of nitrogen in the soil, and with this a marked decline in the produce?

It will not for a moment be supposed that because in the foregoing illustrations and arguments we have confined attention almost exclusively to the nitrogen in the soils, we in any way ignore the importance of a liberal available supply of the mineral constituents, so essential for the effective action of the nitrogen. There is abundant evidence, however, that the failures that have been cited have not been due to a deficiency of mineral constituents.

If, then, the supply of mineral constituents not being defective, the yield of our crops is in the main dependent on the amount of nitrogen which is available to them within the period of their growth from the soil itself, or from manure applied to it, surely the fertility of a soil must be largely measured by the amount of nitrogen it contains, and the degree in which it becomes available. And, if this be so, is not the soil a "mine," as well as a laboratory?

In this connection, speaking here in America, it will not be inappropriate to conclude with a brief reference, such as the limited data at our command will permit, to what we believe must be a characteristic difference between a large proportion of the comparatively recently, or even not yet, broken up soils of this continent, and those which have been long under arable culture on the other side of the Atlantic.

A sample of Illinois Prairie soil, obtained some years ago by Mr. (now Sir) James Caird, and submitted by him for analysis to Dr. Voelcker, to whom we are indebted, not only for his own analytical results, but also for a sample of the soil itself, shows, by almost identical results in the two laboratories, very nearly 0·25 per cent. of nitrogen. We have no special history of this soil, nor do we know the depth to which it was taken; but Dr. Voelcker informs us that the sample supplied to us was a mixture of both soil and subsoil as supplied to him, and that in the separate surface soil he found 0·33 per cent. of nitrogen.

During the present year (1882), between forty and fifty samples of soil from the North-west Territory, taken at intervals between Winnipeg and the Rocky Mountains, were sent over to the High Commissioner in London, and exhibited at the recent show of the Royal Agricultural Society of England, at Reading. The soils were exhibited in glass tubes four feet in length, and are stated to represent the core of soil and subsoil to that depth. Three samples of the surface soils have kindly been supplied to us for the determination of the nitrogen in them:—

No. 1 is from Portage le Prairie, about 60 miles from Winnipeg, and has probably been under cultivation for several years. The dry mould contained 0·2471 per cent. of nitrogen.

No. 2 is from the Saskatchewan district, about 140 miles from Winnipeg, and has probably been under cultivation a shorter time than No. 1. The dry mould contained 0·3027 per cent. of nitrogen.

No. 3 is from a spot about 40 miles from Fort Ellis, and may be considered a virgin soil. The dry mould contained 0·2500 per cent. of nitrogen.

In general terms it may be said that these Illinois and North-west Territory Prairie soils are about twice as rich in nitrogen as the average of the Rothamsted arable surface soils; and, so far as can be judged, they are probably about twice as rich as the average of arable soils in Great Britain. They indeed correspond in their amount of nitrogen very closely with the surface soils of our permanent pasture land. As their nitrogen has its source in the accumulation from ages of natural vegetation, with little or no removal, it is to be supposed that, as a rule, there will not be a relative deficiency of the necessary mineral constituents.* Surely, then, these new soils are "mines" as well as laboratories? If not, what is the meaning of the term *a fertile soil?*

Assuming these soils not to be deficient in the necessary mineral supplies, and that they yield up annually in an available condition an amount of nitrogen at all corresponding to their richness in that constituent, it may be asked—whether they should not yield a higher average produce of wheat per acre than they are reported to do?

The exhausted experimental wheat field at Rothamsted, the surface soil of which at the commencement of the experiments thirty-nine years ago probably contained only about half as high a percentage of nitrogen as the average of these four American soils, yielded over the first eight years 17½; over the next fifteen years, 15¼; over the last fifteen years (including several very bad seasons), only 11⅛ bushels; and over the whole thirty-eight years about 14 bushels per acre per annum.

So far as we are informed, the comparatively low average yield of the rich North-west soils is partly due to vicissitudes of climate, partly to defective cultivation, but partly, also, to the luxuriant growth of weeds, which neither the time at command for cultivation, nor the amount of labour available, render it easy to keep down. Then, again, in some cases, the straw of the grain crops is burnt, and manure is not returned to the land. Still, if there be any truth in the

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* Since the above was in type, we have seen Dr. Voelcker's report on the Illinois Prairie soil above referred to, and find he called attention to its richness in potash and other mineral constituents. He also called attention to the much higher percentage of nitrogen in it than in the soils of this country which he and others had analysed.

views we have advocated, it would seem it should be an object of consideration to lessen, as far as practicable, the waste of fertility of these now rich soils. At the same time it is obvious that, with land cheap and labour dear, the desirable object of bringing these vast areas under profitable cultivation cannot be attained without some sacrifice of their fertility in the first instance, which can only be lessened as population increases.

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