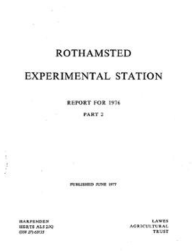
Rothamsted Experimental Station Report for 1976, Part 2



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D. S Jenkinson (1977) *The Nitrogen Economy of the Broadbalk Experiments I. Nitrogen Balance in the Experiments ;* Rothamsted Experimental Station Report For 1976, Part 2, pp 103 - 109 **- DOI: https://doi.org/10.23637/ERADOC-1-34449**

The Nitrogen Economy of the Broadbalk Experiments
I. Nitrogen Balance in the Experiments

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Introduction

The experiments on Broadbalk provide unique material for the study of the nitrogen economy of the soil: plant system in the field. In the main experiment, wheat has been grown on all or part of the field every year since 1843, under a manurial system that has changed little in that time; for details see Johnston and Garner (1969). Measurements of N uptake by the wheat are available for various runs of years over virtually the whole span of the experiment. Soil samples were first taken on a systematic basis in 1865 and the plots have been sampled at irregular intervals ever since. Tiled rains were installed under the centre of each plot in 1849 and by analysing the water from these drains Lawes, Gilbert and Warington (1882) were able to make estimates of the loss of N by leaching and hence draw up an approximate N balance for the experiment.

One of the outstanding features of the experiment is the ability of the soil to give a crop of wheat year after year in the absence of nitrogenous fertilisers. Thus the area receiving P, K and Mg but no nitrogen (plot 05) gave a mean grain yield of 2·4 t ha^{-1} over the three years 1970–72, about half the yield in the plot receiving the optimal amount of N. The source of the N for this crop has never been satisfactorily explained; until recently it had been thought to come from the declining organic N reserves of the soil (Russell, 1961) but we now know that this explanation is not valid.

Another experiment occupies the west end of the field: Broadbalk Wilderness. In 1883 a part of the field that had grown wheat without manure since 1843 was fenced off and allowed to revert to wilderness. Part of the area has been untouched ever since and is now under mixed deciduous woodland. In another part saplings have been removed regularly by stubbing and the ground is covered by a mixed herbaceous vegetation. Both sections of the Wilderness have gained nitrogen steadily since 1883 (Jenkinson, 1971) but again we do not know how this N has been fixed.

The main aims of the work described in this paper were twofold: to construct an N balance sheet for the Wilderness and for certain plots of the wheat experiment from existing data and to investigate some of the pathways by which N is fixed by the soil: plant system in these experiments.

Nitrogen balance in Broadbalk Continuous Wheat

Total nitrogen in the soil. Total N has changed little in the plots receiving inorganic fertilisers alone; Table 1 shows that there have been no consistent changes since 1881 in soils from plots 03–08 and very possibly none since 1865. It follows that changes in the organic N reserves of the soil on these plots can be assumed to be negligible. A decline of only 5 kg ha^{-1} $year^{-1}$ in the organic N content of plot 03 over the whole experiment would have resulted in a loss of 0·6 t N ha^{-1} by 1966, a loss that would easily have been detected had it occurred.

Total N has accumulated in plots receiving farmyard manure (Johnston, 1969b) and the rate of accumulation has declined as the soil approaches its equilibrium N value

https://doi.org/10.23637/ERADOC-1-11

TABLE 1

Total N in Broadbalk topsoils[1,2]

t N ha^{-1}

Year of sampling	Method of sampling	Plot and treatment 22(2B)[3] FYM[4]	03(3) unmanured	05(5) $PKMg^5$	06(6) N_1PKMg^6	07(7) N_2PKMg^6	08(8) N_3PKMg^6
1865[7]	Box	5·11	3·06	3·12	—	3·40	—
1881[7]	Box	5·35	3·06	2·97	3·35	3·67	3·81
1893	Box	6·07	2·88	2·94	3·23	3·55	3·46
1914	Box	6·77	2·71	3·00	3·26	3·49	3·75
1944	Spade	6·47	3·08	3·06	3·26	3·52	3·58
1966	Corer	6·85	2·88	3·11	3·29	3·35	3·43

[1] Results for plots 03–08 to a depth of 23 cm, assuming the weight of the 0–23 cm soil layer to be 2·91 Mkg ha^{-1}, the figure given by Dyer (1902; Table 8) as the mean for all plots not receiving organic fertiliser. In plot 22 the soil bulk density has decreased as organic matter has accumulated. The figure for the total N content of plot 22 at a given date in this table (and in Fig. 1) is the amount in the layer of soil that contained the *same* weight of soil as did the 0–23 cm layer at the beginning of the experiment (assumed to be 2·91 Mkg ha^{-1}). For the 1881, 1893 and 1914 results this correction for soil expansion was made as described by Jenkinson (1971); corrections for the 1865, 1944 and 1966 results were made by extrapolation from the other samplings

[2] Calculated from the % N values given by Johnston (1969b; Table 5.10)

[3] Pre-1968 plot numbers in parentheses

[4] Plot 22 receives 35 t FYM ha^{-1} $year^{-1}$, containing about 225 kg N

[5] Plots 05, 06, 07 and 08 all receive 35 kg P, 90 kg K and 10 kg Mg ha^{-1} $year^{-1}$

[6] N_1, N_2 and N_3 correspond to 48, 96 and 144 kg N ha^{-1} $year^{-1}$. Over the 1852–71 period the applications were a little less; 46, 92 and 138 kg, respectively

[7] N was determined by the soda-lime method in the 1865 and 1881 samples; all the other samples were analysed by the Kjeldahl method. The 1865 and 1881 results have been multiplied by 1·04 to make them comparable with the later Kjeldahl values. This factor is the mean (N by Kjeldahl)/(N by soda-lime) ratio for all the 1893 Broadbalk samples (Dyer, 1902)

(Fig. 1). An exponential curve was fitted to the results plotted on Fig. 1 for the accumulation of N by plot 22, as was done for the plot receiving FYM (7–2) on Hoosfield (Jenkinson & Johnston, 1977). Although both plots receive exactly the same annual dressing of FYM, the predicted equilibrium N content in Broadbalk is 6·90 t ha^{-1}; less than the corresponding value predicted for Hoosfield (7·62 t ha^{-1}). This difference almost certainly arose because Broadbalk was fallowed more frequently than Hoosfield between 1926 and 1966.

Nitrogen in rain. Over the period 1889–1903 the mean annual amount of mineral N carried down in the rain at Rothamsted was 4·4 kg ha^{-1}, of which 1·3 kg was NO_3-N and 3·1 kg NH_4-N. Over the period January 1960 to December 1964 the corresponding total was 5·4 kg ha^{-1}, of which 2·4 kg was NO_3-N and 3·0 kg NH_4-N (see Jenkinson, 1971 for fuller details of N in rain). This trend towards larger values has continued; the water collected on the 1/1000 acre rain gauge over the year April 1969 to March 1970 contained N equivalent to 8·6 kg ha^{-1} of which 3·9 kg was NO_3-N and 4·7 kg NH_4-N (R. J. B. Williams, personal communication).

Nitrogen in seed. Seed rates have ranged from 125 to 210 kg ha^{-1} during the course of the experiment (Johnston & Garner, 1969), so that 2–4 kg N ha^{-1} have entered the soil each year as seed, assuming that seed wheat contains 2% N.

Dry deposition of ammonia. The mean annual ammonia content of the air at Rothamsted over the period January 1960–December 1964 was 4·8 μg NH_3-N m^{-3} (see Jenkinson, 1971, for details). Eriksson (1968) reviving earlier theories, suggested that the soil:plant system absorbs part of this atmospheric ammonia, and he constructed a map of Western Europe

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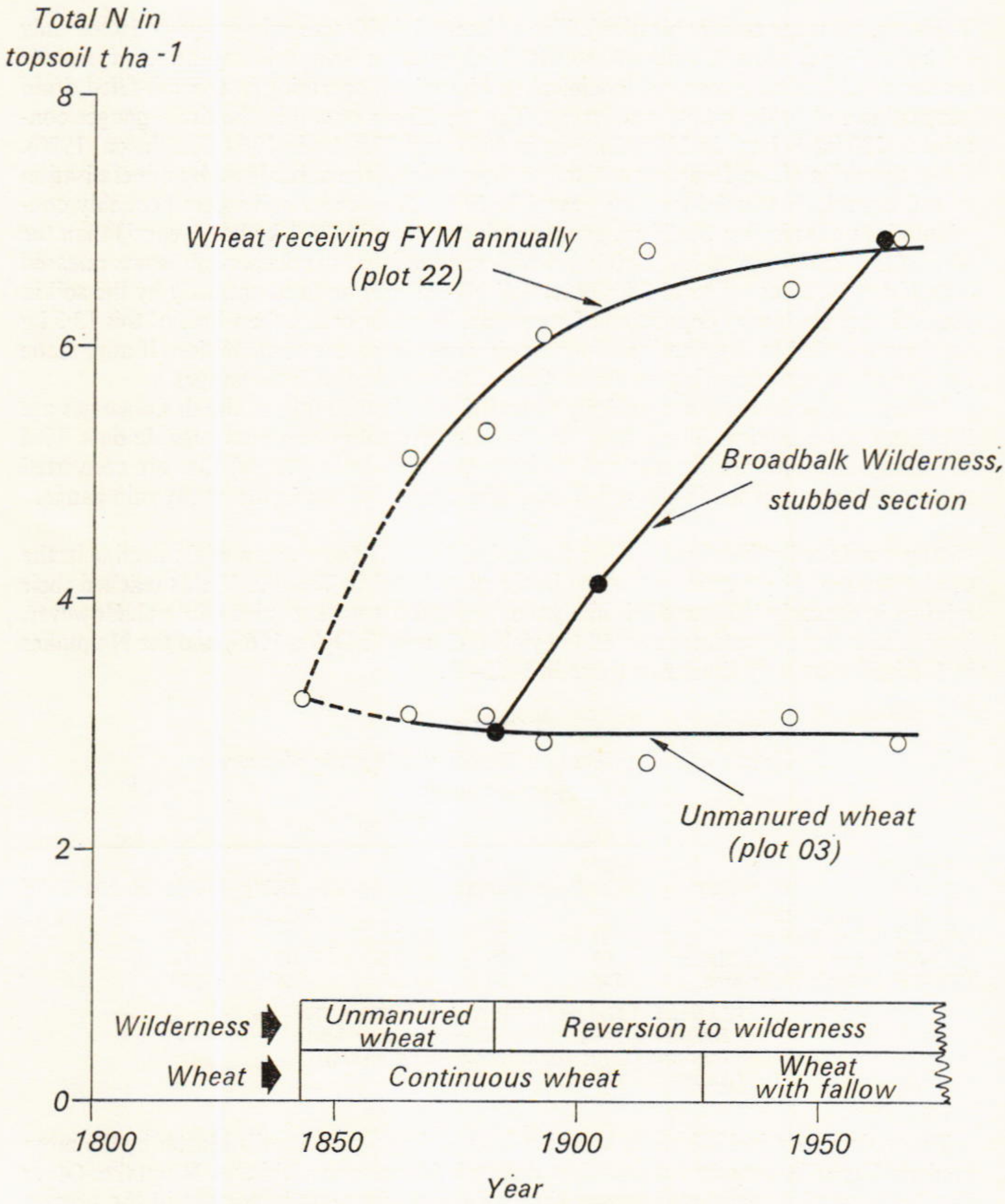

FIG. 1. Nitrogen in the topsoil of (a) the stubbed section of Broadbalk Wilderness, (b) the unmanured plot (03) of the Continuous Wheat experiment and (c) the plot (22) of the Continuous Wheat experiment receiving 35 t FYM ha^{-1} year^{-1}. All measurements on a 0–23 cm basis; corrected (see footnote 1 to Table 1) to allow for the changes in soil bulk density that occur when organic matter accumulates in soil.

for 1958 in which the 'dry' deposition of ammonia at Rothamsted was estimated to be 13 kg N ha^{-1} year^{-1}. Some results from the Rothamsted Drain Gauges can be used to set upper limits for dry deposition on bare soil. The mean quantity of NH_4-N plus NO_3-N leached from all three drain gauges (each of area 1/1000 acre, but differing in the depth of soil they contain) over the year April 1969 to March 1970 was 25·4 kg ha^{-1} (R. J. B.

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Williams, personal communication). The adjacent 1/1000 acre rain gauge collected only 8·6 kg ha^{-1} over the same period, so that 16·8 kg came from mineralisation of organic matter and fixation processes (chemical or biological) operating in the soil-filled drain gauges but not in the empty rain gauge. The top 23 cm of soil in the drain gauges contained 4130 kg N ha^{-1} in 1870, 2620 kg in 1917 and 2250 kg in 1969 (Jenkinson, 1970). From the slope of the decay curve fitted to these results, the annual loss by mineralisation of soil organic N was 3·5 kg ha^{-1} year^{-1} in 1969. The deeper soil layers probably contributed little N; in fact the 20-in. gauge produced more N (29·1 kg ha^{-1} year^{-1}) than the 40-in. (25·1 kg) or the 60-in. (22·0 kg), which suggests that the deeper soil layers released little if any N. Thus up to 13·3 kg N ha^{-1} (16·8–3·5) can be fixed annually by the soil in the drain gauges by dry deposition of ammonia. Whether or not the whole of this 13·3 kg can be attributed to dry fixation of ammonia depends on the contribution, if any, made by blue-green algae growing on the surface of the soil in the drain gauges.

Heterotrophic bacteria are unlikely to contribute significantly as the drain gauges are kept bare of vegetation. There may also be small contributions from organic dust, bird dropping, etc. (presumably received alike by rain and drain gauges) that are converted to ammonium or nitrate in the soil-filled drain gauges but not in the empty rain gauge.

Nitrogen uptake by the wheat. Over the period 1852–71 there was a slight decline in the total uptake of N by grain and straw in the plots listed in Table 2. Yields reached their minima in the early 1920s and it is likely that N uptakes were then also minimal. However, improved cultural practices restored the yields (Garner & Dyke, 1969) and the N uptakes in 1966–67 were very similar to those in 1852–61.

TABLE 2

Uptake of N by wheat on Broadbalk, in grain plus straw

kg N ha^{-1} year^{-1}

		Plot and treatment					
Sampling period	Wheat variety	22 FYM	03 unmanured	05 PKMg	06 N_1PKMg	07 N_2PKMg	08 N_3PKMg
1852–61[1]	Red Rostock	59	26	32	42[4]	64	71[4]
1862–71[1]	Red Rostock	57	20	22		56	
1966–67[2]	Squarehead's Master	63	25	26	41	64	78
1970–72[3]	Cappelle-Desprez	144	34	35	66	104	130

[1] Lawes and Gilbert (1884; Appendix Table 15)
[2] Johnston (1969a; Table 4.2, continuous wheat)
[3] Johnston (1977; Table 1, continuous wheat)
[4] Lawes and Gilbert (1873; Table 44)

The replacement in 1968 of the archaic wheat variety Squarehead's Master by the more modern Cappelle-Desprez resulted in a dramatic increase in yield and N uptake. Other changes were also made at the same time, of which the most important in the present context was that the split dressings of ammonium salts applied between 1884 and 1967 to the plots receiving inorganic N were replaced by a single dressing of 'Nitro-Chalk' applied in the spring. It follows that comparisons between the uptakes of N by the two varieties cannot be made directly, because of the simultaneous changes in manuring. However, the plots receiving farmyard manure (22), nothing (03) and PKMg (05) were not affected by these changes in nitrogen manuring and in all three the uptakes by Cappelle were consistently greater than those by Squarehead's Master.

Losses by leaching. The figures in Table 3 for the losses of NO_3-N over the 30-year period are those given by Lawes, Gilbert and Warington (1882; Table 52). They measured the

https://doi.org/10.23637/ERADOC-1-11

TABLE 3

Nitrogen balance in five plots of the Broadbalk Continuous Wheat experiment over the period 1852–1967

kg N ha^{-1} $year^{-1}$

N contribution	Plot and treatment 03 unmanured	05 PKMg	06 N_1PKMg	07 N_2PKMg	08 N_3PKMg
From soil organic N[1]	0	0	0	0	0
From rain[2]	+5	+5	+5	+5	+5
From seed[2]	+3	+3	+3	+3	+3
From fertiliser	0	0	+48	+96	+144
To crop[3]	−24	−27	−42	−61	−73
To drainage[2]	−12	−14	−21	−35	−48
Net annual gain from (+) or loss to (−) the atmosphere	+28	+33	+7	−8	−31

[1] See Table 1
[2] See text
[3] Mean of 1852–61, 1862–71 and 1966–67 results (Table 2)

NO_3-N concentration in the water from the drain under each plot throughout a number of years, but did not measure the flow rate, knowing that only a part of the water that percolated through a plot emerged from the drain. The amount of percolation was taken as the percolation from the (uncropped) 60-in. drain gauge. The NO_3-N analyses for the drainage from the various plots were grouped into four periods (from spring sowing to the end of May, from the beginning of June to harvest, from harvest to autumn sowing and from autumn sowing to spring sowing) and a mean NO_3-N concentration calculated for each of these periods. The figures given in Table 3 for the annual loss of NO_3-N in drainage were calculated by multiplying these means by the percolation from the drain gauge over the appropriate period of each year.

In five of the 30 years considered by Lawes, Gilbert and Warington, the fertilisers (given as ammonium salts) were applied in spring, in the other 25 in autumn. Between 1884 and 1967 the N fertiliser applications were split, 24 kg ha^{-1} being applied in autumn and the rest in spring. We have no post-1884 data to show how these split applications affected the loss of NO_3-N by leaching but Lawes, Gilbert and Warington's results, comparing spring and autumn applications, indicate that the difference was not great in plots 06–08 when averaged over several years. Neither total soil N nor plant N changed much until 1967, so that these old results probably give a reasonable approximation to the drainage losses in Broadbalk up to then. The changes that took place in the experiment in 1968 are such that the old values are now largely irrelevant. Cappelle removes more N than Squarehead's Master so plots not receiving fertiliser N (03 and 05, Table 2) now contain, on average, less NO_3-N in the soil than they did when growing Squarehead's Master; denitrification and leaching will be correspondingly less.

Nitrogen balance. Table 3 shows the N balance in certain selected plots over the period 1852–1967. It does not apply to the post-1968 results (for reasons just discussed) or to the first eight years of the experiment, when the manurial treatments had not settled into the pattern that remained relatively unchanged until 1968.

The main feature of Table 3 is that there was a steady output of 36 kg N ha^{-1} $year^{-1}$ (offtake in crop plus losses by drainage) from plot 03 and 41 kg from plot 05 over the period under consideration. Of this, 8 kg came from rain and seed N, possibly another 10 kg from dry deposition of ammonia, leaving approximately 18 kg ha^{-1} $year^{-1}$ unaccounted for in plot 03 and 23 kg in plot 05. As N application increased from 0 to

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144 kg ha^{-1} year^{-1} across the series 05, 06, 07 and 08, there was a change from a nett annual gain from the atmosphere to a nett annual loss. This loss immediately suggests denitrification, although the uncertainties in the drainage estimates are such that undue weight should not be placed on the actual figures for the plots receiving fertiliser N. Lawes and Gilbert themselves thought that their drainage figures might be slightly low, in which case denitrification would be less important than indicated by the results in Table 3.

If denitrification takes place in plots receiving N it probably also occurs in plots not receiving N. An approximate upper limit can be set for the amount of N lost by denitrification from plot 05, using the data in Table 3 by assuming (a) that biological fixation is completely suppressed in the plot receiving 144 kg N ha^{-1} year^{-1} (plot 08) and (b) that dry deposition of NH_3-N amounts to 10 kg ha^{-1} year^{-1}. The total input on plot 08 is then 162 kg ha^{-1} year^{-1} (144 +10 + 5 in rain plus 3 in seed). If the system is under steady state conditions, the nett annual unexplained loss is then 41 kg N ha^{-1} year^{-1}, rather than the 31 kg given in Table 3. If it is further assumed, (c) that denitrification accounts for all this loss, (d) that anaerobicity develops at the same time and to the same extent in plot 05 and plot 08 (the soils have similar bulk densities, there is little difference in their total organic content and both are exposed to the same weather), (e) that the amount of denitrification is proportional to the NO_3-N concentration (see Bowman & Focht, 1974, for a discussion of the conditions under which this assumption is valid) and (f) that this NO_3-N concentration is proportional to the figures given in Table 3 for drainage-loss over the year, then the amount of denitrification is given by $14/48 \times 41 = 12$ kg ha^{-1} year^{-1}. This is an upper limit because the NO_3-N concentration in the two plots differ more widely in the spring and autumn, when denitrification is most likely to occur, than they do over the year as a whole (Lawes, Gilbert & Warington, 1882). Taking dry deposition of ammonia to be 10 kg N ha^{-1} year^{-1}, biological fixation in plot 05 over the period 1852–1967 was between 23 and 35 kg ha^{-1} year^{-1}, the first figure being based on the assumption that denitrification did not occur and the second on the assumption that denitrification was maximal (12 kg ha^{-1} year^{-1}). Similar arguments indicate that biological fixation in plot 03 was between 18 and 28 kg ha^{-1} year^{-1} over the same period.

Nitrogen accumulation in Broadbalk Wilderness

Between 1883 and 1964 the stubbed part of the Wilderness accumulated 3930 kg N ha^{-1} in the top 23 cm, a mean accumulation rate of 49 kg ha^{-1} year^{-1} (Jenkinson, 1971). Relatively little N accumulated in the soil below 23 cm. Assuming that the input by rain and dry deposition is the same as in the wheat experiment, the nett gain to be attributed to biological fixation is 34 kg ha^{-1} year^{-1}. The total input from biological fixation will be larger by the amounts of N lost by leaching and denitrification, but the size of these losses is unknown. Soil organic N accumulated very rapidly under the Wilderness; after 81 years the Wilderness soil has accumulated as much N as had the soil which had received 35 t FYM ha^{-1} year^{-1} for 123 years (Fig. 1).

Acknowledgement

We thank A. E. Johnston for help and advice in drawing up the balance sheets for the Broadbalk experiments.

References

Bowman, R. A. & Focht, D. D. (1974) The influence of glucose and nitrate concentrations upon denitrification rates in sandy soils. *Soil Biology and Biochemistry* **6**, 297–301.

Dyer, B. (1902) Results of investigations on the Rothamsted soils. *U.S.D.A., Office of Experiment Station, Bulletin* No. 106, 180 pp.

https://doi.org/10.23637/ERADOC-1-11

ERIKSSON, E. (1968) Air and precipitation as sources of nutrients. In: *Handbuch der Pflanzenernährung und Düngung*. Ed. H. Linser & K. Scharrer. Berlin: Springer-Verlag, Vol. II, Part I, 774–792.

GARNER, H. V. & DYKE, G. V. (1969) The Broadbalk Wheat Experiment, 3. Broadbalk yields. *Rothamsted Experimental Station. Report for 1968*, Part 2, 26–49.

JENKINSON, D. S. (1970) Radiocarbon dating of soil organic matter. *Rothamsted Experimental Station. Report for 1969*, Part 1, 83–85.

JENKINSON, D. S. (1971) The accumulation of organic matter in soil left uncultivated. *Rothamsted Experimental Station. Report for 1970*. Part 2, 113–137.

JENKINSON, D. S. & JOHNSTON, A. E. (1977) Soil organic matter in the Hoosfield Continuous Barley experiment. *Rothamsted Experimental Station. Report for 1976*, Part 2, 87–101.

JOHNSTON, A. E. (1969a) The Broadbalk Wheat Experiment, 4. The plant nutrients in crops grown on Broadbalk. *Rothamsted Experimental Station. Report for 1968*, Part 2, 50–62.

JOHNSTON, A. E. (1969b) The Broadbalk Wheat Experiment, 5. Plant nutrients in Broadbalk soils. *Rothamsted Experimental Station. Report for 1968*, Part 2, 93–115.

JOHNSTON, A. E. (1977) Additions and removals of nitrogen and phosphorus in long-term experiments at Rothamsted and Woburn and the effect of the residues on total soil nitrogen and phosphorus. In: *Agriculture and Water Quality. Ministry of Agriculture, Fisheries and Food, Technical Bulletin* No. 32, 111–144.

JOHNSTON, A. E. & GARNER, H. V. (1969) The Broadbalk Wheat Experiment, 2. Historical introduction. *Rothamsted Experimental Station. Report for 1968*, Part 2, 12–25.

LAWES, J. B. & GILBERT, J. H. (1873) Report of experiments on the growth of barley for 20 years in succession on the same land. *Journal of the Royal Agricultural Society of England* Ser. 2, **9**, 5–79, 79–178.

LAWES, J. B. & GILBERT, J. H. (1884) On the composition of the ash of wheat grain and wheat straw grown at Rothamsted in different seasons and by different manures. *Journal of the Chemical Society* **45**, 305–407

LAWES, J. B., GILBERT, J. H. & WARINGTON, R. (1882) On the amount and composition of the rain and drainage waters collected at Rothamsted. *Journal of the Royal Agricultural Society of England* Ser. 2, **17**, 241–279, 311–350; **18**, 1–71.

RUSSELL, E. W. (1961) *Soil conditions and plant growth*. 9th Ed. London: Longman.

https://doi.org/10.23637/ERADOC-1-11