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Poulton, P. R., Johnston, A. E. and White, R. P. 2022. Response of three cereal crops in continuous arable or ley-arable rotations to fertiliser nitrogen and soil nitrogen at Rothamsted's Woburn Ley-arable experiment. *Soil Use and Management.* https://doi.org/10.1111/sum.12872

WLA Yields 14th March 2022

Response of winter wheat followed by spring barley or winter rye to soil and fertiliser nitrogen when grown in continuous arable or ley-arable rotations on a sandy loam soil in the Woburn Ley-arable experiment, UK.

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Abstract

The concept of improving soil fertility by ley-arable farming, developed in the 1930s in England, was practised on many "mixed" farms that had both arable crops and permanent grass. The practice declined from the 1960s as farms became predominantly arable or grassland. However, there is increasing interest in including leys in arable farming to fix carbon from carbon dioxide in the atmosphere in soil organic matter (SOM). For example, in the United Kingdom a project "Grass and herbal leys in farm network" was launched in 2018 (adas.uk, 2020) and in the European Union (EU) farmers are now required to grow a wider range of crops (ec. europa.eu, 2020.

The Woburn Ley-arable experiment started in 1938 has compared six rotations, two with 3-yr leys, two with 8-yr leys and two with continuous arable crops on the yields of two cereal test crops. The effect of these rotations on SOM is given elsewhere (Johnston *et al.*, 2017). Here we give the yields of both test crops in each of the six rotations for 21 years starting in 1981. We discuss the response to four levels of applied fertiliser nitrogen (N), the effect of rotation, the level of SOM and the availability of soil N. Where no fertiliser N was added, crop yields increased as % N in soil increased, but, with sufficient fertiliser N there was little benefit from the extra N in the soil. Yields of winter wheat were larger after the 3-year grass ley than in the all-arable rotations and larger again following the grass/clover ley. Less fertiliser N was needed to achieve the yields after the leys than in the all-arable rotations. Yields of the second cereal crop following 3- or 8-yr leys were also larger than those in all-arable rotations but there was no difference between the leys. However, the extra N available from the leys and the increases in yield were modest. If leys are to be introduced into mainly arable farming systems, they may need to be subsidised to make them financially viable.

Highlights

- How does ley-arable cropping affect the response to N and yield of three cereals.
- Changes in EU legislation and a new initiative in the UK need long-term, field-based data.
- Yields were larger, and less N was required, following 3- and 8-yr leys than in continuous arable cropping.
- The inclusion of leys in a rotation needs to be cost-effective.

KEYWORDS

cereal yields, ley-arable rotations, arable rotations, response to soil and fertiliser N, soil organic matter

1 | INTRODUCTION

The response of a crop to nitrogen (N) varies greatly yet, biochemically, it might be expected to respond similarly to a given amount of N in all situations (Lawlor *et al*., 2001). In practice this does not seem to be so, and there are several possible reasons. Seasonal differences in the weather and its effect on crop growth has a major impact on the response of a crop to N, as does the availability of other nutrients, especially potassium (K). Milford & Johnston (2007) noted that as a plant responds to N by increasing cell number and cell size, the tissue water content increases and there has to be sufficient plant-available K to maintain cell turgor and thus the ability of the cells to photosynthesise efficiently. The availability of N to the crop when applied either as fertiliser or mineralised from soil organic matter (SOM) varies, especially at periods of maximum growth and at times and positions within the soil profile where roots are active in taking up nutrients. Johnston *et al.* (2009) using Rothamsted data showed that differences in N availability between fields can be caused by differences in the amount of SOM and the rate at which it is mineralised, and the effect of SOM on soil structure. The effects of SOM on the yield of arable crops in Europe have also been assessed by others, including Hijbeek *et al*. (2017) and Oelofse *et al*. (2015) while the latter also showed that increasing levels of SOM did not necessarily increase crop yields.

One way of increasing SOM while maintaining a proportion of arable crops on a farm is ley-arable cropping, *i.e.* having green forage crops, grass and/or legume leys alternating regularly every few years with arable crops on each field on a farm. Ley-arable cropping started in England in the 1930s when many farms had both animals and arable crops. It was considered that the arable crops would benefit from the “fertility” accumulated in the soil from growing leys for three to four years, together with the return of nutrients by grazing animals. Where animals were kept on a farm, any farmyard manure (FYM) produced was applied in autumn or spring to fields growing arable crops in the coming season. To test these concepts in the UK, experiments on ley-arable cropping were started by Rothamsted in 1938 (Boyd, 1968) and by the Grassland Research Institute, Hurley, in 1950 (Clement, 1975). Ley-arable cropping gradually fell out of favour in the 1960s and 1970s for financial and management reasons as more farms became either wholly arable or animal based. As a consequence, ley arable experiments which had been started by both the Agriculture Development and Advisory Service (ADAS) in 1953 (Eagle, 1975) and ICI at Jealott’s Hill in 1944 (Lowe, 1975) were stopped.

However, farmers in the UK do have land in temporary grass. In 2021 out of the total cropped area in the UK of about 6.08 M ha, about 16%, was in temporary grass under 5 years old and about 55% was in cereals, 1.75 M ha in wheat and 1.14 M ha in barley (gov.uk, 2022). Recently, there has been a renewed interest in increasing SOM on cropped land as a contribution to decreasing the amount of carbon dioxide in the atmosphere (Chabbi *et al.*, 2017; Poulton *et al*., 2018) and for the benefits of SOM on soil health (Lal, 2020).
In the UK, ADAS, together with the Agriculture and Horticulture Development Board (AHDB) and the Department for Environment, Food and Rural Affairs (Defra) launched the ‘Grass and herbal leys farm network’ in 2018 (adas.uk, 2020). The purpose of the network, which includes farmers, researchers and industry, is to investigate the long-term impact of including leys within rotations on changes in SOM and soil health. Setting up such a network in the UK partly mirrors the requirement for farmers within the European Union (EU) to grow a greater diversity of crops (ec.europa.eu, 2020). However, in recent years, few papers have reported benefits of including grass or legume leys within an arable rotation.

Cougnon *et al*. (2018) reported larger yields of forage maize following leys compared to following other arable crops with less fertiliser N needed to achieve the larger yield; while Persson *et al*. (2008) reported larger yields of winter wheat following legume/grass leys than in other rotations. Johnston *et al.* (1994) reported larger yields of wheat after 3-yr leys compared to 1- or 2-yr leys but for a following crop of potatoes the largest yields followed 5- or 6-yr leys.

There is much data on various aspects of the effects of ley-arable cropping at Rothamsted because its ley-arable experiments have continued. The first field experiment, started in 1938 on the Woburn Experimental Farm *c*.40 km north of London, was followed in 1949 by two further experiments on Rothamsted Farm (Boyd, 1968). The effects of contrasted cropping over a 70-year period on SOM in the Woburn experiment have been published and show that in all rotations SOM changed towards an equilibrium level related to the input of organic carbon and its rate of decomposition (Johnston *et al.*, 2017). Here we give the yields of the first test crop of winter wheat (*Triticum aestivum;* 1981-2000) and the second test crop; initially spring barley (*Hordeum vulgare;* 1982-1991), and later winter rye (*Secale cereal;* 1997-2001), following three or eight years of treatment cropping. Also discussed are a number of other possible beneficial and negative effects of the leys, including the response of these three cereals to fertiliser N, efficiency of use of the applied N fertiliser, and the availability of N from the leys, especially in the absence of applied fertiliser N.

2 | MATERIALS AND METHODS

2.1 | The structure of the Woburn Ley-arable experiment

The principle underlying the experiment at Woburn has been maintained for >80 years. It was simple – to measure and compare the effects of three years of treatment crops, arable or leys, on the yields of a first and second test crop that followed. By the 1950s, pests and diseases and the low levels of plant-available phosphorus (P) and K in the soil were such that they seriously threatened valid comparisons of the cropping systems being tested. To maintain the sustainability of the experiment many changes were made in the crops grown and soil fertility (for details see Johnston *et al*., 2022). Also, prompted by the inclusion of long leys in the Organic Manuring experiment (Mattingly, 1974), on the same field and soil type, it was decided to introduce 8-year leys into the Ley-arable experiment in 1973. By the late 1970s, the sponsors considered that all reasonable changes had been made in the management of the experiment and that valid comparisons on the yield of two consecutive cereal test crops could now be made. Also, by 1981, although it had not initially been the main aim of the experiment, there were sufficiently large differences in total SOM between the rotations to assess their effect on the accumulation and loss of carbon in SOM in the first 70 years of the experiment at Woburn (Johnston *et al*. 2017).

2.2 | Site and treatment details

The Woburn Ley-arable experiment is on a slightly sloping, 1.6 ha site that had grown arable crops since 1876 (Johnston, 1973). The soil is a sandy loam (Cambric Arenosol; FAO 1990) classified by the Soil Survey of England and Wales in three closely related soil series, Cottenham, Lowland and Flitwick, all developed in drift over Lower Greensand and containing 11-16% clay in the topsoil (Catt *et al.* 1980). The average annual rainfall, 1981-2001 was 661 mm and the average annual temperature was 9.7^{o} C (www.era.rothamsted.ac.uk).

The experiment comprises five blocks, each with eight pairs of plots; each plot is 8.5 m x 19.7 m. Throughout the experiment, on four pairs of plots, the effects of contrasted "treatment crops" (two different leys and two different arable rotations) each lasting three years, on the yields of two arable "test crops" that followed have been measured, together with changes in SOM. On the other four pairs of plots, alternating a 5-year all-arable rotation, with a 5-year ley-arable rotation was tested (see Table 1) but gave little useful information and was stopped after 35 years. Instead, a 10-year rotation with 8-year leys followed by the two arable test crops was introduced. Two "cycles" of these 8-year leys were phased in during the 1970s so that, by 1981, the effects of both 8-yr and 3-yr leys on the yields of the two arable test crops could be compared and these yields compared with those in the all-arable rotation each year. Block III, in the middle of the experiment, was the first block to start with treatment crops in 1938 and the cropping on each plot from 1972 to 1997 is shown in Table 1. Treatment cropping on the other four blocks was phased in from 1939-1942 in the order V, IV, II, I; full details for all five blocks are available from the Electronic Rothamsted Archive (e-RA; Perryman *et al*., 2018. www.era.rothamsted.ac.uk).

2.2.1 | Farmyard manure (FYM) applications.

FYM, 38 t ha^{-1}, was applied every fifth year, to the first test crop, potatoes (then to sugar beet) on one plot in each pair of plots until 1967. Applications stopped when winter wheat replaced sugar beet as the first test crop (see Johnston *et al.* 2022 for details). The effect of this FYM on SOM is discussed by Johnston *et al*. (2017).

2.2.2 | Basal applications and management during the period of the experiment discussed here.

P, K, Mg and chalk are applied as required to maintain the same adequate level of plant-available P (26-45 mg kg^{-1} Olsen P), K (exchangeable K, 250 mg kg^{-1}), Mg (exchangeable Mg, 50 mg kg^{-1}) and soil pH at ~pH 7 in all treatments (Johnston *et al*., 2022). Treatment crops receive appropriate amounts of N. Throughout the experiment all above-ground plant material has been removed following harvest before the plots coming into winter wheat were mould-board ploughed to about 23-25cm, typically in September or October. The wheat was usually drilled in mid-October (range 26th September – 5th November), fertiliser N was applied at stem extension, usually in the middle of April (range 23rd March – 2nd May), and harvest, on average, was in the third week of August (range 4th August – 7th September). Spring barley was drilled in mid-April, N was applied within a few days and harvest was in August (2nd August – 27th August). For winter rye, the dates of drilling, N application and harvest were similar to those for winter wheat. Details of field operations, the meteorological data for each growing season and the annual yields of all crops each year are available in e-RA.

2.2.3 | Nitrogen to test crops.

The four amounts of N tested on four sub-plots, each 4.27 x 9.14 m, within each main plot were chosen to achieve maximum grain yield and relate this to N applied. The amounts of N were rotated so that in time the same total amount of N was applied to each sub-plot. The amounts were 0, 70, 140, 210 kg N ha^{-1} to wheat (0, 63, 126, 189 kg N ha^{-1} in 1981), and 0, 60, 120, 180 kg N ha^{-1} to spring barley. For rye the rates were increased from 0, 30, 60, 90 kg N ha^{-1} (in 1992-96) to 0, 40, 80, 120 kg N ha^{-1} in 1997-2001.

2.2.4 | Soil and crop sampling and analysis.

Since the 1950s, the top 25 cm of soil has been sampled on each plot in the block at the end of the third treatment year (and the eighth treatment year since the 1970s), *i.e.* before ploughing the plots for the first test crop. Samples consisted of 16-25 cores taken with a 2.5

cm diameter semi-cylinder auger. These were air-dried, ground and analysed to determine % soil organic carbon (SOC), pH and plant-available P, K and Mg. (Johnston *et al*., 2022). Since 1980, total soil N has also been determined by combustion (LECO Corp., St Joseph, Michigan, USA). The cereal test crops were harvested by small plot combine taking a 2.0 or 2.1 m strip down the middle of each sub-plot. Yields of grain (and straw when measured) were recorded and samples dried and analysed for N by combustion (LECO Corp. USA).

2.2.5 | Identifying the rotations

Throughout the experiment, a code, based on the treatment crops, has been used to identify each rotation; the code has changed as the treatment crops have changed (see Table1 and Johnston *et al.* 2022). The treatment codes from 1973 to 2001, the period discussed here, are:
All arable rotations. AB: spring barley, spring barley, beans, and AF: bare fallow, bare fallow, beans. The difference between these two rotations in this period was to test whether there was less risk of take-all (*Gaeumannomyces graminis*) and sharp eyespot (*Rhizoctonia solani*) in the wheat and barley test crops in the AF rotation compared to their incidence in the AB rotation (Salt, 1959, Johnston, 1997; Johnston & Poulton, 2005).
Ley rotations. Ln3 and Ln8 grass leys receiving fertiliser N. Lc3 and Lc8 grass/clover leys with 10-15% clover in the seed mixture. The 8-year leys were introduced in 1973. It was difficult to maintain the clover content in the Lc leys, especially in the 8-yr ley.

2.3 | Statistical treatment of the data

In any one year there is no true replication because each of the five blocks is in a different phase of the rotation. However, pairs of plots with and without FYM residues are treated as duplicates; FYM was last applied in 1967. Standard errors for the measured grain yield and N uptake are therefore calculated using data from each of the blocks over multiple 5-yr cycles as replicates.
Three approaches have been used to study the crops response to N, (1) a yield/N response curve has been fitted to the cereal test crop yields for each combination of rotation and year, (2) the response curves have been shifted to superimpose them, (3) the effect of soil N on yield has been investigated.

2.3.1 | Nitrogen response model

The “exponential plus linear” model, described in detail by George (1984), has been widely used for cereal N-response experiments (Dyke *et al.*, 1983; Johnston *et al.*, 1994, Sylvester-Bradley, 2014), The inclusion of the linear term with a declining trend ensures that there is a maximum yield (Ymax) and an associated N application (Nmax) within the range of the rates of N tested. The model is described in terms of four parameters: the linear trend, the asymptotic yield ignoring the trend, the rate of curvature of the exponential curve and the range (the difference between the asymptotic yield and that for zero N):

$$Y = A + B*R^N + C*N \qquad \text{Eqn 1}$$

Where Y is the grain yield in t ha^{-1} and N is the applied N fertiliser in kg ha^{-1}. A is the asymptotic maximum yield, B is the range (the difference between the asymptotic maximum yield and that for zero N). R relates to the rate of curvature of the exponential component and C is the slope of the linear trend (a decline if negative). The values of R and C were constrained to be common for each of the six rotations in 20 years of wheat, nine years of barley and 5 years of rye. Constraining C to be common allows for the subsequent “curve shifting” exercise described below. Where there is evidence for the R parameter to be common across a series of independent responses, as has been seen for similar models of the yield response to applied N (e.g. Addy *et al*., 2020), the values of A, B and C can be estimated by least square fitting as a multiple linear regression in response to N and R raised to the power of N, rather than using an iterative least squares fitting approach for this non-linear function. This approach further allows the exploration of how the A, B and C parameters vary between years and rotation treatments, or for combinations of data, *e.g.* for all years for a particular rotation. Further equations for the estimation of Ymax and Nmax can be found in the Supporting Information.

2.3.2 | Superimposing the yield/N treatment response curves - curve shifting

A “curve shifting” technique has been used to compare and attribute the benefits to cereal yields when they are grown in different rotations, and a range of amounts of N fertiliser are tested on the cereals (Dyke *et al*., 1983, Johnston, 1987, Johnston *et al*., 1994). When the yield/N response relationship is fitted using the model described above the curve for the different rotations has the same shape and the Ymax for each rotation can be shifted diagonally to bring them into coincidence and produce a unified N response curve. The diagonal shift has a vertical component related to the increase or decrease in maximum yield (the response data on the y-axis) and a horizontal component related to the increase or decrease in the applied N needed to achieve this maximum yield (the explanatory data on the x-axis). The results of curve shifting in this experiment are discussed.

2.3.3 | Effect of soil N on yield

The relationship between % N in the topsoil (0-25 cm) and yield was examined using simple linear regression with groups of years, rotations or blocks as the grouping factor (VSN International, 2019; Microsoft Corporation, 2018). We also used Boundary Line Analysis (Webb, 1972) to look at the relationship.

3 | RESULTS AND DISCUSSION

Average grain yields for the first and second cereals in the six rotations are summarised in Table 2. Grain yields for each year, meaned over plots with and without FYM residues, are given in Supplementary Tables 1 and 2 (full details are available from e-RA). The data show that, on average, maximum yields were larger following grass or grass/clover leys than in the all-arable (AB) rotation and were achieved with less fertiliser N. The effects of the treatments on grain yields are considered in four sections.

1. For each of the six rotations the grain yields, response to N and N use efficiency are given for each amount of N tested.
2. The fitted N response curves to determine Ymax and its associated Nmax.
3. Superimposing the fitted N response curves to estimate the effect of the N supplied by the treatment crops and factors other than N.
4. The effect of soil N on cereal yield.

3.1 | Grain yields, nitrogen response and nitrogen use efficiency

FYM was applied only until 1967 to one of each pair of plots but there was still more SOM in these FYM-treated soils in the early 1980s (Johnston *et al*., 2017). However, after 1981 the effects of this extra SOM on the yields of the first and second cereal test crop were often small and inconsistent, thus, the yield given here for each rate of N is the average of plots with and without residues of FYM.

The yields of the first and second cereal in the six rotations varied greatly from year to year on this sandy loam soil (Supplementary Tables 1 and 2). For example, from 1981 to 2000 wheat grain yields in the AB rotation given 140 kg N ha^{-1} varied from 3.44 to 9.94 t ha^{-1} while in the Lc3 rotation with the same amount of N, yield varied from 6.12 to 10.52 t ha^{-1}. The average grain yield, % N in grain, and percent recovery of applied fertiliser N (by the difference method) for each rotation and amount of N applied is shown in Table 2 for winter wheat (1981-2000), for spring barley (1982-1991), and winter rye (1997-2001), when, with increased fertiliser N, the best yields of rye were similar to those of winter wheat. Yields of wheat since 2001 and rye since 2002 are not given here because there were changes in the treatment crops grown; yields are however in e-RA.

When no fertiliser N was applied, yields of all three cereals were consistently a little larger in the AB rotation than in the AF rotation probably because there was a little more SOM in the AB rotation soil (Johnston *et al*., 2017). However, where N was applied the largest yield was often in the AF rotation, especially for wheat in the second 10-year period, 1991-2000, (Supplementary Table 1) probably because the causal agents for take-all and sharp eyespot declined in the second of the two years of fallow as observed elsewhere by Salt (1959).

On average, maximum yields were greater following Ln and Lc leys than in the all-arable (AB) rotation, although not significantly so for winter rye. However, without added fertiliser N, yields of winter wheat following the Ln leys were less than those following the Lc leys. But, for the second test crop, a similar comparison showed that yields following the Ln and Lc leys were essentially the same. The reasons are discussed in the section on curve shifting. Maximum yields following both the Ln8 and Lc8 leys were not larger than those following the corresponding 3-year leys suggesting that in terms of test-crop yield there was no justification for having leys longer than three years on this soil type.

3.1.1 | Nitrogen uptake and recovery of fertiliser nitrogen.

The average N content of the grain and percent N recovered for each treatment are in Table 2. Straw yields were not measured in the period reported here, but, in 2002, yields of both grain and straw were measured and N% determined. On average about 90% of the total N uptake was in the grain so the total recovery of N in grain plus straw will be a little larger than the values given in Table 2. As widely reported, the percentage of fertiliser N recovered declined as the amount of N applied increased. For example, for winter wheat the largest recoveries were 65-73% where 70 kg N ha^{-1} was applied, but the yields were small; with 210 kg N ha^{-1} yields exceeded 7 t ha^{-1}, but N recovery ranged from only 37-54%. The leys might have been expected to improve the recovery of N compared to that in the AB rotation. For most comparisons, and amounts of applied N, N% recovery was similar following the leys and in the AB rotation. For wheat given 210 kg N ha^{-1} in the Lc rotations percent recovery was less than in the AB rotation because N was mineralised from the ploughed-in leguminous residues. Conversely, N% recovered was usually larger in the AF rotation suggesting that after two years of fallow there was very little immediately available N in this soil. These results suggest that there is little benefit from growing short term leys to improve fertilizer N efficiency.

To be considered suitable for bread-making, wheat grain should contain 13% protein (2.28% N in grain dry matter), assuming that other important quality factors *e.g.* Hagberg Falling Number, are also acceptable (Stevens *et al.*, 1988). In the 20 years reported here, the following bread-making varieties were grown: *cv.* Flanders (1981 only), Avalon, Mercia and Hereward. Grain protein varied widely depending on the amount of N applied, treatment and year. For example, where wheat was grown in the all-arable rotation (AB) or following grass leys (Ln3) grain protein equalled or exceeded 13% in 58% and 18%, respectively, of cases where 210 or 140 kg N ha^{-1} was applied. However, where wheat followed grass/clover leys (Lc3) grain protein exceeded 13% in 78% and 32%, respectively, of cases where 210 or 140 kg N ha^{-1} was applied, almost certainly because of the extra N available from the leguminous residues (see below). Additional data on yield and protein content in this experiment were given by Johnston & Poulton (2009) as part of a discussion on nitrogen use in agriculture.

3.2 | Fitted nitrogen response curves to determine the asymptotic maximum yield and its associated nitrogen requirement

The response curve for the yield/ N applied relationship was fitted for each treatment and each year to determine Ymax and its associated Nmax for winter wheat (1981-2000), spring barley (1982-1991; excluding 1983) and winter rye (1997-2001). The average fitted response curve for each cereal and group of years is shown in Figures 1a, c, e. Table 3 shows the average and range in Ymax and Nmax and the considerable annual variation in both for all three cereals.

For winter wheat the average Ymax and Nmax in the AB rotation was 7.10 t ha^{-1} grain, and 175 kg N ha^{-1}. The yield was larger, 7.91 t ha^{-1}, in the AF rotation, presumably because there were fewer root pathogens as postulated by Salt (1959), but more N, 192 kg ha^{-1}, was needed to achieve this larger yield. Following both the 3- and 8-year Ln leys wheat yields were very similar, average 7.65 t ha^{-1}, which was 0.55 t ha^{-1} larger than that in the AB rotation and slightly less N was required to achieve this yield. Yields were larger and very similar following the 3- and 8-year Lc leys, average 8.12 t ha^{-1}, which was 1 t ha^{-1} more than in the AB rotation and significantly less N, 30 kg ha^{-1}, was required to achieve this yield.

For the second test crop in each rotation Ymax was larger for rye than barley but Nmax for rye was smaller than that for barley, possibly because the autumn sown crop was taking up residual fertiliser N applied to the wheat or N that was mineralised from organic residues in autumn. Ymax was very similar for all four ley rotations and always larger than that in the AB rotation and the associated Nmax was smaller than that in the AB rotation. This suggests that very similar amounts of N were being mineralised from the ploughed-in ley residues in the second year.

The average Nmax in these experiments can be compared with N recommendations given in the current Nutrient Management Guide (RB209) (AHDB, 2020). For light sand soils at SNS (Soil Nitrogen Supply) Index 0 soils (the AB and AF rotations) the N recommendation is 180, 140 and 110 kg N ha^{-1} for winter wheat, spring barley and winter rye, respectively, which was very similar to the Nmax, 175, 140 and 125 kg N ha^{-1}, respectively, the three cereals in the AB rotation in this experiment. Following the Ln leys, the Nmax values in Table 3 for wheat, barley and rye are less than those recommended in RB209. It is not possible to make a comparison for the Lc leys because in this experiment they were not grazed as they would be in usual practice.

3.3 | Superimposing the fitted nitrogen response curves to obtain further information

Additional information can be gained from bringing the N response curves for each rotation into coincidence (curve shifting). Here we assume that the horizontal component of the shift on the x-axis, *i.e.* N applied, could be attributed to an effective difference in N supply to the crop at and/or after the fertiliser N was applied. The vertical component on the y-axis, *i.e.* yield, could be attributed to factors other than fertiliser N, *e.g.* soil structure or the mineralisation of SOM providing N to the crop at times of the year and at positions in the soil profile not mimicked by surface-applied fertiliser N in spring.

The Ymax shown in the N response curves in Figures 1 a, c, e, for five of the rotations was brought into coincidence with that for the AB rotation by appropriate diagonal shifts to produce a single unified curve, as shown in Figures 1b, d, f. We used the AB N-response curve rather than to the AF N-response curve because the plots in the AB rotation grew arable crops each year. The percent variance accounted for by the unified curve relating yield and applied N was 91% for wheat, 93% for barley and 94% for rye. This supports our comments in the Introduction, namely that in each rotation the three cereals were responding to N in the same way and that differences in yields were due to the available N supply, the ability of the crop to access that N and the weather.

The vertical and horizontal shifts for each rotation other than the AB are shown in Table 4. For all three cereals following the leys the horizontal shift was positive *i.e.* significantly less fertiliser N was needed to achieve maximum yield, presumably because of the N mineralised from the ley residues. As noted earlier, for winter wheat there was an interesting comparison between the N-equivalent of the Ln and Lc leys; the latter was appreciably larger than the former. For the Ln3 and Ln8 leys it was least, only 5 and 15 kg N ha^{-1}, respectively, but was significantly more, 28 and 30 kg N ha^{-1} for the Lc3 and Lc8 leys, respectively (Table 4). However, for both barley and rye, the second cereal following the winter wheat, the N-equivalent of all four leys was very similar. The difference between the Ln and Lc leys for winter wheat was possibly because the grass ley residues when ploughed-in had a wide C:N ratio and the microbial decomposition of these residues used some of the N which would have been available to the winter wheat. More importantly however, there would be additional N from the leguminous residues after ploughing in the grass/clover leys. For both barley and rye, the second cereal following the winter wheat, the N-equivalent of all four leys was very similar, *i.e.* the additional benefits afforded by the leguminous leys were no longer evident.

For winter wheat the vertical shift for the two Ln rotations was significant at a little more than 0.5 t ha^{-1} grain; it was similar but significantly larger, about 1.0 t ha^{-1}, for the two Lc rotations. For the second test crops there was little difference between the four ley rotations and the average increase was only about 0.6 t ha^{-1} for both spring barley and winter rye; this increase was significant for the barley but not for the rye. The positive vertical shift for the cereals following the leys strongly suggests that there was an additional benefit of the leys other than N supply in spring. This could be due to an improvement in soil structure or the release of N from the ploughed-in ley residues at times and in parts of the soil profile not mimicked by spring-applied fertiliser N. The magnitude of these individual benefits varied from year to year, but the combined benefit due to extra SOM was larger and more frequent. Two other studies support the benefits of having an optimum amount of organic matter in this soil. In 1996/97 Murphy *et al*. (2007) found that there was a significantly larger microbial biomass in the soil following the grass leys compared to the AB rotation (964 *cf.* 518 kg C ha^{-1}) and that, during the growing season, the average normalised *gross* rate of mineralisation was greater following the leys than in the arable rotation soil (2.55 *cf.* 1.74 kg N ha^{-1} day^{-1}). Macdonald *et al* (1989) sampled the soils to 50cm after the wheat was harvested in 1984 and showed that inorganic N in the all-arable rotation soils was about 15 kg ha^{-1} but was larger, about 45-60 kg ha^{-1}, where wheat had followed 3- or 8-yr grass or grass/clover leys, although in that year there was no significant difference between the two types of ley.

3.4 | Effect of soil N on yield

Prout *et al.* (2020) suggested that SOC/clay ratios could be used to assess the structural quality of soils. In this experiment SOC/clay ratios were *c.* 1/11 where leys are included in the rotation but *c.* 1/16 on all-arable rotations which would indicate a moderate and degraded structural condition respectively. Johnston *et al.* (2017) looked at changes in SOC during the experiment, here, we look at the effect that differences in soil N might have on yield. Between 1980-1999, % N in the sandy loam soil (0-25 cm) of the 80 plots in this experiment ranged from 0.051% N to 0.143% N (Johnston *et al.*, 2017). Meaned over all rotations, the five blocks contained 0.094, 0.101, 0.102, 0.116 and 0.105% N on Blocks I, II, III, IV and V respectively, and probably reflected the small differences in clay content of the soil (Catt *et al.*, 1980). However, meaned over the five blocks, and soils with and without applications of FYM before the mid-1960s, soils in the six rotations, AF, AB, Ln3, Ln8, Lc3 and Lc8 contained, on average, 0.078, 0.091, 0.113, 0.110, 0.110 and 0.111% N respectively. It might be expected that at these concentrations of % N in the soil there could be some correlation with yield, particularly on sub-plots not receiving fertiliser N (N0). This was tested for the 20 years of winter wheat. Data for soils with clover leys (Lc3 and Lc8) were excluded because, although % N in soil was similar to that in the Ln3 and Ln8 rotations (Johnston *et al.*, 2017), the extra N mineralised from the leguminous residues confounds the relationship. The simplest associations are simple linear regressions which considered the following factors: FYM residues, block and rotation. There was no modifying effect of the FYM residues on the association between % N in soil and yield at N0. Linear regressions for each of the five blocks have different intercepts but the slopes are not significantly different from one another, implying that the response by the crop to soil N when given no fertiliser N was similar on each block (Table 5). The regression accounts for 37.9 % of the variance. Rotation has a statistically significant interaction with % N in soil meaning that there are different slopes and intersects for each rotation. The regression accounts for 36.7 % of the variance. Examining the regression coefficients for the separate rotations shows that AB, AF and Ln3 have a positive association with yield at N0 and % N in soil, Ln8 has a slightly negative slope.

Figure 2 shows for the three cereals the relationship between % N in the topsoil (0-25cm) and either the yield of grain when no fertiliser N was applied, or the maximum measured yield achieved with fertiliser N. For the second Test crops, barley and rye, data for the grass/clover leys are included. The data are very variable. Where no fertiliser N was applied there was a 4- or 5-fold increase in yield as %N in soil increased from about 0.05 to 0.14% N (Fig 2a, c, e). Where sufficient fertiliser N was applied to the wheat and barley (Fig. 2b, d), this additional N increased yield at all levels of soil N, but, by more at the lower than at the higher concentrations of soil N. A similar result was reported by Loveland & Webb (2003). For rye, the amount of N applied was not sufficient to achieve maximum yield even when the amounts tested were increased in 1997 (and again in 2002). Consequently, the best yields of rye given fertiliser N still showed a response to increasing soil N (Fig 2 f). For wheat and barley, the small increase in yield with applied N and increasing SOM (Fig. 2) supports our contention that the combined benefits from increasing and/or maintaining SOM are a worthwhile aim to optimise grain yields in as many years as possible.

Visual inspection of Figure 2a, c, e suggests that there is an ‘envelope’ or ‘cone’ which encompasses the increasing yield with increasing %N in soil. We were keen to see whether we could use Boundary Line Analysis to describe the data and gather more information about the N available to the crop from SOM. We also wanted to see whether there was an inflexion point in the boundary line relating %N in soil and crop yield and whether this point indicated a critical level of soil N. This technique was first described by Webb (1972) and we used the method outlined by Milne et al. (2006) and Lark & Milne (2016). Unfortunately, it was not possible to obtain any significant results as there was insufficient data and there was no strong affinity to any upper boundary (A. E. Milne; personal communication). However, this approach, and the data, warrants further investigation.

The results in Figure 2 emphasise again that 3- or 8-year grass leys in a 5- or 10-year crop rotation with two arable crops do not increase the amount of readily mineralisable SOM such that it can supply sufficient plant-available N to give maximum yields of currently-available cultivars of high-yielding cereal crops without additional fertiliser N. From the superimposed curves (Figure 1b, d, f) we estimate that a 3-year Lc ley supplied only about 30 kg N ha^{-1} in both the first and second year after ploughing. More importantly, to optimise the use of this mineralised N, and thus decrease the amount of fertiliser N applied, would require a quick laboratory method of analysing the soil. For many years, much time and effort has been spent trying to find such a method (*e.g.* Gasser, 1968; Rasmussen *et al.*, 1998; Curtin *et al.*, 2017), but with limited success. It is probably more important to estimate the total amount of fertiliser N required (and perhaps apply it in more than one application) to produce optimum yield.

4 | CONCLUSIONS

This experiment allows a comparison of the yields of winter wheat. spring barley and winter rye grown in continuous all-arable rotations with those grown in rotations with 3- and 8-yr leys, either all-grass leys with fertiliser N (Ln) or grass/clover leys without fertiliser N (Lc) when the herbage is always cut for conservation, *i.e*. the leys were not grazed by cattle or sheep. By the late 1970s, soils with Ln and Lc leys in each of the five blocks of the experiment had similar concentrations of both SOC (*c*. 1.0 – 1.2 % C) and total N, which were greater than in soils in arable rotations (Figures 1 and 2 in Johnston *et al.*, 2017). Maximum yields of wheat following both types of ley were greater than those in the all-arable (AB) rotation and less fertiliser N was needed to achieve this yield. In addition, wheat yields following the Lc leys were consistently larger than those following the Ln leys and tended to have a greater protein content. This effect was short-lived because, for the second test crop yields were very similar following both the Lc and Ln leys. Two factors could explain these differences: (1) there was more readily mineralisable organic N in the first year following the ploughing-in of the Lc leys compared to the Ln leys. (2) ploughed-in Ln residues have a wider C: N ratio than ploughed-in Lc residues and some inorganic N that had been released by mineralisation of organic N may have been immobilised. There was little or no benefit from growing leys for longer than three years.

That the individual N response curves (Figure 1) could be brought into coincidence by suitable horizontal and vertical shifts implies, as might be expected, that winter wheat, spring barley and winter rye are individually responding to their N supply in a similar way in each rotation. However, the seasonal variability in the crop's response to applied fertiliser N suggests that we are not able to accurately predict the availability of the N supply from SOM, especially in relation to the amount and rate of mineralisation of the organic N throughout crop growth, or the ability of the growing crop to access this N supply. That variability will undoubtedly be related to year-to-year differences in the weather. In a recent paper, Addy *et al.* (2020) modelled the effects of weather on the yield response of winter wheat to applied nitrogen on the Broadbalk Wheat Experiment at Rothamsted between 1968 and 2016. For sites that are only 25 km apart, we would expect the weather to be similar, and that some of the weather variables identified as influencing the model parameters and hence shape of the fitted response curves would also be similar. On Broadbalk, for example, total rainfall in October, February and June had a significant effect on the parameters of the yield N-response curves as did mean air temperature in November, April and May. It is hoped that the effects of the weather on the yield response of winter wheat on the Woburn Ley-arable experiment will be the subject of another paper.

On this sandy loam soil, including 3- or 8-yr grass leys in rotation with arable crops for several decades only increased soil N by about 20% compared to the change in continuous arable rotations. The yield benefits to the following cereals of including those leys in the rotation were modest although less fertiliser N was needed to achieve maximum yield. In a recent review, Sylvester-Bradley & Kindred (2021) considered the effects of recent large increases in the price of natural gas and the implications that this might have on the cost and availability of fertiliser N. They conclude that this might lead to a reduction in the amount of fertiliser N applied to cereals. However, the conflict between Ukraine and Russia is likely to lead to a shortage of wheat grain on the World markets and a large increase in price. In consequence farmers elsewhere in Europe may choose to put more land into cereals and maximise yields where they can assuming that the break-even price ratio between the cost of fertiliser and the value of the grain is favourable. It seems sensible therefore to make the best use of N mineralised from SOM. However, to achieve this would require a rapid, reliable method to determine the amount of N available from SOM. Maintaining, or increasing, SOM is important. It can lock-up CO_2-C from the atmosphere, improve soil water holding capacity and increase the amount of N that might be mineralised. In this experiment, between 1938 and 1973, a 1-yr hay crop in a 5-yr arable rotation maintained the level of SOM (Johnston *et al*, 2017). Other options such as adding bulky organic manures may increase SOM (Poulton *et al.*, 2017), but, as with the inclusion of leys, these options need to be cost-effective for the farmer. Either the leys themselves must be profitable or the benefit to any following crop must be sufficient to justify their inclusion. It is difficult to see how such rotations could be profitable unless the leys are subsidised.

ACKNOWLEDGEMENTS

We thank farm staff at Woburn and Rothamsted who have managed the experiment over >80 years, the many scientific staff involved with sample processing, members of the Analytical Unit, the Statistical departments and of e-RA who helped to curate the data and Suzanne Clark and Andrew Mead for helpful discussion. We also thank the Lawes Agricultural Trust and Rothamsted Research. The Rothamsted Long-term Experiments National Capability is supported by the UK Biotechnology and Biological Sciences Research Council (BBS/E/C/000J03000).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The data supporting this study are available through the electronic Rothamsted Archive (e-RA; www.era.rothamsted.ac.uk).

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