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RESEARCH ARTICLE

Response of three cereal crops in continuous arable or ley-arable rotations to fertilizer nitrogen and soil nitrogen at Rothamsted's Woburn Ley-arable experiment

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Abstract

Rothamsted's Woburn Ley-arable experiment, started in 1938 on a sandy loam soil, provides valuable real-world data on the effects of all-arable and ley-arable rotations. In this study, six rotations were compared from 1973 to 2001. Two had 3-year arable "treatment" crops, two had 3-year leys, and two had 8-year leys; the leys being all-grass given fertilizer nitrogen (Ln3 and Ln8), or grass/clover (Lc3 and Lc8). Here, we present the yields of two test crops, winter wheat (1981–2000) followed by spring barley (1982–1991) or winter rye (1997–2001) in each of the six rotations, and their response to four rates of fertilizer N and soil N. From fitted yield/N response curves, we show that maximum wheat yields were least (7.10 t ha^{-1}) in the AB rotation, slightly higher, but not significantly so (7.65 t ha^{-1}) following Ln leys but significantly higher (8.12 t ha^{-1}) following Lc leys. Significantly less fertilizer N (30 kg ha^{-1}) was needed to achieve the higher yields following Lc leys. Yields of the second cereal following the leys were 0.3–0.8 t ha^{-1} higher than those in the AB rotation; these increases were not statistically significant. However, significantly less fertilizer N, 26–38 kg N ha^{-1}, was required to achieve those yields. There was no difference found between the type of ley. The initial benefit of the Lc leys was short-lived. If leys are to be introduced into mainly arable farming systems, they may need to be subsidized to make them financially viable.

KEYWORDS

Cereal crops, fertilization, ley-arable rotations, soil N, SOM

1 | INTRODUCTION

Concern about climate change and the role that CO_2 in the atmosphere plays has led scientists in recent years to consider methods to limit/decrease its concentration. One suggestion is to remove the CO_2 via plants and fix the carbon (C) in SOM. Much C can be fixed in this way when both shallow- and/or deep-rooted species are grown over long periods (Poulton et al., 2017). Another way of increasing SOM, while maintaining a proportion of arable crops on a farm is ley-arable cropping, that is, having green forage crops, grass and/or legume leys alternating regularly every few years with arable crops on each field. The effect of SOM on the yield of arable crops has been assessed by others, including Johnston et al. (2009), Johnston and Poulton (2009), Cougnon et al. (2018), Hijbeek et al. (2017) and Oelofse et al. (2015); the latter showed that increasing SOM did not necessarily increase yield. Testing ley-arable systems has been recently proposed in the UK (adas.uk, 2020), but they were previously practised in England from the 1930s and then declined from the 1960s as farms became predominantly arable or grassland.

Rothamsted first tested ley-arable cropping in 1938. The Woburn Ley-arable experiment (Boyd, 1968) on a sandy loam soil still continues, though there have been changes in its management to maintain a viable experiment (Johnston et al., 2022). From 1973 to 2001, six rotations were compared: two with 3-year leys, two with 8-year leys and two with continuous arable crops, the latter chosen to minimize the risk of building-up soil-borne pests and diseases. The effects of these treatment crops lasting 3 or 8 years were measured by the yields of two cereal test crops that followed. Two types of leys were tested: all-grass given fertilizer N, Ln3 and Ln8; and grass/clover, Lc3 and Lc8. The effect of these rotations on SOM is given below (Section 3.4) and by Johnston et al. (2017). Over a period of >80 years, on this sandy loam soil, including such leys in ley-arable rotations only increased SOM by about 20% compared with the change in continuous arable rotations.

To persuade growers to include leys in their rotation, they will need some indication of any benefit they may have on the arable crops grown. Here, we give for all six rotations the yields of the two following test crops, winter wheat 1981–2000, then spring barley, 1982–1991 or winter rye 1997–2001. We discuss the response of these three cereals to fertilizer N, the efficiency of use of the applied N and the availability of soil N.

2 | MATERIALS AND METHODS

2.1 | The structure and treatments in the Woburn Ley-arable experiment

The core treatments have been maintained for >80 years. They sought to measure and compare the effects of 3 years of arable or ley treatment crops on the yields of two arable test crops that followed. Eight-year leys were introduced in the early 1970s (Table 1). By the 1950s, pests and diseases and low levels of plant-available phosphorus (P) and potassium (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 the application of plant nutrients (Johnston et al., 2022; Poulton et al., 2022). By the 1970s, it was considered that all necessary changes had been made in the management of the experiment and that valid comparisons of the six rotations on the yield of two consecutive cereal test crops could now be made.

2.2 | Site and treatment details

The 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) 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°C (www.era.rothamsted.ac.uk).

There are five blocks, with each phase of the rotations present each year, and each block has eight pairs of plots; each plot is 8.5 m × 19.7 m. Plots 1 and 2, 3 and 4, etc., were paired (see generic plan of the experiment in Johnston et al., 2022) and one of each pair tested farmyard manure (FYM). On half of each block, there are four pairs of plots, which measure the effects of two different leys and two different arable rotations (the treatment crops) each lasting 3 years, on the yields of two arable "test crops" that follow. Starting with treatment crops on Block III in 1938 (Table 1), the other four blocks were phased in from 1939 to 1942. Treatments on the other four pairs of plots in each block have varied and, during the period discussed here, included a test of 8-year leys. Details of the treatments and yields for all five blocks are available from the Electronic Rothamsted Archive (e-RA; Perryman et al., 2018. www.era.rothamsted.ac.uk).

2.3 | 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 following the 8-year leys). before ploughing the plots for the first test crop. Each sample comprised 16–25 cores taken with a 2.5-cm-diameter semicylinder auger. After being air-dried and ground, they were analysed to determine % organic carbon, 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 subplot. Yields of grain (and straw when measured) were recorded and samples dried and analysed for N by combustion (LECO Corp. USA).

TABLE 1 Treatment crops and test crops[a], 1973–1997, Block III[b], Woburn Ley-arable experiment

	Continuous rotations				Alternating rotations[c] then 8–year leys[d]			
	Arable		**Ley-arable**		**1st cycle**		**2nd cycle**	
Year	AB[e]	AF[f]	Ln3[g]	Lc3[h]	Ln8[i]	Lc8[j]	Ln8[k]	Lc8[l]
1973	P	P	Ln1	Lc1	Ln1	Lc1	P	P
1974	B	B	Ln2	Lc2	Ln2	Lc2	B	B
1975	H	B	Ln3	Lc3	Ln3	Lc3	H	B
1976	W	W	W	W	Ln4	Lc4	W	W
1977	B	B	B	B	Ln5	Lc5	B	B
1978	B	F	Ln1	Lc1	Ln6	Lc6	Ln1	Lc1
1979	B	F	Ln2	Lc2	Ln7	Lc7	Ln2	Lc2
1980	O	O	Ln3	Lc3	Ln8	Lc8	Ln3	Lc3
1981	W	W	W	W	W	W	Ln4	Lc4
1982	B	B	B	B	B	B	Ln5	Lc5
1983	B	F	Ln1	Lc1	Ln1	Lc1	Ln6	Lc6
1984	B	F	Ln2	Lc2	Ln2	Lc2	Ln7	Lc7
1985	BE	BE	Ln3	Lc3	Ln3	Lc3	Ln8	Lc8
1986	W	W	W	W	Ln4	Lc4	W	W
1987	B	B	B	B	Ln5	Lc5	B	B
1988	B	F	Ln1	Lc1	Ln6	Lc6	Ln1	Lc1
1989	B	F	Ln2	Lc2	Ln7	Lc7	Ln2	Lc2
1990	BE	BE	Ln3	Lc3	Ln8	Lc8	Ln3	Lc3
1991	W	W	W	W	W	W	Ln4	Lc4
1992	R	R	R	R	R	R	Ln5	Lc5
1993	B	F	Ln1	Lc1	Ln1	Lc1	Ln6	Lc6
1994	B	F	Ln2	Lc2	Ln2	Lc2	Ln7	Lc7
1995	BE	BE	Ln3	Lc3	Ln3	Lc3	Ln8	Lc8
1996	W	W	W	W	Ln4	Lc4	W	W
1997	R	R	R	R	Ln5	Lc5	R	R

Note: P, potatoes; H, 1-year hay; F, fallow; O, winter oats; BE, winter beans; W, winter wheat; B, spring barley; R, winter rye.

Ln1–Ln8, first, second, third year, etc., of a grass + N ley: Lc1–Lc8, first, second, third year, etc., of a grass + clover ley.

Each of the eight rotations (AB, AF, etc.) was grown on pairs of plots in each of five blocks. One plot in each pair received FYM; 38 t ha^{-1} applied every fifth year until the mid-1960s. The last applications of FYM were to Blocks IV, II, I, III and V in 1963, 1964, 1965, 1966 and 1967, respectively.

[a] Test crops are highlighted. Plots were divided to test four rates of N when test crops were grown. The rates of N rotated so that, over time, the C inputs on the four subplots were similar.

[b] Treatment cropping started in 1938 on Block III, and in 1939, 1940, 1941 and 1942 on Blocks V, IV, II and I, respectively.

[c] On four pairs of plots treatment crops alternated between arable and ley rotations.

[d] The alternating rotations were replaced by 8–year grass leys with N or 8–year grass+clover leys. The 1st cycle of these longer leys started in 1973 on Block III and in 1974, 1975, 1976 and 1977 on Blocks V, IV, II and I, respectively. The 2nd cycle of 8-year leys started in 1978 on Block III and in 1979, 1980, 1981 and 1982 on Blocks V, IV, II and I, respectively. The delay in starting the 2nd cycle of 8–year leys meant that the effects of all of the different treatment rotations on the yield of the following test crops could be measured every 5 years.

[e] AB treatment crops: potatoes, cereal, 1–year hay from 1938 to 1975; barley, barley, beans (or oats) from 1978 to 1995.

[f] AF treatment crops: potatoes, cereal, root crop from 1938 to 1975; fallow, fallow, beans from 1978 to 1995.

[g] Ln3 treatment crop: 3 years grazed grass + clover leys with N from 1938 to 1970; 3-year grass leys with N since 1973.

[h] Lc3 treatment crop: 3-year lucerne or sainfoin leys from 1938 to 70; 3 year grass + clover leys since 1973.

[i] Ln8 treatment crop: alternating treatment crops from 1938 to 1970; 8-year grass leys with N since 1973 (1st cycle).

[j] Lc8 treatment crop: alternating treatment crops from 1938 to 1970; 8-year grass+clover leys since 1973 (1st cycle).

[k] Ln8 treatment crop: alternating treatment crops from 1938 to 1975; 8-year grass leys with N since 1978 (2nd cycle).

[l] Lc8 treatment crop: alternating treatment crops from 1938 to 1975; 8-year grass + clover leys since 1978 (2nd cycle).

2.4 | The rotations from 1973 to 2001

A code, based on the current treatment crops, is used to identify each rotation (Johnston et al., 2022). The treatment codes and cropping from 1973 to 2001 are in Table 1:

2.4.1 | All-arable rotations

AB: spring barley, spring barley and beans; and AF: bare fallow, bare fallow and 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 with their incidence in the AB rotation (Johnston, 1997; Johnston & Poulton, 2005; Salt, 1959).

2.4.2 | Ley rotations

Ln3 and Ln8; 3- and 8-year grass leys receiving fertilizer N, and Lc3 and Lc8; 3- and 8-year grass/clover leys with 10%–15% clover in the seed mixture. It was difficult to maintain the clover content of the Lc leys.

2.4.3 | Test crops

First test crop is winter wheat followed by either spring barley or winter rye.

2.5 | Farmyard manure (FYM) applications

Initially, FYM, 38 t ha^{-1}, was applied every fifth year, to the first test crop (potatoes or sugar beet) on one of each pair of plots. In 1967, applications stopped when winter wheat replaced sugar beet as the first test crop (Johnston et al., 2022). For the effect of this FYM on SOM, see Johnston et al. (2017).

2.6 | Basal fertilizer applications during the period discussed here

The same adequate levels 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 (~pH 7) are maintained in all soils by applications of fertilizer and chalk (Johnston et al., 2022; Poulton et al., 2022).

2.7 | Nitrogen to test crops

Since 1973, as each block comes into the first or second cereal test crop, each main plot has been divided into four subplots, each 4.27 × 9.14 m, to test four rates of fertilizer N. The rates were chosen to achieve yields up to the maximum. The amounts of N applied were rotated so that in time the same total amount was applied to each subplot. The four rates, N_0, N_1, N_2 and N_3 were as follows: 0, 70, 140 and 210 kg N ha^{-1} to wheat (0, 63, 126 and 189 kg N ha^{-1} in 1981), and 0, 60, 120 and 180 kg N ha^{-1} to spring barley. For rye, the rates increased from 0, 30, 60 and 90 kg N ha^{-1} (1992–96) to 0, 40, 80 and 120 kg N ha^{-1} in 1997–2001. The % recovery by grain for each rate of fertilizer N was calculated as the uptake with applied N *minus* N uptake at N_0 as a percentage of N applied.

2.8 | Statistical treatment of the data

In any 1 year, there is no true replication because each of the five blocks was in a different phase of the rotation. However, pairs of plots with and without FYM residues are treated as duplicates. Standard errors for the measured grain yield and N uptake are calculated using data from each of the blocks over multiple 5-year cycles as replicates.

2.9 | Nitrogen response model

The "exponential plus linear" model has been widely used for cereal N response experiments (Dyke et al., 1983; Johnston et al., 1994; Sylvester-Bradley et al., 2014), including the linear term ensures that there is a maximum asymptotic yield (Y_{max}) and its associated N application (N_{max}). 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):

$$Y = A + B^{*}R^{N} + C^{*}N \tag{1}$$

where Y is the grain yield in t ha^{-1} and N is the applied N fertilizer in kg ha^{-1}. A is the asymptotic maximum yield and 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, 9 years of barley and 5 years of rye. Constraining C to be common allows for the subsequent "curve shifting" described later. 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 (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 nonlinear 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, for example, for all years for a particular rotation. Further equations for the estimation of Y_{max} and N_{max} can be found in the Supporting Information, Appendix S1.

2.10 | Superimposing the yield/N treatment response curves—curve shifting

A "curve shifting" technique has previously 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 fertilizer are tested (Dyke et al., 1983; Johnston, 1987; Johnston et al., 1994). When the same model is used for all the yield/N response relationships, the curves have the same shape and the Y_{max} for each rotation can be shifted diagonally to bring it into coincidence with the other Y_{max} and produce a unified N response curve.

2.11 | Relationship between % N in soil and yield

This relationship between the topsoil (0–25 cm) and yield was examined using simple linear regression with groups of years, rotations or blocks as the grouping factor (Microsoft Corporation, 2018; VSN International, 2019). We also used boundary line analysis (Webb, 1972) to look at this relationship.

3 | RESULTS AND DISCUSSION

3.1 | Measured grain yields and their nitrogen content

After 1981, the difference in yield between each pair of plots with and without FYM prior to 1967 was often small and inconsistent and the average yield on these two adjacent plots is used here.

The measured grain yields of each of the three cereals varied greatly from year to year (Tables S1 and S2). Increasing the amount of N applied in 1997–2001 increased best rye yields to those similar to winter wheat. In this discussion, we mainly use yields from the fitted response curves.

The yields of grain, N content of the grain and per cent N recovered for each rotation and each amount of fertilizer N applied are in Table 2. Where no fertilizer N was applied, yields of all three cereals were 0.2–0.7 t ha^{-1} higher (not always significantly) in the AB rotation (Table 2), which had a little more SOM, than the AF rotation (Johnston et al., 2017). However, where N was applied the highest yield for wheat was often in the AF rotation: average 7.89 t ha^{-1} in 1991–2000 (Table 2, Table S1) probably because the causal agents for take-all and sharp eyespot declined in the second of the 2 years of fallow as observed elsewhere by Salt (1959).

The N content of the grain and per cent N recovered for each rotation are in Table 2. Straw was not sampled and analysed but in 2002 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 shown in Table 2. As widely reported, the percentage of fertilizer 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% to 54%. The leys did not improve the recovery of N compared to that in the AB rotation. For wheat with 210 kg N ha^{-1} in the Lc rotation, per cent recovery was less than in the AB rotation because N was mineralized from the ploughed-in leguminous residues. Conversely, N% recovered was usually larger in the AF rotation, suggesting that after 2 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.

Grain protein, one criterion for identifying wheat suitable for bread making (Stevens & Baldwin, 1988), varied widely depending on the amount of N applied, treatment and year. For example, for wheat grown in the AB rotation, or following grass leys (Ln3 and Ln8) grain protein equalled or exceeded 13% in 58% and 18% cases, where 210 or 140 kg N ha^{-1}, respectively, was applied. However, where wheat followed grass/clover leys (Lc3 and Lc8) grain protein exceeded 13% in 78% and 32%, respectively, when the same amount of N was applied, probably because extra N was available from the recently ploughed-in leguminous residues.

Additional data on yield and protein content in this experiment were given by Johnston and Poulton (2009) as part of a discussion on nitrogen use in agriculture.

TABLE 2 Effect of preceding cropping on the grain yield, grain N content and % recovery of fertilizer N by the grain of the 1st and 2nd test crops, Woburn Ley-arable experiment.

	Grain yield, t ha^{-1} at 85% dry matter				**Grain N content, kg ha^{-1}**				**Recovery of fertilizer N by grain, %**		
	1st test crop, winter wheat, 20 year average, 1981–2000										
	N applied[a], kg ha^{-1}										
Rotation[b]	0	70	140	210	0	70	140	210	70	140	210
AB	2.81	5.83	6.73	7.06	40	85	118	138	65	56	47
AF	2.60	6.20	7.45	7.89	38	89	125	150	73	62	54
Ln3	3.78	6.55	7.43	7.62	56	101	134	149	65	56	45
Ln8	4.24	6.81	7.54	7.39	61	106	136	144	65	54	40
Lc3	5.26	7.55	8.02	7.88	78	123	149	158	65	51	38
Lc8	5.18	7.47	7.77	7.76	78	125	145	155	67	48	37
Within Rotation	F-ratio$_{(5\ 95)}$ = 13.87, $p < 0.001$				F-ratio$_{(5\ 95)}$ = 24.79, $p < 0.001$						
SED	0.226				3.65						
Rotation * N	F-ratio$_{(15684)}$ = 11.05, $p < 0.001$				F-ratio$_{(15684)}$ = 4.95, $p < 0.001$						
SED	0.283				4.92						
	2nd test crop, spring barley, 9 yr average, 1982-1991[c]										
	N applied, kg ha^{-1}										
	0	60	120	180	0	60	120	180	60	120	180
AB	2.29	4.56	5.41	5.14	32	64	87	91	53	46	33
AF	1.87	4.61	5.51	5.56	28	64	85	97	60	48	38
Ln3	4.15	5.69	5.93	5.59	57	85	100	102	47	36	25
Ln8	4.45	5.70	5.82	5.43	62	87	98	101	42	30	22
Lc3	4.16	5.64	5.85	5.39	60	87	101	99	45	34	22
Lc8	4.61	5.98	5.92	5.69	65	93	102	105	47	31	22
Within Rotation	F-ratio$_{(5\ 40)}$ = 24.63, $p < 0.001$				F-ratio$_{(5\ 40)}$ = 28.90, $p < 0.001$						
SED	0.149				2.73						
Rotation * N	F-ratio$_{(15288)}$ = 12.22, $p < 0.001$				F-ratio$_{(15288)}$ = 4.24, $p < 0.001$						
SED	0.232				4.45						
	2nd test crop, winter rye, 5 yr average, 1997–2001										
	N applied, kg ha^{-1}										
	0	40	80	120	0	40	80	120	40	80	120
AB	3.19	5.00	6.44	6.92	30	48	67	81	45	46	43
AF	2.48	4.44	5.55	6.32	23	40	54	72	43	39	41
Ln3	5.05	6.61	7.42	7.14	49	67	83	91	45	43	35
Ln8	5.35	6.91	7.56	7.64	55	70	87	96	38	40	34
Lc3	4.97	6.43	7.21	7.12	50	67	82	90	43	40	33
Lc8	4.98	6.77	7.16	7.12	51	72	85	93	53	43	35
Within Rotation	F-ratio$_{(5\ 20)}$ = 15.47, $p < 0.001$				F-ratio$_{(5\ 20)}$ = 22.24, $p < 0.001$						
SED	0.302				3.60						
Rotation * N	F-ratio$_{(15144)}$ = 1.94, $p < 0.05$				F-ratio$_{(15144)}$ = 0.75, not significant						
SED	0.451				5.05						

[a] In 1981, wheat received 0, 63, 126 and 189 kgN ha^{-1}.

[b] For rotation cropping, see text.

[c] Excludes 1983 as extra N was applied to all except N0 plots.

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

The model described previously was used to determine the response curve for the yield/ N applied relationship for each treatment and each year. From the fitted response curve, Y_{max} and its associated N_{max} were determined 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 Figure 1a,c,e. Table 3 shows the average and range in Y_{max} and N_{max} and the considerable variation in both for all three cereals.

For winter wheat, the average Y_{max} and N_{max} in the AB rotation was 7.10 t ha^{-1} grain, and 175 kg N ha^{-1}. The yield was higher, 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 higher 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} more than that in the AB rotation and 5–15 kg ha^{-1} less N was required to achieve this yield, but neither the yield increase nor the reduction in the amount of N required was significant. Yields were significantly higher 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 (Table 3).

For the second test crop in each rotation, Y_{max} was higher for rye than barley but N_{max} for rye was less than that for barley, possibly because the autumn sown crop was taking up residual fertilizer N applied to the wheat or N that was mineralized from organic residues in autumn. For both barley and rye, Y_{max} was very similar for all four ley rotations and 0.3–0.8 t ha^{-1} higher than that in the AB rotation but not significantly so. However, the associated N_{max} was significantly less (average 30 kg N ha^{-1}) less than that required to achieve maximum yield in the AB rotation. This suggests that very similar amounts of N were being mineralized from the ploughed-in ley residues in the second year (Table 3).

3.3 | Superimposing the fitted nitrogen response curves

Bringing the N response curves for each rotation into coincidence (curve shifting) gave additional information about the yield/N response relationship. Here, the shift in each case was diagonal with a horizontal and vertical component. The shift on the x-axis, that is, N applied, could be attributed to an effective difference in N supply in each rotation to the crop at and/or after the fertilizer N was applied. The vertical component on the y-axis, that is, yield, could be attributed to factors other than fertilizer N, for example, soil structure or the mineralization of SOM providing N to the crop at times of the year and at positions in the soil profile not mimicked by surface-applied fertilizer N in spring.

The Y_{max} shown in the N response curves in Figure 1a,c,e, for five of the rotations was brought into coincidence with that for the AB rotation to produce a single unified curve (Figure 1b,d,f). The per cent variance accounted for by the unified curve was 91% for wheat, 93% for barley and 94% for rye. This supports our view that the three cereals were responding similarly to N and differences in yield were due to the availability of this N for uptake by roots.

The vertical and horizontal shifts for each rotation other than AB are shown in Table 4. The horizontal shift was positive for all three cereals following the leys, that is, significantly less fertilizer N was needed to achieve maximum yield, because N was mineralized from the ley residues. For winter wheat, there was a difference between the N-equivalent of the Ln and Lc leys; 5 and 28 kg N ha^{-1}, respectively (Table 4). However, for the second cereal (barley and rye), the N-equivalent of both leys was very similar, suggesting that extra N from the mineralized Lc residues lasted only 1 year.

For winter wheat, the vertical shift for the Ln rotation was significant at a little more than 0.5 t ha^{-1} grain, and higher, about 1.0 t ha^{-1}, for the Lc rotation. For the second test crops, there was little difference between these four ley rotations and the increase about 0.6 t ha^{-1} for both spring barley and winter rye was significant for barley but not for rye. This 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, possibly an improvement in soil structure.

Two other studies support the benefits of maintaining 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 with the AB rotation (964 cf. 518 kg C ha^{-1}) and that, during the growing season, the average normalized *gross* rate of mineralization 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 50 cm 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-year grass or grass/clover leys, although in that year there was no significant difference between the two types of ley.

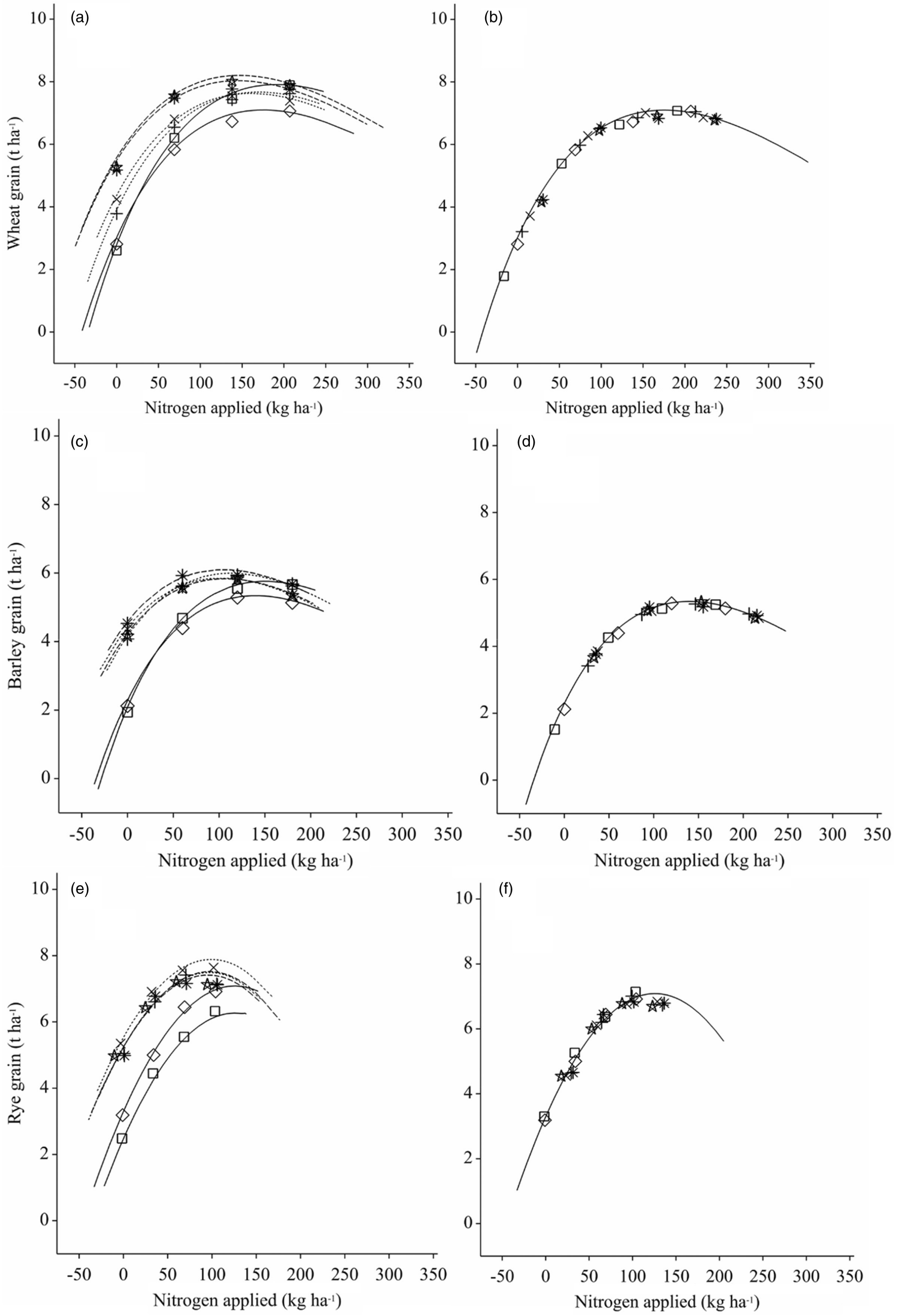
(a)
Wheat grain (t ha-1)
10
8
6
4
2
0
-50
0
50
100
150
200
250
300
350
Nitrogen applied (kg ha-1)
(b)
(c)
Barley grain (t ha-1)
(d)
(e)
Rye grain (t ha-1)
(f)

FIGURE 1 Response to fertilizer N by three cereals grown as the first test crop, (a) winter wheat, and the second test crop, (c) spring barley or (e) winter rye following different rotations. The individual response curves were then brought into coincidence with the AB rotation by appropriate vertical and horizontal shifts: (b) winter wheat, (d) spring barley, (f) winter rye. The rotations were (◊) all-arable, AB; (□) arable with fallows, AF; (+) 3-year grass ley with N, Ln3; (x) 8-year grass ley with N, Ln8; (star) 3-year grass/clover ley, Lc3; (*) 8-year grass/clover ley. Each individual response curve was fitted to 160 values for wheat, 72 for barley and 40 for rye; symbols indicate the mean yield at each N rate. Woburn Ley-arable experiment.

TABLE 3 Estimated mean maximum yields, Y_{max}, and associated mean nitrogen application, N_{max}, in the model for winter wheat, spring barley and winter rye, Woburn Ley-arable experiment

	Winter wheat 1981–2000		Spring barley 1982–1991[a]		Winter rye 1997–2001	
Rotation	Y_{max}, t ha^{-1}	N_{max}, kg ha^{-1}	Y_{max}, t ha^{-1}	N_{max}, kg ha^{-1}	Y_{max}, t ha^{-1}	N_{max}, kg ha^{-1}
AB mean	7.10 (0.427)	175 (5.9)	5.34 (0.606)	140 (7.6)	7.07 (0.741)	125 (12.1)
range	2.87–10.32	102–217	2.10–8.11	105–176	4.60–9.02	50–128
AF mean	7.91 (0.316)	192 (5.0)	5.76 (0.515)	150 (6.0)	6.25 (0.751)	125 (6.3)
range	4.89–10.94	154–224	3.68–8.13	125–183	5.07–8.28	107–146
Ln3 mean	7.67 (0.308)	170 (4.8)	5.99 (0.453)	113 (6.6)	7.49 (0.820)	96 (10.5)
range	5.10–10.21	125–205	3.96–7.96	72–136	5.14–9.82	61–136
Ln8 mean	7.63 (0.266)	160 (3.8)	5.85 (0.474)	102 (5.5)	7.88 (0.787)	99 (12.0)
range	5.56–9.97	122–185	3.62–7.83	72–133	5.33–9.73	50–128
Lc3 mean	8.20 (0.281)	147 (7.9)	5.84 (0.525)	107 (5.5)	7.49 (0.873)	97 (14.9)
range	6.29–10.62	38–189	3.42–8.12	84–128	5.14–9.82	41–125
Lc8 mean	8.03 (0.288)	145 (7.7)	6.10 (0.486)	104 (4.1)	7.41 (0.812)	95 (10.3)
range	6.27–10.27	55–193	3.79–8.24	86–114	5.05–10.18	62–131

Note: Figures in parentheses are standard errors for Y_{max} and N_{max} derived from the estimated values for each year.

[a] The 1983 data for spring barley was not used in the response curve fitting exercise as an extra 60 kgN ha^{-1} was applied to all, except the N0, treatments following prolonged heavy rain in April and May.

3.4 | Effect of soil nitrogen on yield

Between 1980 and 1999, %N in the top 25 cm soil in the five blocks varied with the rotation; the AF, AB, Ln3, Ln8, Lc3 and Lc8 soils contained, on average, 0.078%, 0.091%, 0.113%, 0.110%, 0.110% and 0.111% N, respectively. Soils with a history of root crops or bare fallows (AF) contained least N, those which had grown leys in the rotations (Ln or Lc) contained most N (Johnston et al., 2017). Blocks I, II, III, IV and V contained, on average, 0.094%, 0.101%, 0.102%, 0.116% and 0.105% N, respectively, with Block I, at the top of the slight slope, containing least N. For the 20 years with wheat yields, we looked for a relationship between %N in soil and yield, especially on subplots without fertilizer N (N_0) but excluding the Lc plots where extra N could be mineralized from the clover residues. Three factors were considered, block, rotation and FYM residues, and the simplest associations were simple linear regressions. Linear regressions for each of the five blocks have different intercepts on the yield (y-axis), but the slopes are not significantly different from one another, implying that the response by the crop to soil N on the N_0 soils was similar on each block (Table 5). The regression accounts for 37.9% of the variance. Rotation had a statistically significant interaction with % N; there are different slopes and intersects for each rotation. The regression accounts for 36.7% of the variance. The regression coefficients show that AB, AF and Ln3 have a positive association with yield at N_0 and % N in soil, Ln8 has a slightly negative slope. There was no modifying effect of the FYM residues on the association between % N in soil and yield at N_0.

Figure 2 shows for the three cereals and all six rotations, the relationship between % N in the topsoil (0–25 cm) and the yield of grain when either no fertilizer N was applied, or the maximum yield with fertilizer N. The data are very variable. Where no fertilizer N was applied, there was a fourfold or fivefold increase in yield as % N in soil increased from about 0.05–0.14% N (Figure 2a,c,e). Where sufficient fertilizer N was applied to the wheat and barley (Figure 2b,d), this additional N increased yield at all levels of soil N, more so at the lower soil % N. A similar result was reported by Loveland and Webb (2003). For rye, too little N was applied even after 1997 to achieve maximum

TABLE 4 Vertical and horizontal shifts required to bring the fitted yield response curves for five rotations into coincidence with that for the AB rotation, Woburn Ley-arable experiment.

	Winter wheat		Spring barley		Winter rye	
	1981–2000		1982–1991[a]		1997–2001	
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
Rotation	Shift[b]	Shift[c]	Shift[b]	Shift[c]	Shift[b]	Shift[c]
AF	0.81 (0.102)	−17 (3.0)	0.42 (0.098)	−10 (3.2)	−0.82 (0.23)	0 (5.9)
Ln3	0.57 (0.098)	5 (3.2)	0.62 (0.092)	27 (3.9)	0.42 (1.70)	29 (6.5)
Ln8	0.53 (0.097)	15 (3.4)	0.51 (0.090)	38 (4.3)	0.81 (1.59)	26 (6.4)
Lc3	1.10 (0.096)	28 (3.8)	0.50 (0.091)	33 (4.1)	0.44 (1.68)	28 (6.5)
Lc8	0.93 (0.096)	30 (3.8)	0.76 (0.091)	35 (4.2)	0.34 (1.79)	30 (6.6)

Note: Figures in parentheses are the standard errors of the estimated vertical and horizontal shifts.

[a] The 1983 data for spring barley was not used in the response curve fitting exercise as an extra 60 kg N ha^{-1} was applied to all, except the N0, treatments following prolonged heavy rain in April and May.

[b] Vertical shift is the estimated shift in maximum yield, t ha^{-1}, compared with the yield in the AB rotation. A negative value indicates that the fitted yield was lower than that for the AB rotation.

[c] Horizontal shift is the estimated shift in effective spring applied N fertilizer, kg ha^{-1}, compared with the AB rotation. A negative value indicates that more N was required to achieve the same yield as that in the AB rotation.

TABLE 5 Regression coefficients for the yield of wheat[a] given no fertilizer N versus % N in soil[b], Woburn Ley-arable

Source	Estimate	S.E.	t (154)	*p*	
% N in soil	38.53	5.370	7.17	<0.001	
Block I	−0.917	0.493	−1.86	0.065	ns
Block II	−0.793	0.561	−1.41	0.159	ns
Block III	0.345	0.572	0.60	0.547	ns
Block IV	−0.669	0.632	−1.06	0.282	ns
Block V	−0.063	0.586	−0.11	0.915	ns
Source	**Estimate**	**S.E.**	**t(152)**	***p***	
Rotation AB	−3.93	1.17	−3.35	0.001	
Rotation AF	−1.03	1.10	−0.93	0.352	ns
Rotation Ln3	0.64	1.59	0.40	0.686	ns
Rotation Ln8	5.05	1.81	2.78	0.006	
%N.Rotation AB	73.8	12.7	5.82	<0.001	
%N.Rotation AF	46.7	14.0	3.34	0.001	
%N.Rotation Ln3	27.7	13.9	1.99	0.048	
%N.Rotation Ln8	−7.3	16.4	−0.45	0.655	ns

[a] Yield of winter wheat grain, t ha^{-1} at 85% dry matter, 1981–2000. Grown on each of the five blocks in four of the 20 years.

[b] Soil sampled prior to ploughing and drilling winter wheat.

yield. Consequently, the best yields of rye given fertilizer N still showed a response to increasing soil N (Figure 2f). For wheat and barley, the small increase in yield with applied N and increasing SOM (Figure 2) supports our contention that the combined benefits from increasing and/or maintaining SOM are a worthwhile aim to optimize 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. Consequentially, boundary line analysis (Milne et al., 2006; Webb, 1972) was tested, but there were insufficient data to give significant results (A. E. Milne; personal communication).

4 | CONCLUSIONS

The yields of both the first test crop (winter wheat) and the second (barley or rye) varied greatly from year to year. Besides soil factors like N supply and soil structure,

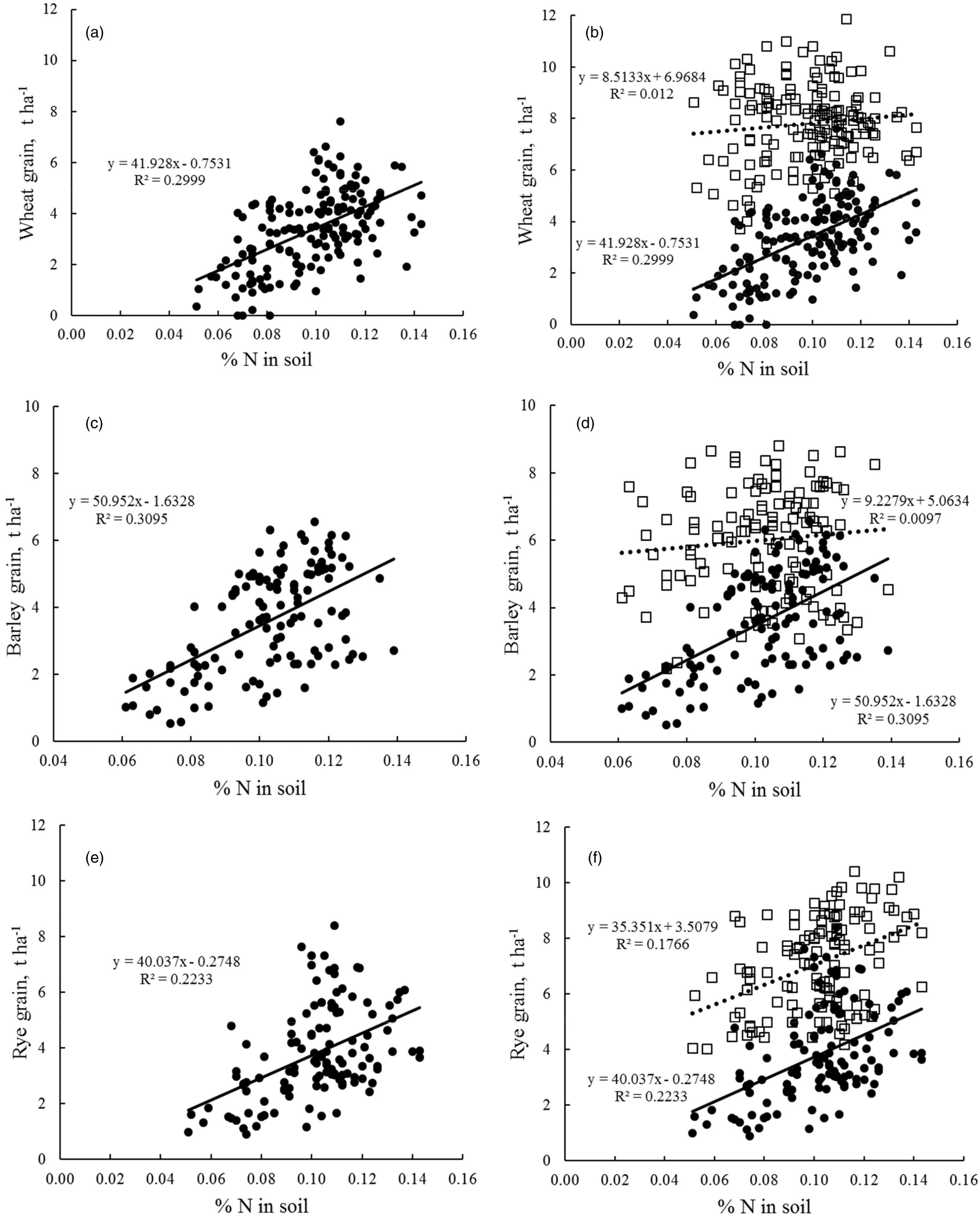

FIGURE 2 Response by three cereals to % N in soil (0–25 cm). Yields of (a) wheat grain without fertilizer N compared with (b) maximum yield with fertilizer N; (c) barley grain without fertilizer N compared with (d) maximum yield with fertilizer N; (e) rye grain without fertilizer N compared with (f) best yield with fertilizer N. Yields without fertilizer N (●); with fertilizer N (□). Woburn Ley-arable experiment

differences in weather, temperature and rainfall will have also been important. All these factors could be considered in another paper indicating their relative importance.

In 1938, grazing pasture was widely practised on many mixed farms and a grazed ley was one of the original treatments in the Ley-arable experiment. However, managing sheep on small plots, measuring the herbage available for them, together with recording grazing days and live weight increases became more difficult. Thus, when the types of leys and their treatment were to be changed in the late 1960s, grazing was discontinued and testing the grass + N, Ln, and grass/clover, Lc, became the ley treatments (Johnston et al., 2022). The Ln and Lc leys will have the same atmospheric input of N. The difference is in the amount of N applied either as fertilizer (Ln) or fixed biologically (Lc) and their effect on yield and SOM.

The average maximum wheat yield was 7.65 and 8.12 t ha^{-1} following the Ln and Lc leys, respectively, and the N associated with these yields was 165 and 146 kg N ha^{-1}. This suggests that there was more readily mineralizable organic N in the ploughed-in leguminous (Lc) residues compared with grass (Ln) residues, which increased yield and lessened the need for fertilizer N. However, for the second test crop of barley, there was little additional N from the Lc leys. Yields of barley on the Ln and Lc treatments averaged 5.92 and 5.97 t ha^{-1}, respectively, and 108 and 106 kg N ha^{-1} were associated with these yields (Table 3); this was significantly less fertilizer N than that required to achieve maximum yield (5.34 t ha^{-1}) in the all-arable rotation. The effects on the yields of winter rye were similar.

The seasonal variability in crop response to a wide range of applied fertilizer N suggests that we are not able to accurately predict the availability of the N supply from SOM and to adjust fertilizer N recommendations accordingly, especially in relation to the amount and rate of mineralization of the organic N throughout crop growth, or the ability of the growing crop to access this N supply. However, predicting the amount of fertilizer N to apply to get the optimum economic yield will remain paramount if there is increasing interest in including more leys in arable cropping systems.

In the first 10 years, 1981–1990, growing winter wheat, and 9 years, 1982–1991, of spring barley, we did compare the recommended N applications in the then-current MAFF RB209 (MAFF, 1994) for both these cereals and the N_{max} determined for these years using the curve shifting technique described here. For the three rotations being tested, arable, grass + N leys and grass/clover leys, the *average* recommended N application and N_{max} varied by <5%, but there were large discrepancies for individual years (Johnston, 2001, Table 14). Only in *ca.* 33% of the observations was N_{max} within ±10 kg N ha^{-1} of the recommendation. This was because of variation in Y_{max} because of variability in N supply each year.

Making recommendations for N applications could become even more difficult and require ever more complex models. In two reviews, Sylvester-Bradley and Kindred (2021) and Berry et al. (2022) noted the recent large increases in the price of natural gas and the implications that this might have on the cost and availability of fertilizer N. They concluded that this might lead to a reduction in the amount of fertilizer N applied to cereals. But the conflict in Europe has led to a shortage of wheat grain on world markets and a large increase in price. Consequently, farmers may choose to put more land into cereals where they can, depending on the break-even price ratio between the cost of fertilizer and the value of the grain. It seems sensible therefore to make the best use of N mineralized from SOM. If farmers are to be encouraged to include leys in any rotation to maintain or increase SOM, then the leys themselves must be profitable or the benefit to any following crop must be sufficient to justify their inclusion.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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