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ORIGINAL PAPER

Effect of Different Organic Amendments on Actual and Achievable Yields in a Cereal-Based Cropping System

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Abstract

Soil fertility is at risk in intensive cropping systems when using an exclusive regime of inorganic fertilisers without returning sufficient organic matter to the soil. Our objective was to evaluate the long-term effects of commonly used organic amendments interacting with different rates of inorganic nitrogen fertiliser on crop yields of winter wheat. Yield data from winter wheat were collected for five seasons between 2013 and 2019 from a continuous field trial based at Rothamsted Research, SE England. Organic amendments (anaerobic digestate, compost, farmyard manure, and straw at a rate of 0 and 2.5 ton C per hectare) and five rates of inorganic nitrogen fertiliser (NH_4NO_3 at 0, 80, 150, 190, 220 kg N ha^{-1}) were applied to winter wheat grown in an arable rotation. At the same inorganic N rate, grain yields for the different organic amendment treatments (excluding the straw treatment) were statistically similar but significantly greater than the unamended control treatment. The nitrogen rate required for optimum yields tended to be lower in plots receiving a combination of organic amendments and mineral fertiliser. Based on the observed and modelled response functions, organic amendments excluding straw increased maximum achievable yields compared to non-amended controls. The size of the effect varied between seasons and amendments (+4.6 to +19.0% of the control yield), increasing the mean maximum achievable yield by 8.8% across four seasons. We conclude that the application of organic amendments can increase the yield potential in winter wheat substantially over what is achievable with inorganic fertiliser only.

Keywords Organic amendments · Plant nutrition · Winter wheat · Grain yield modelling · Linear plus exponential

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1 Introduction

In many intensive modern agricultural systems, there is limited emphasis on maintenance or long-term improvement of soil conditions, but considerable pressure for the highest production including the application of large amounts of inorganic fertilisers. This often results in detrimental effects on soil organic carbon concentration, soil fertility, and productivity (Reeves 1997; Su et al. 2006; Johnston et al. 2009). The general trend of soil degradation under intensive arable farming was also confirmed by Prout et al. (2020), who estimated that 38% of arable soils in England and Wales are degraded based on their soil organic matter concentration relative to the clay content. Concurrently, there is increasing global awareness of the importance of soil health for the resilience of agricultural systems and the provision of public goods for society. In the United Kingdom (UK), the environmental damage costs associated with reductions in ecosystem services resulting from degraded soils were estimated at about 1.2 billion GBP per year, mainly due to losses of soil organic carbon, with direct consequences on productivity and greenhouse gas (GHG) emissions (Graves et al. 2015). Worldwide, a loss of 20 million tonnes of grain yield has been attributed to soil degradation alone (Rickson et al. 2015). Therefore, it is essential to develop management options that can improve the sustainability of intensive agriculture while simultaneously maintaining or even increasing productivity and profitability. Developing improved management decisions for soil health using reliable and affordable evidence as an engagement vehicle has the potential to reduce annual environmental damage costs substantially. Consequently, improving soil health is an essential component of the UK Government's 25-year plan to improve the environment (DEFRA 2018c).

Among many soil properties, soil organic matter (SOM) content is often identified as the most important indicator of soil quality given its importance for many soil properties and processes (Cordovil et al. 2007). Because of its importance for soil fertility and the wide scope of interactions with other soil characteristics (e.g. bulk density, aggregate stability, water holding capacity, biodiversity), sufficient levels of SOM are essential to increase or maintain crop yields (Reeves 1997; Johnston et al. 2009; Oldfield et al. 2019). Accordingly, low SOM levels [Loveland and Webb 2003 mention $< 2\%$ SOC, equivalent to 3.4% SOM, as the threshold] are related to poor soil quality and known to result in lower yields (Palm et al. 1997; Vanlauwe et al. 2001a; Oldfield et al. 2019) or higher N rates for optimal yields (Schjønning et al. 2018). Increasing or at least maintaining SOM is therefore an essential target for sustainable soil management. To achieve that goal, it is necessary to provide organic matter inputs to soils as a source of carbon (e.g. crop residues, organic amendments, root exudates), but it needs to be applied together with the right proportions of nutrients to maintain stoichiometry (Kirkby et al. 2011; Kirkby et al. 2013). This combined use of inorganic fertilisers and organic amendments, or at least the retention of crop residues in the soil (Alvarez 2005; Ladha et al. 2011), are thought to be the best management options to boost SOM and soil fertility as well as promote sustainability and productivity in agriculture (Cooke 1967; Weinhold et al. 2004; Johnston et al. 2009). However, adjustment of both components is necessary to get the best effects. If, for example, animal manure is applied at high rates or on SOM-deprived soils with low nutrient retention capacity, N leaching (Hartl et al. 2003), volatilisation (Nakhshiniev et al. 2014) or surface runoff of P can occur (Yan et al. 2013), reducing available nutrients to the crop and causing negative environmental consequences. Hua and Zhu (2020) have reported that long-term application of organic amendments may increase P use efficiency, reducing losses of P to the environment. However, nutrients contained in organic amendments are usually not readily available to plants, having first to be mineralised into an inorganic form (Diacono and Montemurro 2010). The resulting slow release of nutrients from organic amendments makes their optimal management complicated and organic amendment applications need to be controlled to minimise nutrient losses to the environment while simultaneously meeting crop demand (Wortman et al. 2012; van Zwieten 2018).

Organic amendments can be used as a complement to inorganic fertiliser, and in situations where the combined nutrient content of organic amendments and inorganic fertilisers are optimised, crop yields are often maintained or even increased (Reeves 1997; Celestina et al. 2019). However, it remains disputed if observed yield increases due to organic amendment application can be fully attributed to the effect of added nutrients or if other beneficial effects on soil characteristics also contribute to the observed yield increases. Wei et al. (2016) conducted a meta-analysis of 32 long-term experiments in China, comparing the use of only organic or inorganic fertilisers with the combined use of organic and inorganic fertilisers. They found an average yield increase of 8% by combining organic and inorganic fertilisers on wheat, maize and rice. This positive effect of either organic inputs or SOM on crop yields was confirmed in other studies (Monreal et al. 1997; Agegnehu et al. 2016; Vanlauwe et al. 2001b; Oldfield et al. 2019). However, the effect of nutrients is seldomly separated from other beneficial effects of organic fertilisers in such studies (Oelofse et al. 2015; Wei et al. 2016). To address this issue, Hijbeek et al. (2017) conducted a meta-analysis of 20 European long-term experiments where P and K supply were assumed to be non-limiting and reported no significant positive yield effect of organic amendments (+ 1.4 % ± 1.6) when sufficient N was applied. Schjønning et al. (2018) conducted an analysis of almost 1000 field experiments and found that the separation of N and non-N (derived from SOM) effects on crop yields are hard to distinguish; however, they did find a positive effect of N, while the non-N effect on yields seemed to be inexistent or even negative. But through modelling they found that by increasing SOC, the necessary N application to obtain optimum yields is lower.

To address these contradictory results in a common UK cropping system, we analysed crop performance in a continuously cropped field experiment at Rothamsted Research. This experiment's design included matched nutrient controls (for nitrogen), which allowed us to quantify the response of the crop yield to increasing nitrogen rates in plots that had received different types of organic amendments, or which remained unamended. Using winter wheat yield data from this trial, we aim to evaluate (a) the effects of different organic amendments on yield of winter wheat, (b) if the application of organic amendments leads to a reduction of the nitrogen fertiliser threshold required for optimum yields and (c) if organic amendment applications increase yield potentials beyond what can be achieved with treatments solely fertilised with inorganic fertiliser, using a crop response modelling approach.

2 Materials and Methods

2.1 Description of the Experimental Site

To investigate the effect of adding different types and rates of organic matter amendments as well as different nitrogen rates on the nitrogen use efficiency and yield of crops, the "Fosters organic amendment" experiment was studied over 7 consecutive seasons between 2012 and 2019 (see also Thomas et al. 2019). The trial is based at Rothamsted Research in Harpenden, Hertfordshire, in the southeast of England (51.82 N, 0.37 W). The site is situated at an altitude of 130 m above sea level, has a temperate climate with a mean annual temperature at about 10°C and mean annual rainfall of about 700 mm (see Table 1 for an overview of climatic conditions during the experimental seasons). The seasonal weather data showed relatively dry conditions in 2016/2017 and 2018/2019, but the longest dry period occurred in 2016/2017. Average temperatures indicated a colder season in 2012/2013 and heat waves did occur in 2016/2017 and 2018/2019. The soil is characterised as a silty clay loam Eutric Cambisol of the Batcombe series (Bolton 1977), with total organic carbon of 1.6% and a pH of 7.0. This corresponds in the international classification to a Profundic Chromic Endostagnic Luvisol (IUSS Working Group 2015).

2.2 Experimental Design

The trial consisted of 220 (inversion) ploughed plots of 9 × 6 m each (allowing harvest of a 2-m central strip), arranged as a randomised block design in 4 blocks. Replications were either 2 or 4 depending on the crop rotation (2 in year 2013, 2015, 2016; 4 in 2017 and 2019; see Table 2). The trial was divided into 10 rows and 22 columns (5 rows and 11 columns per block). There was a 3-m interval in between rows, providing access for farm vehicles used for crop management operations. Treatments considered for this study included five rates of nitrogen (ammonium nitrate) fertiliser (0, 80,150, 190, 220 kg N ha^{-1}) and two carbon (C) rates for the organic amendments (0 and 2.5 tonnes C ha^{-1} year^{-1}). Plots rotate each season in terms of inorganic N application, reducing the N rate each year, and once they reached N0 kg N ha^{-1}, plots returned to N220; organic amendment treatments were fixed and did not rotate. This study focused on the effects of the organic matter and fertiliser treatments on grain yield of winter wheat grown between 2013 and

Table 1 Weather data at the experimental site and for the experimental years. Seasonal values were calculated for the period between drilling and harvest (further details in Table 2). Air temperature was measured at 1-m height, soil temperature at 0.2-m depth. Dry days are days where no precipitation was reported

Annual	Rainfall (mm)	Dry days	Mean air temperature (°C)	Mean soil temperature (°C)
2013	750	156	9.4	9.8
2015	781	135	10.5	10.8
2016	678	139	10.2	10.9
2017	692	143	10.6	10.9
2019	743	160	10.6	10.8
Seasonal	Rainfall (mm)	Dry days	Mean air temperature (°C)	Mean soil temperature (°C)
2012/2013	568	107	6.5	7.2
2014/2015	674	115	9.6	10.1
2015/2016	666	113	10.4	10.8
2016/2017	540	126	9.9	10.3
2018/2019	520	143	9.7	9.9

Table 2 Crop rotations in the Fosters experiment from 2013 to 2019 (*ww*, winter wheat; *sb*, spring barley; *wo*, winter oats; *wosr*, winter oil seed rape) and basic crop management information. Only years with winter wheat were considered in this study (crops sown in 2014 were winter oil seed rape and spring barley, and crop sown in 2018 was winter oil seed rape)

Block	2013	2015	2016	2017	2019
Rotation 1	ww	wo	ww	ww	ww
Rotation 2	sb	ww	sb		
Organic amendment application date	17–23 /10/2012	15–18 /09/2014	30/09 to 05/10/2015	10/10/2016	11–12 /09/2018
Drilling date	08/11/2012	22/10/2014	15/10/2015	27/10/2016	05/10/2018
Seed rate (seeds m^{-2}) *	450	400	350	375	350
1st N application	17/04/2013	13/03/2015	21/03/2016	15/03/2017	05/04/2019
2nd N application	14/05/2013	30/04/2015	26/04/2016	21/04/2017	13/05/2019
Harvest date	20/08/2013	12/08/2015	08/08/2016	24/08/2017	13/09/2019

*Because of varying germination percentages, the seed rate is adjusted every season, but the viable seed rate is kept constant

2019. Details on the seasons and crops included are given in Table 2. The 2014 and 2018 seasons were not included because no wheat was grown in these seasons.

All crop residues except for stubbles were removed from the plots before organic amendment application. The organic amendments used were anaerobic digestate (AD, in fibrous form from vegetable waste), compost (COMP, from a mix of green and food waste), farmyard manure (FYM, from cattle, composted for 1 year) and STRAW (wheat and/or barley grown on the same trial in the previous season). There was also a control (NIL) with no organic amendment applied. Organic amendments were applied manually after harvest in autumn, after farmyard manure was chopped with a muck spreader and straw was chopped with a bale chopper/shredder. The organic amendments were then incorporated into the topsoil by ploughing. The amount of amendment applied was calculated for each organic amendment based on its carbon content (see details below). Prior to application, three sub-samples of each amendment were analysed for fresh weight, dry weight and total C and N by LECO (TruMac Combustion Analyser, MI, USA). Total C content and moisture levels were then used to calculate the quantity of each amendment required for each C rate.

2.3 Field Management

Soil preparation consisted of ploughing to about 23-cm depth, followed by harrowing. Winter wheat (*Triticum aestivum* L. c.v. “Crusoe”) was planted between October and early November depending on the year, with a row spacing of 12.5 cm and a sowing rate of 350 seeds m^{-2} (see Table 2 for further details). Nitrogen fertiliser was applied with a spreader (booster rate after emergence, 0N plots were shielded with a plastic cover during application) and by hand during the growing season (one or two splits depending on the treatment). Inorganic fertiliser used was ammonium-nitrate at varying rates, and sulphate of potash (SOP) at 111 kg ha^{-1} each year (except for the 2017 season). No P was applied in the seasons analysed because available soil P (Olsen P) was sufficient throughout the trial (> 16 mg l^{-1}) according to Steinfurth et al. (2022) who determined 15 mg P kg^{-1} soil as the critical Olsen P value for maximum yields based on the analysis of 55 European long-term experiments in Europe. Even lower critical values were reported by the same authors for heavy textured soils as on our site. Standard pest management was conducted by the farm management.

Harvest of grain and straw was carried out using a Haldrup C65 plot combine over an area of 9 × 2 m across the centre of each plot. Sub-samples of grain and straw were oven dried at 80 °C for 48 h after collection. Yield was calculated at 85% dry matter based on the moisture content determined at harvest for sub-samples.

2.4 Nutritional Content of Organic Amendments

The 5-year average total carbon concentration was 24, 35, 43 and 45% in compost, farmyard manure, anaerobic digest and straw, respectively (Table 3). Total nitrogen concentration 5-year average was 1.4, 2.5, 1.9 and 0.5% in compost, farmyard manure, anaerobic digest and straw, respectively. Thus, the 5-year average C:N ratio was 17, 14, 23 and 90 in compost, farmyard manure, anaerobic digest and straw, respectively. To achieve the same amount of C, the actual applied amounts of compost, farmyard manure, anaerobic digest and straw were 10.37, 7.23, 5.85 and 5.53 t ha^{-1}, respectively (5-year average). This corresponded to the average amount of N applied of 145, 181, 111 and 28 kg N ha^{-1} for compost, farmyard manure, anaerobic digest and straw, respectively. Anaerobic digestate had the highest concentration of

Table 3 Mean values and standard error (in brackets) for total organic C, total N and C:N ratio of the amendments for all seasons and three replications per season. In addition, average values for selected macro- and micronutrient concentrations of the amendments are given but these were only measured in 2014 and 2015 (three replications per season)

Nutrient	Compost	Farmyard manure	Anaerobic digestate	Straw
Total C (%)	24.2 (1.41)	33.7 (2.06)	43.7 (0.42)	44.6 (0.35)
Total N (%)	1.6 (0.11)	2.5 (0.13)	1.8 (0.12)	0.5 (0.03)
C:N (-)	15.8 (1.51)	13.6 (1.07)	24.2 (1.85)	88.1 (6.13)
P (g kg^{-1})	2.2	4.2	5.1	0.6
K (g kg^{-1})	10.2	20.7	16.6	13.0
Ca (g kg^{-1})	20.0	13.0	8.3	4.3
S (g kg^{-1})	2.1	3.1	3.4	0.9
Fe (g kg^{-1})	5.3	4.2	2.2	0.2
Zn (mg kg^{-1})	72	230	51	9
Mn (mg kg^{-1})	235	437	120	70

phosphorus (P) and sulphur (S), potassium (K) was highest in farmyard manure (Table 3), compost had the highest concentration of Ca and Fe and farmyard manure had the highest concentration of Zn and Mn. Across all amendments, farmyard manure had the lowest C:N ratio and a good supply of other nutrients, whereas straw had the highest C:N ratio and was low in most nutrients.

2.5 Data and Statistical Analysis

The effects of nitrogen fertiliser and organic amendments on grain yield were tested by analysis of variance (ANOVA, $p < 0.05$), using the GenStat software (Release 16.1). Each individual nitrogen fertiliser rate and each individual organic amendment treatment were treated as a factor, and by using the standard error of the ANOVA analysis as reference, the means for each treatment were compared. If for two treatments, the treatment means were situated within the standard error (mean ± SE), it was considered that there was no significant difference between them; a significant difference was assumed if the treatment mean was outside the SE boundaries. For the organic amendment comparison, the control plots without organic amendment application (NIL) were treated as a reference to allow comparison with the selected organic amendments. Similarly, the N0 treatment with the corresponding organic amendment treatment was used as a control for the higher N rate treatments of the same organic amendment treatment. Residual plots were used to attest for the normality of the data.

2.6 Calculated Fractional Change in Yields

The fractional change in yields due to treatment effects was calculated by comparing (Eq. 1) the different organic amendment treatment yields (Y_t) with the respective control treatment yield (Y_{nil}) and (Eq. 2) optimum yields for each organic amendment treatment (Yopt.t) with the optimum yield for the control treatment (Yopt.nil).

$$\text{Fractional change } Yt = ((Yt/Ynil) - 1) \times 100 \quad (1)$$

$$\text{Fractional change } Yopt = ((Yopt.t/Yopt.nil) - 1) \times 100 \quad (2)$$

The differences between both treatments were expressed as a percentage of the control treatment yield, which proved to be an effective variable in the characterisation of the role of organic amendments in winter wheat yields. To assess differences between treatments, a least significant difference (LSD) test ($p < 0.05$) was performed.

2.7 Response Modelling Approach

To predict yield values for a continuous range of N fertilisation rates, yield values were modelled using a "linear plus exponential model" (see Eq. 3), provided by the GenStat software (Release 16.1),

$$y = a + br^x + cx \quad (3)$$

where y represents the predicted yield, x is the inorganic nitrogen rate applied, and a, b, c and r are constants. This equation is based on the work of Crowther and Yates (1941, in George 1984), who first modelled yield response to fertiliser by using "the asymptotic exponential or Mitscherlich equation". Further work on the equation led to the addition of a linear term transforming the equation into the form we use in this paper, which better agrees with the rapid yield increase at lower nitrogen application rates and the subsequent plateau observed at higher nitrogen rates. The modelling analysis was based on five data points corresponding to the 5 different nitrogen rates applied in the experiment. The resulting fitted terms of equations were used across the nitrogen treatment range, from 0 to 220 kg ha^{-1}, obtaining individual yield values for any N rate and allowing to estimate maximum yields and corresponding N rate for each treatment and season.

3 Results

3.1 Effect of Organic Amendments and Nitrogen Rates on Winter Wheat Yields

The analysis of variance (2-way ANOVA) tested the effect of different nitrogen fertiliser rates, of organic amendment additions and the interaction of both factors on winter wheat yields (data not shown). The analysis showed that the separate effect of the different nitrogen fertiliser rates and the organic amendments were highly significant ($p < 0.01$) for all years tested. The interaction between the two factors did not have a significant effect on yield with exception of the 2015 season (p < 0.05).

An overview of the grain yields dependent on organic amendment treatment and the results of the corresponding statistical analysis are shown in Fig. 1. The range of grain yields within each organic amendment treatment is large because it includes results from all five nitrogen treatments. Average yields between organic amendment treatments generally decreased from anaerobic digestate to compost to farmyard manure to straw and control (NIL), but small deviations from this general trend occurred. The statistical analysis indicated that anaerobic digest (AD), compost (COMP) and farmyard manure (FYM) applications influenced grain yield in a very similar way throughout the experiment, with exception of 2016 where AD application resulted in higher yield values than all other treatments (Fig. 1). The AD, COMP and FYM treatments resulted in higher grain yield than the STRAW and NIL treatments for all years tested. Correspondingly, STRAW and NIL treatments resulted in consistently lower grain yield than all other treatments. In the first three seasons analysed, the NIL treatment yielded slightly but significantly ($p < 0.05$) higher than the STRAW treatment, but in 2017 and 2019 yields of both were not significantly different anymore.

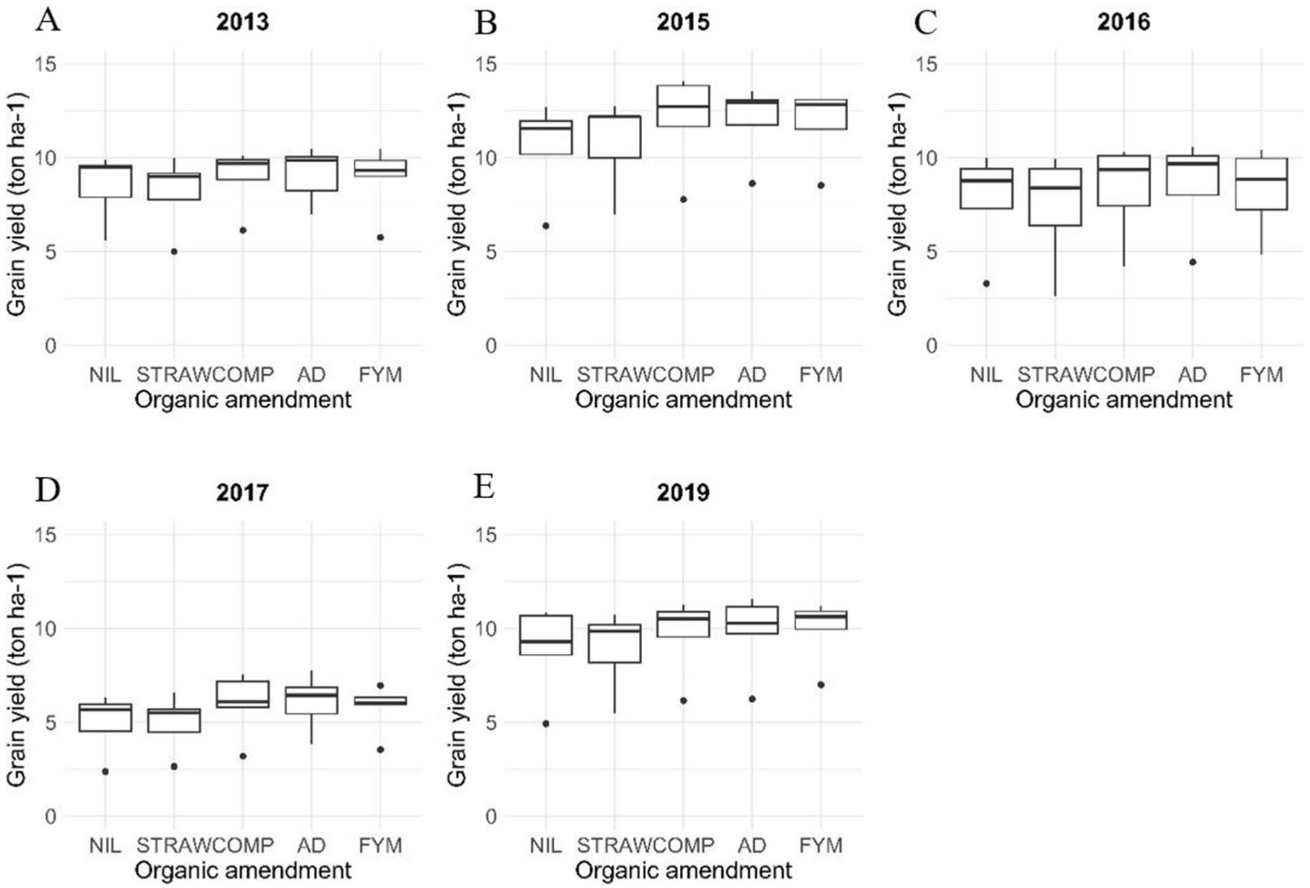

Fig. 1 Boxplot and statistical results for the effect of organic treatments on the grain yield of winter wheat in the seasons 2013 (**A**), 2015 (**B**), 2016 (**C**), 2017 (**D**) and 2019 (**E**). Shown are the grain yields for each organic amendment treatment but across all N treatments. The treatments are anaerobic digest (AD), compost (COMP), farmyard manure (FYM), straw (STRAW), and the control without organic amendment application (NIL). The boxplots show the median, first and third quartiles (Q1 and Q3) and the minimum (minimum = Q1 − 1.5 * interquartile range) and maximum (maximum = Q3 + 1.5 * interquartile range) for each year of the experiment analysed. Boxes with the same small letter are not significantly different according to the LSD test, $p < 0.05$

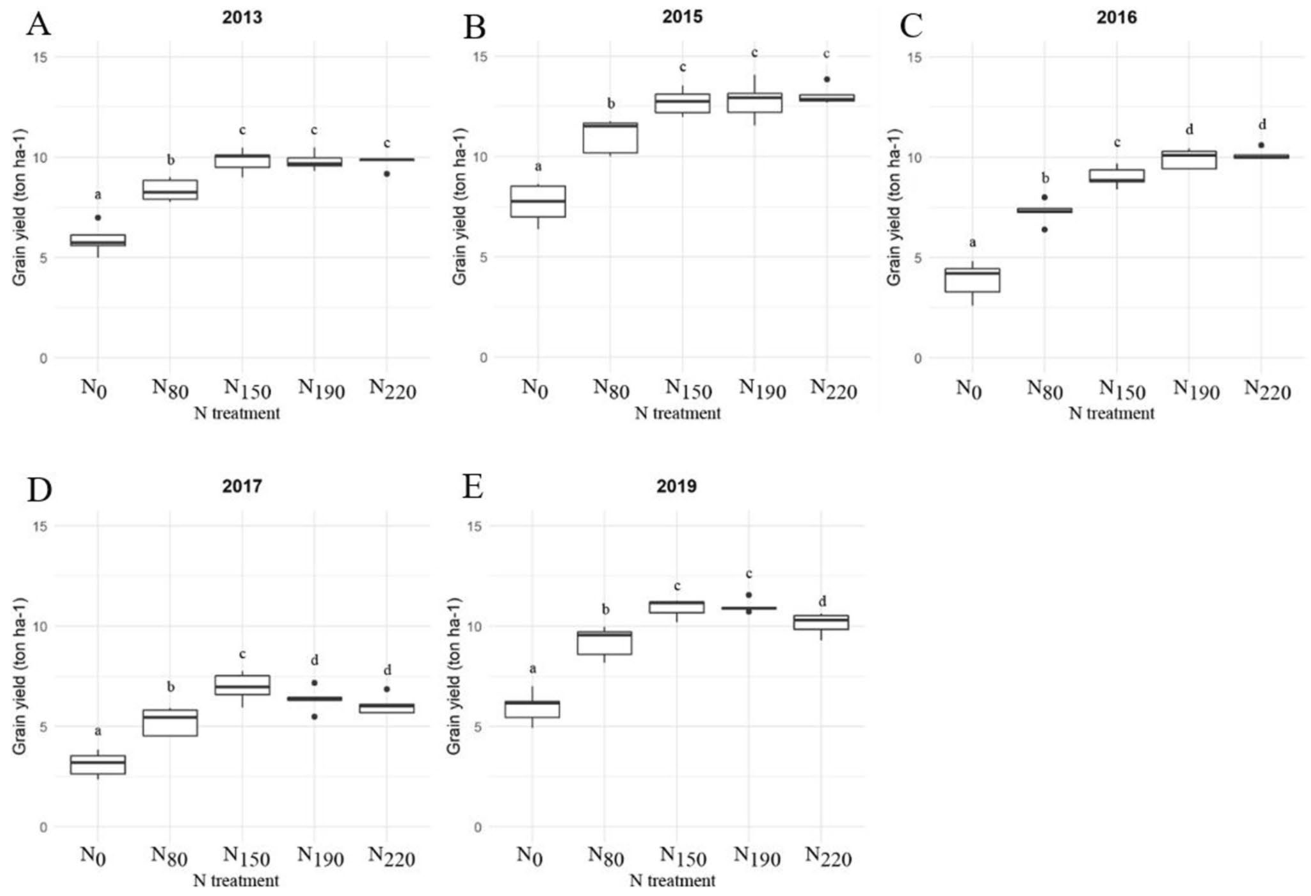

Fig. 2 Boxplot and statistical results for the effect of nitrogen rates on the grain yield of winter wheat in the seasons 2013 (**A**), 2015 (**B**), 2016 (**C**), 2017 (**D**) and 2019 (**E**). Shown are grain yields for each N treatment across all OA treatments. The N rates used were 0, 80, 150, 190 and 220 kg N ha^{-1} per season. The boxplots show the median, first and third quartiles (Q1 and Q3) and the minimum (minimum = Q1 − 1.5 * interquartile range) and maximum (maximum = Q3 − 1.5 * interquartile range) for each year of the experiment analysed. Boxes with the same small letter are not significantly different according to the LSD test, $p < 0.05$

Figure 2 gives an overview of grain yields dependent on nitrogen rate (across all organic amendment treatments) together with the corresponding results of the statistical analysis of the N treatments. The highest yields were achieved in the year 2015 (favourable and well-distributed rains) and lowest yields occurred in the 2017 season (a year with a long drought period and low seasonal rainfall, Table 1). When comparing the different nitrogen fertiliser rates (0, 80, 150, 190, 220 kg N ha^{-1}), the two lowest rates had always significantly lower yields than all other treatments, and the nitrogen control had always the lowest yield results (Fig. 2). In the first experimental year, the grain yield of treatments N150, N190 and N220 were not significantly different from each other. A yield plateau was also observed in 2016 but only from N190 onwards. Decreasing yield responses occurred in 2019 (only for N220), and in 2017 (a year with a long drought period), yields peaked in N150 and decreased for N190 and N220.

3.2 Nitrogen Threshold for Optimum Yields

To analyse the nitrogen threshold for optimum yields (i.e. the nitrogen rate that leads to the highest yield), we determined the nitrogen rate that achieved the best yield result (highest yield) for each amendment treatment (Table 4). The results show that, when compared with the control treatment (NIL, no organic amendment applied), the application of organic amendments led to a reduction in the optimum nitrogen rate for maximum yields. This happened in all seasons and treatments for compost, farmyard manure and anaerobic digest, with the exception of the anaerobic digest treatment in 2016 and 2019. For the organic amendment treatments, the highest yields were often achieved with a rate of 150 or 190 kg N ha^{-1} instead of the highest rate (220 kg N ha^{-1}, N220). For the straw treatment, the optimum N rate for the highest yield was the same as for the control in 2015, 2016 and 2019. The lowest N rates for maximum yields were

Table 4 Optimal nitrogen rate for maximum wheat grain yields, depending on the organic amendment. Seasonal nitrogen fertiliser rates increased from N0 to N220 corresponding to the application of 0, 80, 150, 190 and 220 kg N per ha, respectively. The control without organic amendment (NIL) serves as a control and shaded cells indicate a reduced N requirement

Organic amendment	Cropping season				
	2013	2015	2016	2017	2019
Anaerobic digest	N190	N150	N220	N150	N190
Compost	N150	N190	N190	N150	N150
Farmyard manure	N150	N190	N190	N150	N150
Straw	N190	N220	N220	N150	N190
NIL	N220	N220	N220	N190	N190

observed across treatments in 2017, which was the lowest yielding season (drought year/season).

3.3 Calculated Yield Benefit from Amending the Soil

To evaluate the yield benefit of the OA treatments, we calculated the yield increase as the fractional change between yield in the OA-treated plots and yield in the control treatment (see Eq. [1] above) for each nitrogen treatment separately. Table 5 shows the fractional change results for all organic amendment treatments, for all five seasons of the experiment and for all nitrogen rates.

Anaerobic digest, compost and farmyard manure generally show positive results in terms of grain yield when compared to the unamended control treatment. The highest relative yield increases resulting from anaerobic digest, compost and farmyard manure applications reached up to 62%, 35% and 49%, respectively, and were observed for treatments without mineral N application (N0). Smaller and often not significant yield increases were observed when organic amendments were applied alongside higher N rates. The straw treatment did not follow the trend of the other organic amendments, causing lower grain yields than the control treatment in about half of the observations. The greatest yield decrease due to straw application was −20.8%. For the beneficial organic amendments, the general trend was that the fractional yield increase decreased with increasing N rate. Nevertheless, yield benefits occurred even at the highest N rate, but the magnitude varied from year to year.

For the three beneficial organic amendment treatments, different effects occurred between years and N rates. Generally, the lowest yield gains from organic amendments were observed in the first trial season (2012/13), and yield gain trends were generally higher in later seasons. The highest but not always significant relative yield gains due to organic amendment use occurred for most N rates in the 2017 season, which was the lowest yielding season across all years (a drought-affected year), indicating that organic amendments can have the greatest positive impact on winter wheat yield in sub-optimal growing conditions. Across years but for individual N treatments, the anaerobic digest treatment had the lowest yield gains in the N190 treatment, compost application had lowest yield gains in N220 and farmyard manure application had low yield gains in N190 and N220. In the straw treatment, yield losses were lowest in the N220 treatment, and in 2019, a yield gain was observed (N220: 5.7%).

We also calculated the relative yield difference between the optimum N treatments with and without organic amendment application for each organic amendment treatment and all seasons (see Eq. [2] above). The results (Table 6) show the yield advantage due to organic amendment application but note that optimum yields were not necessarily achieved with the same N rate (they were often lower for organic amendment treatments). The results showed variable but similar yield gains due to anaerobic digest, compost and farmyard manure application, ranging between 2 and 23%, which due to the experimental error were not always significant. The highest gains were achieved in 2017, a year with a long drought period. Low or negative yield gains were observed for the straw treatment.

3.4 Modelled Response Curves

Modelled response curves for all organic amendment treatments are shown in Fig. 3, and details on modelled optimum yields and respective N application rates are given in Table 7. The modelled results obtained agree very well with the results described in the previous section (e.g. Table 5 and 6), confirming that the amended treatments did influence the optimal nitrogen rate required and maximum yields achieved. In the first season (2013), the organic amendment treatments did not increase maximum yields (even decreased yield at higher N

Table 5 Fractional change (% relative yield difference) between yield in the amended treatments and yield in the control treatments with the same nitrogen level (calculated using equation (1), see text). Shown are the results for all organic amendments, for all seasons of the experiment and for all nitrogen rates

Season	Organic amendment applied																			
	Anaerobic digestate					Compost					Farmyard manure					Straw				
N rate	N0	N80	N150	N190	N220	N0	N80	N150	N190	N220	N0	N80	N150	N190	N220	N0	N80	N150	N190	N220
2013	24.8*	4.4	5.7	9.5	−0.3	9.4	11.9	6.3	1.1	−0.2	2.7	14.1	10.2	−2.7	−0.5	−10.7	−1.8	−5.4	4.2	−7.4
2015	35.5*	15.4*	13.3*	11.8*	3.0	22*	14.5*	6.5	21.6*	9.1*	33.8*	13.1*	9.5*	13.7*	1.3	9.7	−1.8	1.9	5.5	0.6
2016	34.6*	9.6	10.3*	7.1	6.1	27.8*	1.8	6.7	9.2	1.2	46.3*	−1.0	0.8	10.7*	−0.2	−20.8	−12.5*	−4.3	0.1	−0.5
2017	62.2*	20.5	30.4*	1.9	20.6	34.8	28.3	26.7*	13.6	7.4	49.3	30.9	17.0	0.3	5.9	11.5	−0.9	10.8	−13.0	0.1
2019	26.4*	13.2*	4.5	6.5	10.7	24.8*	11.2	5.6	0.2	13.0*	41.8*	16.1	5.0	0.6	14.2*	10.6	−4.8	−4.5	−1.3	5.7

*Significant difference to control based on LSD test, $p < 0.05$

Table 6 Fractional change (% relative yield difference) between the optimum N treatment with and without organic amendment (OA) application for each OA treatment and all seasons (calculated using equation [2], see text). The results show the yield advantage due to OA application but note that optimum yields of OA treatments were often achieved with lower N rates

Year of application	Anaerobic digestate	Compost	Farmyard manure	Straw
2013	5.9*	2.0	5.8*	0.7
2015	6.8*	10.8*	3.6*	0.6
2016	6.1*	3.0	4.4*	−0.5
2017	22.8*	19.3*	10.2*	4.4
2019	6.5*	3.8*	3.1*	−1.3

*Significant difference to control based on LSD test, $p < 0.05$

rates) but reduced the N requirement to reach maximum yields (Table 7). From the second season onwards, organic amendment treatments, except for the straw treatment, did increase optimum yields (all four remaining seasons) and decreased the N application required to get maximum yields (2015, 2016, 2017). However, the N rate decrease to achieve maximum yields depended on the organic amendment treatment and the year. The straw treatment had, in all but 1 year, a negative effect on the maximum yield and an inconsistent effect on the N rate needed to obtain the maximum yield (−11 to +14 kg N ha^{-1} of the optimum N rate of the NIL treatment).

3.5 Fractional Change Calculations After Modelling

The fractional change calculations were conducted based on the optimum nitrogen rate that achieved the highest yield after fitting the linear plus exponential model. Therefore, the fractional change calculations show the gain or loss in yield when compared with the control (NIL) treatment (Table 8). Again, the results show a negative yield response from organic amendment application in the first season and in most seasons for the straw treatment. But in all following seasons, the organic amendment treatments anaerobic digest, compost and farmyard manure had higher maximum yields than the control (NIL) treatment without organic amendment application (except farmyard manure in 2017), and the increases ranged between 4.6 and 19.0%, varying considerably between seasons. The average yield increase across the four seasons and three organic amendment treatments was 8.8% and the greatest average yield increase was observed in the compost treatment.

4 Discussion

The main objectives of this study were to investigate if organic amendments (OA) can increase crop yields and if these increases are mainly due to an improved N nutrition

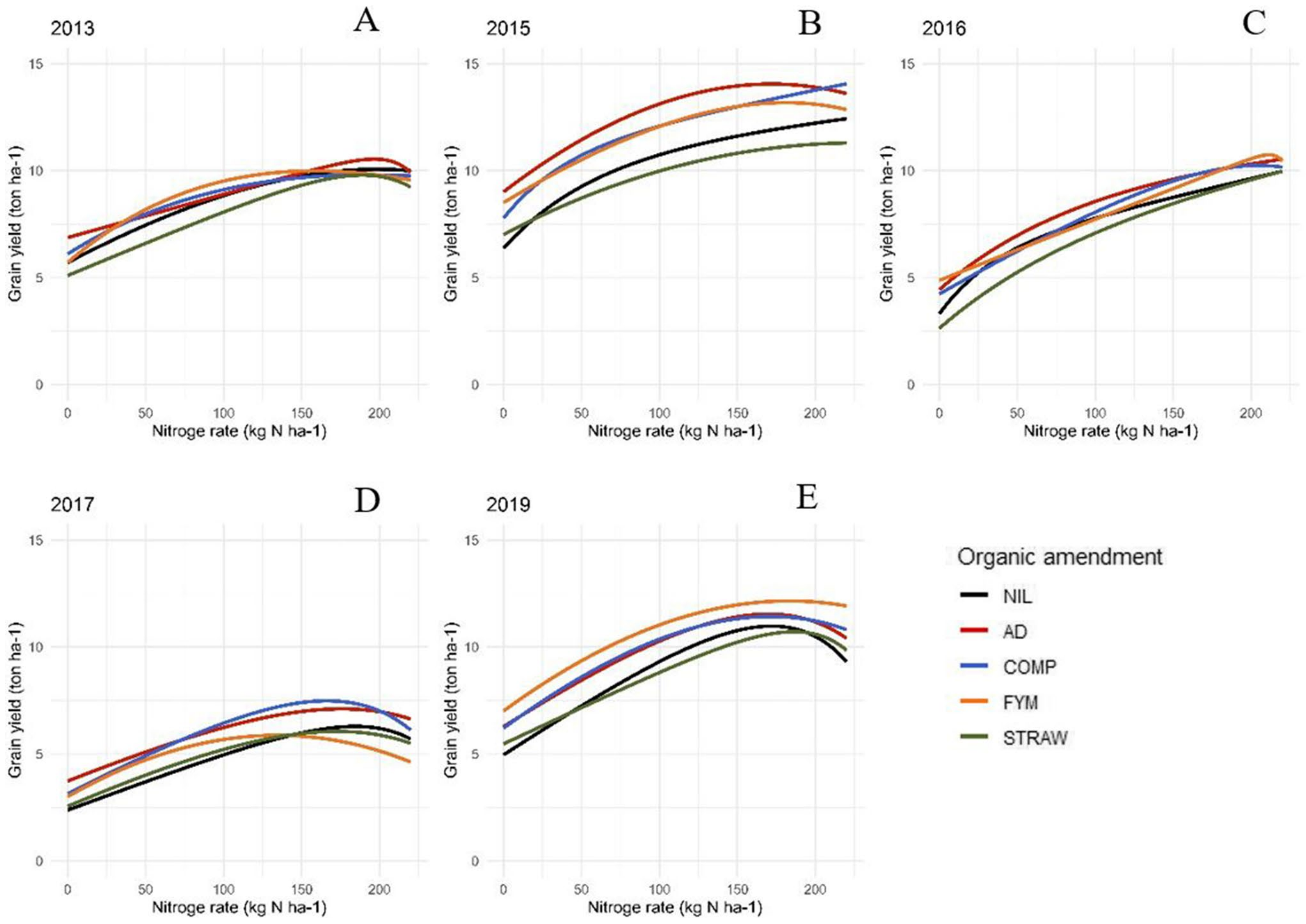

Fig. 3 Modelled nitrogen response curves for the different organic amendment treatments and winter wheat grain yield in the seasons 2013 (**A**), 2015 (**B**), 2016 (**C**), 2017 (**D**) and 2019 (**E**). The relative variance accounted for and given for each season is valid across all models in one season. Correlation coefficients for individual response curves were always > 0.96 (data not shown)

of the crop. For this objective, we analysed a continuous field trial representing the most common cropping system in the UK. Although different crops were grown in the experiment, we focused our analysis on winter wheat because it was the most frequent crop and allowed an evaluation of treatment effects over several seasons. It was also the crop which according to the analysis of Hijbeek et al. (2017) did not exhibit any positive yield effect of organic amendment application. Hijbeek et al. (2017) as well as Johnston et al. (2009) report positive yield effects of OA application for spring crops (including potato, maize, sugar beet, spring barley), arguing that a higher soil organic carbon content would provide a food source containing energy to increase the activity of soil organisms whose movements improve soil structure, reduce the resistance of the soil to root penetration, allow faster root development and therefore preferentially help spring crops, which grow in a much shorter season. We hypothesised that in this experiment, conducted at one single site with closely monitored environmental conditions for all years (rainfall, temperature, soil characteristics, etc.), the effect of the organic amendments applied will mostly depend on the quantity and dynamics of nutrients contained and released, and the beneficial effect of remaining organic compounds on soil chemical, physical and biological functions (e.g. increased cation exchange rate, low but continuous nutrient release, lower bulk density, better soil aggregation, more beneficial microbiome).

With regard to N and P, relatively high amounts were applied with farmyard manure and compost, medium amounts with anaerobic digestate and low amounts with straw. The contents of most other nutrients were similar in all OAs, with exception of higher Zn and Mn concentrations in farmyard manure. Given the same environmental conditions across treatments, the speed of decomposition and the release of nutrients will depend largely on the C/N ratio with a threshold value at around C/N = 24, above which little net mineralisation is expected (Janssen 1996; Reyes-Torres et al. 2018). Much higher C/N ratios like in straw result in N immobilisation, causing yields below the control even if high amounts of N are applied. This effect has been

Table 7 Seasonal modelled optimum yields and related nitrogen thresholds, as well as yield differences compared with the organic amendment control (NIL) and the difference in N rate needed for optimum yield

Amendment	Yield max ($t\ ha^{-1}$)	Yield difference ($t\ ha^{-1}$)	N rate ($kg\ ha^{-1}$)	N difference ($kg\ ha^{-1}$)	Yield max ($t\ ha^{-1}$)	Yield difference ($t\ ha^{-1}$)	N rate ($kg\ ha^{-1}$)	N difference ($kg\ ha^{-1}$)
Season	2013				2015			
NIL	10.1	-	198	-	12.4	-	220	-
Anaerobic digestate	9.8	−0.3	192	−6.0	14.1	1.7	172	−48.0
Compost	9.9	−0.2	158	−40.0	14.1	1.7	220	0.0
Farmyard manure	9.8	−0.3	189	−9.0	13.2	0.8	181	−39.0
Straw	9.8	−0.3	189	−9.0	11.3	−1.1	220	0.0
Season	2016				2017			
NIL	9.7	-	220	-	6.3	-	184	-
Anaerobic digestate	10.5	0.8	220	0.0	7.1	0.8	176	−8.0
Compost	10.2	0.5	205	−15.0	7.5	1.2	166	−18.0
Farmyard manure	10.7	1.0	211	−9.0	5.9	−0.4	134	−50.0
Straw	9.7	0.0	220	0.0	6.1	−0.2	173	−11.0
Season	2019							
NIL	10.9	-	172	-				
Anaerobic digestate	11.5	0.6	170	−2.0				
Compost	11.4	0.5	171	−1.0				
Farmyard manure	12.2	1.3	183	11.0				
Straw	10.7	−0.2	186	14.0				

reported by several studies (Cheng et al. 2012; De Neve et al. 2004); however, Hijbeek et al. (2017) found a neutral effect of straw application (i.e. no negative yield effect). The reason could be a counteracting positive effect of straw applications on physical and chemical soil characteristics through a slow accumulation of soil organic matter which can only be observed in long-term trials as analysed by Hijbeek et al. (2017). This is also indicated by the slowly improving yield performance of the straw treatments in this study. Mineralisation of OAs with a C/N ratio considerably below 24 as observed in compost and farmyard manure is relatively fast and tends to release free nitrogen to the soil and crops (e.g. Reyes-Torres et al. 2018), explaining the lowest N rates needed to achieve highest yields in most seasons of our trial. Anaerobic digestate with a C/N ratio close to 24 will be mineralised slightly slower and therefore contribute less N to the crop. However, farmyard manure was the only organic amendment that did significantly increase yields in the study of Hijbeek et all. (2017), although not for winter wheat and not if applied with straw, straw + green residues or slurry. And all organic amendments except straw are expected to release mineral nitrogen to the crop during spring when most mineralisation occurs (Möller and Müller 2012).

Table 8 Fractional yield changes due to organic amendments at the maximum yield as a percentage of the control (NIL) treatment. The results are based on the modelled yield response shown in Table 8 and Fig. 3. Note that maximum yields for each treatment were achieved at different levels of N applied.

Year of application	Anaerobic digestate	Compost	Farmyard manure	Straw
	Yield change compared to the control treatment (%)			
2013	−3.0	−2.0	−3.0	−3.0
2015	13.7	13.7	6.5	−8.9
2016	8.2	5.2	10.3	0.0
2017	12.7	19.0	−6.3	−3.2
2019	5.5	4.6	11.9	−1.8

Apart from these effects, different amounts of total N were applied with the different organic amendments to achieve the target of 2.5 $t\ ha^{-1}$ C applied, i.e. 145, 181, 111 and 28 $kg\ N\ ha^{-1}$ for compost, farmyard manure, anaerobic digestate and straw, respectively. Assuming that compost, farmyard manure and anaerobic digestate mineralised with similar speed, and that about 30% of the total organic amendment amount was mineralised within the first season (Sorensen et al. 2016), the seasonal contribution of plant available N from compost, farmyard manure and anaerobic digestate would be about 44, 54 and 33 $kg\ N\ ha^{-1}$. Taking also N release from residual organic amendment from previous seasons into account, these N contributions can explain the observed decrease in the optimum nitrogen rate for maximum yields by 30 to 70 $kg\ N\ ha^{-1}$. Note that especially the compost and farmyard manure treatments with higher N contributions and better mineralisation indicators performed well. Not mineralised amendments contribute to an accumulation of SOC and nitrogen in the soil which is indicated by the results of Thomas et al. (2019) who analysed the same trial. After five seasons, the soil of the non-straw amendments had a 7% greater total carbon concentration (1.60% versus 1.49% in the untreated control, as well as a greater total N concentration (0.16% in the soil receiving the maximum application rate and 0.15% in the untreated control soil).

The N response for all treatments seems typical, showing a declining response with increasing N rate. Response curves peaked at relatively low N rates in the years 2017 and 2019 which is easy to explain in the low-yielding season of 2017 but harder to understand in the high-yielding season 2019. In the same seasons, the response curves indicate negative returns to N application at the highest N rates. In 2017, this is most likely due to other yield-limiting factors than N, especially drought and/or diseases. No above-ground diseases were observed but below-ground diseases, such as take-all, *Rhizoctonia* and *Pythium* are common and known to negatively influence wheat yields (Cook 2001). Especially in the case of drought, high N supply can have negative effects by increasing transpiration from excessive biomass and exhausting scarce water reserves ('haying off'), given the role of nitrogen on crop transpiration (Dziedek et al. 2016). The lack of a significant interaction between organic amendment and N treatments in four out of five seasons indicates that the effect of applied mineral N is mostly independent of the organic amendment used, even if the yield gain from applied N is small like in the straw treatments. Only in 2015, a significant interaction was observed (data not shown), possibly caused by the high yield observed in the compost N190 treatment, which might be an exceptional observation.

We do believe that most agronomists and soil scientists would agree that applying organic amendments is beneficial for crop growth in some way. The magnitude of the effect will, of course, depend on the type and the amount of organic amendment applied, the nutrients contained in the amendment, the crop grown and a range of other management and environmental factors. But whether this positive effect is limited to the amount of nutrients applied with the organic amendment or if there is an "additional yield effect" (Janssen 1996), lifting yields beyond the nutrient effect, is debated (Oldfield et al. 2018). The "additional yield effect" could be explained with the many beneficial effects of an increased SOM content, such as reduced bulk density (Soane 1990; Johnston et al. 2009), increased water and nutrient retention capacity (Diaz-Zorita et al. 1999; Johnston et al. 2009), better pore continuity (Neal et al. 2020), increased soil biodiversity (Kavamura et al. 2018) and reduced N losses (Neal et al. 2020), to list the most important mechanisms. However, Loveland and Webb (2003) could not confirm a significant negative yield effect of low SOC concentrations in the soils of England and Wales. Similarly, Oelofse et al. (2015) did not find a positive correlation between winter wheat yields and SOC in Denmark. No beneficial effect of SOC on a range of crops in 20 long-term trials in Europe was also reported by Hijbeek et al. (2017). In contrast, the meta-study of Oldfield et al. (2019) reports an increase in wheat and maize yields with increasing SOC, plateauing at around 2% SOC. The same authors also stress that around two thirds of the world's maize and wheat fields have SOC below 2%, and the same is true for the soil of our experiment. These divergent reports could be explained by the wide variety of management and environmental factors affecting crop yields, including the often high N rates used, masking any significant SOC effect. But the same argument is not valid for the study of different organic amendments and their effects in long-term trials by Hijbeek et al. (2017) because within each trial, management and environmental factors were controlled. However, contrary to Hijbeek et al. (2017), we did observe additional yield effects of organic amendments even for winter sown wheat, and in all seasons except the first (even if not always significant, the trend was always positive). Based on the modelled response functions, the size of the effect (with a mean of + 8.6% grain yield across four seasons and all three higher quality organic amendments tested) did vary between seasons and between organic amendments tested but was consistent even at highest yield levels. Having used a predictive approach to confirm our assumptions from the descriptive approach, and by using the adjusted r-squared value as a measure of fit, we are confident about the validity of these predictions. We observed across the board a general positive yield effect from applying organic amendments with the exception of the straw treatment (5-season average of −3.4% grain yield). These yield increases were achieved with the same or less inorganic N applied. The size of the average additional yield effect is similar to that described by Hijbeek et al. (2017) for potatoes and maize (+7 and + 4%, respectively), and the same authors also found a beneficial effect for farmyard manure (+ 2.2%). And it is below the potential yield gains resulting from SOC concentrations of 2% reported by Oldfield et al. (2019) which were 10 ± 11 % (mean ± SD) for maize and 23 ± 37 % for wheat. The same authors estimated potential N fertiliser reductions associated with increasing SOC amount to 7% and 5% of global N fertiliser inputs across maize and wheat fields, respectively, which would be a substantial reduction of greenhouse gas emissions from agriculture.

Climate as well as general soil conditions and crop management at our site should be very similar to many of the sites analysed for the study of Hijbeek et al. (2017). But our trial did use more beneficial organic amendments (anaerobic digestate, compost and farmyard manure) than their study (straw + green residues, slurry and farmyard manure), and the analysis across several sites may mask significant effects at some sites. Therefore, we conclude that additional yield effects due to organic amendment application can also be expected in high-yielding winter wheat, but the increase is likely to vary in time and space and is dependent on higher quality, more labile organic amendments (C/N ratio at or below 24).

The actual use of organic amendments will not be driven by increased yields alone but by a range of other factors. The first issue is the availability of organic amendments. In 2017, organic fertilisers in the form of manure or slurry were applied to 25% of the total area of arable crops grown in the UK (DEFRA 2018a). Across all farm types, cattle slurry (49%) accounted for the greatest source of organic fertiliser, followed by farmyard manure (farmyard manure, 38%), biosolids (treated sewage sludge) and industrial wastes (including compost, brewery effluents, and paper waste), each accounting for ~2% of the organic fertiliser applied. On-farm processing of waste using anaerobic digestion is carried out by 5.4% of farms (DEFRA 2018b). Although we could not detect positive effects of straw application, the removal of straw residues practised on 73% of UK farms seems questionable if only for the loss of important nutrients; for example, it removes 10% more P and 50% more K compared to the removal of grain alone (DEFRA 2018c). Another issue is of course the costs related to OA treatments. In most cases, the OAs will be available at no cost, but transport, storage and application carry costs that farmers will need to consider when deciding on their use. Knowing that there is a positive yield response even in intensive crop cultivation could help them to make a decision for the use of OAs.

Depending on the characteristics of the organic amendment (N concentration, C/N ratio), the availability of NPK to the crop can be estimated as outlined in detail by the Nutrient Management Guidelines for the UK (AHDB 2021). This can give an estimation of the savings from reduced inorganic fertiliser needs and the guidelines also specify details of application rates to minimise losses to the environment and maximise efficiency of the applied nutrients. Unfortunately, aerobic digestate was not yet included in the updated guidelines although it is an increasingly available organic amendment. In the guidelines, application rates differ between sandy and clayey soils but an additional guide to the usefulness of organic amendment applications could be the SOC/clay ratio which gives an indication to what extent clay minerals at a specific site are saturated by organic matter and to what extent the soil can store additional organic matter applied (Prout et al. 2020, 2022). The results of Hijbeek et al. (2017) on which crops profit most from organic amendment applications (root and spring crops) could further help to decide where to apply organic amendments even though we could not confirm their finding that winter wheat did not show an additional yield effect. This way, organic amendments can be used most efficiently within a farm, given that the total supply only covers about one fourth of the total arable area per year. Unclear remains whether it is more beneficial to apply small amounts regularly or to rotate the application of bigger amounts.

Additional effects of organic amendments can contribute to an increasing sustainability of the cropping system. Replacement of inorganic fertilisers directly reduces greenhouse gas emission produced during fertiliser production. Slow nutrient release from organic amendments possibly reduces losses from leaching and gaseous losses. Increased soil organic carbon improves soil structure and pore connectivity, which reduces gaseous nitrogen losses further (Neal et al. 2020). Small changes in SOC can also increase the soil water holding capacity contributing to higher yields in dry years, most likely an effect seen in the 2017 season (Table 7). Increased SOC will contribute to carbon sequestration and improve the overall greenhouse gas balance of the cropping system, compared to situations where no organic amendments were added. Losses can be minimised further by considering the form and timing of application of organic amendments (Goss et al. 2013). And beneficial use of organic amendments is an element of the circular economy where “wastes” are turned into resources.

5 Conclusion

The main objectives of this study and of the trial analysed were to investigate if organic amendments can increase yields of winter wheat and if these increases are mainly due to an improved N nutrition of the crop. Based on the results we conclude that more “labile” amendments (C/N ratio below 24) and at a substantial rate (2.5 t C ha^{-1} per year) can have the effect of increasing maximum yields above a mineral fertilised control treatment by an average of about 8.8%. This is an increase of the achievable yield since higher N rates with inorganic fertiliser could not match the yields with organic amendments. Based on these results and similar reports for other crops, we therefore believe that recycling organic wastes can improve productivity of intensive systems and reduce reliance on inorganic N fertilisers. Especially in the current situation with high fertiliser costs and high grain prices, possibly here to stay, both effects should be very interesting for farmers and encourage the increased use of organic amendments. In addition, the use of organic amendments can also help to reduce the carbon footprint of arable farming, thereby contributing towards the national goal of NetZero by 2050. And finally, application of organic amendments will also improve a range of other soil characteristics beneficial for the delivery of ecosystem services. But reaching these objectives and outcomes will require better management of organic amendments at the farm but also the regional and country level.

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by XA and CLT. The first draft of the manuscript was written by XA and all authors commented on previous versions of the manuscript. SMH responded to the reviewers' comments and all authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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