A comparison of the effects of cropping sequence, fertilization and straw management on the yield stability of winter wheat (1986–2017) in the Broadbalk Wheat Experiment, Rothamsted, UK.

# Abstract

The development of resilient cropping systems with high yield stability is becoming increasingly important due to future climatic and agronomic challenges. Consequently, it is essential to be able to evaluate the effects of differing agronomic management practices, such as cropping sequences, and nutrient supply on the stability of crop yields. Long-term experiments are a valuable resource for investigating these effects, providing a sufficient number of years for accurate stability parameter estimation. The objective of the current study was to evaluate the effects of cropping sequence (#1: continuous vs rotational), fertilization (#2: mineral vs organic) and straw management in the case of continuous wheat (#3: removal vs incorporation) on the yield stability of winter wheat; yield risk (the probability of yield falling below a threshold yield level) and inter-annual yield variability were used as stability indicators of the effects. Long-term yield data from the Broadbalk Wheat Experiment (Rothamsted, United Kingdom) were analysed using a mixed model. Overall, the results showed that rotational cropping combined with supply of sufficient nutrients (N, P, and K) from mineral fertilizers, especially mineral N supply, ensured stable wheat yields whilst reducing the yield risk

# Introduction

Optimized agronomic management strategies – particularly cropping sequences and nutrient management – are the most important agronomic factors which can be used to maximize the yield potential of wheat cropping systems. With regard to the current and future agronomic challenges (e.g. climate change, sustainable crop production and food security for a growing world population) it is becoming increasingly important to evaluate the effects of different strategies on the stability of crop yields in the long term (Albers *et al.*, 2017; Knapp and van der Heijden, 2018) and to help develop resilient crop production systems for the future (Ray *et al.*, 2015; Berti *et al.*, 2016). Long-term experiments (LTEs) provide a valuable resource for investigating the long-term effects of differing agronomic management, soil, annual weather and biotic factors, e.g. pest and diseases (Johnston and Poulton, 2018). Ideally, field experiments with relatively large plots under constant management for 20 years or more are required to provide sufficient data to evaluate yield stability (Grosse and Hierold, 2017). A valid statistical analysis fitting the experimental design is needed to accurately evaluate the yield stability, or risk, of crops over the years and to describe how yield is affected by different agronomic factors (Piepho, 1996, 1998, 2000). Yield risk is defined here as the probability that the yield falls below a certain threshold (Eskridge, 1990). The risk calculation is based on a combined analysis of the mean and variability of crop yields and follows the cumulative distribution function. Payne (2015) and Onofri *et al.* (2016) recommended that a mixed model approach using residual (restricted) maximum likelihood (REML) should be used for this kind of analysis.

The objective of the current study is to present a comparison of the effects that cropping sequences (#1: continuous vs rotational), fertilization (#2: mineral vs organic) and, for continuous wheat, straw management (#3: removal vs incorporation) have on the yield stability of winter wheat. The stability of crop yields is determined by yield risk (probability of yield falling below a threshold yield level) and inter-annual yield variability, based on the long-term (established in 1843) Broadbalk Wheat Experiment at Rothamsted. In addition, an assessment of system resilience by considering yield stability and yield level is provided.

# Materials and methods

## Experimental design and data

The current study was based on the Broadbalk Winter Wheat Experiment located at Rothamsted Research, Harpenden, United Kingdom (Herts, AL5 2JQ, UK; 51°48ʹ N, 0°22ʹ W, 128 m a.s.l.). The experiment was established by Lawes and Gilbert in 1843 (Lawes and Gilbert, 1864; Macdonald *et al.*, 2018), where wheat has been grown continuously or in rotation every year since.

The field slopes downwarded by 1 degree from West to East. According to the FAO (Food and Agriculture Organization of the United Nations) soil classification, the soil was a Chromic Luvisol (FAO, 2015). The soil texture class was a clay loam to silty clay loam over clay-with-flints and chalk was present below about two metres. The top-soil (0–23 cm) contained about 250 g/kg sand, 500 g/kg silt, and 250 g/kg clay (Gregory *et al.*, 2010). However, the clay content varied (190–390 g/kg) across the site (Watts *et al.*, 2006) and increased with soil depth (Jenkinson *et al.*, 2008): 300 g/kg (23–46 cm); 500 g/kg (46–69 cm); but then decreased 490 g/kg (69–92 cm). The soil was drained with tile drains (5 cm in diameter and 60–75 cm deep) installed in the centre of each strip. The drains discharged into the main drain at the east side of the field. Soil organic carbon contents and total nitrogen contents were determined (App. A) by high temperature combustion of finely ground soil in the presence of oxygen (LECO CNS) and subtraction of carbonate-C determined by liberation of carbon dioxide with dilute acid. From the 1950`s lime was applied when necessary to ensure that yields were not limited by soil acidity and that there was no more than one pH unit difference between plots. The pH value of the soil ranged from 7.0 to 8.0 (0–23 cm depth), which could be considered as a site pH (Macdonald *et al.*, 2018). The mean annual air temperature and rainfall (30 year mean) at Rothamsted was 9.8°C and 733 mm respectively (annual/monthly temperature and rainfall data in App. B–C) (Rothamsted Research, 2019).

Since 1968 the Broadbalk experiment contained 10 sections (Section 0 to 9) and 20 treatments (18 or 19 per section). The experiment included five sections in rotation (sections 2,3,4,5,7) with each phase of the rotation present every year (see field plan; App. D). The other sections were in continuous winter wheat. The plot lengths within each section varied between 15.2 m (Section 0), 28.0 m (Section 1), and 23.2 m (Sections 2,3,4,5,7), each with a plot width of 6 m (except treatment strips 2.1 and 2.2 which were each 4 m wide). Different fertilizer treatments were applied to strips within each section. The sections included different crop managements, with continuous wheat and wheat in rotation, and different straw management practices (incorporation vs. removal). The experiment predated modern principals of statistical design, consequently it had no true spatial replication.

A more detailed description of the current design of the Broadbalk Wheat Experiment is available in the Rothamsted Guide to the Classical Experiments (Macdonald *et al.*, 2018).

For the analysis, a partial dataset (1986–2017, marked as red frames in field plan; see App. D) with, in most cases, unchanged sections and treatments was used to ensure comparability and accurate estimates of yield stability. The partial dataset was selected to provide a comparison between the yield stability of continuous wheat (sections 0–1), with or without straw incorporation, with those of first wheat in rotation (sections 2,3,4,5,7), and between crops treated with different mineral fertilizers and/or organic manure (fertilization treatments), as described in Table 1. Yield data from sections 6 (no fungicides), 8 (no herbicides) and 9 were not included in the analysis. The dataset was obtained from the electronic Rothamsted Archive ‘e-RA’ (Perryman *et al.*, 2018), and included grain yields of winter wheat (at 850 g/kg dry matter).

Since 2001, P was withheld on many strips until levels of plant-available P decrease to optimal agronomic level. On most strips N was applied as a single dose in spring (April). Fertilizers P, K, Mg, and farmyard manure (FYM) were applied in autumn, usually between the end of September and mid-October. Since 1968 FYM and autumn fertilizers (P, K, Mg) were applied to the fallow sections of the rotational sections but fertilizer N had not been applied. Oats in rotation did not receive mineral N or FYM; potato and maize received the same fertilizer rates as wheat. For the incorporated wheat straw (section 0) an approximate amount of nutrients of 480 g/kg C (≙ 2592 kg C/ha), 5 g/kg N (≙ 27 kg N/ha), 3 g/kg P (≙ 16 kg P/ha), 11.6 g/kg K (≙ 63 kg K/ha), and 1.2 g/kg Mg (≙ 6 kg Mg/ha) could be assumed, based on the analysis of straw yields (mean 5.4 t/ha) from the adjacent section 1. The wheat straw was that quantity normally removed by baling and had been incorporated in Section 0 since autumn 1986; previously the straw was removed at harvest. The stubble (10–15 cm height) and part of the chaff remained for all sections.

As a consequence of the management problems with field horsetail (*Equisetum arvense* L.), no wheat was sown on Section 0 in autumn 2002; instead the section was used in 2003 and 2004 to test various combinations of herbicides. In autumn 2014, no winter wheat could be sown due to unfavourable weather conditions; instead, spring wheat was sown in March 2015. Consequently, these three years (2003, 2004, 2015) were excluded from the dataset.

After autumn ploughing, winter wheat was usually sown around mid-end October at a seed rate of about 350 seeds/m2. As well as the exception noted above when spring wheat was sown in March 2015, unfavourable conditions in autumn also resulted in winter wheat being sown very late in January 2001 and February 2013; these were included in the statistical analysis. During the selected experimental period, the following short-strawed winter wheat cultivars (grain-straw ratio of 1:0.8) were grown: Brimstone (1985–1990); Apollo (1991–1995); Hereward (1996–2012); Crusoe (2013–2018). Pesticides were applied where necessary; exceptions being sections 6 (no fungicides) and 8 (no herbicides) which were not used in the analysis. No irrigation was used in the experiment. Winter wheat was harvested around mid-end August at full grain maturity (GS 92–94). At harvest, a yield strip (2.1 m wide and 15–28 m long: 32–59 m²) was cut, from the centre of each plot by a small plot combine harvester, leaving a stubble of 10–15 cm in all plots.

## Statistical analysis

To account for the experimental design, a mixed model was fitted, based on REML, as recommended by Raman *et al.* (2011) and Onofri *et al.* (2016). Each plot had a different section×treatment combination with no repetition or randomization, so that plot errors and section×treatment×year interactions (= residual) could not be separated. The main effects for ‘section’ and ‘treatment’ as well as the interaction effect ‘section×treatment’ were modelled as fixed; the main effect for ‘year’ and the interaction effect with section×treatment were modelled as random. Furthermore, an autoregressive model AR(1) was used for the residual effect to account for autocorrelation of yields on the same plot across years due to time-varying processes and experimental changes in fertilization, cropping sequence and cultivars (Piepho *et al.*, 2015). Pairwise comparisons were performed (*P* < 0.05; all *P*-values corrected by Sidak for multiple testing) between the mean yields of winter wheat for: (a) treatments within a section, and (b) between sections within a treatment. The section×treatment combinations were tested for a linear trend of wheat yields over the years (1986–2017), but there was no evidence of a temporal trend.

Each ‘section×treatment’ combination was assumed to have a specific variance component (stability variance) for the interaction with years. Specific variances () were computed as the sum of stability variance of a section×treatment combination and the variance of the year main effect. These REML-based estimates of specific variances were used as measures of inter-annual yield variability (year-to-year) in accordance with Shukla’s ‘stability variance’ (Piepho, 1998, 1999), with lower values indicating fewer variable yields across years (= higher yield stability). The model allowed yield variability to be determined independently of the yield level, as recommended by Shukla (1972). Yield variability might be wrongly interpreted if there is a systematic dependency of variation from the mean (Döring and Reckling, 2018). In this analysis, no such dependencies were found.

Based on the model described above, the parameters ‘section×treatment’ specific means and standard deviations (based on the specific variances ; see above) were used in a second step for the analysis of yield risk according to Eskridge (1990). As shown in equation 1, the yield risk described the probability *p*(*i*) that the wheat yield in a ‘section×treatment’ combination *i* falls below a certain threshold yield level (= threshold δ) during the analysed trial period (1986–2017):

where was the cumulative density function of the standard normal distribution. The standard normal distribution of yields was verified by the Shapiro–Wilk Test of Normality (sig. 0.339; *P* < 0.05). The yield risk (probability of not achieving a threshold yield level) was calculated for a broad range of thresholds δ according to the range of observed yields between δ = 0–13 t/ha (in steps of 0.1 t/ha). These results were graphically modelled as curve progressions for specific ‘section×treatment’ combinations (x-axis: thresholds; y-axis: risk values; Fig. 2). Additionally, yield risk comparisons of continuous wheat versus first wheat in rotation for the different fertilization treatments are presented in Figure 3. These graphs were generated by plotting the yield risk, *p*(*i*) values per threshold δ, of one ‘section×treatment’ combination (x-axis) against the yield risk, *p*(*i*) values per threshold δ, of another ‘section×treatment’ combination (y-axis) to compare directly their yield risks over the full range of threshold yield levels (δ = 0–13 t/ha; in steps of 0.1 t/ha).

For statistical analysis, the software SAS (Version 9.4; SAS Institute Inc.; Cary, North Carolina, United States) and SPSS (Version 24; IBM SPSS Statistics; Armonk, New York, United States) were used. The syntax for the model is presented in Appendix E.

# Results

## Yield

The mean yield over all sections and treatments during the trial period 1986–2017 was 6.53 t/ha (Fig. 1; range of yield values in App. F). In the FYM N3 treatment straw removal led to a significantly higher mean yield for continuous wheat compared with that when straw was incorporated, in all other treatments there were no significant effects of straw management on continuous wheat yields. The cropping sequence showed a significant effect on the mean yield, with significantly higher yields for first wheats in rotation compared with continuous wheat crops.

Over all sections, the application of FYM combined with mineral N supply (FYM N3) resulted in the highest mean yields (up to 9.6 t/ha), followed by mineral fertilizers with 192 kg N/ha (N4 (P) K Mg). In contrast, applying FYM alone resulted in a lower mean yield. The lowest mean yield (4.7 t/ha) was recorded with N2 (P) K Mg, which received 96 kg N/ha, in the continuous wheat section with straw removal (Fig. 1).

## Yield risk

The yield risk, e.g. the risk of not achieving the threshold yield level depending on the fertilization treatment, has been shown for continuous wheat (Fig. 2a) and first wheat in rotation (Fig. 2b). For all analysed sections the yield risk was highest in the N2 (P) K Mg and FYM treatments, which is indicated by left-hand side curve progressions (Fig. 2a–b). There was a higher risk yield loss on the N2 (P) K Mg and FYM treatments at lower yield levels (higher slope/gradient of curves at thresholds = 3–5 t/ha) compared to the FYM N3 and N4 (P) K Mg treatments. In contrast, the yield risks in treatment N4 (P) K Mg and especially in treatment FYM N3 were much lower, which is indicated by the right-hand side curve progressions (Fig. 2a–b).

The comparison of continuous wheat versus first wheat in rotation (Fig. 3a–d) showed that the yield risk in a diverse cropping sequence was much lower than in continuous wheat (indicated by convex curve progressions). The reduced risk of yield loss associated with crop rotation was evident in all treatments, but was most pronounced with N4 (P) K Mg, which received a larger amount of N fertilizer (Fig. 3d). Furthermore, there was a positive effect of straw removal in the continuous wheat sections with FYM supply (Fig. 3a–b); there was a higher yield risk under straw incorporation than under straw removal, which is indicated by the more convex curve progression of the black curve compared to the grey curve. This effect was not evident on the minerally fertilized plots, N2 (P) K Mg and N4 (P) K Mg, where the yield risk of the two continuous wheat sections were similar (relatively equal progressions of black and grey curves; Fig. 3c–d).

Comparing the section×treatment combinations by setting the threshold yield at the overall mean = 6.5 t/ha (grey guide lines in Fig. 3a–d), the lowest yield risks were found for first wheat in rotation receiving FYM combined with N fertilizer (FYM N3: Fig. 3b), and for treatment with high mineral N input (N4 (P) K Mg: Fig. 3d). In contrast, higher yield risks were found for continuous wheat with FYM application only (Fig. 3a), and the highest risk was found for continuous wheat with less N fertilizer (N2 (P) K Mg: Fig. 3c).

## Inter-annual yield variability

In the continuous wheat section with straw incorporation, the highest inter-annual yield variability (Fig. 4) was found for low mineral N supply (N2 (P) K Mg). A lower variability (indicating more stable yields) was determined for higher mineral fertilization (N4 (P) K Mg), and the lowest variability was associated with FYM combined with mineral N fertilizer (FYM N3). In the continuous wheat section with straw removal, the yield variability was lowest for higher mineral N input (N4 (P) K Mg), and higher yield variability was obtained in the N2 (P) K Mg and FYM N3 treatments. The most unstable yields were found with FYM application only. The highest yield variability of first wheat in rotation was shown for FYM especially if combined with mineral N (FYM N3). Mineral fertilization led to somewhat lower yield variability of first wheat in rotation and variability was lowest in N2 (P) K Mg (Fig. 4).

Overall, the results of the inter-annual yield variability varied between the sections and treatments. Comparing all section×treatment combinations, the lowest yield variability (= 1.00; indicating the most stable yields) was found for continuous wheat with straw removal with the largest amount of N (N4 (P) K Mg). In contrast, the highest yield variability (= 2.18) was obtained for the first wheat in rotation receiving FYM plus mineral N (FYM N3; see Fig. 4).

## System resilience

A high system resilience was found for first wheat in rotation receiving 192 kg/ha of mineral fertilizer N (N4 (P) K Mg) combining high mean yield level (8.8 t/ha) with greater yield stability, indicated by low inter-annual variability (filled black square in Fig. 5) and low yield risk (right-hand side curve progression in Fig. 2b; convex curves in Fig. 3d). High yield resilience was also observed for the rotational wheat with FYM N3; this treatment had the highest mean yield level (9.6 t/ha), low yield risk (right-hand side curve progression in Fig. 2b), but much higher inter-annual variability (square with stripes in Fig. 5).

In contrast, the continuous wheat section with straw removal and FYM N3 (circle with stripes in Fig. 5) showed a lower yield level, but with stable yields and relatively low yield risk (right-hand side curve progressions in Fig. 2a). Continuous wheat with straw removal receiving higher amounts of mineral N supply (N4 (P) K Mg) showed less system resilience, resulting in lower yield levels with slightly higher risk (Fig. 2a), but also slightly lower inter-annual yield variability (filled black circle in Fig. 5) compared to treatment FYM N3.

The poorest system resilience, combining high risk + low and varying yields, was found for both continuous wheat sections with less mineral N (96 kg N/ha; N2 (P) K Mg: left-hand side curve progressions in Fig. 2a; patterned diamond and patterned circle in Fig. 5). Similarly poor system resilience was shown by continuous wheat with FYM only (left-hand side curve progression in Fig. 2a; filled white diamond and white circle in Fig. 5).

# Discussion

## Impact of cropping sequence (#1)

Cereal rotations with a large proportion of winter wheat are typical of large areas of northern Europe and other temperate or humid climates, particularly where crop diversity is constrained by physical or economic factors (Lithourgidis *et al.*, 2006). Despite environmental concerns, growing winter wheat continuously or the rotation ‘break crop/wheat/wheat’ might be recommended occasionally as financially the most profitable ‘cropping sequence’ (Sieling *et al.*, 2005; Steinmann and Dobers, 2013). However, unfavourable preceding crops and continuous wheat inevitably cause yield losses (e.g. Engström and Lindén, 2009; Angus *et al.*, 2015). Yields of wheat grown after a two-year break (break crops: fallow-potato or oat-maize) were larger than yields of continuous wheat, almost certainly because the effects of soil borne pests and diseases, particularly take-all root disease (*Gaeumannomyces graminis* var. *tritici*), are minimized (Macdonald *et al.*, 2018). This yield benefit clearly reduced the yield risk in this current study, which was lower (in all treatments) for the first wheat crop in the rotation than for continuous wheat crops. In contrast, the inter-annual yield variability was higher for the first wheat in rotation, especially in cropping systems with FYM plus mineral N (FYM N3). A possible explanation for this could be that although the higher yield potential of wheat grown in rotation, compared to monoculture, resulted in larger yields when environmental conditions (e.g. annual weather and/or soil conditions) were favourable, it also led to more variable yields when environmental conditions were unfavourable. Also, the effects of the preceding crops in the rotation and the additional FYM application should be considered, mainly because the specific amount of crop residues and its mineralization or immobilization will differ over the years causing variability in the subsequent wheat yields. Potatoes are shallow rooted and often leave significant amounts of plant-available N in sub-soil (Macdonald *et al.*, 1997). This may result in higher and perhaps less risky and variable yields in the subsequent wheat crop. Maize is deeper rooted and may thus leave smaller mineral N residues and less available water for the subsequent crop than potatoes (Brouwer and Heibloem, 1986). This could have resulted in lower and more variable yields for the subsequent wheat crop.

These Broadbalk results stand in contrast to some LTE-studies, where lower inter-annual yield variability of wheat grown in rotations compared to monoculture has been reported (e.g. Arshad *et al.*, 2002; Elen, 2002; Babulicová, 2008). Some other studies have found that wheat inter-annual yield variability was not affected significantly by growing wheat continuously or did not differ among cropping systems, as a consequence of the high production ability of wheat in the long-term (Procházková *et al.*, 2003; St-Martin *et al.*, 2017). The current results also showed no clear pattern of yield variability over all of the sections and treatments. A definitive explanation of why wheat yields were partly more unstable in rotation than in monoculture (see FYM N3) cannot be given at the moment; further research on this is needed. A valid statistical analysis of the dependency between yield variability and available soil parameters (soil organic carbon and total N, see App. A) (possible hypothesis: ‘lower yield variability due to higher soil organic carbon content’), could not be performed due to insufficient data. A comparative study considering different LTEs with a similar trial set-up should be considered to verify these findings and to check their multi-environmental applicability. Overall, reducing inter-annual yield variability should not be the sole objective; instead, achieving a good compromise (e.g. favourable combination) between yield level, inter-annual yield variability and yield risk is a better approach with more practical relevance. Based on the Broadbalk Experiment, the first wheat in rotation receiving a higher mineral N supply (N4 (P) K Mg) showed a very good compromise between high and stable yields plus low risk for yield reductions.

There are relatively few long-term wheat experiments with different cropping systems that can be used to analyse the effects on inter-annual yield variability (e.g. Varvel, 2000; Nel *et al.*, 2003; Lithourgidis *et al.*, 2006; Smith *et al.*, 2007; van der Bom *et al.*, 2017), and even fewer on yield risk (e.g. Nielsen and Vigli, 2018; Macholdt *et al.*, 2019a). Thus, additional studies that focus explicitly on these topics and incorporate a time period long enough to capture a greater range of climatic conditions are necessary to accurately quantify the long-term impact of different agronomic management treatments on the stability of crop yields.

## Impact of mineral fertilizers and organic manure (#2)

The highest impact on the yield stability of winter wheat, here determined by yield risk and yield variability, was found for the mineral N supply. A study of Häner and Barbant (2006) showed that the impact of mineral N fertilizer on the yield variation (32%) of winter wheat was comparable to that for environmental conditions (35%). In the current study, larger amounts of mineral N fertilizer led to high and stable wheat yields with relatively low production risk, which was also observed in other comparable LTEs by Varvel (2000), Chloupek *et al.* (2004), Hao *et al.* (2007), Lollato *et al.* (2019), and Macholdt *et al.* (2019a). A possible reason for this is that the mineral N buffered against environmental variability. Under conditions of sufficient plant-available N supply and higher accumulative soil N content with related higher mineralisation rates, wheat plants could exploit the prevailing growing conditions better and be more resilient to environmental stress (St-Martin *et al*., 2017). Therefore, higher plant-available N supply could be assumed to be a very important factor in reducing inter-annual yield variability (Knapp and van der Heijden, 2018), providing there are no other constraints on plant growth, like pests or diseases, soil acidity or compaction, among others. Soil mineral N on Broadbalk is known to fluctuate annually and so is not measured routinely (Glendining et. al., 1996). Weather conditions also affect crop development and yield. In a recent study by Addy et al. (2020) the wheat yield responses to applied N on Broadbalk were particularly sensitive to mean temperature in November, April and May, and to total rainfall in October (Addy et. al., 2020).

In contrast, the highest inter-annual yield variability and yield risk was observed in treatments with lower levels of mineral N fertilizer or FYM only. These findings are in line with long-term studies of Kravchenko *et al.* (2005), Smith *et al.* (2007), and Maltas *et al.* (2013), where yield and yield stability were lower in organically manured and low-input systems than in high-input mineral N systems. However, when N was limiting, any forms of organic manure (like FYM) had a positive long-term effect on wheat yields and soil sustainability parameters like the organic carbon content (see App. A).

The combination of FYM and mineral N fertilizer (FYM N3) resulted in a very good combination of low yield risk with high and stable wheat yields compared to FYM only. A meta-analysis based on 20 LTEs in Europe by Hijbeek *et al.* (2017) showed similar results, where organic inputs led to increased wheat yields even when sufficient mineral nutrients were provided. The supply of manure combined with mineral N fertilizer can improve not only the yield of wheat (Ellmer *et al.*, 2001; Barzegar *et al.*, 2002; St-Martin *et al.*, 2017), but also improves the yield stability (Berzsenyi *et al.*, 2000; Macholdt *et al.*, 2019b). This stabilizing yield effect can be confirmed for the yield risk of continuous wheat in the Broadbalk Wheat Experiment, but regarding inter-annual yield variability not for rotational wheat. There are several positive aspects of this combination of fertilization on different soil properties, such as: (1) accumulation of total and plant-available nutrients (Kulhánek *et al.*, 2014; Mazur and Mazur, 2015); (2) physical improvements as a result of better aggregate stability, water infiltration rate, water holding capacity, structure quality, porosity (Barzegar *et al.*, 2002; Pagliai *et al.*, 2004); (3) advantages in soil microbial biomass and activity (Clark *et al.*, 2008; Tlustos *et al.*, 2017); and (4) enhanced soil fertility (Edmeades, 2003; Maltas *et al.*, 2013; Johnston and Poulton, 2018). All these positive aspects provide more favourable growing conditions for wheat plants and may improve the buffer function (resilience) of the soil, which reduces the negative impact of biotic and abiotic stressors on plants and finally results in higher and reduced yield risk of wheat, as observed in the Broadbalk Experiment at Rothamsted.

However, increased losses of inorganic N because of leaching from plots with higher N fertilizer rates and large annual applications of FYM have been reported (Powlson *et al.*, 1989; Goulding *et al.*, 2000; Hawkesford, 2014). The annual FYM inputs on the Broadbalk Wheat Experiment are large and not typical of commercial agriculture in the UK. Consequently, from an environmental perspective (especially nitrate leaching) they are probably unsustainable (Macdonald *et al.*, 2017). The FYM treatments are not intended to be representative of current farm practice, but are useful from a scientific perspective, for example to examine soil organic matter dynamics (Poulton *et al*., 2018).

## Impact of straw management (#3)

In the treatments with FYM and FYM N3 yields in the continuous wheat sections where the straw was baled and removed had a lower risk of loss, but a higher inter-annual yield variability, compared to those where straw was incorporated. Straw incorporation (since autumn 1986) has had only a small, and variable, effect on soil C and N (Glendining *et al.*, 1996; Poulton *et al.*, 2018). Based on soil analysis, the C:N ratio was around 10:1 and did not differ between the two continuous wheat sections with and without straw (App. A). The FYM and FYM N3 treatments have received high annual FYM applications (c. 248 kg N ha-1; see Tab. 1) over a long period, so the soil N content has been increased substantially. This has resulted in a narrow C:N ratio.

A possible explanation for the higher risk in the section with straw incorporation and additional FYM application (especially without mineral N supply) could be that the mineral N availability may be limited for a short period soon after straw incorporation due to microbial immobilization of N. This may influence subsequent crop establishment. Turley *et al.* (2003) also found wheat yield reductions caused by straw incorporation into soil, which ranged from 5–8% on clay soils to 3–18% on silty clay loam soils (study based on six sites in England). Babulicová (2008) found significant negative yield effects of straw incorporation on continuous winter wheat, with effects becoming more significant over the trial period of 32 years. In contrast, Powlson *et al.* (2011) found straw incorporation has increased wheat yields (continuously grown). However, lower inter-annual yield variability and potential benefits in terms of C sequestration of straw incorporation might need to be offset against possible yield losses (yield risk) or lower yield levels, which is also for policy makers to consider.

During an earlier experimental period (1968–1985) of the Broadbalk Wheat Experiment, where the straw had been removed in both continuous wheat sections, some differences in mean yield between sections 0 and 1 already existed in plot 2.1 receiving FYM N3; from 1969–1975, with straw removal from both sections, the mean wheat yields in treatment with FYM N3 were higher (6.2 t ha-1) in plots of section 1 (straw removal) than in plots of section 0 (4.6 t ha-1; later on straw incorporation, since 1986). Both plots were fertilised and treated identically, hence there might be also other pre-existing differences between the plots, such as underlying soil differences (could not be verified). These differences were not evident in plots with FYM, N2 or N4 treatments and yields were similar in the FYM N3 plots in the ten years preceding this study (1977-1985). However, in respect of the earlier difference, the effects of straw management in the plots where wheat was grown continuously are inconclusive and require further investigation.

When just inorganic N was applied (N2 and N4 treatments) straw incorporation did not appear to have an effect on yield risk. Here, N availability and subsequent crop establishment did not seem to be affected, even in plots with straw incorporation. However, taking the inter-annual yield variability into account, stabilizing yield effects for continuous wheat as a consequence of straw removal and mineral N fertilization became evident; this was especially the case where more N was applied (N4). The possible reasons for the stabilizing effects of mineral N fertilization have been discussed in the previous section.

# Conclusion

The current study demonstrated that the long-term Broadbalk Wheat Experiment, can be used to characterize the long-term yield stability of different cropping systems and helped to better understand the impact of agronomic managements on yield responses. Overall, the Broadbalk results highlighted the scope for improving the resilience and stability of wheat yields through the use of crop rotations (#1) and sufficient fertilizer N with or without organic manure (#2). The impact of straw management (#3: removal vs incorporation) when wheat was grown continuously was not conclusive and warrants further investigation. When straw was incorporated and wheat got inputs of manure (FYM and FYM N3 treatments) the inter-annual yield variability was lower, but yield risk was higher, compared to straw removal. When just inorganic N was applied (N2 and N4 treatments) straw management did not appear to have an effect on yield risk, but on inter-annual yield variability. When straw was removed yields were more stable compared to straw incorporation, especially when wheat received higher mineral N amounts (N4).

Further studies are needed to validate the robustness of the results and their applicability in different environments or under future climate predictions. A better understanding of how agronomic management practices could help carbon sequestration and guard against environmental variability is also needed. The risk assessment approach presented here, with the mixed model analysis based on REML stability parameter estimates, can be applied in a wider agronomic context and offers the opportunity for further and deeper analysis of LTEs. The approach could be used by researchers in the wider field of agronomy, but it also provides a valuable opportunity for farmers, advisors and policy makers to evaluate various farming practices affecting the yield risk of cropping systems (or rather production risk including economic factors) with regard to climate change adaptation and sustainability.

# References

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# Tables and Figures

**Tab. 1.** Description of sections and fertilization treatments used for the analysis of yield stability (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Fig. 1.** Mean yield of winter wheat depending on fertilization treatment for continuous winter wheat (straw incorporation and straw removal) and first wheat in rotation (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Fig. 2 (a-b).** Yield risk comparison of fertilization treatments over a range of threshold yield levels for (a) continuous wheat (straw incorporation and straw removal) and (b) first wheat in rotation (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Fig. 3 (a-d).** Yield risk comparison of continuous wheat (straw incorporation and straw removal) versus first wheat in rotation for fertilization treatments (a) FYM, (b) FYM N3, (c) N2 (P) K Mg, (d) N4 (P) K Mg (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Fig. 4.** Inter-annual yield variability depending on fertilization treatment for continuous wheat (straw incorporation and straw removal) and first wheat in rotation (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Fig. 5.** Comparison of mean yield versus inter-annual yield variability of winter wheat depending on fertilization treatment for continuous winter wheat (straw incorporation and straw removal) and first wheat in rotation (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Appendix A.** Soil analysis results of soil organic carbon and total nitrogen contents for the years 1987, 1992, 1997, 2000, 2005, 2010 in continuous wheat sections with straw removal depending on fertilization treatment (Broadbalk Wheat Experiment Rothamsted)

**Appendix B.** Annual and monthly mean temperature (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Appendix C.** Annual and monthly sum of precipitation (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Appendix D.** Field plan of the Broadbalk Wheat Experiment Rothamsted (1998–2017)

**Appendix E.** SAS syntax for REML based yield and yield stability assessment model (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

**Appendix F.** Box and whisker plots for yield of winter wheat depending on fertilization treatment for continuous winter wheat (straw incorporation and straw removal) and first wheat in rotation (Broadbalk Wheat Experiment Rothamsted, 1986–2017)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sections** | | **Fertilization treatments\*** | | | |
| **FYM N3**  Strip 2.1 | **FYM**  Strip 2.2 | **N2 (P) K Mg**  Strip 7 | **N4 (P) K Mg**  Strip 9 |
| **Continuous wheat  with straw incorporation**  Section 0 | Grain yield of winter wheat from 1986-2017.  Straw chopped and incorporated since 1986. | **Farmyard manure:**  from cattle  35 t of fresh material  248 g dry matter per kg fresh manure  364 g C/kg dry matter  249 kg N  49 kg P  325 kg K  34 kg Mg  **Mineral fertilization:**  N3 = 144 kg N (before 2005: 96 kg N) | **Farmyard manure:**  from cattle  35 t of fresh material  248 g dry matter per kg fresh manure  364 g C/kg dry matter  249 kg N  49 kg P  325 kg K  34 kg Mg | **Mineral fertilization:**  N2 = 96 kg N  90 kg K  35 kg Mg every 3rd year  35 kg P (before 2001) (P): P has not been  applied since 2001, due to large amounts of plant- available P in the soil | **Mineral fertilization:**  N4 = 192 kg N  90 kg K  35 kg Mg every 3rd year 35 kg P (before 2001) (P): P has not been  applied since 2001, due to large amounts of plant- available P in the soil |
| **Continuous wheat  with straw removal**  Section 1 | Grain yield of winter wheat from 1986-2017.  Straw baled and removed since 1986. |
| **First wheat in rotation** Sections 2,3,4,5,7 | Grain yield of winter wheat from 1986-2017, each year from one of the five identical and time-shifted sections (2,3,4,5,7) consecutively.  For analysis yield of first wheat in rotation was used (marked: bold).  Cropping sequences:  1986-1997: fallow–potato–**wheat**–wheat–wheat  1998-2017: oat–forage maize–**wheat**–wheat–wheat  Cereal straw baled and removed.  Potato leaves and maize stubble incorporated. |

Notes: The numbering/naming of sections and fertilization treatments (strips) were kept identical according to the field plan (App. D) and official trial description of Rothamsted Research ([www.era.rothamsted.ac.uk/Broadbalk](http://www.era.rothamsted.ac.uk/Broadbalk)). \*values stated per hectare, applied annually, unless stated otherwise. N applied as a single dressing in all cases; N (= Nitrogen) applied as ammonium nitrate; P (= Phosphorus) as triple superphosphate; K (= Potassium) as potassium sulphate; Mg (= Magnesium) as Kieserite.

## Tab. 1

Fertilization treatment:

Note:Different capital letters indicate significant\* differences between the four fertilizer treatments at a given section and different Roman numerals indicate significant\* differences between the three sections at a given treatment level (\**P* < 0.05). The range of yield values for each section×treatment combination are presented in Appendix F. Continuous wheat with straw incorporation (Section 0); continuous wheat with straw removal (Section 1); first wheat in rotation (Sections 2,3,4,5,7). Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

## Fig. 1

Note: 1probability of yield falling below a threshold yield level (range between 0–13 t/ha). Continuous wheat with straw incorporation (Section 0); continuous wheat with straw removal (Section 1); first wheat in rotation (Sections 2,3,4,5,7). Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

## Fig. 2 (a-b)

δ = 6.5 t/ha

δ = 6.5 t/ha

**a**

**b**

**c**

Continuous wheat with straw incorporation versus first wheat in rotation  
Continuous wheat with straw removal versus first wheat in rotation  
Guide line for yield risk at threshold δ 6.5 t/ha(mean yield over all sections×treatments×years)

δ = 6.5 t/ha

δ = 6.5 t/ha

**Legend:**

Note: Yield risk is defined as probability of yield falling below a threshold yield level . Data mapped using *p*(*i*) values per threshold δ(range 0–13 t/ha) of one ‘section×treatment’ combination (x-axis) against *p*(*i*) values per threshold δ (range 0–13 t/ha) of another ‘section×treatment’ combination (y-axis). Continuous wheat with straw incorporation (Section 0); continuous wheat with straw removal (Section 1); first wheat in rotation (Sections 2,3,4,5,7). Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

## Fig. 3 (a-d)

Note: 1according to Shukla’s stability variance: lower values indicating more stable yields. Continuous wheat with straw incorporation (Section 0); continuous wheat with straw removal (Section 1); first wheat in rotation (Sections 2,3,4,5,7). Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

Fertilization treatment:

## Fig. 4

High and stable yields

High and varying yields

Low and varying yields

Low and stable yields

Note: 1according to Shukla’s stability variance (lower values indicating more stable yields, see Fig. 4); 2mean yield over all of the sections×treatments×years: 6.53 t/ha (underlying yield data in Fig. 1). Section 0: continuous wheat with straw incorporation; Section 1: continuous wheat with straw removal; Rotation: first wheat in rotation. Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

## Fig. 5

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Fertilization treatment** | **Year of soil analysis in continuous wheat sections with straw removal** | | | | | |
| **1987** | **1992** | **1997** | **2000** | **2005** | **2010** |
| Soil organic carbon content 0-23 cm [g/kg] | FYM N3 | 23.4 | 26.7 | 26.2 | 27.5 | 25.6 | 28.9 |
| FYM | 28.2 | 26.8 | 29.3 | 28.9 | 29.9 | 29.7 |
| N2 (P) K Mg | 11.1 | 10.7 | 10.2 | 11.1 | 10.6 | 10.5 |
| N4 (P) K Mg | 10.8 | 11.1 | 10.5 | 11.6 | 11.0 | 11.2 |
| Total nitrogen content 0-23 cm [g/kg] | FYM N3 | 2.3 | 2.7 | 2.7 | 2.6 | 2.6 | 2.8 |
| FYM | 2.7 | 2.7 | 3.0 | 2.7 | 2.9 | 2.9 |
| N2 (P) K Mg | 1.2 | 1.2 | 1.2 | 1.1 | 1.2 | 1.1 |
| N4 (P) K Mg | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |

Note: Analysis of air-dried soil ground to < 2mm. Analysis methods for 1987 were Tinsley for soil organic carbon and Kjeldahl for total nitrogen. Analysis methods for 1992, 1997, 2000, 2005 were combustion and manometry. Broadbalk soil chemical properties available at: <http://www.era.rothamsted.ac.uk/Broadbalk/bbksoilchem> (accessed on 17/12/2019). Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

## Appendix A

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Harvest year** | **Annual mean temperature\***  **Oct-Sept [°C]** | **Monthly mean temperature\* [°C]** | | | | | | | | | | | |
| **October** | **November** | **December** | **January** | **February** | **March** | **April** | **May** | **June** | **July** | **August** | **September** |
| 1986 | 8.2 | 11.0 | 3.5 | 6.3 | 2.9 | -2.2 | 4.6 | 5.7 | 10.8 | 14.5 | 16.0 | 14.2 | 11.3 |
| 1987 | 9.0 | 11.1 | 7.4 | 5.4 | 0.0 | 3.1 | 3.5 | 10.0 | 9.6 | 12.8 | 15.5 | 15.4 | 13.7 |
| 1988 | 9.3 | 9.7 | 5.8 | 5.3 | 4.8 | 4.3 | 6.0 | 7.8 | 11.6 | 13.5 | 14.5 | 15.5 | 13.3 |
| 1989 | 10.3 | 10.6 | 4.9 | 6.6 | 5.3 | 5.4 | 7.6 | 6.3 | 13.0 | 14.3 | 18.2 | 16.8 | 15.2 |
| 1990 | 10.3 | 11.6 | 5.6 | 5.1 | 5.9 | 7.0 | 7.8 | 7.5 | 12.1 | 13.2 | 16.8 | 18.2 | 13.0 |
| 1991 | 9.3 | 11.7 | 6.4 | 3.7 | 3.1 | 0.8 | 7.5 | 7.4 | 9.8 | 12.0 | 16.9 | 17.4 | 14.4 |
| 1992 | 10.0 | 9.7 | 6.5 | 4.0 | 3.6 | 4.8 | 7.3 | 8.6 | 13.5 | 15.5 | 16.6 | 15.9 | 13.5 |
| 1993 | 9.4 | 7.7 | 7.1 | 3.4 | 5.8 | 3.9 | 6.3 | 9.5 | 11.7 | 15.1 | 15.3 | 14.8 | 12.4 |
| 1994 | 9.7 | 8.9 | 4.6 | 5.3 | 4.9 | 3.1 | 7.6 | 8.0 | 10.7 | 14.7 | 18.8 | 16.4 | 13.0 |
| 1995 | 10.6 | 10.1 | 9.8 | 6.1 | 4.4 | 6.2 | 5.3 | 9.0 | 11.5 | 13.8 | 18.8 | 19.1 | 13.5 |
| 1996 | 9.3 | 13.0 | 7.5 | 2.0 | 3.9 | 2.0 | 4.0 | 8.4 | 8.8 | 14.8 | 16.7 | 16.6 | 13.5 |
| 1997 | 10.1 | 11.4 | 5.5 | 2.6 | 1.7 | 6.3 | 8.1 | 8.6 | 11.5 | 14.3 | 16.6 | 19.6 | 14.5 |
| 1998 | 10.3 | 10.1 | 8.1 | 5.5 | 4.8 | 6.1 | 7.3 | 7.7 | 12.7 | 14.4 | 15.7 | 16.3 | 15.0 |
| 1999 | 10.4 | 10.2 | 5.3 | 5.5 | 5.2 | 4.8 | 7.3 | 9.4 | 13.0 | 13.8 | 17.8 | 16.5 | 16.0 |
| 2000 | 10.2 | 10.5 | 7.4 | 4.4 | 4.5 | 5.9 | 7.2 | 7.8 | 12.0 | 15.3 | 15.3 | 17.1 | 15.0 |
| 2001 | 9.9 | 10.4 | 6.6 | 5.5 | 3.0 | 4.7 | 5.4 | 7.8 | 12.6 | 14.3 | 17.5 | 17.3 | 13.3 |
| 2002 | 10.6 | 13.5 | 6.9 | 3.3 | 5.4 | 6.8 | 7.4 | 9.4 | 11.8 | 14.4 | 16.4 | 17.4 | 14.3 |
| 2003 | 10.7 | 10.1 | 8.4 | 5.9 | 3.9 | 3.7 | 7.3 | 9.2 | 12.2 | 16.3 | 17.9 | 19.2 | 14.6 |
| 2004 | 10.4 | 9.2 | 8.3 | 4.6 | 4.7 | 5.0 | 6.2 | 9.1 | 12.0 | 15.5 | 16.4 | 18.1 | 15.3 |
| 2005 | 10.2 | 10.7 | 7.4 | 4.8 | 5.4 | 3.7 | 6.6 | 8.9 | 11.4 | 15.7 | 16.8 | 16.2 | 15.3 |
| 2006 | 10.5 | 13.3 | 5.8 | 4.0 | 4.0 | 3.2 | 4.8 | 8.5 | 12.4 | 16.1 | 20.3 | 16.4 | 17.4 |
| 2007 | 10.9 | 13.2 | 7.9 | 6.1 | 6.8 | 5.8 | 7.0 | 11.2 | 12.1 | 15.3 | 15.8 | 15.6 | 14.1 |
| 2008 | 10.2 | 10.6 | 6.8 | 4.8 | 6.4 | 5.4 | 5.9 | 8.0 | 13.4 | 14.5 | 16.6 | 16.6 | 13.5 |
| 2009 | 9.9 | 9.5 | 6.8 | 3.4 | 2.2 | 3.7 | 6.9 | 10.0 | 12.4 | 15.1 | 16.6 | 17.3 | 14.7 |
| 2010 | 9.6 | 11.3 | 8.6 | 2.7 | 1.2 | 2.8 | 6.2 | 9.0 | 10.5 | 15.6 | 18.0 | 15.8 | 13.8 |
| 2011 | 9.8 | 10.5 | 5.1 | -0.3 | 3.8 | 6.2 | 6.5 | 12.1 | 12.5 | 14.3 | 15.4 | 15.8 | 15.3 |
| 2012 | 10.3 | 12.8 | 9.3 | 5.7 | 5.5 | 3.3 | 8.0 | 7.4 | 12.0 | 13.8 | 15.7 | 17.3 | 13.4 |
| 2013 | 9.2 | 9.7 | 6.5 | 4.5 | 2.7 | 2.7 | 2.5 | 7.6 | 10.5 | 13.7 | 18.7 | 17.4 | 13.7 |
| 2014 | 11.0 | 12.3 | 6.2 | 5.8 | 5.7 | 6.1 | 8.1 | 10.5 | 12.4 | 15.4 | 18.6 | 15.7 | 15.6 |
| 2015 | 10.1 | 12.9 | 8.6 | 5.1 | 4.2 | 3.7 | 6.6 | 9.2 | 11.3 | 14.3 | 16.6 | 16.3 | 12.7 |
| 2016 | 11.1 | 11.0 | 9.4 | 9.9 | 5.0 | 4.8 | 5.5 | 7.7 | 12.6 | 15.1 | 17.5 | 17.8 | 16.3 |
| 2017 | 10.5 | 10.8 | 5.7 | 5.4 | 3.1 | 5.9 | 8.8 | 9.0 | 13.2 | 16.8 | 17.5 | 16.0 | 13.6 |

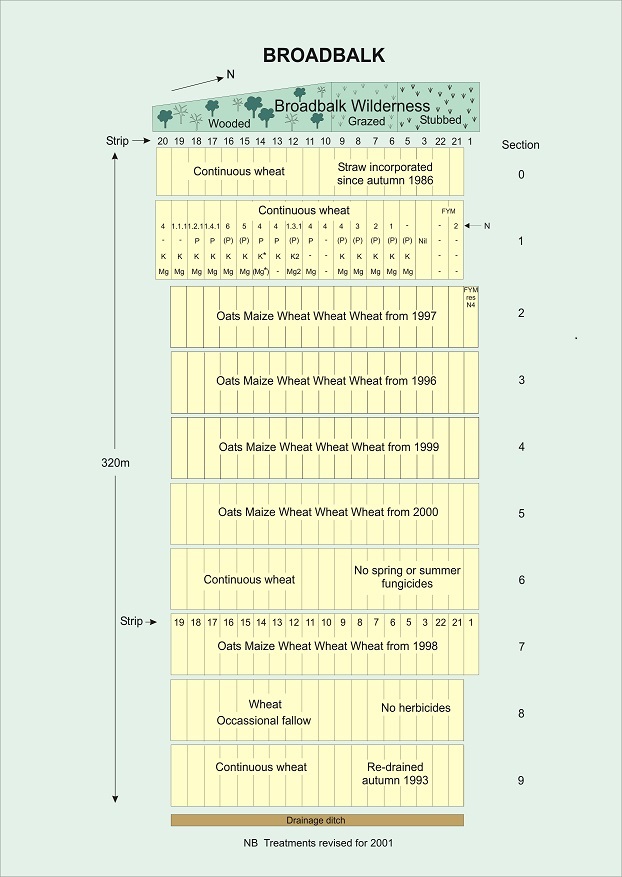
Note: \*measured in 2 m height above soil surface. Source was the e-RA electronic Rothamsted Archive.

## Appendix B

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Harvest year** | **Annual total precipitation Oct-Sept [mm]** | **Monthly precipitation [mm]** | | | | | | | | | | | |
| **October** | **November** | **December** | **January** | **February** | **March** | **April** | **May** | **June** | **July** | **August** | **September** |
| 1986 | 688.3 | 22.4 | 50.5 | 108.2 | 85.2 | 25.9 | 56.4 | 84.1 | 61.7 | 16.4 | 44 | 103.6 | 29.9 |
| 1987 | 717.4 | 87.7 | 85.4 | 82.2 | 15.3 | 27.9 | 56.4 | 47.2 | 63.6 | 89.9 | 61.5 | 60.4 | 39.9 |
| 1988 | 872.9 | 198.7 | 59 | 29.5 | 136.7 | 41.9 | 65.1 | 29.2 | 49.8 | 56.6 | 94.7 | 60.2 | 51.5 |
| 1989 | 501.9 | 70.2 | 29.5 | 20 | 38.9 | 52.9 | 61.1 | 97.9 | 4.2 | 27.7 | 46.7 | 37.9 | 14.9 |
| 1990 | 663.7 | 63.3 | 38.5 | 156.8 | 96.5 | 108.5 | 16.3 | 26.5 | 1.5 | 51.7 | 14.8 | 52.1 | 37.2 |
| 1991 | 726.5 | 91.1 | 39 | 62.2 | 83 | 54.4 | 28 | 73.5 | 14.6 | 100.4 | 73.4 | 45.5 | 61.4 |
| 1992 | 712.4 | 28.6 | 58.6 | 15.8 | 24.6 | 21.4 | 56.8 | 63.9 | 103.1 | 35.7 | 62.2 | 114.2 | 127.5 |
| 1993 | 833.5 | 70.6 | 114.4 | 49.8 | 89.5 | 8.2 | 23.1 | 89.5 | 44.7 | 131 | 58.9 | 39.3 | 114.5 |
| 1994 | 795.9 | 123.7 | 56.2 | 109.7 | 103 | 54.2 | 55.3 | 65.3 | 68.5 | 18.3 | 23.2 | 53.5 | 65.0 |
| 1995 | 682.4 | 88.4 | 40.8 | 90.5 | 127.8 | 83.8 | 54.7 | 11.3 | 28.4 | 28.2 | 18.6 | 2 | 107.9 |
| 1996 | 499.8 | 30.9 | 49.8 | 92.9 | 52.5 | 70.6 | 26.4 | 25.8 | 31.4 | 5.9 | 47.2 | 49.2 | 17.2 |
| 1997 | 567.8 | 46.7 | 116.3 | 26.3 | 12.8 | 87.7 | 11.5 | 15.2 | 30.7 | 116.6 | 42.7 | 49.1 | 12.2 |
| 1998 | 774.5 | 53.7 | 82.2 | 61.1 | 69.9 | 8.9 | 63 | 115 | 20.3 | 102.8 | 39.4 | 28.6 | 129.6 |
| 1999 | 801.8 | 115.4 | 81.3 | 68.2 | 111.4 | 23.9 | 37.8 | 48.9 | 19.3 | 83.2 | 23.2 | 118.7 | 70.5 |
| 2000 | 738.5 | 46.5 | 35.6 | 95.9 | 25.4 | 74.6 | 13.1 | 132.5 | 90.4 | 12.7 | 48.5 | 72.6 | 90.7 |
| 2001 | 1101.6 | 166.7 | 138.6 | 107.7 | 76.1 | 110.4 | 91.4 | 83.7 | 50.1 | 27.8 | 56.1 | 119.2 | 73.8 |
| 2002 | 724.2 | 115.7 | 49 | 19.5 | 69.4 | 84 | 49.3 | 55.7 | 81 | 29.2 | 93.5 | 52.3 | 25.6 |
| 2003 | 662.9 | 89.3 | 132.9 | 112.6 | 96 | 25.6 | 23.5 | 37.7 | 43.2 | 45.1 | 39.6 | 2.3 | 15.1 |
| 2004 | 784.1 | 37.9 | 137.4 | 90.6 | 90 | 27 | 47.4 | 82.2 | 51.6 | 32.4 | 49.8 | 113.4 | 24.4 |
| 2005 | 670.2 | 126.4 | 73.6 | 40.4 | 33.8 | 36.2 | 43.2 | 65.6 | 44.4 | 44 | 39 | 58.6 | 65.0 |
| 2006 | 667.5 | 88.4 | 53.2 | 51 | 29.2 | 41.4 | 49.5 | 51 | 89 | 15 | 35.6 | 110 | 54.2 |
| 2007 | 942.4 | 105 | 104.4 | 95 | 91.6 | 97.4 | 57.6 | 2.8 | 135.8 | 72.4 | 86.8 | 64.4 | 29.2 |
| 2008 | 875.8 | 57.1 | 80 | 67.1 | 103.2 | 21.9 | 108.5 | 53.5 | 87 | 35.3 | 88.2 | 107.8 | 66.2 |
| 2009 | 681.2 | 74.3 | 91.1 | 42 | 70.4 | 73.9 | 37.3 | 46.7 | 24.8 | 68.1 | 73.3 | 63.4 | 15.9 |
| 2010 | 759.7 | 39.1 | 146.1 | 105.2 | 47.3 | 77.2 | 45.2 | 18.7 | 38.4 | 23.5 | 31.7 | 127.6 | 59.7 |
| 2011 | 602.4 | 84.9 | 54.8 | 35.3 | 84.6 | 56.8 | 10 | 5.2 | 23.6 | 83 | 44.6 | 81.2 | 38.4 |
| 2012 | 872.8 | 25.2 | 36.4 | 82.4 | 58 | 24.7 | 34.7 | 168.6 | 52.6 | 166.5 | 128.4 | 54.9 | 40.4 |
| 2013 | 788.1 | 115.8 | 100.4 | 114.2 | 62.7 | 43.4 | 83.1 | 32.8 | 56 | 24.6 | 47.4 | 57.5 | 50.2 |
| 2014 | 947.5 | 108.8 | 59.5 | 123.1 | 176.2 | 141.9 | 28.2 | 31.5 | 82.8 | 30.5 | 36.9 | 113.3 | 14.8 |
| 2015 | 817.9 | 95.7 | 108.2 | 64 | 81.9 | 54.6 | 26.1 | 31 | 68.4 | 26.7 | 132.6 | 83.2 | 45.5 |
| 2016 | 767.6 | 64.6 | 84 | 81.8 | 92.3 | 46.9 | 84.3 | 62 | 39.4 | 84.8 | 27.1 | 30.1 | 70.3 |
| 2017 | 637.9 | 30.1 | 85.7 | 26.2 | 70.2 | 38.7 | 40.4 | 10.9 | 70.5 | 39.1 | 72.6 | 66.6 | 86.9 |

Note: Source was the e-RA electronic Rothamsted Archive.

## Appendix C

  
Note: The red highlighted strips (fertilization treatments) and sections in the Broadbalk field plan were used for analysis. Strip 2.1: FYM N2 (N3 since 2005); Strip 2.2: FYM; Strip 7: N2 (P) K Mg; Strip 9: N4 (P) K Mg. Section 0: continuous wheat with straw incorporation; Section 1: continuous wheat with straw removal; Sections 2,3,4,5,7: first wheat in rotation; further description of fertilization treatments and sections in Tab.1.

**9**

**7**

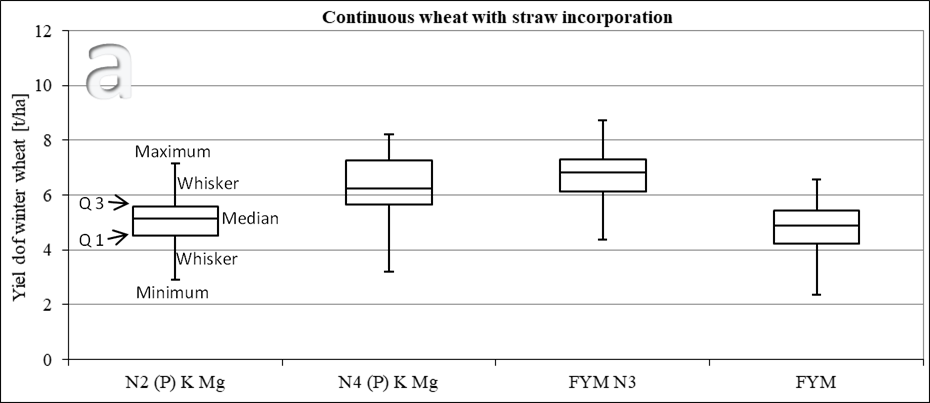
**2.2 2.1**

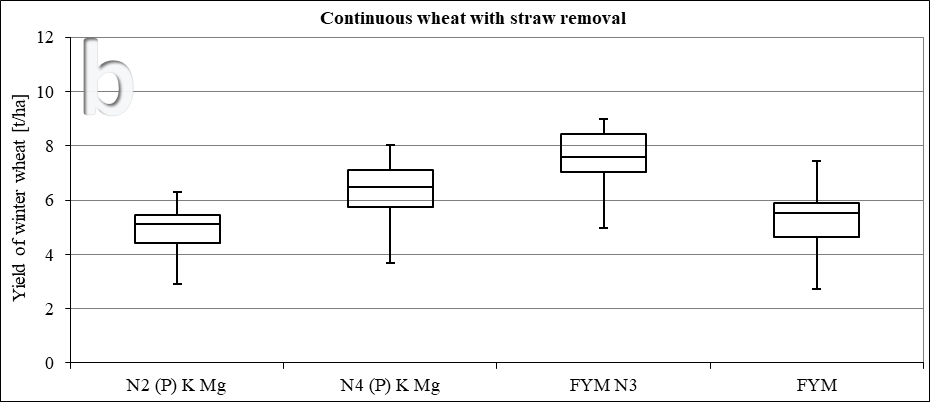
## Appendix D

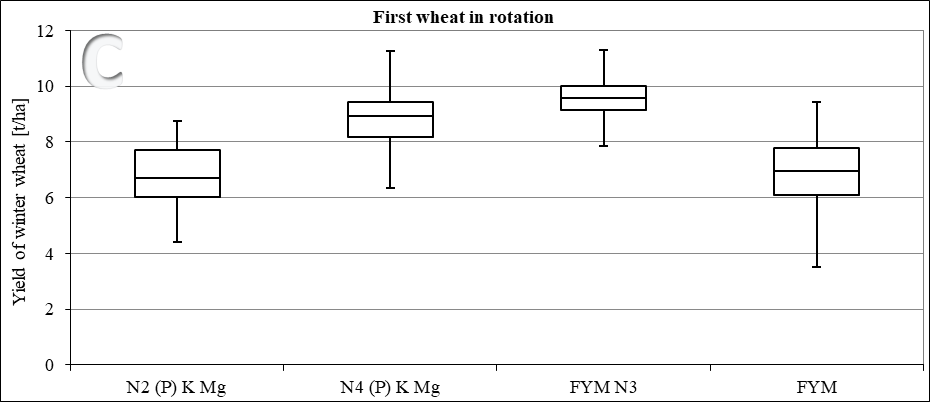
proc glimmix data=a lognote;  
class section treatment year;  
model yield=section|treatment;  
random int/sub=year;  
random year/group=section\*treatment;  
random year/sub=section\*treatment type=ar(1) residual;  
lsmeans section\*treatment;  
run;

Note: Akaike`s Information Criterion (AIC) = 1006.21. Description of sections and fertilization treatments used for the analysis in Tab. 1; Broadbalk field plan in App. D.

## Appendix E







Note: The Box and whisker plots show the minimum, first quartile (Q1), median, third quartile (Q3), whiskers, and maximum, as indicated in the first graph. Description of sections and fertilization treatments in Tab. 1; Broadbalk field plan in App. D.

## Appendix F