The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial

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ABSTRACT

The performance of winter wheat was evaluated under organic (ORG) and conventional (CON) management systems in the Nafferton Factorial Systems Comparison (NFSC) long-term field trial. The present study separates out the crop protection and fertility management components of organic and conventional production systems using two levels each of crop protection (CP) and fertility management (FM). The experimental design provided the four combinations of crop protection and fertility (CON-CP CON-FM, CON-CP ORG-FM, ORG-CP CON-FM and ORG-CP ORG-FM) to evaluate their effects on yield, quality (protein content and hectolitre weight) and disease levels during the period 2004–2008. The conventional management system (CON-CP CON-FM) out-yielded the organic management system (ORG-CP ORG-FM) in all years by an average of 3.1 t ha^{-1}, i.e. 7.9 t ha^{-1} vs. 4.8 t ha^{-1}. Fertility management was the key factor identified limiting both yield and grain protein content in the ORG management system. The CON-FM produced on average a 3% higher protein content than ORG-FM in all years (12.5% vs. 9.7%). However the ORG-CP system produced higher protein levels than CON-CP although it was only in 2008 that this was statistically significant. In contrast to protein content it was ORG-FM which produced a higher hectolitre weight than the CON-FM system (71.6 kg hl^{-1} vs. 71.0 kg hl^{-1}). The clear and significant differences in yield and protein content between the ORG-FM and CON-FM systems suggest a limited supply of available N in the organic fertility management system which is also supported by the significant interaction effect of the preceding crop on protein content. The pRDA showed that although fertilisation had the greatest effect on yield, quality and disease there was also a considerable effect of crop protection and the environment.

1. Introduction

Significant increases in the yield of wheat have been achieved during the last half century by changes in agronomic practice in particular the increased use of synthetic fertilizers and pesticides and the selection of cultivars that are suited to these conditions. For example, much of the advances made with wheat have been achieved by the introduction of dwarfing genes thereby improving the harvest index (Austin, 1999). However during recent years it has become increasingly evident that a yield plateau has been reached for many crops (Olesen et al., 2011). Maintaining and increasing yields in a sustainable way is important as the world population continues to expand, towards 9 billion people by 2050 with competing demands for land being used for energy production.

Conventional farming relies heavily on the application of a range of modern management systems and external inputs to achieve high yields (Hole et al., 2005). A consequence of this has been the increasing levels of resistance to pesticides observed in recent years (Heap, 1997; Jutsum et al., 1998; Moss, 2004) together with increased environmental impacts linked to the intensive use of pesticides and inorganic fertilizers (Tilman et al., 2002). Some pests can now overcome single control measures such as resistance genes or pesticides more rapidly than scientists can develop new pest control solutions for crops including wheat (Dogimont et al., 2010). This increasing pest threat is occurring at a time when key pesticides are being withdrawn and resistance genes are breaking down under intense selection pressure caused by extensive cropping and climate change (Birch et al., 2011). The potential consequences of

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changes in the EU Pesticide Directive (91/414/EEC) are likely to have major impacts on crop production in member states as they will require the withdrawal of around 20% of active ingredients in the near future (Hillocks, 2012) with the result that more food is going to have to be produced with fewer pesticides. For example, in wheat production azole fungicides (which are currently widely used for Septoria and powdery mildew control) may not be available in the future, if registration is withdrawn due to these compounds having endocrine disrupting activity (Chandler, 2008)

Sustaining continuous arable crop productivity for future generations without compromising environmental sustainability is a key challenge for the future. Organic farming seeks to avoid the direct and routine use of synthetic fertilizers, pesticides and growth regulators (Lampkin, 2002; Ammann, 2008) and for this relies upon; crop rotation, cultivation system, sowing date and varietal resistance. Low input and organic farming systems were usually shown to result in lower and more variable yield as a consequence of much longer crop rotations and reduced fertilizer and pesticide inputs (Wolfe et al., 2008). Reduced crop density may also result in lower competitiveness against weeds and higher weed pressure where yields are more dependent on the availability of N mineralised from soil organic matter and manure and other organic matter-based N-inputs e.g. legume crops in the rotation (Doltra et al., 2011). Insufficient nutrient (and especially N) supply in organic farming systems may therefore be primarily due to (a) insufficient organic fertiliser inputs and (b) a mismatch between crop demand and soil mineralisation processes which are dependent on soil microbial activity which in turn is affected by environmental conditions in the soil especially temperature and soil matric potential (Pang and Lettey, 2000). European Union environmental legislation currently limits organic matter inputs to on average 170 kg N ha^{-1} $year^{-1}$ which is insufficient to allow maximum yields of modern short straw wheat varieties (Tétard-Jones et al., 2012).

Between 1950 and 1980, average mineral N fertilizer inputs for winter wheat increased from 50 to 180 kg ha^{-1} but have risen only slowly since then (Jaggard et al., 2010). Adding large quantities of reactive nitrogen fertilisers can have negative environmental impacts since inorganic N, in particular nitrate, can be dispersed into surface and groundwater, leading to eutrophication (Vitousek et al., 1997). In addition, the manufacture of N fertilizers is energy intensive and relies on non-renewable fossil fuels (the production of 1 kg N fertilizer requires 38 MJ of fossil energy) (Refsgaard et al., 1998) and results in significant emissions of greenhouse gases (IPCC 2006). These environmental concerns, coupled with increasing fuel costs and a desire for improved sustainability, have led many farmers to seek alternative N and P management strategies (Peoples and Craswell, 1992). Similarly rock phosphate reserves are a limited resource and there is renewed concern for more sustainable and efficient use of P in agriculture. Restricted availability and/or high costs of P fertilizers in the future pose a threat to maintaining the yields of arable crops but also to global food security (Cordell et al., 2009).

Sustainable arable crop production can be achieved by identifying the key areas of production in terms of nutrient management and crop protection to achieve long-term sustainable yields. The aim of this study was to determine the effect of different production system components, i.e. year, previous crop, rotational position together with crop protection (CP) and fertility management (FM) practices on the yield and quality (protein content and hectolitre weight) of winter wheat grown as part of the Nafferton Factorial Systems Comparison (NFSC) long-term field trial since 2004.

2. Materials and methods

2.1. Site description

The data recorded in this study were taken from the Nafferton Factorial Systems Comparison (NFSC) long-term field trial which is based at Nafferton Farm in northeast England (54:59:09 N; 1:43:56 W). The large field trial (6 ha) was established in 2001 to study the effects of low-input and organic food production systems on crop productivity, sustainability, environmental impacts and food quality. The soil is a uniform sandy clay loam formed in slowly permeable glacial till deposits; *Cambic Stagnogley* (Avery, 1980); *Stagnic Cambisol* (FAO, 1998) with an average soil organic matter content at the start of the experiment of 3.3%. Soil profile information also recorded at the start of the experiment included (60.5% sand, 22.5% silt 17.0% clay, pH of 6.3, $P = 62.9$ mg kg^{-1} C/N = 8.6) Weather data was recorded by an on-site automated station for the duration of the experimental period (Table 1).

2.2. Experimental layout

The trial consists of a series of four experiments established within four replicate blocks and each with a split-split-split-plot design with three factors as described in Eyre et al. (2011b). The main factor is an 8 year crop rotation with the comparison between a conventional cereal intensive rotation and a diverse legume rich crop rotation typical of organic production. Within each main plot (12 m × 96 m) two levels of crop protection are compared i.e. organic (ORG-CP) following UK requirements for certified organic production (Soil Association, 2010) and conventional (CON-CP) which follows the British Farm Assurance Scheme. Each crop protection sub-plot (12 m × 48 m) is further split into two fertility management sub-sub-plots (12 m × 24 m) i.e. organic (ORG-FM; using compost as a fertility amendment) and conventional (CON-FM; using mineral NPK fertilizer as a fertility amendment). This design also allows the experiment to be analysed within each level

Table 1
Mean daily air temperature, radiation and mean monthly rainfall for the Nafferton Factorial System Comparison (NFSC) field trial related to harvest years 2004–2008.

	Mean air temperature (°C)				Mean radiation (MJ m^{-2})				Rainfall (mm)			
	2004	2005	2007	2008	2004	2005	2007	2008	2004	2005	2007	2008
Sep	12.8	13.0	15.0	12.3	8.7	9.0	8.6	8.5	39.2	18.6	71.4	23.2
Oct	7.9	9.1	11.2	9.5	5.2	4.2	4.2	4.9	39.8	94.8	85.4	15.8
Nov	7.1	6.9	7.2	6.9	2.1	2.0	2.3	2.0	30.6	27.2	33.8	48.8
Dec	3.7	4.8	5.2	3.9	1.2	1.3	1.2	1.2	75.6	31.6	65.4	31.6
Jan	4.5	5.4	6.1	5.1	1.5	1.8	1.8	1.5	80.8	40.2	52.2	87.8
Feb	4.3	3.7	4.6	4.4	4.2	3.5	3.3	4.1	30.6	42.4	59.2	10.0
Mar	4.8	6.2	6.1	4.7	6.6	5.5	6.8	7.3	33.2	53.2	22.6	19.6
Apr	8.2	7.3	9.3	6.2	9.6	11.2	12.6	9.9	58.4	91.8	13.4	72.2
May	10.3	9.6	10.0	10.6	15.2	14.9	14.7	14.3	20.2	28.2	50.6	8.4
Jun	13.7	13.7	12.9	12.6	15.1	14.9	11.4	14.4	86.0	55.0	117.7	57.2
Jul	13.9	14.6	13.9	14.8	13.8	13.6	14.7	13.0	88.2	69.8	69.2	103.8
Aug	15.2	14.5	14.0	14.8	10.1	12.6	12.4	10.0	148.8	25.6	35.8	115.4

Table 2
Crop rotation sequence and previous cropping for the NFSC field trial from 2004 to 2008.

Expt.	Rotation	2002	2003	2004	2005	2006	2007	2008
1	**ORG**	G/C	Wheat	Potato	Beans	Potato	S. barley	G/C
	CON	G/C	Wheat	**Wheat**	W. barley	Potato	**Wheat**	W. barley
2	**ORG**	G/C	G/C	**Wheat**	Potato	Beans	Potato	S. barley
	CON	G/C	G/C	**Wheat**	**Wheat**	W. barley	Potato	**Wheat**
3	**ORG**	G/C	G/C	Potato	G/C	G/C	**Wheat**	Potato
	CON	G/C	G/C	Potato	Grass	Grass	**Wheat**	**Wheat**
4	**ORG**	G/C	Potato	S. barley	G/C	G/C	G/C	**Wheat**
	CON	G/C	Potato	**Wheat**	W. barley	G/C	G/C	**Wheat**

Crop data used as part of this study is highlighted in bold. G/C is grass/clover.

of crop rotation, as four separate production systems: fully organic (ORG), organic crop protection with conventional fertility management (ORG-CP CON-FM), conventional crop protection with organic fertility management (CON-CP ORG-FM), and fully conventional (CON). The trial was established in 2001 with a grass/clover (G/C) ley to allow uniformity and allow baseline measurements to be made for each system. Instead of starting all crops in all rotations in the first year a staggered start was used so that each phase of the rotation was replicated in time (Table 2). Findings from the Nafferton Factorial Systems Comparison (NFSC) trial relating to metal contents in wheat (Cooper et al., 2011a), life-cycle analysis (Cooper et al., 2011b), ground beetle species distribution (Eyre et al., 2011a) and weed cover (Eyre et al., 2011b) have been published previously.

2.3. Agronomic management

Winter wheat (*Triticum aestivum*) variety Malacca was grown in all harvest years with the exception of 2006 when no wheat was grown. Malacca has good milling qualities and is aimed at the breadmaking market and was introduced commercially to the UK in 1999. In 2005 wheat was only grown in the conventional rotation after a first crop of wheat and therefore no analysis of the effect of preceding crop was possible (Table 2). Wheat was grown as a 2nd wheat crop in 2004, 2005 and 2008, following grass/clover in 2004, 2007 and 2008, grass in 2007 and following potato in 2004, 2007 and 2008.

Full details of the agronomic management and crop protection practices used for wheat crops in all seasons are shown in Table 3. All wheat crops were drilled within a 3 week period from the end of September to early October at a seed rate of 400 seeds m^{-2}. Seed used in organic crop protection sub-plots was produced to organic seed production standards (Soil Association, 2010) with no seed pesticide dressings while seed for conventional crop protection sub-plots had commercial insecticide and fungicide seed coatings.

Weed control was carried out mechanically in the legume rich rotation (ORG) and ORG-CP CON-FM sub-plots using an Einbock (Model A-4751) tine weeder with a minimum number of 2 passes per season and by means of conventional herbicides in the CON-CP ORG-FM and CON systems (Table 3). In the CON-CP ORG-FM and CON systems fungicides and plant growth regulators were used according to commercial practice at the first timing T1 (GS31–33), second timing T2 (GS37-41) and third timing T3 (GS59-62) of crop growth (Zadoks et al., 1974).

No fertiliser N inputs were included in the organic rotation, i.e. ORG-FM. Conventional fertiliser application (CON-FM) was 180 kg N ha^{-1} to first wheat crops (50 kg N ha^{-1} in mid-March and 130 kg N ha^{-1} in mid-April) and 210 kg N ha^{-1} to second wheat's (80 kg N ha^{-1} in mid-March and 130 kg N ha^{-1} in mid-April) applied as ammonium nitrate (34.5%N). Phosphorous and potassium were applied to CON-FM sub-plots as superphosphate and potassium chloride (equivalent to 64 kg P_2O_5 ha^{-1} and 96 kg K_2O ha^{-1}; 0.20.30 Carrs Fertiliser Co., U.K.).

Wheat straw was baled and removed following harvest in each year. Grass and grass/clover crops were cut and removed 3 times during each growing season. Potato crops were cut prior to harvest and then residues incorporated into the soil.

2.4. Plant sampling and analysis

Foliar diseases *Septoria tritici* and powdery mildew (*Erysiphe gramminis* f. sp. *tritici*) were monitored on the top two leaves L1 (flag leaf) and L2 (leaf 2) on two dates in 2004 (GS61 and GS71) and four dates in 2005 (beginning at GS55), 2007 (beginning at GS47) and 2008 (beginning at GS45) through to maturity. Measurements were collated and the resultant Area Under the Disease Progress Curve (AUDPC), i.e. severity x days was used as a single quantitative measure in assessing the relationship between disease and yield (Jeger, 2004).

Indirect measurements of leaf chlorophyll concentration were taken with a SPAD hand-held chlorophyll metre (SPAD 502 Plus) at GS60 (just prior to anthesis) in 2005, 2007 and 2008.

Crops were harvested using a plot combine (Claas Dominator 38; Class UK Ltd, Bury St Edmunds UK). Prior to harvest samples of 4×0.5 m rows were removed from each plot for determination of total biomass, harvest index (HI) and yield components. Thousand grain weight (TGW) was determined on triplicate samples of 1000 grains using an electronic seed counter. Grain number was calculated as the ratio between grain yield and average grain weight. Harvest index was calculated as the ratio between grain yield and above-ground biomass, expressed as a percentage. A sample of grain (about 500 g) was taken off the combine at harvest for determination of grain moisture content and for subsequent determination of grain quality parameters. Grain N concentration was determined by a LECO TruSpec C/N Analyzer (Leco Corp., St Joseph, MI, USA) and multiplied by 5.83 to obtain grain protein concentration. Hectolitre weight was determined using a Farm-Tec chrondometer calibrated to British Standard BS EN ISO 7971-2:2029 (Farm-Tec, Whitby, U.K.).

2.5. Statistical analysis

Analyses of variance were derived from linear mixed-effects models (Pinheiro and Bates, 2000). Fixed effects were season, previous crop, crop protection and fertility management, with block, season, previous crop and crop protection random effects, given the nested structure of the trial (Crawley, 2007), applied where necessary. The effects of the fixed factors on yield, yield components, HI, protein, hectolitre weight, chlorophyll content and disease levels (*S. tritici* and powdery mildew) were determined. The analyses were carried out in the R statistical environment (R Development Core Team, 2012) and residual normality was assessed using the qqnorm function in R. Where necessary, data was cube root transformed to achieve normality. The combined data for season were analysed first, and where interaction terms were significant, further analyses were conducted at each level of the interacting factor.

Table 3
Crop management details for winter wheat grown in the NFSC long-term field trial 2004–2008. Active ingredients for each product are shown in brackets.

	2004	2005	2007	2008
Previous crops	G/C, wheat, potato	Wheat	G/C, grass, potato	G/C, wheat, potato
Sowing date	7 October 2003	14 October 2004	4 October 2006	26 September 2007
Harvest date	30 August 2004	23 August 2005	24 August 2007	29 August 2008
Herbicides				
Applied in autumn (Oct–Nov)		Optica (phenoxycarboxylic acid): 1 l ha^{-1}	IPU (isoproturon): 2.5 l ha^{-1}	IPU (isoproturon): 2.5 l ha^{-1}
			Optica (phenoxycarboxylic acid): 0.5 l ha^{-1}	Optica (phenoxycarboxylic acid): 1 l ha^{-1}
		Protugan (isoproturon): 3 l ha^{-1}	Stomp (pendimethalin): 2.5 l ha^{-1}	
		PDM 33 EC (pendimethalin): 1.5 l ha^{-1}		Stomp (pendimethalin): 2.5 l ha^{-1}
Applied in winter (Dec–Feb)	Claydon (ND): 1 l ha^{-1}	Optica (phenoxycarboxylic acid): 1 l ha^{-1}		
	Protugan (isoproturon): 2 l ha^{-1}	PDM 33 EC (pendimethalin): 4 l ha^{-1}		
Applied in spring/summer (Mar–Jun)	Cleancrop (propaquizafop): 0.5 l ha^{-1}	Cleancrop (propaquizafop): 0.5 l ha^{-1}	Cleancrop (propaquizafop): 0.5 l ha^{-1}	Fluroxy 200 (fluroxpyr): 1 l ha^{-1}
			Fluroxy 200 (fluroxpyr): 1 l ha^{-1}	
Fungicides				
T1 applied in Apr		Bravo 500 (chlorothalonil): 1 l ha^{-1}	Bravo 500 (chlorothalonil): 1 l ha^{-1}	
		Corbel (fenpropimorph): 0.2 l ha^{-1}	Justice (proquinazid): 0.125 l ha^{-1}	
			Opus (epoxiconazole): 0.5 l ha^{-1}	
T2 applied in May	Bravo 500 (chlorothalonil): 1 l ha^{-1}	Bravo 500 (chlorothalonil): 0.75 l ha^{-1}		Bravo 500 (chlorothalonil): 1 + 1 l ha^{-1}
	Opus (epoxiconazole): 0.5 l ha^{-1}	Tern (fenpropidin): 0.15 l ha^{-1}		Comet 200 (pyraclostrobin): 0.3 l ha^{-1}
	Tern (fenpropidin): 0.25 l ha^{-1}	Twist (trifloxystrobin): 0.25 l ha^{-1}		Justice (proquinazid): 0.125 l ha^{-1}
				Opus (epoxiconazole): 0.5 + 0.6 l ha^{-1}
T3 applied in Jun			Amistar (azoxystrobin): 0.6 l ha^{-1}	Bravo 500 (chlorothalonil): 1 l ha^{-1}
			Bravo 500 (chlorothalonil): 0.4 l ha^{-1}	Comet 200 (pyraclostrobin): 0.3 l ha^{-1}
			Tern (fenpropidin): 0.25 l ha^{-1}	Opus (epoxiconazole): 0.6 l ha^{-1}
Plant growth regulators				
Applied at T1	Atlas (chloromequat 700): 2.3 l ha^{-1}	Atlas (chloromequat 700): 2.3 l ha^{-1}	Atlas (chloromequat 700): 2.3 l ha^{-1}	Atlas (chloromequat 700): 2.3 l ha^{-1}

Differences between significant main effect and interaction means were determined using Tukey's Honest Significant Difference (HSD) tests, based on mixed-effects models. Years with more than one preceding crop (2004, 2007, 2008) were analysed separately with previous crop, crop protection and fertility management as fixed effects.

The relationship between weather (air temperature, radiation, rainfall), organic and conventional management and previous crops and wheat yield and quality parameters, using data from all four years, was assessed using partial redundancy analysis (pRDA), with trial blocks as covariables. Automatic forward selection of weather and agronomic variables within the pRDA was used to assess their significance using Monte Carlo permutation tests. The pRDA was carried out using the CANOCO package (Ter Braak and Šmilauer, 1998).

3. Results

3.1. Yield

There was a significant effect of growing season on the yield (Table 4a) of winter wheat grown in the long-term trial with 2004 producing the highest yield (6.7 t ha^{-1}) and 2007 the lowest (5.7 t ha^{-1}). Conventional crop protection (CON-CP) and fertility management (CON-FM) resulted in a significant yield increase of 1.8 and 1.3 t ha^{-1} respectively when compared with the main effects of ORG-CP and ORG-FM. In terms of crop protection the increased yield of the CON-CP system was likely due to significantly more ears m^{-2} and heavier TGW when compared with the ORG-CP system. Similarly with respect to fertility management the increased yield of the CON-FM system was attributed to significantly higher ($p < 0.001$) values for all yield components, i.e. ears m^{-2}, grains ear^{-1} and TGW than in the ORG-FM system (Table 4a).

In all years, the yield of the CON-CP was always significantly higher than the corresponding ORG-CP system (Table 5a). The same was true in the fertility management system where CON-FM always outperformed the ORG-FM system except for 2004 where no difference was observed and this was supported by little difference in both ears m^{-2} and grains ear^{-1}. The conventional management system (CON-CP CON-FM) always outperformed the organic management system (ORG-CP ORG-FM) in all years by an average 3.1 t ha^{-1} i.e. 7.9 vs. 4.8 t ha^{-1}. The ORG-CP CON-FM and CON-CP ORG-FM were intermediate between the fully organic and fully conventional systems with average yields of 5.7 and 6.0 t ha^{-1} respectively across all four years.

Table 4a
Main effect (means and *p*-values) of harvest year, crop protection and fertility management on the yield and quality of winter wheat grown in the Nafferton Factorial Systems Comparison (NFSC) field trial (2004–2008). Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

	Yield ($t\ ha^{-1}$)	Ears m^{-2}	Grains ear^{-1}	TGW (g)	Harvest index	Protein (%)	Hectolitre wt. ($kg\ hl^{-1}$)
Year (YR)							
2004	6.7 a	475 a	34.7 b	35.4 a	52.5 a	11.4 a	68.9 b
2005	6.3 ab	464 ab	43.2 a	35.3 a	52.0 a	10.7 b	73.0 a
2007	5.7 b	445 ab	34.2 b	36.8 a	47.9 b	11.6 a	72.8 a
2008	5.9 b	420 b	36.4 b	32.6 b	48.3 b	10.7 b	68.2 b
Crop protection (CP)							
Organic	5.2	419	35.8	33.0	47.1	11.4	69.5
Conventional	7.0	473	36.1	36.5	52.3	10.8	70.8
Fertility management (FM)							
Organic	5.4	402	33.3	37.6	50.3	9.5	71.0
Conventional	6.7	490	38.6	31.9	49.1	12.7	69.2
ANOVA *p-values*							
YR	<0.01	<0.05	<0.01	<0.001	<0.01	<0.01	<0.001
CP	<0.001	<0.001	NS	<0.001	<0.001	<0.001	<0.001
FM	<0.001	<0.001	<0.001	<0.001	<0.05	<0.001	<0.001
YR × CP	<0.01	NS	<0.05	NS	<0.05	<0.001	<0.001
YR × FM	<0.001	<0.001	<0.001	<0.05	NS	<0.001	<0.001
CP × FM	<0.001	NS	NS	<0.001	<0.05	NS	<0.001
YR × CP × FM	NS	NS	NS	<0.01	NS	NS	NS

In common with yield, Harvest Index (HI) was highest in 2004 and lowest in 2007 and was significantly higher under CON-CP compared with the ORG-CP system. With respect to fertility management HI was significantly higher in the ORG-FM than in the CON-FM system when averaged across all years (Table 4a). Within the CON-CP system there was little difference in HI between the ORG-FM and CON-FM with the exception of 2004 when the former had a higher HI at 56.1% vs. 54.3% (Table 5a).

3.2. *Quality*

Grain protein content was highest in 2007 (11.6%) and lowest in both 2005 and 2008 (10.7%) and similar to yield was significantly higher under CON-FM than ORG-FM (Tables 4a and 5a) by more than 3.0% points across all years. The ORG-CP system gave a significantly higher protein content of 0.6% points than the CON-CP system when averaged across all years (Table 4a) but it was only in 2008 that this was significantly different with an increase of 1.1% points (Table 5a).

The reverse was true for hectolitre weight where the ORG-FM system gave a higher weight than the CON-FM system in all years and especially in 2007 and 2008 where this was 2.4 and 2.6 $kg\ hl^{-1}$ higher respectively (Tables 4a and 5a). There was no significant difference between crop protection regimes in 2004 and 2005, but in both 2007 and 2008 CON-CP resulted in a higher hectolitre weight.

Chlorophyll content showed no difference between years or in response to crop protection system (Table 4b) but did show a major difference with respect to fertility management: the CON-FM had much higher SPAD readings than the ORG-FM system. There was also a significant year x FM interaction in chlorophyll content (Table 5b) where the CON-FM system gave much higher values than ORG-FM in both 2007 and 2008 with no difference in 2005.

3.3. *Disease*

Disease infection levels with *S. tritici* and powdery mildew were assessed on both the flag leaf (L1) and leaf 2 (L2) and are presented in Table 4b. *Septoria tritici* infection on both L1 and leaf 2 was much lower in 2008 than in other years but significantly higher ($p < 0.001$) in the ORG-CP than the CON-CP system in all years with the exception of 2005 (Table 5b). There was no difference between

Table 4b
Main effect (means and *p*-values) of harvest year, crop protection and fertility management on the chlorophyll content and disease of winter wheat grown in the Nafferton Factorial Systems Comparison (NFSC) field trial (2004–2008). Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

	Chlorophyll (SPAD units)	*S. tritici* L1	*S. tritici* L2	*P. mildew* L1	*P. mildew* L2
Year (YR)					
2004	ND	215.2 b	551.1 a	5.1 b	50.3 b
2005	44.2	297.4 a	780.2 a	149.4 a	244.8 a
2007	40.2	158.2 b	289.4 b	0.3 b	2.0 c
2008	41.0	60.3 c	133.2 c	0.0 b	0.1 c
Crop protection (CP)					
Organic	41.1	224.7	485.2	19.5	47.8
Conventional	41.1	76.0	211.4	10.6	25.3
Fertility management (FM)					
Organic	36.9	144.4	377.3	0.6	3.6
Conventional	45.3	156.3	320.2	29.5	69.5
ANOVA *p-values*					
YR	NS	<0.001	<0.001	<0.001	<0.001
CP	NS	<0.001	<0.001	<0.001	<0.01
FM	<0.001	NS	<0.001	<0.001	<0.001
YR × CP	NS	<0.001	<0.001	<0.001	<0.001
YR × FM	<0.001	<0.001	<0.001	<0.001	<0.001
CP × FM	NS	<0.001	<0.001	<0.001	<0.01
YR × CP × FM	NS	<0.001	<0.01	<0.001	<0.001

Table 5a
Effect of (and interaction between) crop protection (CP) and fertility management (FM) practices on the yield and quality of winter wheat in the NFSC field trial (2004–2008). Within rows, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

Parameter	Year	Organic CP		Conventional CP		ANOVA *p-values*		
		ORG-FM	CON-FM	ORG-FM	CON-FM	CP	FM	CP × FM
Yield (t ha^{-1})	2004	5.9 b	5.4 b	7.3 a	7.9 a	<0.001	NS	<0.05
	2005	4.5 d	6.6 b	6.0 c	8.1 a	<0.01	<0.001	NS
	2007	4.5 d	5.6 b	5.0 c	7.6 a	<0.001	<0.001	<0.001
	2008	4.4 d	5.2 c	5.8 b	8.1 a	<0.001	<0.001	<0.001
Ears m^{-2}	2004	447 c	454 bc	490 b	509 ab	<0.05	NS	NS
	2005	311 d	526 b	374 c	644 a	<0.05	<0.001	NS
	2007	374 c	476 b	386 c	545 a	<0.05	<0.001	<0.05
	2008	352 c	429 b	414 b	487 a	<0.05	<0.001	NS
Grains ear^{-1}	2004	31.7 c	34.2 b	36.8 a	36.0 ab	<0.01	NS	NS
	2005	40.8 b	45.2 a	40.6 b	46.3 a	NS	<0.05	NS
	2007	30.8 b	40.0 a	28.9 b	37.1 a	NS	<0.001	NS
	2008	34.3 b	38.5 a	32.5 b	40.3 a	NS	<0.001	<0.05
TGW (g)	2004	38.0 b	30.1 d	39.8 a	33.9 c	<0.001	<0.001	NS
	2005	36.7 a	32.3 b	38.2 a	33.8 b	NS	<0.001	NS
	2007	39.4 a	30.1 c	40.2 a	37.4 b	<0.001	<0.001	<0.001
	2008	33.7 b	27.5 c	36.5 a	32.8 b	<0.001	<0.001	<0.05
Harvest index	2004	50.8 b	48.8 b	56.1 a	54.3 a	<0.001	<0.05	NS
	2005	52.8 a	49.8 b	52.9 a	52.4 a	NS	NS	NS
	2007	46.6 c	45.1 c	49.4 ab	50.6 a	<0.01	NS	NS
	2008	46.0 b	43.7 d	51.8 a	51.8 a	<0.001	NS	NS
Protein (%)	2004	10.2 b	13.1 a	9.7 c	12.8 a	<0.05	<0.001	NS
	2005	9.3 b	12.3 a	9.1 b	12.0 a	NS	<0.001	NS
	2007	9.7 c	13.7 a	9.6 c	13.1 b	<0.05	<0.001	NS
	2008	9.6 c	12.9 a	8.7 d	11.5 b	<0.001	<0.001	<0.05
Hectolitre wt. (kg hl^{-1})	2004	69.4 a	68.0 c	68.9 b	68.6 b	NS	<0.01	<0.01
	2005	73.9 a	71.7 b	73.4 a	72.9 ab	NS	NS	NS
	2007	73.8 ab	69.8 c	74.2 a	73.4 b	<0.001	<0.001	<0.001
	2008	69.1 b	64.9 c	69.8 a	68.9 b	<0.001	<0.001	<0.001

ORG-FM and CON-FM in flag leaf AUDPC for *S. tritici* but for L2 ORG-FM AUDPC was significantly higher ($p < 0.001$) than in the CON-FM system. Powdery mildew infection levels were very low in all years except for 2005 and as with *S. tritici* were significantly lower in the CON-CP than the ORG-CP system when averaged across all years. However in individual years for both L1 and L2 significant differences between the ORG and CON crop protection systems were observed in both 2005 and 2007. There was a significant effect of fertility management: the CON-FM had significantly higher AUDPC for powdery mildew than the corresponding ORG-FM system (Tables 4b and 5b). Furthermore fertility management in the CON system always showed significantly higher AUDPC that the corresponding ORG system in all years with the exception of 2008 when powdery mildew disease levels were very low (Table 5b). Disease levels of both *S. tritici* and powdery mildew were greater on L2 than L1 (Table 4b).

Table 5b
Effect of (and interaction between) crop protection (CP) and fertility management (FM) practices on the chlorophyll content and disease of winter wheat in the Nafferton Factorial Systems Comparison (NFSC) field trial (2004–2008). Within rows, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

Parameter	Year	Organic CP		Conventional CP		ANOVA *p-values*		
		ORG-FM	CON-FM	ORG-FM	CON-FM	CP	FM	CP × FM
Chlorophyll (SPAD units)	2005	43.7	44.0	44.2	44.7	NS	NS	NS
	2007	36.0 b	45.1 a	34.7 b	44.8 a	NS	<0.001	NS
	2008	36.4 c	45.1 b	36.4 c	46.3 a	NS	<0.001	NS
S. tritici L1	2004	289.7 a	353.7 a	126.6 b	89.8 b	<0.001	NS	NS
	2005	450.2 a	264.1 b	311.0 b	164.3 c	<0.05	<0.01	NS
	2007	207.3 b	256.9 a	97.4 c	69.9 d	<0.001	NS	<0.001
	2008	55.8 b	170.8 a	7.0 c	4.3 c	<0.001	<0.001	<0.001
S. tritici L2	2004	747.3 b	838.6 a	334.3 c	284.2 c	<0.001	NS	<0.05
	2005	1354.3 a	475.7 c	1064.3 b	225.4 d	<0.05	<0.001	NS
	2007	342.4 a	353.4 a	278.2 b	180.2 c	<0.001	<0.05	<0.01
	2008	172.0 b	327.1 a	18.9 c	13.2 d	<0.001	<0.001	<0.001
P. mildew L1	2004	0.0 b	9.8 a	0.2 b	10.2 a	NS	<0.001	NS
	2005	7.1 c	388.8 a	5.4 c	196.4 b	<0.05	<0.001	<0.05
	2007	0 b	1.2 a	0 b	0 b	<0.05	<0.05	<0.05
	2008	0 b	0.0	0 b	0 b	NS	NS	NS
P. mildew L2	2004	9.5 b	108.0 a	4.0 b	79.6 a	NS	<0.001	NS
	2005	32.2 c	646.3 a	6.0 c	294.8 b	<0.05	<0.001	<0.05
	2007	0 b	6.5 a	0 b	1.4 b	<0.05	<0.001	<0.05
	2008	0 b	0.3 a	0 b	0 b	NS	NS	NS

Table 6
Effect of (and interaction between) previous crop (PC) and fertility management (FM) practices on the yield, quality, chlorophyll content and disease of winter wheat in the Nafferton Factorial Systems Comparison (NFSC) field trial (2004–2008). Within rows, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

Parameter	Grass/clover		Grass		Wheat		Potatoes		ANOVA *p-values*		
	ORG-FM	CON-FM	ORG-FM	CON-FM	ORG-FM	CON-FM	ORG-FM	CON-FM	PC	FM	PC × FM
Yield (t ha^{-1})	5.9 b	6.5 a	4.0 c	6.2 ab	5.4 b	7.1 a	5.2 b	6.8 a	NS	<0.001	<0.01
Ears m^{-2}	429 bc	460 b	358 d	468 b	378 d	526 a	404 cd	502 ab	NS	<0.001	<0.001
Grains ear^{-1}	35.7 b	38.9 a	27.1 c	42.7 a	35.8 b	41.5 a	29.7 c	33.9 b	<0.001	<0.001	<0.001
TGW (g)	37.1 a	31.7 b	39.2 a	33.5 b	37.5 a	31.4 b	37.9 a	32.0 b	NS	<0.001	NS
Harvest Index	51.2	50.8	49.2	48.1	51.5	50.2	48.2	46.1	NS	NS	NS
Protein (%)	10.0 b	12.9 a	9.8 bc	13.2 a	9.3 cd	12.5 a	8.9 d	12.6 a	<0.05	<0.001	<0.05
Hectolitre wt. (kg hl^{-1})	70.6 b	68.0 c	74.2 a	71.0 b	70.7 b	69.5 b	70.7 b	69.9 b	<0.05	<0.001	NS
Chlorophyll (SPAD units)	37.7 c	45.7 a	33.6 d	44.3 a	40.4 b	45.5 a	34.0 d	45.0 a	<0.05	<0.001	<0.001
S. tritici L1	87.8	129.4	169.8	172.8	204.2	167.4	151.5	175.6	NS	NS	NS
S. tritici L2	234.0	277.1	375.0	287.6	622.7	350.4	321.8	356.2	NS	NS	NS
P. mildew L1	0.1 b	4.1 b	0 b	0.2 b	2.1 b	101.2 a	0 b	1.4 b	<0.01	<0.01	<0.001
P. mildew L2	4.4 b	44.1 b	0 b	2.4 b	7.2 b	183.9 a	0.1 b	11.2 b	<0.01	<0.001	<0.001

Analysis of the effect of previous crop (PC) showed clear effects on grain protein %, hectolitre weight, chlorophyll content and powdery mildew disease levels (Table 6). Although grain yield was not affected by PC there was a significant PC × FM interaction which was associated with the very low yield of 4.0 t ha^{-1} in the ORG-FM where grass was the PC and this was reflected in the low number of ears m^{-2}, grains ear^{-1} and chlorophyll content. Significant effects of PC on grain quality were recorded. No effect of PC on protein content was observed when CON-FM was used but with ORG-FM the use of grass/clover leys as pre-crop resulted in significantly higher protein content than wheat and potatoes. There were significant effects of PC and FM on specific weight which was highest in ORG-FM following grass as PC and lowest in the CON-FM system following grass/clover as PC.

3.4. Multivariate analysis

The biplot derived from the pRDA (Fig. 1) shows the relationship between weather, agronomic management and wheat yield and quality parameters. Axis 1 explained 34.2% of the variability and axis 2 a further 11.4%. Organic and conventional fertility management were strongly associated with both axes, with the influence of crop protection limited to axis 2. Winter wheat, along the positive axis 1, was opposite the other three previous crops (grass, potatoes and grass/clover) which had less influence. Rainfall and air temperature had opposite effects along axis 2 to radiation. All disease parameters were strongly related to the positive axis 1 and were especially associated with winter wheat as a previous crop. The yield, grain, ear, protein and harvest index parameters were also along this part of axis 1 but were most strongly associated with CON-FM, and to a lesser extent to CON-CP and rainfall. Thousand grain weight was the only wheat parameter along the negative axis 1, but was only weakly associated with grass and grass/clover previous crops, whilst hectolitre weight showed no allegiance to any weather or agronomic variable. Air temperature (F = 39.82) explained the most additional variance, but conventional fertility management (F = 22.34), winter wheat as a previous crop (F = 16.11), rainfall (F = 8.08), conventional crop protection (F = 7.31) and radiation (F = 7.08) (all p = 0.002) also significantly affected the relationship between the weather, management variables and the wheat parameters

4. Discussion

4.1. Yield differences, seasonal effects and organic versus conventional production systems

No extreme weather conditions were evident during the four experimental years that wheat was grown. However, leading up to harvest both July and August of 2004 and 2008 were very much wetter than average and these conditions coincided with the end of the grain filling period and grain ripening. For the wheat crop harvested in August 2007 the mild September in 2006 would have encouraged establishment and a warm April in 2007 rapid development during the early stages of stem extension. Radiation was particularly low in June of 2007 which could have been a contributory factor to the low yield in that year.

Averaged across the four years of the study the conventional production system produced a wheat yield of 7.9 t ha^{-1} compared with 4.8 t ha^{-1} for the organic production system. This 40% reduction is consistent with many other studies comparing these production systems for wheat where differences have been identified depending on site, year and management systems used (Mader et al., 2002; Mason et al., 2007; Murphy et al., 2007; Przystalski et al., 2008; Annicchiarico et al., 2010; Jones et al., 2010). Jones et al. (2010) compared the productivity of 19 wheat cultivars released from 1934 to 2000, grown on two organic and two non-organic sites in the UK over 3 growing seasons (harvests 2005–2007) and observed a 44% yield reduction under organic conditions. Murphy et al. (2007) examined the performance of 35 wheat genotypes in paired organic and non-organic systems in the USA and observed a 25% reduction in yield in the organic system. This was consistent with the work of Przystalski et al. (2008) who compared the performance of winter wheat in organic and non-organic cropping systems (non-synthetic versus synthetic nitrogen fertilisers) in France, Switzerland and the UK and found that yield was 33% lower when grown under an organic production system. Annicchiarico et al. (2010) examined the performance of 7 wheat genotypes in ten regions of Italy over 2 seasons 2005–2006 and 2006–2007 and showed yield reduction of 28% in the organic production system, i.e. 5.51 t ha^{-1} vs. 7.68 t ha^{-1}. Mason et al. (2007) observed a 0.5 t ha^{-1} reduction in the yield of 27 Canadian spring bread wheat cultivars under an organic management system which was associated with average weed biomass of 134 g m^{-2} under organic management and 1.4 g m^{-2} under conventional management. In the Nafferton long-term trial, Eyre et al. (2011b) have previously reported that weed cover was higher under organic than conventional management but the response varied among species, and was often modified by differences in crop protection and fertility management. Nevertheless, more severe weed competition in crops grown according to organic standards may have been at least partially responsible for yield differences between treatments.

Mader et al. (2007) showed that the yield of wheat was 14% lower in an organic versus conventional production system in a 21 year agrosystem comparison in central Europe and largely attributed this to a 71% reduction in soluble nitrogen input to the organic system. The synchronisation of nitrogen availability with

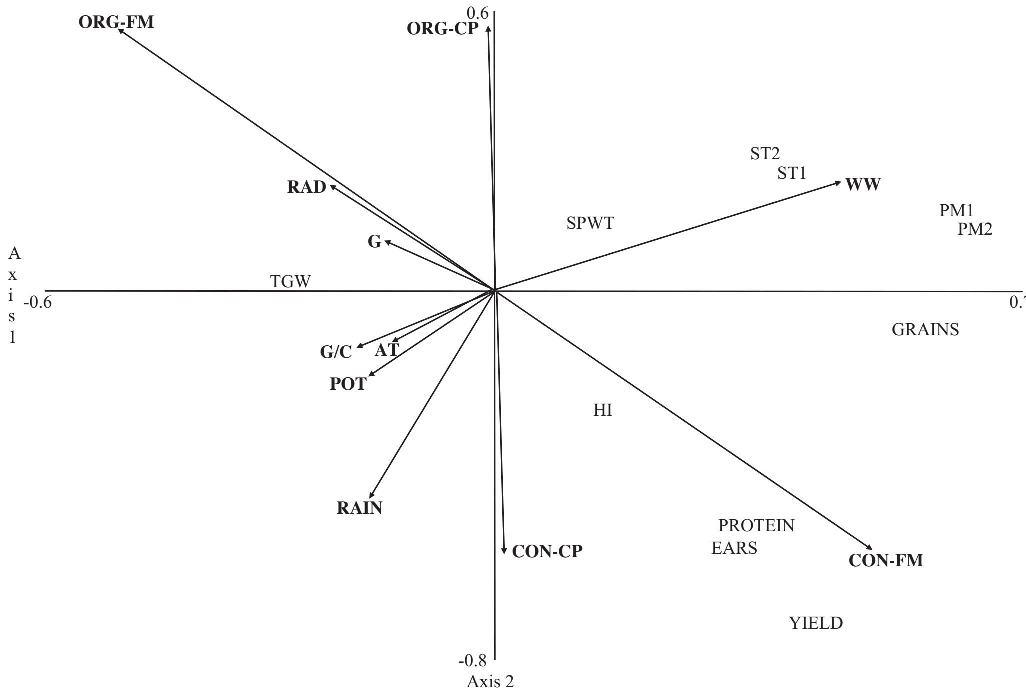

Fig. 1. Biplot showing the relationship between management (ORG-FM, CON-FM, ORG-CP and CON-CP), weather (AT – air temperature, RAD – radiation and RAIN – rainfall), and pre-crop (WW – wheat, G – grass, G/C – grass/clover, POT – potato) on yield, yield components (EARS – ears m^{-2}, GRAINS – grains ear^{-1} and TGW – thousand grain weight), Harvest index (HI) quality (PROTEIN – protein and SPWT – hectolitre weight) and disease levels (ST1, ST2 *Septoria tritici* and PM1, PM2 powdery mildew on leaves 1 and 2 respectively) of wheat grown in the Nafferton Factorial System Comparison long-term field trial 2004–2008.

crop nutrient demand has been shown to be a major challenge in organic production systems. Indeed Mader et al. (2007) identified the importance of the previous crop in the rotation and particularly grass/clover leys which supply substantial amounts of nutrients over a prolonged period following incorporation, thereby minimising reductions in yield and quality. In the present study no fertiliser N inputs were made to the ORG-FM plots grown after grass or grass/clover leys and hence N supply would have been dependent on the breakdown of fertility-building crops used in the rotation. Yield of the ORG-FM system was highest in the first cropping year (2004) at 6.6 t ha^{-1} and was similar to the yield of the CON-FM system, but in subsequent years (2005, 2007 and 2008) differences were large. Clearly yield of the ORG-FM was not limited by N availability in 2004, presumably because of the preceding 3 years of fertility building grass/clover ley in the rotation. The lower yields in wheat crops following wheat or potato pre-crops were probably due to a significantly lower N-availability for organic compared to mineral fertiliser inputs used. This is supported by the lower chlorophyll contents (an indicator of N-supply) found in crops under ORG-FM and previous studies (Jones et al., 2010) which suggested that more modern wheat cultivars (such as Malacca) have a relatively poor ability to take up nitrogen in organic compared to non-organic conditions.

Wheat yields from the two lower-input systems, i.e. ORG-CP CON-FM and CON-CP ORG-FM (which gave an opportunity to separate out the major components differing between the two systems, i.e. crop protection and fertility management) were intermediate between the fully organic and fully conventional systems with average yields of 5.7 and 6.0 t ha^{-1} respectively.

The pRDA showed that although fertilisation had the greatest effect on yield and most other parameters, crop protection, rainfall, temperature and preceding crop also had a considerable effect on yield. It was therefore not just conventional fertiliser making the differences, but a combination of management, weather and previous crop.

4.2. Quality

There is modest information on genotype responses to both conventional and organic production systems for common wheat grain quality traits. Although Mader et al. (2002) found a lower wheat yield in organic when compared to conventional systems, nutritional value and baking quality were unaffected by the farming system. Jones et al. (2010) found a mean protein concentration of 128 mg g^{-1} from conventional production which was higher than the 116 mg kg^{-1} found in an organic production system and also observed low protein concentration in some seasons influenced by weather (in particular wetter and cooler conditions during May–July). Similarly L-Baeckstrom et al. (2004) and Hannell et al. (2004) have shown that protein content in organically grown wheat was 1–2% points lower than that of wheat grown under a conventional management system. From the present study the key to high protein content was CON-FM which gave protein contents that were about 3% points higher than ORG-FM in all years. Interestingly, ORG-CP, i.e. non-use of chemical crop protection inputs resulted in higher protein levels than CON-CP. Higher protein content in wheat from conventional systems using mineral fertilisers was also reported in some previous studies (Mader et al., 2007). In contrast, Shier et al. (1984) found no difference in wholemeal protein content between organic and conventional management systems which was attributed to adequate soil N levels in both systems. In the present study there was a clear and significant difference between the ORG-FM and CON-FM systems effects on protein content even in 2004 when yields from both systems were the same suggesting a limited supply of available N especially later in the season in the organic system when protein content is being determined. This also supported by the significant interaction (PC × FM) with the previous crop used on protein content: under the CON-FM system, the previous crop had no effect but under ORG-FM there was a significantly higher grain protein content with grass/clover than both wheat and potatoes.

Przystalski et al. (2008) found that protein content was significantly lower when wheat was grown under an organic production system and that TGW and hectolitre weight were always smaller in organic conditions. Hectolitre weight affects the productivity and efficiency of flour milling and therefore provides a good indication of grain quality (Halverson and Zeleny, 1988) with a minimum value >76 kg hl^{-1} required for high quality bread making flour in the UK. In this study, whilst ORG-FM produced lower protein content, it produced a higher hectolitre weight than the CON-FM system but in general hectolitre weights were low (about 70 kg hl^{-1}) and well below the UK threshold requirement of 76 kg hl^{-1} for top quality milling wheat. This is likely to be a varietal effect as Mallaca was grown in every year of the study and although it is a good quality milling wheat variety in general it is known to produce grain with a relatively low hectolitre weight (HGCA, 2008). Hectolitre weight was somewhat higher in conventional than organic systems for Canadian Western Hard Spring wheat (Mason et al., 2007) while no differences in protein content were observed. However Murphy et al. (2007) identified differences in hectolitre weight between production systems on 35 advanced soft winter wheat breeding lines grown in the USA depending on year/location. Where yield was higher in conventional than in organic production systems reflecting low levels of N input in the latter, hectolitre weight was also higher. However in situations where there were no differences in yield between production systems in particular associated with the use of fertility-building green manures in the cropping rotation, hectolitre weight in the organic system was equal to or higher than in the conventional system. Annicchiarico et al. (2010) also found higher but non-significant differences in hectolitre weight between conventional (82.3 kg hl^{-1}) and organic (81.2 kg hl^{-1}) production systems. Mason et al. (2007) also observed a modest reduction (1.3%) in hectolitre weight of organic versus conventional production systems. This supports the conclusion from this and other studies (Gooding et al., 1999) that achieving acceptable hectolitre weight is a relatively minor issue in organic wheat production systems compared with producing high yields of grain with high protein content.

4.3. Disease

Septoria tritici disease levels were much lower in 2008 than in other years while powdery mildew was very low in all years except for 2005. The particularly low *S. tritici* level in 2008 is likely to be linked to the particularly low rainfall in May as Shaw and Royale (1993) identified rainfall as the major driver of disease development after the start of stem extension although pRDA showed a strong association with wheat as a previous crop rather than rainfall. Both diseases were significantly higher under ORG-CP than the corresponding CON-CP management system. There was a significant effect of fertility management in that the CON-FM resulted in significantly higher AUDPC for powdery mildew than ORG-FM. In contrast, for *S. tritici* higher disease severity on L2 was found under ORG-FM. This confirms previous studies which compared the effects of organic versus conventional management systems on foliar disease levels in winter wheat and reported that the incidence of powdery mildew increases with N-input levels, while effects of fertilisation on *S. tritici* were generally smaller and more variable (von Tiedemann, 1996; Olesen et al., 2000). Leitch and Jenkins (1995) observed greater severity of *Septoria* diseases in wheat in response to increased N application rates and Ishikawa et al. (2012) suggested that there may be an optimum N concentration in wheat for *S. tritici* to develop. This may have been reflected in the different fertility levels in the CON and ORG production systems in this study. The pRDA showed a strong association between disease levels and winter wheat as the preceding crop suggesting the carry-over of inoculum from one wheat crop to the next was also an important driver for *S. tritici* disease severity. This indicates the risk associated with growing two wheat crops in succession in an organic system (where no effective fungicide treatments are available). Growing two wheat crops in succession is common practice in conventional systems, but there is also usually a yield penalty and a greater requirement for fungicide applications in the second wheat.

5. Conclusions

Averaged over the four years of this study, yield of wheat from the organic production system was 40% lower than that achieved from the conventional system. Yield differences between the management systems were especially large in 2005, 2007 and 2008. Wheat quality was particularly affected by fertility management with protein content for the CON-FM always about 3% points higher than ORG-FM in all years. However, the reverse was true for hectolitre weight where ORG-FM was higher than CON-FM. Nitrogen supply to the organic management system would have been solely dependent on the mineralisation driven N-supply from soil organic matter inputs and clearly limited both grain yield and protein content. This emphasises the role that grass/clover as a preceding crop has to nitrogen supply in an organic production system especially from the decomposition of below ground residues. The use of (a) higher organic fertiliser based N-inputs and (b) the use of organic fertilisers with a greater content of plant available N (e.g. chicken manure pellets and biogas digestate) may increase both yields and protein content. However, the maximum organic fertiliser based N-input permitted under current environmental legislation in any one year is 250 kg N ha^{-1} and average annual inputs over the whole rotation are not permitted to exceed 170 kg N ha^{-1}. The pRDA showed that although fertilisation had the greatest effect on yield, quality and disease there was also a considerable effect of crop protection and the environment. It was not just conventional fertiliser making the differences, but a product of management, weather and previous crops. Future research to improve yields in organic production systems should therefore focus on improving the fertiliser use efficiency from organic fertilisers and fertility building crops via breeding (selection of varieties with higher nitrogen uptake efficiency from organic fertiliser inputs) and agronomic approaches (e.g. use of split dose application of organic fertilisers and/or the use of organic fertilisers with a higher content of readily available forms of N).

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