The influence of organic and conventional fertilisation and crop protection practices, preceding crop, harvest year and weather conditions on yield and quality of potato (*Solanum tuberosum*) in a long-term management trial

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ABSTRACT

The effects of organic versus conventional crop management practices (fertilisation, crop protection) and preceding crop on potato tuber yield (total, marketable, tuber size grade distribution) and quality (proportion of diseased, green and damaged tubers, tuber macro-nutrient concentrations) parameters were investigated over six years (2004–2009) as part of a long-term factorial field trial in North East England. Inter-year variability (the effects of weather and preceding crop) was observed to have a profound effect on yields and quality parameters, and this variability was greater in organic fertility systems. Total and marketable yields were significantly reduced by the use of both organic crop protection and fertility management. However, the yield gap between organic and conventional fertilisation regimes was greater and more variable than that between crop protection practices. This appears to be attributable mainly to lower and less predictable nitrogen supply in organically fertilised crops. Increased incidence of late blight in organic crop protection systems only occurred when conventional fertilisation was applied. In organically fertilised crops yield was significantly higher following grass/red clover leys than winter wheat, but there was no pre-crop effect in conventionally fertilised crops. The results highlight that nitrogen supply from organic fertilisers rather than inefficient pest and disease control may be the major limiting factor for yields in organic potato production systems.

1. Introduction

Evidence suggests that organic arable cropping systems generally produce lower, more variable yields than systems employing synthetic fertilisers and chemical crop protection measures (Smith et al., 2007). Recent reviews by De Ponti et al. (2012) and Seufuret et al. (2012) concluded that organic arable yields average 80% and 75% of conventional production respectively. However, the yield gap varies between crop species, with tuber crops having a greater yield gap than cereals. For example, De Ponti et al. (2012) report that organic tuber crop production averages 70% of conventional in European studies, but with high variability (37–114%). The relatively large, variable yield gap between organic and conventional potato production has been mainly attributed to inadequate control of diseases and pests, particularly of late blight caused by *Phytophthora infestans* (Finckh et al., 2006). Fertilisation regimes have also been reported to contribute to lower yields in organic potato production systems (Van Delden, 2001; Haase et al., 2007). However, results from long-term factorial studies in which the relative effect, and interactions between fertilisation and crop protection practices used in organic and conventional farming systems are compared are not currently available.

The main objectives of the study presented here were to (a) quantify the relative effects of fertilisation regimes (mineral NPK versus composted cattle manure) and crop protection practices (based on standard pesticide, fungicide and herbicide treatments or mechanical weed control and Cu-fungicides only), (b) investigate interactions between fertilisation regimes and crop protection

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Table 1
Growing season weather conditions 2004–2009.

Year	Parameter	April	May	June	July	August	September
2004	Precipitation (mm)	58	20	86	88	149	19
	Mean solar radiation (kW m^{-2})	0.11	0.18	0.18	0.16	0.12	0.10
	Mean Relative humidity (%)	85	84	84	84	79	67
	Mean air temperature (°C)	8.2	10.3	13.7	13.9	15.2	13
	Mean soil temperature (°C at 10 cm)	8.8	12.6	15.6	15.5	16.7	13.8
2005	Precipitation (mm)	92	28	55	70	26	54
	Mean solar radiation (kW m^{-2})	0.13	0.17	0.17	0.16	0.15	0.11
	Mean Relative humidity (%)	81	78	81	81	81	83
	Mean air temperature (°C)	7.3	9.6	13.7	14.6	14.5	13.2
	Mean soil temperature (°C at 10 cm)	8	10.7	14.6	16.2	15.6	14.4
2006	Precipitation (mm)	36	33	79	99	27	37
	Mean solar radiation (kW m^{-2})	0.13	0.19	0.17	0.16	0.13	0.10
	Mean Relative humidity (%)	55.0	61.2	49.5	75.3	74.1	84.4
	Mean air temperature (°C)	8.3	10.6	12.6	14.7	15.1	16.6
	Mean soil temperature (°C at 10 cm)	9.3	12.0	15.0	16.1	15.4	14.1
2007	Precipitation (mm)	13	51	118	69	36	23
	Mean solar radiation (kW m^{-2})	0.15	0.17	0.13	0.17	0.14	0.10
	Mean Relative humidity (%)	77	77	83	80	78	78
	Mean air temperature (°C)	9.3	10.0	12.9	13.9	14	12.3
	Mean soil temperature (°C at 10 cm)	10.5	12.9	14.9	15.7	15.5	13.3
2008	Precipitation (mm)	72	7	57	101	107	158
	Mean solar radiation (kW m^{-2})	0.12	0.17	0.17	0.15	0.12	0.08
	Mean Relative humidity (%)	77	72	71	72	71	67
	Mean air temperature (°C)	6.2	10.7	12.6	14.7	14.7	12.1
	Mean soil temperature (°C at 10 cm)	6.8	12.2	14.6	15.9	15.5	13.1
2009	Precipitation (mm)	36	33	79	99	27	37
	Mean solar radiation (kW m^{-2})	0.13	0.19	0.17	0.16	0.13	0.10
	Mean Relative humidity (%)	55.0	61.2	49.5	75.3	74.1	84.4
	Mean air temperature (°C)	8.3	10.6	12.6	14.7	15.1	16.6
	Mean soil temperature (°C at 10 cm)	9.3	12.0	15.0	16.1	15.4	14.1

regimes and (c) investigate the relative effects of climatic and agronomic drivers on potato yield and quality parameters.

2. Materials and methods

2.1. Site description

The data presented were collected from potato crops grown during the 2004–2009 seasons as part of the Nafferton Factorial Systems Comparison (NFSC) trial at Newcastle University's Nafferton Experimental Farm, Northumberland, UK (54:59:09 N; 1:43:56 W). The soil of the 4 ha trial site is a uniform clay loam formed in slowly permeable glacial till deposits; *Cambic Stagnogley* (Avery, 1980); *Stagnic Cambisol* (FAO, 1998). Weather data recorded by an on-site automated station for the experimental period is presented in Table 1.

2.2. Field trial design

The NFSC trial was established in 2001 and consists of four plots (24 × 96 m) each representing a different stage in the rotation, replicated four times in a randomised block design (Fig. 1). The main plots are split into two sub-plots (12 × 96 m) consisting of 'organic' (rich in legume and horticultural crops as recommended by organic farming principles) or 'conventional' (less diverse, cereal-based) eight year rotations (Figure 1 and Table 2). Each rotation is split into two sub-sub-plots (12 × 48 m) in which crop protection was carried out either to organic (Soil Association) or conventional (Red Tractor Assured) standards. The crop protection treatments are further split into two fertility management sub-sub-sub-plots (12 × 24 m) managed to either organic or conventional farming standards. The arrangement of crop protection and fertiliser treatments is randomised, and 10 m and 5 m uncultivated grass buffer strips are established between crop protection sub-subplots and fertility management sub-sub-subplots respectively (Fig. 1)

2.3. Agronomic management

The trial field was managed conventionally prior to 2000, and initially all plots were cropped with untreated grass/red clover ley until 2003 in compliance with organic conversion standards (Soil Association, 2010). In order to facilitate the presence of a different rotational stage simultaneously in each of the four main plots, first cultivation year was staggered, meaning two of the four plots remained in grass/red clover until 2004.

The same potato variety (*Sante*, which is widely used by both organic and conventional producers in the UK) was cultivated in all treatment plots. *Sante* is a variety exhibiting moderate to high resistance to both foliar and tuber blight (Agrico UK, 2012). Potatoes were grown following winter cereals (wheat or barley) in the conventional rotation, and following winter cereals or field beans in the organic rotation (Table 2). As a result of the staggered rotation described above, potatoes were also grown following a grass/clover ley as pre-crop in the 2004 season (Table 2). Potatoes were sown in late April or early May using a commercial planter in rows that were 75 cm apart with a spacing of 35 cm between seed tubers within the row. Ridging was carried out in late June in all plots to control weeds mechanically and to keep tubers covered with soil to minimise greening.

Whenever potatoes were grown within either rotation, they were always grown adjacent to vegetables i.e. these 12 × 24 m plots were planted with one half (6 × 24 m) with potatoes and the other 6 × 24 m half of the plot with vegetables (cabbages, lettuces, onions, and carrots) on the other 6 × 24 m half of the plot. The location of potato/vegetable plots was reversed the next time that these crops appeared in the rotational sequence, so that potatoes were not grown on the same plot areas at any time from 2002 to 2009.

Conventionally fertilised potatoes received 180 kg N ha^{-1} as ammonium nitrate, plus P_2O_5 and K_2O additions of 135 and 200 kg ha^{-1} in the form of 0:20:30 compound fertiliser in late April or early May. Organically fertilised potatoes received 170 kg N ha^{-1}

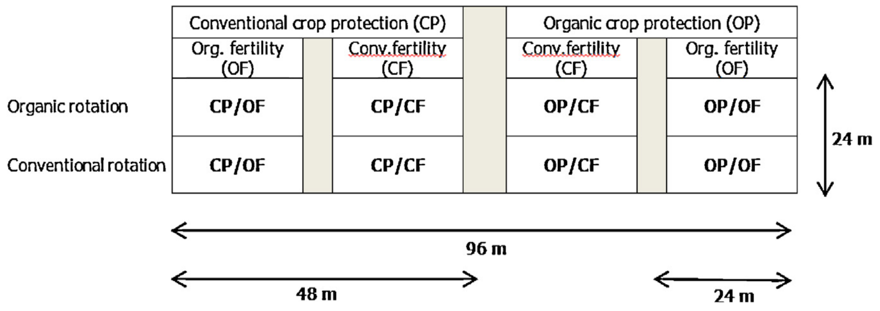

Fig. 1. Trial plot layout.

Table 2
Trial crop rotation sequence 2002–2009.

Plot	Rotation	2002	2003	2004	2005	2006	2007	2008	2009
1	**ORG**	G/C	w. wheat	**potato/veg**	beans	**potato/veg**	s. barley	G/C	G/C
	CON	G/C	w. wheat	w. wheat	w. barley	**potato/veg**	w. wheat	w.barley	G/C
2	**ORG**	G/C	G/C	w. wheat	**potato/veg**	beans	**potato/veg**	s. barley	G/C
	CON	G/C	G/C	w. wheat	w.wheat	w. barley	**potato/veg**	w. wheat	w. barley
3	**ORG**	G/C	G/C	**potato/veg**	G/C	G/C	w.wheat	**potato/veg**	Beans
	CON	G/C	G/C	**potato/veg**	Grass	Grass	w.wheat	w. wheat	w. barley
4	**ORG**	G/C	potato	s. barley	G/C	G/C	G/C	w. wheat	**potato/veg**
	CON	G/C	potato	w. wheat	w. barley	G/C	G/C	w. wheat	w. barley

(G/C = Grass/Clover).
Crop data presented as part of this study in bold.

as composted dairy cattle farm yard manure in late March or early April.

Conventional treatments received 3.35 kg a.i. ha^{-1} aldicarb (Temik®) insecticide as surface-applied granules at planting in late April or early May until 2007, when it was replaced with 5.0 kg a.i. ha^{-1} oxamyl (Vydate) thereafter. Post-planting in early May, 1750 g a.i. ha^{-1} linuron was applied as a residual herbicide. Late blight control treatments used in conventional crop protection plots were two or three 1.2 kg a.i. ha^{-1} applications of metalaxyl-M and mancozeb (Fubol Gold®) and three to five 150 g a.i. ha^{-1} applications of fluazinam (Shirlan®) fungicides from late June at intervals of 10–14 days. Diquat 800 g a.i. ha^{-1} (Reglone®) dessicant was applied to kill haulms prior to harvest (late August to early September). In organically protected crops weed control was achieved via two additional ridging passes performed in late May and early June. Organically protected crops received five applications of copper oxychloride sprays from late June onwards up to a maximum permissible limit of 6 kg ha^{-1} yr^{-1} elemental copper at intervals of 10–14 days. Haulms were removed in late August or early September with a mechanical flail about two weeks before harvest. Irrespective of the crop protection system, the timing of defoliation was dictated by the extent of late blight infection in the foliage, but this was never necessary before late August.

2.4. *Crop assessments*

Foliar diseases were monitored weekly, and following first foliar symptoms of late blight (*Phytophthora infestans*), the percentage affected leaf area was estimated over the whole area of each plot at intervals of 2–3 days until crop defoliation using a standard protocol (James, 1971). Measurements were collated, and the resultant Area Under Disease Progress Curve (AUDPC) was used as a single quantitative measure, where

$$\text{AUDPC} = \sum_{i=1}^{n} \left[\frac{(Y_{i+1} + Y_i)}{2[T_{i+1} + T_i]} \right]$$

In which, Y_i is the foliar blight severity (%) at the *i*th assessment, Ti is the time (days) at the *i*th assessment, n is the total number of assessments. The estimates of AUDPC were normalized by dividing with the total area of the graph (i.e. the number of days from first appearance of the disease till end of the observation period) to provide a *Relative* Area Under Disease Progress Curve (RAUDPC) (Fry, 1978).

Leaf chlorophyll concentration was estimated at 60% (Growth Stage III) and 80% (Growth Stage IV) maturity on a representative sample of 100 plants per plot using a hand-held chlorophyll meter SPAD-502 plus device (Konica Minolta) which measures the leaf greenness as an optical response of a leaf exposed to light which is translated to chlorophyll concentrations and measured in SPAD units (Smeal and Zhang, 1994).

Total tuber fresh weight yield was determined on a 10 m length of one of the two central rows in each plot (there were six rows per plot). A tuber sub-sample of approximately 100 kg was obtained. Tubers were separated into >85, 65–85, 46–65 and <45 mm size fractions by passing the tubers over a set of square-mesh riddles. Unmarketable tubers were those that were mechanically or slug damaged, affected by growth cracks, common scab or tuber blight or were green, and were removed and recorded. Marketable yield was defined as tubers 45–85 mm in size, excluding unmarketable tubers.

A 200 mg sub-sample of undamaged tubers was freeze dried and ground before being subjected to acid digestion (1 mL of 30% H_2O_2 and 5 mL of 65% HNO_3) in a closed-vessel microwave reaction system (MarsExpress; CEM Corp., Matthews, NC, U.S.A.). The 1 h digestion program consisted of the following four steps: step 1, ramp to 180 °C in 15 min; step 2, hold at 180 °C for 10 min; step 3 ramp to 205 °C in 15 min; step 4 hold at 205 °C for 20 min. At the end of the digestion, samples were cooled to room temperature and filtered through Whatman grade 589/3 Blue Ribbon quantitative filter papers. Macronutrients (N, P, K, S, Ca, Mg) in the digestate were analysed with an inductively coupled argon plasma optical emission spectrometer (Vista-Pro Axial; Varian Pty Ltd, Musgrave, Australia).

2.5. *Statistical analyses*

Analyses of variance were derived from linear-mixed effects models (Pinheiro and Bates, 2000). The fixed effects of harvest

Table 3
Treatment main effects on tuber yield and size distribution means (±SE) and ANOVA *P*-values.

Factor	Total tuber yield (fresh weight t ha^{-1})	Marketable tuber yield (fresh weight t ha^{-1})	% weight tubers of different sizes (mm)			
			>85	65–85	45–65	<45
Harvest year						
2004	51.7 ± 1.7	48.1 ± 1.8	0.33 ± 0.14	38.8 ± 2.0	54.0 ± 1.6	3.4 ± 0.4
2005	41.1 ± 1.3	36.9 ± 1.3	1.77 ± 0.53	19.1 ± 2.2	70.6 ± 1.8	7.4 ± 0.7
2006	31.2 ± 1.6	24.9 ± 1.6	0.13 ± 0.09	16.3 ± 1.8	62.1 ± 1.2	15.1 ± 1.1
2007	40.0 ± 1.5	32.7 ± 1.7	0 ± 0	10.8 ± 1.6	69.8 ± 1.0	14.3 ± 1.1
2008	35.6 ± 3.2	28.8 ± 3.4	0.29 ± 0.20	14.5 ± 3.0	62.7 ± 2.3	18.4 ± 3.4
2009	39.2 ± 2.0	31.4 ± 2.0	1.14 ± 0.68	16.6 ± 3.1	63.0 ± 3.5	9.9 ± 1.1
Crop protection (CP)						
Organic	36.6 ± 1.3	30.3 ± 1.4	0.49 ± 0.18	17.0 ± 1.6	63.6 ± 1.1	12.4 ± 1.0
Conventional	43.8 ± 1.3	38.2 ± 1.4	0.43 ± 0.14	23.4 ± 1.7	62.7 ± 1.3	10.1 ± 0.9
Fertility management (FM)						
Organic	34.0 ± 1.1	28.0 ± 1.2	0.19 ± 0.08	13.8 ± 1.4	66.5 ± 1.0	14.6 ± 1.1
Conventional	46.4 ± 1.2	40.6 ± 1.3	0.73 ± 0.21	26.6 ± 1.6	59.8 ± 1.3	7.9 ± 0.6
ANOVA *P*-values						
Year	<0.0001	<0.0001	0.0139	<0.0001	<0.0001	0.0001
Crop protection	<0.0001	<0.0001	0.7667	<0.0001	0.4043	0.0012
Fertility management	<0.0001	<0.0001	0.0126	<0.0001	<0.0001	<0.0001
Year × CP	0.0020	0.0009	0.4132	0.0012	0.0003	0.0031
Year × FM	<0.0001	<0.0001	0.0935	0.1780	0.0018	<0.0001
CP × FM	0.0319	0.0729	0.6241	0.1281	0.0119	0.0594
Year × CP × FM	0.7055	0.7734	0.3888	0.2152	0.2066	0.8729

year, previous crop, crop protection and fertility management on yield (total tonnage and marketable), tuber size distribution, proportion of discarded tubers (green, cracked, blighted, affected with common scab or mechanically or slug-damaged), foliar blight occurrence and tuber macro-nutrient concentrations were assessed. Random effects were trial blocks, previous crop and crop protection management, given the nested structure of the trial, and were applied where appropriate. Differences between individual treatment and significant interaction means were determined using Tukey's HSD test, based on a mixed-effects model. The factorial statistics were carried out in the R statistical environment (R Development Core Team, 2009). Data normality was tested using the qqnorm function in R (Crawley, 2007). Most data was normally distributed but fresh weight, cracked tuber, tuber and foliar blight data was normalised by cube root transformation, as was scabbed and slug damaged tuber data, following the removal of 2004 and 2005 data. 2004 and 2005 data was also removed from leaf chlorophyll measurements at the 60% and 80% growth stages respectively.

Years with more than one preceding crop (2004 grass clover or winter wheat; 2006 and 2007 beans or winter barley; Table 2) were tested separately with pre-crop, crop protection and fertility management as main effects for 2004, and year, pre-crop, crop protection and fertility management as main effects for 2006 and 2007.

The relative effects of weather variables (air and soil temperature, relative humidity, radiation) and agronomic (previous crop, fertility management, crop protection) on tuber yield and quality parameters was assessed using a 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 in the CANOCO package (Ter Braak and Šmilauer, 1998).

3. Results

3.1. Effects of fertilisation and crop protection

3.1.1. Yield

Total and marketable yields were significantly greater with conventional than organic fertility management and with conventional than organic crop protection (Table 3). The cumulative effect of organic fertility and crop protection resulted in yields in a fully organic system (organic crop protection and fertility) that were 56.5% of those in the 'conventional' system over the six recorded seasons of the experiment. The gap in marketable yield between fertilisation regimes was markedly greater than that between crop protection systems (Table 3). There were significant interactions between (a) year and fertilisation regime, and (b) year and crop protection practice. The size of the yield gap between conventional and organic fertility was highly variable, although mean fresh weight and marketable yields were significantly greater with conventional fertility regime in all six study years, attributable to significantly greater average tuber size (Table 3). (Supplementary Table S1). In contrast, significant effects of crop protection on yield were detected in two out of the six seasons (2006 and 2007) only, (Supplementary Table S1). Marketable yield differences between crop protection regimes in 2006 and 2007 were attributable both to larger tuber size and fewer discarded tubers in crops under conventional crop protection.

Different preceding crops are represented simultaneously in the 2004, 2006 and 2007 seasons (Table 2). A significant interaction between previous crop and fertility management system was observed in 2004: while yield of organically fertilised potatoes was significantly (approx. 20%) greater following grass clover than wheat, yield was unaffected by preceding crop in the conventionally fertilised treatments (Supplementary Table S3). However, in 2006 and 2007, there was no significant yield difference between potato crops grown following beans or winter barley in any of the management systems.

3.2. Disease incidence and unmarketable tubers

Foliar blight caused by *P. infestans* was the only major pest or disease detected during the study. Throughout the six year experimental period foliar blight severity was relatively low (Table 4), with the exception of the 2007 season, when a significant interaction between crop protection and fertilisation was detected (Table S2). In 2007 late blight severity was not affected by fertilisation regime when conventional crop protection protocols were used, but under organic crop protection late blight severity was

Table 4
Treatment main effects on foliar observation means (±SE) and ANOVA *P*-values.

Factor	Leaf chlorophyll 60%	Leaf chlorophyll 80%	Foliar blight RAUDPC
Harvest year			
2004	ND[a]	34.7 ± 0.81	0.92 ± 0.41
2005	45.0 ± 0.78	ND[a]	0 ± 0
2006	46.7 ± 1.08	42.2 ± 1.09	0 ± 0
2007	40.1 ± 0.54	35.4 ± 0.71	7.03 ± 2.51
2008	43.4 ± 0.76	35.4 ± 1.45	3.82 ± 2.57
2009	43.2 ± 0.35	40.8 ± 0.74	1.26 ± 0.79
Crop protection (CP)			
Organic	43.3 ± 0.65	37.6 ± 0.71	4.48 ± 1.29
Conventional	43.8 ± 0.61	37.6 ± 0.75	0.18 ± 0.13
Fertility management (FM)			
Organic	40.7 ± 0.47	33.4 ± 0.46	0.60 ± 0.22
Conventional	46.5 ± 0.52	41.8 ± 0.54	4.06 ± 1.29
ANOVA *P*-values			
Year	<0.0001	<0.0001	0.0003
Crop protection	0.2587	0.9557	<0.0001
Fertility management	<0.0001	<0.0001	0.0002
Year × CP	0.1932	0.3150	<0.0001
Year × FM	<0.0001	<0.0001	0.0020
CP × FM	0.6000	0.7582	0.0214
Year × CP × FM	0.5555	0.0297	0.0410

[a] ND: no data, only 2005–2009 (GS 60%) and 2004, 2006–2009 (GS 80%) data were included in analysis.

significantly increased when conventional fertilisation regimes were used. Blight severity in organically protected *and* fertilised crops did not differ from that recorded in conventionally protected crops. Tuber blight-incidence was low in all systems in all years. The only significant treatment effect was observed in 2004 when grass/clover was included as a pre-crop. Tuber blight incidence in the conventionally protected crop following grass/clover was significantly lower than (a) potato crops under organic crop protection with grass/clover or wheat as pre-crop and (b) potato crops under conventionally crop protection following winter wheat (Table 5).

The proportion of damaged tubers was relatively low in all production systems, but significant effects of fertiliser and crop protection regimes were observed. Proportion of green and cracked tubers was significantly greater with both organic crop protection and fertility management (Table 5). The proportion of tubers with scab symptoms was significantly greater in organically fertilised crops, while the proportion of tubers with symptoms of slug damage was significantly greater in crops under organic crop protection (Table 5). The overall proportion of discarded tubers was significantly greater in crops under organic crop protection, while fertilisation had no significant effect on total discards (Table 5).

Significant interactions between year and fertilisation and/or crop protection were detected for a number of tuber yield and quality parameters (Tables 1–5). When results for individual years were examined, differences between fertilisation or crop protection regimes were found to be significant in some but not all years (individual results not shown). There was a significant interaction between crop protection and fertility management across all years for total tuber yield, the proportion of tubers in the 45 to 65 mm size category and foliar blight incidence (Fig. 2). Under conventional crop protection the relative yield differences between organically and conventionally fertilised crops was greater (30%) than in crops under organic crop protection (22%). Under conventional crop protection the organic fertilisation regime resulted in 9.5% more tubers in the 45–65 mm category, compared to 3.8% under organic fertilisation. Under conventional crop protection fertilisation had no effect on foliar blight, while under organic crop protection, foliar blight severity was six times greater in conventionally fertilised crops (Fig. 2).

A significant 3-way interaction between year, crop protection and fertilisation was detected in the proportion of green and cracked/mechanically-damaged tubers. When 2-way ANOVA were carried out for individual years, a higher proportion of green tubers were detected (a) in crops under organic crop protection in 2004, 2006 and 2007 and (b) in conventionally fertilised crops in 2005, 2006 and 2007 (individual results not shown). In 2006 a significant interaction between fertilisation and crop protection was detected, with conventional fertilisation increasing the number of green tubers under organic, but not conventional crop protection (Fig. 2). A higher proportion of cracked and mechanically damaged tubers was detected in crops under organic crop protection

Table 5
Treatment main effects on damaged tuber means (± SE) and ANOVA *P*-values.

Factor	Tuber % by weight					
	Green	Cracked	Blighted	Scabbed	Slug damaged	Discarded[a]
Harvest year						
2004	0.63 ± 0.17	0.68 ± 0.20	0.86 ± 0.15	ND[b]	ND[b]	2.2 ± 0.3
2005	0.53 ± 0.14	0.16 ± 0.07	0.04 ± 0.04	ND[b]	ND[b]	0.7 ± 0.1
2006	3.56 ± 0.50	0.15 ± 0.08	1.11 ± 0.23	0.37 ± 0.11	0.55 ± 0.12	5.7 ± 0.5
2007	1.28 ± 0.23	1.38 ± 0.33	0.53 ± 0.47	0 ± 0	1.45 ± 0.30	4.6 ± 0.5
2008	1.03 ± 0.47	0 ± 0	0.95 ± 0.25	0 ± 0	1.42 ± 0.29	3.4 ± 0.5
2009	2.73 ± 0.40	2.33 ± 1.08	0.89 ± 0.51	0.18 ± 0.11	1.54 ± 0.41	7.7 ± 1.3
Crop protection (CP)						
Organic	2.55 ± 0.29	1.12 ± 0.29	0.98 ± 0.25	0.19 ± 0.07	1.47 ± 0.23	6.3 ± 0.5
Conventional	0.83 ± 0.13	0.41 ± 0.12	0.55 ± 0.10	0.12 ± 0.06	0.85 ± 0.15	2.8 ± 0.2
Fertility management (FM)						
Organic	1.35 ± 0.22	1.30 ± 0.29	0.67 ± 0.12	0.22 ± 0.08	1.01 ± 0.19	4.6 ± 0.5
Conventional	2.03 ± 0.27	0.23 ± 0.09	0.87 ± 0.25	0.09 ± 0.05	1.31 ± 0.21	4.5 ± 0.4
ANOVA *P*-values						
Year	0.0002	0.0013	0.0164	0.0427	0.0668	<0.0001
Crop protection	<0.0001	0.0007	0.1453	0.3731	0.0331	<0.0001
Fertility management	0.0004	<0.0001	0.8597	0.0043	0.2683	0.9701
Year × CP	<0.0001	0.0001	0.2803	0.1138	0.4001	<0.0001
Year × FM	0.0445	<0.0001	0.7176	0.0054	0.9350	0.7297
CP × FM	0.2054	0.0904	0.0402	0.5184	0.8339	0.8689
Year × CP × FM	0.0246	0.0028	0.7779	0.9344	0.1465	0.1396

[a] Also includes mechanically damaged tubers.
[b] ND: no data, only 2006–2009 data were included in analysis.

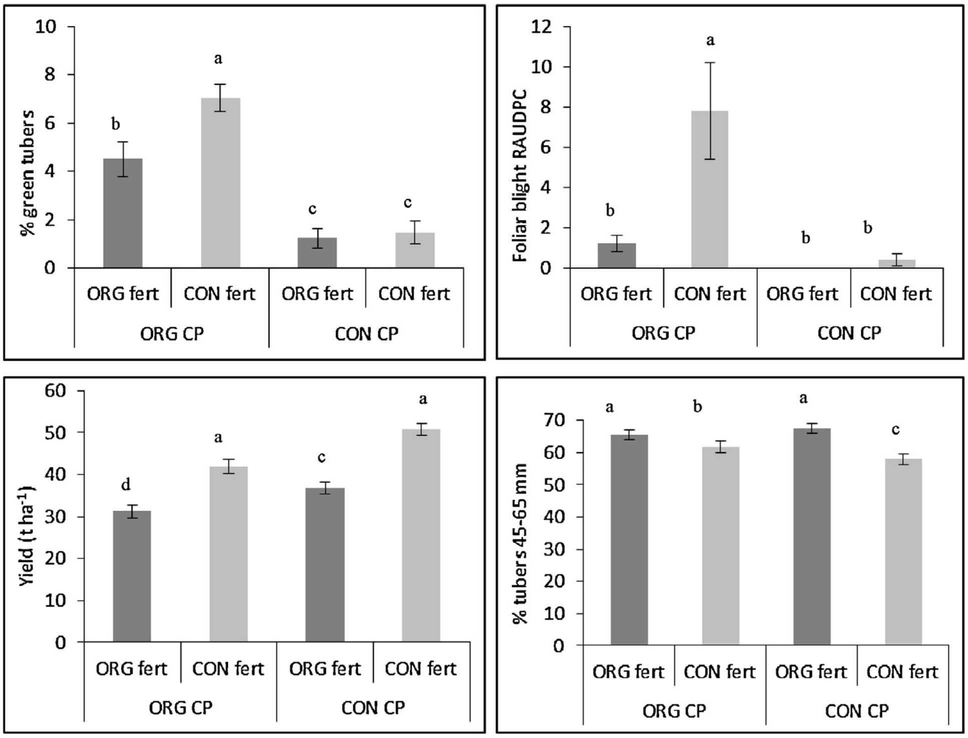

Fig. 2. Crop protection by fertility management interaction plots (green tubers 2006 only). Bars labelled with same letter are not significantly different (Tukey's test $P > 0.05$).

in 2007, and in organically fertilised tubers in 2004, 2007 and 2009 (individual results not shown).

3.3. *Leaf chlorophyll and tuber mineral concentrations*

Leaf chlorophyll and tuber nutrient levels were primarily assessed to provide an indirect measure of the effect of agronomic treatments on macro-nutrient availability/supply to crops. Leaf chlorophyll (SPAD) readings at both 60% and 80% crop maturity were significantly higher for plants under conventional fertilisation (Table 4). SPAD readings decreased between growth stages, and this decline was proportionally greater in organically fertilised plants (Table 4). Significant interactions between year and fertilisation were also detected: when differences between fertilisation regimes were compared in individual years in which SPAD assessments were made (2004, 2006, 2007, 2008 and 2009), while readings were higher in conventionally fertilised plots in all years, the size of the difference varied significantly between years (individual results not shown). A significant 3-way interaction between year, crop protection and fertilisation was detected at growth stage 80%. In 2004 there was no significant effect of crop protection regime when crops were grown under conventional fertilisation, but in organically fertilised crops significantly higher concentrations of chlorophyll were detected in crops under organic crop protection (Table S2). In contrast, in 2007 there was no significant effect of crop protection when crops were grown under organic fertilisation, but in conventionally fertilised crops significantly higher concentrations of chlorophyll were detected in crops under organic crop protection (Table S2).

Both conventional fertilisation and crop protection practices resulted in significantly higher tuber nitrogen concentrations: conventional fertilisation regimes resulted in >40% higher tuber N concentrations than organic fertilisation, while conventional crop protection resulted in a small (<10%) increase in tuber N concentrations (Table 6). Small, but significant increases in tuber sulphur, calcium and magnesium concentrations were also observed in tubers from conventionally fertilised plants (Table 6).

For a number of macronutrient parameters significant interactions between year and fertilisation or crop protection were detected (Table 6). When results for individual years were examined, differences between fertilisation or crop protection regimes were found to be significant in some but not all years (individual results not shown). A significant interaction between crop protection and fertilisation was only detected for S (Table 4). Under organic crop protection no significant effect of fertilisation could be detected, while organic fertilisation resulted in lower S concentrations in tubers when crops were grown under conventional crop protection (Fig. 2). A significant 3-way interaction between year, crop protection and fertilisation was detected for K concentrations in tubers. When separate 2-way ANOVA were carried out for individual years, higher K concentrations were detected in crops under (a) organic fertilisation regime in years 2004, 2005 and 2009 and (b) organic crop protection in 2007 (individual results not shown). A significant interaction between crop protection and fertilisation was detected in 2005 only, with organic fertilisation resulting in higher tuber-K concentrations under organic, but not conventional crop protection (Fig. 2).

3.4. *Effects of weather and agronomic variables*

The biplot derived from the pRDA showing the relationship between weather and agronomic variables with tuber yield and quality parameters is shown in Fig. 3. Axis 1 explained 42.2% of variability and axis 2 a further 13.4%. Fertilisation management was the most important variable, with conventional management along both positive axes. The influence of conventional crop protection, relative humidity and the previous crops of grass/clover and winter wheat were opposite to those of organic crop protection, air and soil temperature, radiation and the previous crops of winter barley and beans. Higher tuber N and leaf chlorophyll concentrations were strongly associated with conventional fertility, as were fresh

Table 6
Treatment main effects on tuber nutrient concentration means ± SE and ANOVA *P*-values.

Factor	N	P	K	S	Ca	Mg
Harvest year						
2004	11.1 ± 0.5	1.61 ± 0.03	17.3 ± 0.2	1.12 ± 0.03	0.29 ± 0.02	0.92 ± 0.02
2005	11.4 ± 0.6	1.46 ± 0.04	14.4 ± 0.5	1.11 ± 0.02	0.20 ± 0.01	0.80 ± 0.03
2006	14.0 ± 0.5	1.57 ± 0.04	14.9 ± 0.2	1.32 ± 0.02	0.33 ± 0.01	0.98 ± 0.02
2007	9.6 ± 0.4	1.97 ± 0.03	11.9 ± 0.2	1.17 ± 0.02	0.37 ± 0.02	1.31 ± 0.03
2008	13.2 ± 0.9	1.92 ± 0.06	13.2 ± 0.2	1.21 ± 0.03	0.45 ± 0.02	0.92 ± 0.04
2009	13.1 ± 0.7	1.82 ± 0.04	13.3 ± 0.4	1.31 ± 0.03	0.37 ± 0.02	0.87 ± 0.04
Crop protection (CP)						
Organic	12.4 ± 0.4	1.73 ± 0.03	14.3 ± 0.3	1.22 ± 0.02	0.35 ± 0.01	1.03 ± 0.03
Conventional	11.4 ± 0.4	1.71 ± 0.03	14.4 ± 0.3	1.20 ± 0.01	0.32 ± 0.01	0.98 ± 0.02
Fertility management (FM)						
Organic	9.8 ± 0.3	1.74 ± 0.03	14.3 ± 0.3	1.19 ± 0.02	0.30 ± 0.01	0.95 ± 0.02
Conventional	14.0 ± 0.3	1.70 ± 0.03	14.3 ± 0.3	1.22 ± 0.01	0.37 ± 0.01	1.05 ± 0.03
ANOVA *P*-values						
Year	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Crop protection	0.0001	0.5514	0.9804	0.2508	0.0351	0.0071
Fertility management	<0.0001	0.0978	0.6679	0.0417	<0.0001	<0.0001
Year × CP	0.0142	0.0364	0.0305	0.0276	0.7885	0.0137
Year × FM	0.0676	0.0011	<0.0001	0.0103	0.0015	0.0001
CP × FM	0.1426	0.5810	0.3208	0.0021	0.0753	0.8189
Year × CP × FM	0.6343	0.8092	0.0068	0.4680	0.4583	0.2169

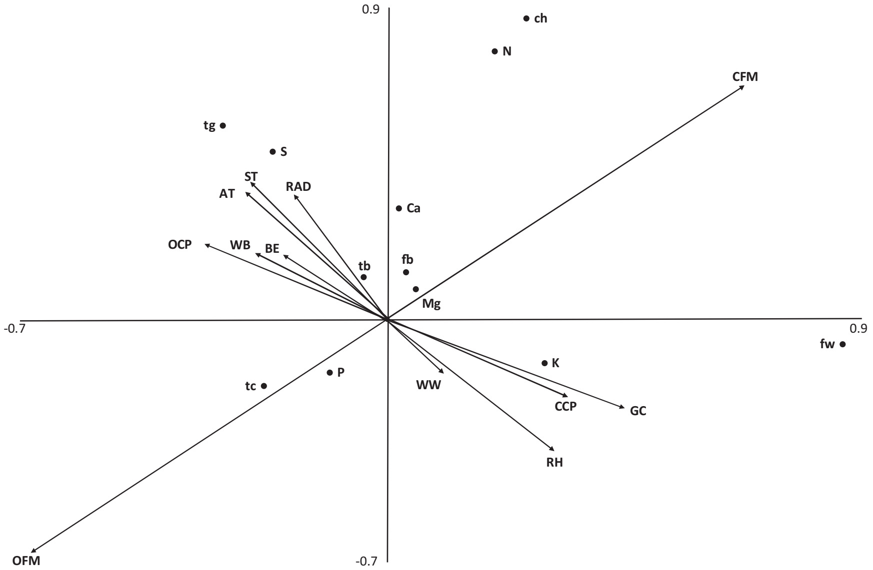

Fig. 3. Biplot showing the relationship between management (OFM organic fertility, CFM conventional fertility, OCP organic crop protection, CCP conventional crop protection), previous crop (GC grass/clover, WW winter wheat, WB winter barley, BE beans) and weather (AT air temperature, ST soil temperature, RAD radiation, RH relative humidity) variables and tuber yield (fw), quality (tf foliar blight, tb tuber blight, tg total green tubers, ch leaf chlorophyll) and mineral parameters (Ca, K, N, P, Mg, S).

weight yield and tuber K, which were also positively influenced by previous grass/clover and, to a lesser extent, conventional crop protection and relative humidity. Higher tuber P and total number of cracked tubers were associated with organic fertility. Air and soil temperature and radiation had the greatest influence on tuber S and the total number of green tubers, especially following winter barley and beans. Tuber Ca was highest with conventional management but there was only a limited effect of the weather and agronomic variables on tuber Mg, foliar blight and tuber blight. Organic fertility management explained the greatest amount of additional variance (F = 48.5), with winter wheat (F = 22.4) and grass/clover (F = 19.9) as previous crops, organic crop protection (F = 18.1), soil (F = 16.3) and air temperature (F = 16.2) and radiation (F = 6.5) (all *P* = 0.002) also having significant effects on tuber yield and quality parameters.

4. Discussion

Previous studies have concluded that the yield gap between organic and conventional potato production systems is mainly caused by greater incidence of pests and diseases in organic production systems. In particular, the exclusion of late blight control fungicides (other than copper-based) has been suggested as a major cause of lower yields and yield instability in organic potato production systems (Struik, 2009; Lammerts van Bueren et al., 2008; Finckh et al., 2006). In contrast, the results from the six year study presented here indicate that the yield gap between organic and conventional production systems is mainly caused by differences in fertilisation regimes. The finding of similar P and K, but 30% lower N concentrations in organically fertilised tubers indicates that limitation in N availability was the main reason for the lower yields in organically fertilised crops. This conclusion is supported by the findings that (a) significantly lower leaf chlorophyll concentrations (SPAD readings), which have previously shown to be positively correlated with N supply for a wide range of crops including potato (Gianquinto et al., 2004) were recorded in organically fertilised crops overall and (b) the greatest yield gaps were recorded in the same years (2006 and 2008) that the greatest difference in leaf chlorophyll concentrations were detected between organically and conventionally fertilised crops (Supplementary Tables S1 and S2).

Previous studies have suggested that the yield gap between organic and conventional crops is positively correlated with the absolute yield of the conventional system (De Ponti et al., 2012), but in this study no relationship between conventional crop yields and the yield gap could be detected (Supplementary Table S1). It is well established that nutrient (particularly N) supply to crops from organic matter inputs is closely related to microbial mineralisation processes in soil, especially for inputs such as composted manure which have a very low content of readily plant available NH_4–N and NO_3–N (Finckh et al., 2006; Haase et al., 2007). The variability in the yield gap between organic and conventional potato crops may therefore have been caused by a greater impact of contrasting climatic conditions on mineralisation-driven N supply from organic fertilisers, as previously suggested by Smith et al. (2007), since mineralisation is known to depend on both soil temperature and moisture (Cassman and Munns, 1980). For example, the lower than average April soil temperatures and extremely dry May in 2008 are likely to have resulted in low N-mineralisation rates in soil, thus explaining the higher than average difference in leaf chlorophyll estimates, tuber N concentration and total tuber yields between organically and conventionally fertilised crops. This conclusion is supported by the results of the RDA analysis, which indicate that leaf chlorophyll, tuber N concentrations and total tuber yield decreased with soil and air temperatures (Figure 3). Weather conditions prior to planting of crops may also have affected nutrient availability and yield in potato crops. For example, precipitation patterns over the winter period affect leaching-losses and thereby nitrogen availability to spring planted potato (Van Delden, 2001). It should be acknowledged however, that organically fertilised potatoes grown under a cool temperate climate as in this study may be more susceptible to restricted nitrogen mineralisation due to low spring temperatures than those in other potato growing areas (e.g. Mediterranean climates). Therefore care should be taken in extrapolating these results to other agro-climatic zones.

A survey of potato production experts by Tamm et al. (2004) also concluded that sub-optimal N supply is a major reason for lower yield in organic compared to conventional potato production in Europe. Potato crops have a relatively low root density and maximum depth (Vos and Groenwold, 1989) and typically recovery of nitrogen fertiliser is lower than for cereal crops. As a result, relatively high applications of mineral nitrogen fertiliser are required to achieve yields close to the genetic yield potential in conventional production systems and permissible annual organic fertiliser applications may be insufficient to achieve yields close to the genetic yield potential of modern main crop potato varieties such as *Sante*. The organic fertiliser input level used in the study (composted cattle manure equivalent to 170 kg N ha^{-1} $year^{-1}$) is the maximum mean annual farm input level of organic fertiliser allowed under the Nitrate Pollution Prevention Regulations (Statutory Instrument No. 2349) for Nitrate Vulnerable Zones in England under the EC Nitrates Directive (91/676/EEC). This is also the annual average limit under UK organic certification standards (Soil Association, 2010).

Although the total amount of nitrogen applied as organic or mineral fertiliser was similar (170 and 180 kg ha^{-1} respectively), previous studies into N-release from manure suggest that the proportion available to the potato crop from the manure compost application was considerably lower than that from mineral fertiliser (Berry et al., 2004; Finckh et al., 2006). For example Berry et al. (2004) reported that a 150 kg N ha^{-1} (25 t) application of composted farm yard manure contains 6 kg ha^{-1} of available nitrogen (NH_4–N and NO_3–N), with a further 12 kg ha^{-1} mineralised over the six months following application. Available N concentrations in the composted cattle manure used in the experiment were very low, resulting in N supply being reliant on N mineralisation processes in the soil. Strategies to increase N supply to organic potato crops could therefore be to increase organic fertiliser inputs to the maximum 250 kg N ha^{-1} permitted under both the legislation (S.I. 2349) and organic farming standards (Soil Association, 2010) in potato production years. This may also be combined with the use of higher available N organic fertilisers such as slurries or chicken manure pellets.

Potato blight is widely considered to be the main crop protection challenge in both conventional and organic potato production (Tamm et al., 2004; Speiser et al., 2006; Hospers-Brands et al., 2008). However, high foliar blight severity was only detected in 2007 in this study, and significant effects of crop protection on yield were only detected in the 2006 and 2007 seasons. In 2007 a high late blight infestation occurred only in mineral fertilised crops under organic crop protection (use of Cu-fungicides only); while in crops managed to organic farming standards (Soil Association, 2010) late blight infestation was not significantly different to conventionally managed crops (mineral fertilised crops receiving standard chemosynthetic herbicide, pesticides and fungicide treatments). This confirms previous studies which showed that high mineral nitrogen fertiliser inputs increase foliar blight severity (Carnegie and Colhoun, 1983; Lambert et al., 2005; Ros et al., 2008). Overall, late blight infestation in the organic system appeared successfully managed by a combination of crop rotation, copper-oxychloride treatment and use of a relatively blight resistant variety (*Sante*). Other recent studies have concluded that the use of chitting/presprouting and especially the use of more blight resistant main crop potato varieties can (a) further reduce foliar blight severity and increase yields or (b) allow Cu-fungicides to be omitted without reductions in yield in organic potato production systems (Speiser et al., 2006; Hospers-Brands et al., 2008). However, the relatively low severity and impact of late blight over the six year experimental period supports the conclusion of Tamm et al. (2004) that the contribution of late blight to yield differential between organic and conventional production may have been overestimated in previous studies. The vast majority of previous studies regarding yield differences between organic and conventional crops did not allow fertilisation and crop protection contributions to yield gaps to be quantified as separate factors. Additionally, N supply was not usually directly measured (e.g. via SPAD meter assessments). As a result yield gaps may often have been wrongly attributed to the effects of late blight.

Late blight was the only major above-ground disease or pest detected in during the six year study. The greatest yield differential between crops under organic and conventional crop protection was detected in 2007, the year with the highest foliar blight severity (Supplementary Tables S1 and S2). However, potatoes are susceptible to a range of soil borne pests and diseases and these (while not measured directly during the study) may have contributed to the difference in marketable yield between organic and conventional crops (Finckh et al., 2006). This is supported by the finding of lower losses due to (a) scab infections under conventional fertilisation regimes and (b) slug damage under conventional crop protection regimes. These results confirm previous studies which showed that scab damage increases when organic fertilisers are applied to potato crops (Huber and Watson, 1970) and that aldicarb and its replacement oxamyl although primarily used to control cyst nematode in potato, possess mulluscide properties common to other carbamate pesticides and therefore reduce slug populations in soils However, undersized or green tubers accounted for a larger proportion (>50%) of non-marketable tubers than diseased/damaged tubers which indicates that insufficient nutrient supply was the main factor responsible for the yield difference between organic and conventional production systems. This conclusion is also supported by the finding that organic fertilisation regimes resulted in lower total and marketable tuber yields in all six years, while crop protection affected yields in only 2 of the six years (Supplementary Table S1). Early season weed competition in organic systems in the absence of residual herbicide application may also be a factor contributing to lower yields in organically protected systems (Thakral et al., 1989; Van Gessel and Renner, 1990). Weed abundance was not directly measured in the trial, although two additional ridging passes were deemed sufficient to control weed competition.

Results reported here indicate that planting potato after a three year grass/clover ley (rather than after wheat) will significantly increase yields of potato crops under organic fertilisation regimes. This confirms results by Káš et al. (2009) who reported higher yield in organically (but also conventionally) fertilised potato following grass/clover leys compared to winter wheat. However, growing potato immediately after long ley periods is known to increase the risk of tuber damage from wireworms and other soil pests which accumulate in soils under grass/clover over time (Keiser et al., 2012).

5. Conclusions

The use of data from a factorial systems trial has enabled an assessment of the relative importance of the crop protection, fertilisation and pre-crop related factors affecting yield and quality of potatoes grown under organic farming systems. The study has demonstrated that inefficient nutrient supply (especially N) from organic fertilisers contributed more than the limited use of chemo-synthetic crop protection products to the lower yield in organic compared to conventional potato production. In particular, it appears that the effects of late blight on yield were lower than previously thought. Results also indicated that climatic drivers may affect yields in organic systems more than in conventional systems (e.g. via their effect of N-mineralisation rates from organic matter in soil), but results from a wider range of years would be required to model the relative yield stability in contrasting potato production systems.

These findings suggest that research focused on (a) identifying improved fertilisation regimes for organic systems (e.g. the use of organic fertilisers with a greater available N-content) and (b) breeding for improved N uptake and utilisation efficiency from organic fertilisers is at least as important as on-going efforts to breed for resistance to late blight (and other diseases and pests) and develop novel crop protection products/approaches for organic potato production systems. Rapidly increasing cost and the limited availability/non-renewable nature of mineral fertilisers are likely to result in an increase in the recycling of organic waste to agricultural land and an overall increase in the use of organic fertilisers, with countries such as China already setting targets for increases in organic fertiliser use. Improving the nutrient use efficiency of organic fertilisers in crops such as potato is therefore an important goal for both organic *and* conventional production systems.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2013.03.004.

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