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Effect of Climate, Crop Protection, and Fertilization on Disease Severity, Growth, and Grain Yield Parameters of Faba Beans (*Vicia faba* L.) in Northern Britain: Results from the Long-Term NFSC Trials

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Abstract: Faba beans are one of the most suitable grain legume crop for colder, maritime climates. However, there is limited information on the effect of changing from conventional to organic production methods and potential impacts of global warming on the health and performance of faba bean crops in Northern Europe. We therefore assessed the performance of faba beans grown with contrasting crop protection (with and without pesticides) and fertilization (with and without P and K fertilizer input) regimes used in organic and conventional production in seven growing seasons. Conventional crop protection and fertilization regimes had no effect on foliar disease severity, but resulted in small, but significant increases in faba bean yields. The overall yield gap between organic and conventional production regimes was relatively small (~10%), but there was substantial variation in yields between growing seasons/years. Redundancy analysis (RDA) showed that climate explanatory variables/drivers explained the largest proportion of the variation in crop performance and identified strong positive associations between (i) temperature and both straw and grain yield and (ii) precipitation and foliar disease severity. However, RDA also identified crop protection and variety as significant explanatory variables for faba bean performance. The relatively small effect of using P and K fertilizers on yields and the lack of a measurable effect of fungicide applications on foliar disease severity indicate that the use of these inputs in conventional faba beans may not be economical. Results also suggest that the yield gap between organic and conventional faba bean production is significant, but smaller than for other field crops.

Keywords: grain legumes; faba beans; organic production; conventional production; P fertilizer; K fertilizer; fungicides; herbicides; climate change; redundancy analysis

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1. Introduction

Grain legumes are important food and feed crops and account for ~15% of the arable cropped area and ~13% of the production of all grain crops (cereals, pulses and oilseeds) globally [1,2]. Grain legumes can account for a substantial proportion of total protein intake in human diets, especially in developing countries, and they are an important component of the Mediterranean diet, which is linked to a range of health benefits including a lower incidence of major chronic and degenerative diseases such as obesity, type-2 diabetes, certain cancers, and cardiovascular diseases [2–4].

In organic farming systems, grain legume crops are of particular importance, because EU-organic farming standards [5] (i) prohibit the use of mineral N-fertilizers, and organic soil management therefore relies on symbiotic N-fixation by legume crops to maintain soil fertility and a balanced supply of N:P:K supply to crops [6] and (ii) require a large proportion of animal feed to be produced on-farm, thus limiting the use of imported concentrate feed crops.

Grain legume crops are also widely recognized to provide important ecosystem services in arable cropping systems, which include (i) the capacity to fix atmospheric nitrogen, (ii) a reduction in the greenhouse gas emissions/carbon footprints of arable rotations, (iii) a reduction in the dependence on mineral fertilizers and (iv) the diversification of arable crop rotations with an associated increases in above- and below-ground biodiversity and reduction in weed, pest, and disease pressure in subsequent crops [2,7–11].

In Europe, grain legumes currently account for less than 2% of arable cropped land, but they are an important high-protein component of the concentrate feed used in European livestock production [2]. As a result, ~70% of high-quality grain legume protein used for animal feed is currently imported, with soybean accounting for nearly 90% of imports [2]. The European Commission is therefore actively supporting an expansion of grain legume production in Europe [2,12]. However, since there are currently no suitable soya varieties for cultivation in colder maritime climates, efforts to increase grain legume production in Northern Europe have focused on spring-sown grain legume crops i.e., Faba bean (*Vicia faba* L.), lupins (*Lupinus albus* L.) and field pea (*Lathyrus oleraceus Lam.*), which were reported to have a similar yield stability to spring cereals [12]. Faba beans are considered to be more suitable for loam, clay loam, loamy clay and clay soils, while lupins and peas are recommended for grain legume production on lighter soils [13]. Fields/soils with no recent legume cultivation in Northern Britain were also recently reported to contain high enough populations of faba bean-specific *Rhizobium* bacteria to facilitate effective colonization and the development of functional nodules on bean roots and up to 400 kg N/ha/annum to be fixed by the faba bean/*Rhizobium* symbiosis [14]

Conventional production protocols for grain legumes recommend the use of (i) mineral P and K (but not N) fertilizer inputs and (ii) pesticides for weed, pest, and disease control, while in organic production fertilizer inputs to legume crops are not recommended and crop protection usually involves mechanical weed control only [15–20]. However, in contrast to other arable crops (e.g., cereals, potato, field vegetables) [21–26], there is limited information on the impact of the contrasting fertilization and crop protection protocols used in conventional and organic production systems on faba bean crop health, yield, protein content, and other performance parameters.

The objectives of the study reported here were therefore to (i) identify/quantify effects of growing season and contrasting crop protection and fertilization regimes used in organic and conventional farming on selected crop health, growth, grain yield, and other performance parameters in faba bean crops by ANOVA, and (ii) to estimate the relative importance of climate (precipitation, radiation, temperature) and agronomic (crop protection, fertilization, variety) explanatory variables/drivers on selected crop health and performance parameters using redundancy analyses (RDA).

This was achieved by assessing the faba bean crops grown in the diverse crop rotation main plots of the Nafferton Factorial Systems Comparison (NFSC) trials [20–22,25] in seven growing seasons.

2. Materials and Methods

2.1. Location and Experimental Design

The results reported were obtained by monitoring the performance of faba bean (*Vicia faba* L.) crops within the long-term Nafferton Factorial Systems Comparison (NFSC) trials, which were located at Newcastle University's Nafferton Experimental Farm, Northumberland, UK (54°5900900 N; 1°4305600 W). The soil in the six hectare field used for the experiments is a uniform sandy clay loam (60.5% sand, 22.5% silt 17.0% clay) formed in a slowly permeable glacial till deposit classified as a Cambic Stagnogley [27] or Stagnic Cambisol [28], which had a mean organic matter content of 3.3%, a P-content of 62.9 mg/kg, a C/N-ratio of 8.6, and a pH of 6.3. at the beginning of the NFSC trials [21].

The experimental design of the NFSC trials has been described In detail previously [20–22,25] and a diagram of the NFSC trials was published by McKenzie et al. [20]. Briefly, the NFSC had four blocks, divided into four sub-blocks for the four replicate experiments. In each of the four experiments, the performance of crops grown in two contrasting crop rotations was compared, specifically a non-diverse, arable crop rotation typical for conventional farming, and diverse crop rotation typical for organic farming systems (see Supplementary Table S1 for details of the crop rotations used). However, in a given year/growing season, the four replicate experiments were at different stages of the same 8-year crop rotation (Supplementary Table S1). Faba bean crops were included only in the diverse crop rotation main plots and results reported here were from crops grown after potato crops in the rotation (Supplementary Table S1).

In the diverse rotation main plots, faba bean performance was compared in two crop protection subplots that either used only mechanical weed control (organic crop protection protocol, OP) or herbicide and fungicide applications (conventional crop protection protocol, CP) (see Figure 1 for the dimensions of the crop protection subplots and Table 1 for details of the crop protection protocols used).

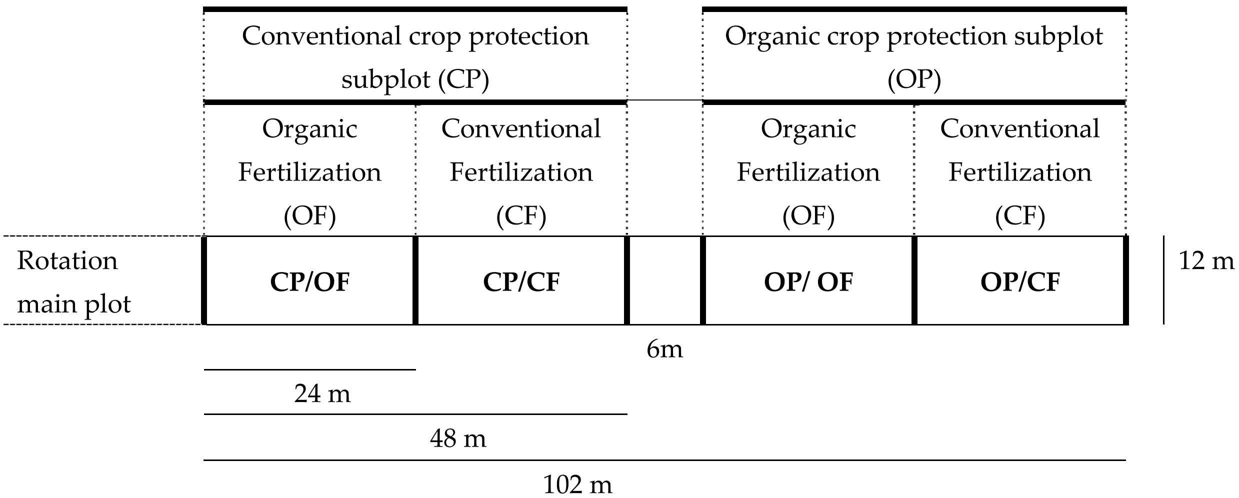


Figure 1. Experimental design for faba bean grown in the Nafferton Factorial Systems Comparison trial (NFSC) in the Organic Rotation.

Table 1. Agronomic protocols used for spring faba bean grown in the NFSC trial 2005 to 2017.

Year	2005	2006	2009	2010	2013	2014	2017
Sowing date	22/04	11/04	27/03	16/04	09/04	11/04	04/04
Seed rate (seeds/m^2)	55	55	60	60	60	60	60
Faba bean variety	Nile	Fuego	Fuego	Fuego	Fuego	Babylon	Babylon
Harvest date	03/10	11/09	01/10	12/10	23/09	30/09	06/10
Organic fertilization (OF)	No input	No input	No input	No input	No input	No input	No input
Conventional fertilization (CF)							
Fertilization date	21/04	10/04	30/03	25/03	9/04	4/04	4/04
Fertilizer rate (kg/ha)	60 P/90 K	60 P/90 K	60 P/90 K	60 P/90 K	40 P/100 K	100 K	60 P/90 K

Table 1. *Cont.*

Year	2005	2006	2009	2010	2013	2014	2017
Organic crop protection (OP)	mwc-only	mwc-only	mwc-only	mwc-only	mwc-only	mwc-only	mwc-only
Conventional crop protection (CP)							
Herbicides applied	25/04	16/04	01/04	30/04	18/04	24/04	13/04
Herbicide	Battalion	Battalion	Pendi-methalin	Pendi-methalin	Pendi-methalin Clomazone	Pendi-methalin	Pendi-methalin
Herbicide rate (L/ha)	2.8	2.8	3.0	3.0	3.0	3.0	3.0
Fungicide applied	30/06	20/06	12/06	22/06	21/06	12/06	12/07 10/08
Fungicide	Bravo 500 [1]	Bravo 500 [1]	Bravo 500 [1]	Bravo [1]	Alto Elite [1]	Alto Elite [1]	Bravo [1]
Fungicide rate (L/ha)	1.5	1.5	1.5	1.5	1.0	1.0	1.5

mwc, mechanical weed control; [1], fungicides with activity against chocolate spot and rust, but not downy mildew.

In each of the two crop protection subplots, faba bean performance was compared in two fertilization sub- subplots that received either no fertilizer input (organic fertilization regime, OF) or mineral P and K fertilizer inputs (conventional fertilization regime, CF) (see Figure 1 for dimensions of the crop protection subplots and Table 1 for details of the fertilization regimes used).

The varieties used in the experiments changed over time to allow comparison with commercial faba bean crops in the same region. Specifically, Nile was used in the 2005 growing season, Fuego in the 2006, 2009, 2010, and 2013 seasons and Babylon in the 2014 and 2017 seasons (Table 1). According to the UK pulse growers and processors research organization (PGRO), the resistance levels against (i) downy mildew were 5, 4, and 8 for Nile, Fuego, and Babylon, respectively, (ii) chocolate spot were 6.5 and 8 for Fuego and Babylon, respectively, and (iii) rust was 4 for Fuego [16]. Information on the resistance level of Nile against chocolate spot and rust and Babylon against rust was not available [16]. Variety was not included as an experimental factor, because the same varieties of faba beans were used by organic and conventional farmers and variety was therefore not a factor that contributed to difference in performance between commercial organic and conventional production in Northern Britain [16].

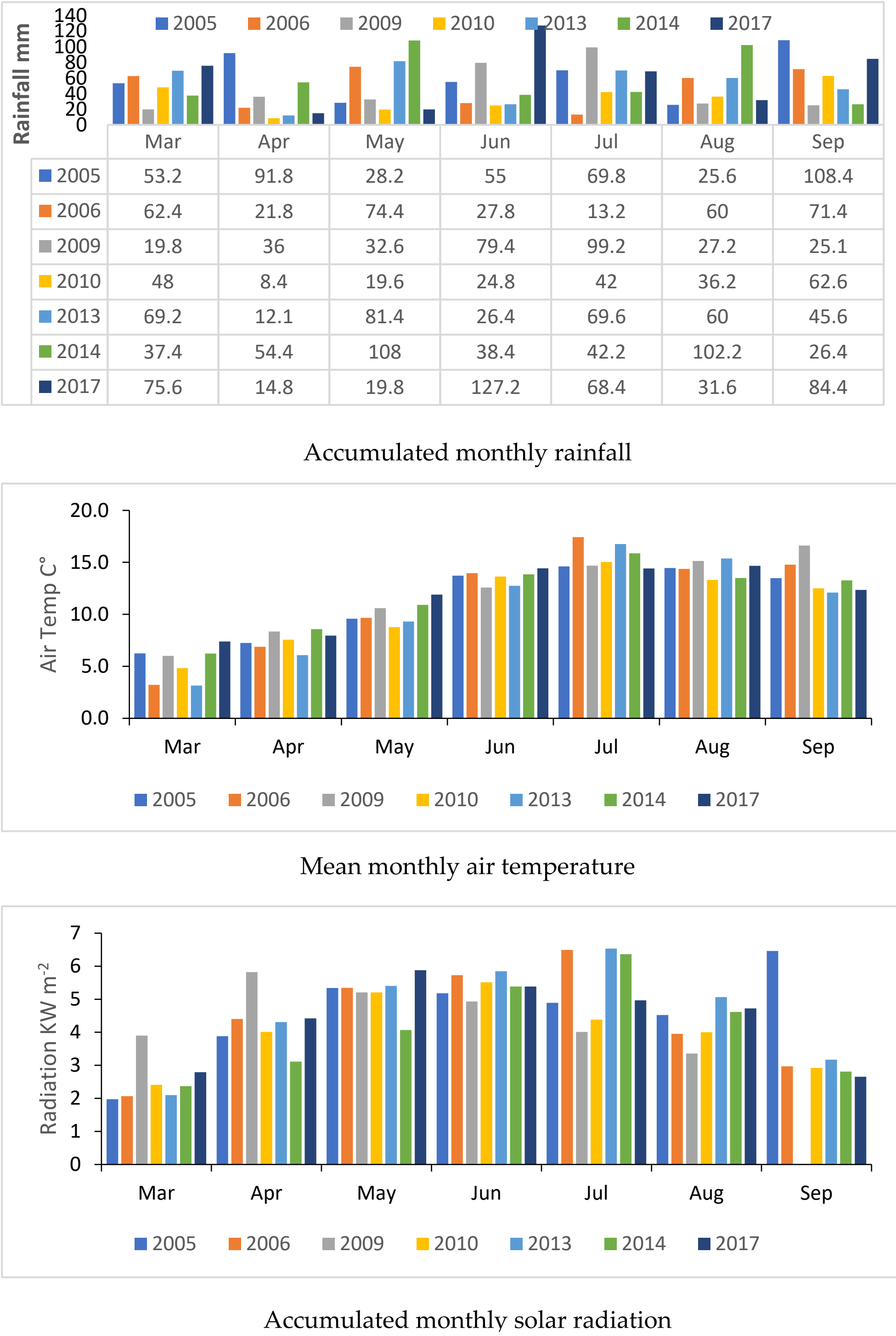
Climatic conditions during each growing season (Figure 2) were recorded by an on-site automated whether station, which was located adjacent to the trial area.

Faba bean seeds were obtained from Finney Lock Seeds Ltd. (The Olde Ale-House Centre, 8 Caistor Rd., Grimsby, DN37 7HY, UK; Lock Seeds Ltd. is now owned by Horizon Seeds, 3 Langton Green, Eye IP23 7LZ, UK; https://www.horizonseeds.com/ (accessed on 22 December 2023)).

2.2. Crop Assessments during the Growing Season

Plant emergence was determined four weeks after sowing and crop growth stages were monitored throughout the season according to the description by Weber and Bleiholder [29,30] and Lancashire et al. [31].

Crops were monitored for symptoms of insect pest damage and foliar disease symptoms in all years. No symptoms of insect pest activity/damage were detected, while symptoms of foliar disease were detected in all seven faba bean growing seasons. However, due to resource limitations, detailed foliar disease assessments were only carried out in four growing seasons/years (2009, 2013, 2014 and 2017). Disease scoring was carried out by assessing the % leaf coverage for chocolate spot (*Botrytis fabae*), downy mildew (*Peronospora vicia*) and rust (*Uromyces faba*). Foliar disease severity was monitored every two weeks from GS65 to GS85 by assessing 20 plants (selected at random) in each plot. For each plant, disease levels were assessed in the upper, middle, and lower third of the plant canopy. The Area Under Disease Progress Curve (AUDPC) was then calculated according to the method described by Fry [32].



	Mar	Apr	May	Jun	Jul	Aug	Sep
2005	53.2	91.8	28.2	55	69.8	25.6	108.4
2006	62.4	21.8	74.4	27.8	13.2	60	71.4
2009	19.8	36	32.6	79.4	99.2	27.2	25.1
2010	48	8.4	19.6	24.8	42	36.2	62.6
2013	69.2	12.1	81.4	26.4	69.6	60	45.6
2014	37.4	54.4	108	38.4	42.2	102.2	26.4
2017	75.6	14.8	19.8	127.2	68.4	31.6	84.4

Figure 2. Accumulated monthly rainfall, mean monthly air temperature, and accumulated monthly solar radiation during the field bean growing seasons 2005, 2006, 2009, 2010, 2013, 2014, 2017 in the Nafferton Factorial System Comparison (NFSC) trials.

At maturity, faba bean samples were removed from an area of 0.25 m^2 in each plot to determine the yield components (number of pods/m^2, seeds per pod, 1000-seed/grain weight, harvest index and seed/grain and straw yield). Seed/Grain samples were oven dried at 70 °C for 48 h, in an air-forced oven. Dry samples were ground to a fine powder using a Retsch ZM200 mill (Retsch GmbH, Haan, Germany) fitted with a 0.5 mm mesh. Ground samples were stored in air-tight vials prior to further analysis. Combine seed yields were determined using a Claas Plot Combine and seed/grain yields were presented at 15% moisture content.

2.3. Determination of Seed/Grain Protein Concentration

All seed material was analyzed for total N by Dumas combustion using an Elementar vario Macro Cube analyzer (Elementar UK Ltd., Stockport, UK). The percentage of protein in faba bean was calculated by multiplying N concentration in the seed by 5.61 as recommended by Kadam et al. [33].

2.4. Statistical Analysis

The effects of year, crop protection, and fertilizer input type on reported parameters were determined using an ANOVA derived from a linear mixed-effect model [34] in R [35]. The hierarchical nature of the split-split-plot design was reflected in the random error structures that were specified as block/year/crop protection. Where analysis at a given level of a factor was carried out, that factor was removed from the random error term. All data were checked for normal distribution of the residuals using QQ-plots. Differences between the four crop management protocols and interaction means were assessed using Tukey's contrast in general linear hypothesis testing (glht) function of the multcomp package in R [35]. Real means and standard errors of means were generated by using the "tapply" function in R.

Redundancy analysis (RDAs) was used to assess the effects of weather and agronomic variables (crop protection, fertilization, and variety) on yield components and disease severity of faba bean. Redundancy analyses (RDA) were carried out using the CANOCO 5 package [36]. Automatic forward selection of the environmental and agronomic factors within the RDAs was used and their significance in explaining additional variance was calculated using Monte Carlo permutation tests.

3. Results

3.1. Crop Health

No insect pest activity/damage was detected in faba beans crops. Disease severity was only recorded in the 2010, 2013, 2014, and 2017 growing seasons/years, and in each season chocolate spot (*Ascochyta fabae*) was the main disease detected on leaves (Table 2). The only other foliar diseases detected were rust (*Uromyces faba*) in the 2013, 2014, and 2017 growing seasons and downy mildew (*Peronospora vicia*) in the 2009 season. However, downy mildew and rust severity were very low compared with chocolate spot (Table 2; Supplementary Table S2). Significant main effects were only detected for year/growing season, with *Ascocyta fabae* severity found to be highest in 2014 and lowest in 2017 (Table 3). It is important to highlight that ANOVA detected significant effects of crop protection and fertilization on grain yield and other crop performance parameters (Tables 2 and 3), but not *Ascocyta fabae* disease severity (Table 2).

Table 2. Effects of year/growing season, crop protection, and fertilization regime on chocolate spot (*Ascochyta fabae*) disease severity (AUDPC) on faba bean leaves in the top, middle, and bottom third of the crop canopy, and plants/m^2, pods/m^2, seeds/pod, grain, and straw yield, seed/grain protein content, thousand grain weight (TGW) and harvest index of faba bean crops at maturity. Data shown are main effect means ± SE.

	Chocolate Spot Severity (AUDPC)			Plants/	Pods/	Grain Yield	Straw Yield	HI
Factor	**Top**	**Middle**	**Bottom**	**m^2**	**m^{-2}**	**(t/ha)**	**(t/ha)**	**%**
Year (variety)								
2009 (Fuego)	60 ± 4 b	100 ± 9 b	50 ± 7 b	49 ± 1 ab	445 ± 17 a	6.3 ± 0.2 a	3.6 ± 0.3 a	61 ± 1 a
2013 (Fuego)	86 ± 23 b	170 ± 19 b	53 ± 14 b	50 ± 2 a	365 ± 17 bc	4.5 ± 0.2 b	2.4 ± 0.1 c	59 ± 1 a
2014 (Babylon)	190 ± 6 a	219 ± 6 a	375 ± 28 a	43 ± 2 b	410 ± 15 ab	5.5 ± 0.3 a	2.6 ± 0.1 bc	60 ± 1 a
2017 (Babylon)	1 ± 1 c	10 ± 2 c	9 ± 2 c	45 ± 3 ab	330 ± 22 c	2.4 ± 0.3 c	3.1 ± 0.3 ab	48 ± 3 b

Table 2. *Cont.*

Factor	Chocolate Spot Severity (AUDPC) Top	Middle	Bottom	Plants/ m^2	Pods/ m^{-2}	Grain Yield (t/ha)	Straw Yield (t/ha)	HI %
Crop protection								
Conventional	106 ± 16	140 ± 15	147 ± 28	47 ± 1	422 ± 12	5.0 ± 0.2	2.9 ± 0.1	58 ± 1
Organic	98 ± 13	157 ± 13	159 ± 27	46 ± 1	352 ± 13	4.6 ± 0.3	2.7 ± 0.1	57 ± 1
Fertilization								
Conventional	102 ± 13	153 ± 15	145 ± 24	48 ± 2	382 ± 13	5.0 ± 0.2	2.8 ± 0.1	57 ± 1
Organic	102 ± 17	143 ± 14	160 ± 30	45 ± 1	392 ± 14	4.5 ± 0.2	2.7 ± 0.1	58 ± 1
ANOVA								
Main effects								
Year (YR)	0.0083	0.0015	<0.0010	T	0.0136	0.0005	0.0285	0.0053
Crop prot. (CP)	NS	NS	NS	NS	0.0053	NS	NS	NS
Fertilization (FT)	NS	NS	NS	NS	NS	0.0022	NS	NS
Interaction								
YR × CP	NS	NS	NS	NS	T	NS	NS	NS
YR × FT	NS	NS	NS	NS	0.0090	0.0003	0.0036	NS
CP × FT	NS	NS	NS	NS	NS	NS	NS	NS
YR × CP × FT	NS	NS	NS	NS	NS	NS	NS	NS

HI, harvest index; Crop prot., crop protection. NS, not significant, T, trend (0.1 > p > 0.05). Within each column, means followed by the same letter are not significantly different (General Linear Hypothesis Test; p < 0.05). NS, not significant (p > 0.05).

Table 3. Effects of year/growing season, crop protection, and fertilization regime on the number of plants/m^2, pods/m^2, seeds/pod, grain, and straw yield, seed/grain protein content, and harvest index of faba bean crops at maturity grown in the Nafferton Factorial Systems Comparison (NEFG) trials between 2005 and 2017. Data shown are main effect means ± SE.

Factor (Variety)	Plants/m^2	Pods/m^{-2}	Seeds per Pod	Grain Yield (t/ha)	Protein Content (%)	Straw Yield (t/ha)	Harvest Index %
Year							
2005 (Nile)	41 ± 1 c	319 ± 12 c	2.2 ± 0.1 d	5.8 ± 0.2 a	25.6 ± 0.1 a	2.6 ± 0.1 bc	60 ± 1 ab
2006 (Fuego)	57 ± 3 a	346 ± 18 b	3.1 ± 0.2 d	2.6 ± 0.2 c	24.7 ± 0.2 b	2.1 ± 0.1 cd	55 ± 1 b
2009 (Fuego)	49 ± 1 abc	445 ± 17 a	9.3 ± 0.4 b	6.3 ± 0.2 a	NA	3.6 ± 0.3 a	61 ± 1 ab
2010 (Fuego)	47 ± 2 abc	373 ± 26 abc	10.1 ± 1.1 a	2.1 ± 0.2 c	19.5 ± 0.3 e	1.7 ± 0.1 d	62 ± 2 a
2013 (Fuego)	50 ± 2 ab	365 ± 17 bc	8.5 ± 0.3 ac	4.5 ± 0.1 b	21.5 ± 0.3 d	2.4 ± 0.1 cd	59 ± 1 ab
2014 (Babylon)	43 ± 2 c	410 ± 15 ab	8.2 ± 0.3 abc	5.5 ± 0.3 a	21.4 ± 0.1 d	2.6 ± 0.1 bcd	60 ± 1 ab
2017 (Babylon)	45 ± 3 bc	330 ± 22 c	7.3 ± 0.5 c	2.4 ± 0.3 c	23.5 ± 0.2 c	3.1 ± 0.3 ab	48 ± 3 c
Crop protection							
Conventional	47 ± 1	401 ± 10	6.6 ± 0.3	4.7 ± 0.2	22.5 ± 0.3	2.7 ± 0.1	58 ± 1
Organic	47 ± 1	345 ± 10	7.8 ± 0.4	4.0 ± 0.2	22.8 ± 0.3	2.4 ± 0.1	58 ± 1
Fertilization							
Conventional	49 ± 1	375 ± 10	7.4 ± 0.4	4.5 ± 0.2	22.6 ± 0.3	2.6 ± 0.1	58 ± 1
Organic	45 ± 1	373 ± 11	7.1 ± 0.4	4.2 ± 0.2	22.7 ± 0.3	2.5 ± 0.1	59 ± 1
ANOVA							
Main effects							
Year (YR)	0.0008	0.0016	<0.0001	<0.0001	<0.0001	0.0008	0.0009
Crop protection (CP)	NS	0.0010	0.0010	0.0021	NS	T	NS
Fertilization (FT)	0.0426	NS	NS	0.0126	NS	NS	T
Interactions							
YR × CP	NS	0.0167	0.0044	T	0.0490	NS	NS
YR × FT	NS	0.0294	0.0276	<0.0001 [1]	NS	0.0130	NS
CP × FT	NS	NS	NS	NS	NS	NS	NS
YR × CP × FT	NS	NS	NS	NS	NS	NS	NS

NA, not available. NS, not significant, T, trend (0.1 > p > 0.05). Within each column, means followed by the same letter are not significantly different (General Linear Hypothesis Test p < 0.05). [1], see Figure 3 for interaction means ± SE.

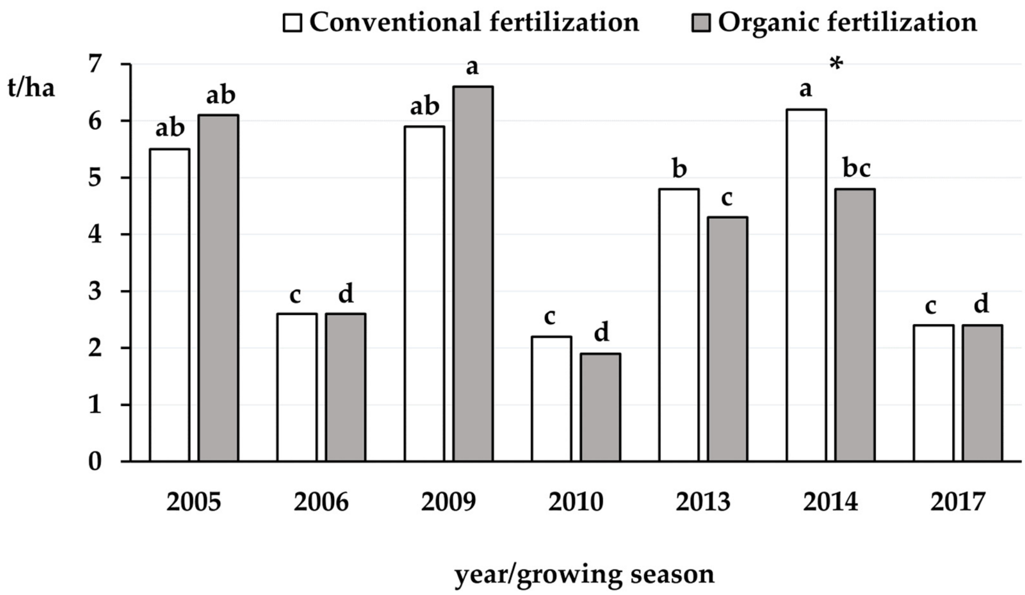


Figure 3. Effect of year/growing season and fertilization regime on faba bean grain yields. Data shown are interaction means. Bars for the same fertilization regime labeled with the same lower-case letter are not significantly different (General Linear Hypothesis Test $p < 0.05$). *, years in which a significant difference between fertilization regimes was detected (General Linear Hypothesis Test $p < 0.05$).

3.2. Crop Performance

Year/growing season (with associated variation in weather conditions) had a significant main effect on crop emergence and all crop performance parameters monitored at harvest (Tables 2 and 3; Supplementary Table S3). The relative impact of different climatic explanatory variables/drivers (soil and air temperature, radiation, precipitation rainfall) was therefore further investigated by redundancy analyses (see Section 3.3 below).

Crop protection had a significant main effect on the number of pods/m^2, seeds/pod and grain yields when data from all seven year were included in the ANOVA (Table 3), which were all ~12% higher with conventional compared with organic crop protection regimes (Table 3). When crop performance data from the four years (2009, 2013, 2014, 2017) in which disease severity was recorded were analyzed separately, the same trends were found, but only the main effect of crop protection on the number of pods/m^2 was significant (Table 2).

Fertilization had a significant main effect on plant density at harvest and grain yield when data from all seven year were included in the ANOVA (Table 3), which were both ~8% higher in crops fertilized with mineral P and K compared with unfertilized crops (Table 3). When crop performance data from the four years in which disease severity was recorded were analyzed separately, the same trends were found, but only the main effect of crop protection on grain yield was significant (Table 2).

Significant year x crop protection and year × fertilization were also detected for some crop performance parameters (Tables 2 and 3; Figure 3; Supplementary Table S3).

When data from all seven year were included in the ANOVA, we detected significant 2-way interactions between year and crop protection for pods/m^2, seeds per pod and grain protein content (Table 3). However, no significant interactions were detected for the same parameters when crop performance data from the four years in which disease severity was recorded were analyzed separately (Table 2).

In contrast, significant interactions between year and fertilization were detected for pods/m^2, grain yield, and straw yield when data from (i) all seven years (Table 3) and (ii) only the four years in which disease severity was recorded (Table 2) were included in the ANOVA.

When these interactions were further investigated, significant differences between crop protection and fertilization regimes were only detected in some, but not all years/growing season. Also, in the years in which significant effects were detected, the trend (higher means with conventional compared with organic crop protection or fertilization) was the same as the main effects detected for crop protection and/or fertilization. Redundancy analyses were carried out to further investigate the relative effect of specific climatic parameters on crop performance (see below). The only exception was the interaction between year and fertilization detected for grain yield (Table 3, Figure 3). When this interaction was further investigated, grain yields were higher with conventional fertilization in 2010, 2013, and 2014, while organic fertilization resulted in higher grain yields in 2005 and 2009 (Figure 3). However, the difference between fertilization regimes was only significant in 2014 (Figure 3).

3.3. Associations between Climatic and Agronomic Drivers, and Faba Bean Health and Performance

Partial redundancy analyses (RDA) were designed to investigate associations between climate (radiation, air and soil temperature, precipitation) and agronomic (crop protection and fertilization regimes used in organic and conventional farming and/or faba bean variety) explanatory variables/drivers and crop health and performance response variables. Four separate partial redundancy analyses (RDA) were carried out, because (i) disease severity was only assessed in four growing seasons (2010, 2013, 2014, and 2017), (ii) different varieties were used in the seven growing seasons, and (iii) some performance parameters (grain protein content and thousand grain weight) were not assessed in the 2009 growing season (Table 4; Supplementary Table S3).

RDA1 was based on data from six years (2005, 2006, 2010, 2013, 2014, 2017) and included (i) all climatic and all agronomic drivers as active explanatory variables, and (ii) all crop performance (but not crop health) parameters as response variables (Table 4).

In RDA1, the explanatory variables accounted for 49.4% of total variation, and precipitation, radiation, crop protection, and variety were identified as significant ($p < 0.01$) explanatory variables for the crop performance parameters assessed. In RDA1, radiation was identified as the strongest climate driver and variety as the strongest agronomic driver for crop performance (Table 4).

Using variety as a passive explanatory variable in RDA2 (Table 4) resulted in (i) the remaining active explanatory variables (climate, crop protection and fertilization) accounting for a substantially lower proportion of the total variation (18.8%) compared with RDA1, and (ii) only precipitation and crop protection being identified as significant drivers (Table 4). Also, precipitation accounted for a larger proportion of the variation in RDA2 (9.6%) than RDA1 (5.3%), while crop protection accounted for a similar proportion of the variation in RDA2 (6.8%) and RDA1 (6.7%) (Table 4).

In the biplot resulting from RDA1 grain and straw yield, and TGW was positively associated with precipitation and temperature and the variety Babylon (along the positive axes 1 and 2) (Figure 4). Grain protein was positively associated with the same drivers (along the positive axis 1) and also positively associated with organic crop protection and the variety Nile (along the positive axis 1 and the negative axis 2) (Figure 4). In contrast, the plants/m^2, pods/m^2, seeds/pod, and harvest index were negatively associated with precipitation and temperature, but positively associated with conventional crop protection and the variety Fuego (along the negative axis 1) (Figure 4).

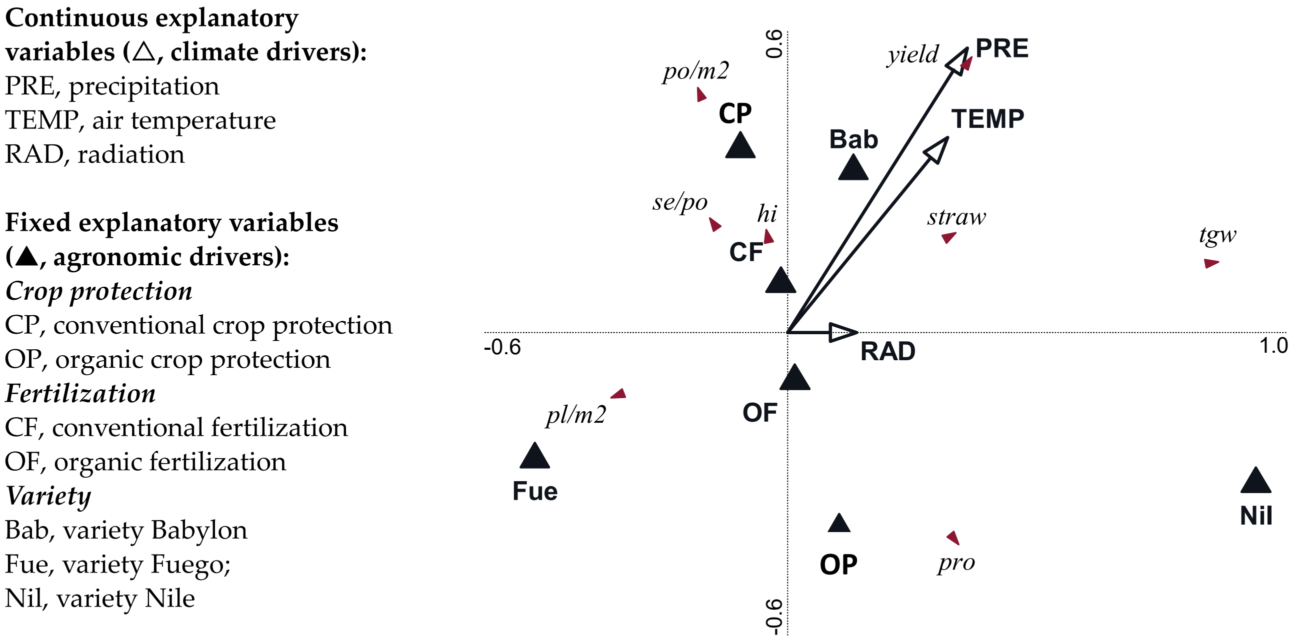


Figure 4. Biplot resulting from RDA1 showing the associations between climate and agronomic explanatory variables/drivers and crop performance response variables. Data included were from six growing seasons/years (2005, 2006, 2010, 2013, 2014, 2017). In the biplot, the horizontal axis 1 explains 33.6% of the variation and the vertical axis 2 a further 15.0%. **Crop performance response variables** (▲): pl/m^2, plants/m^2; po/m^2, pods/m^2; se/po, seed/pod; yield, grain yield; pro, grain protein content; thousand grain weight; hi, harvest index.

Table 4. Proportion of variation explained, *F*-values and *p*-values of explanatory variables of redundancy analyses (RDA) investigating associations between climate and agronomic explanatory variables, and crop health and/or selected crop performance parameters response variables.

Explanatory	% Variation Explained				*F*-Value (*p*-Value)			
Variables/Drivers	**RDA1 [1]**	**RDA2 [2]**	**RDA3 [3]**	**RDA4 [4]**	**RDA1 [1]**	**RDA2 [2]**	**RDA3 [3]**	**RDA4 [4]**
Climate								
Precipitation (PRE)	5.3	9.6	0.5	2.4	10.1 (**)	11.1 (**)	0.5 (^{NS})	3.5 (*)
Radiation (RAD)	10.8	0.8	0.6	8.7	17.1 (**)	1.0 (^{NS})	0.6 (^{NS})	9.0 (**)
Temperature (TEMP)	0.9	1.0	14.8	20.0	1.7 (^{NS})	1.2 (^{NS})	12.6 (**)	26.1 (**)
Total climate	**17.0**	**11.4**	**15.9**	**13.7**				
Crop protection								
Conventional (CP)	6.7	6.8	6.1	14.7	11.7 (^{NC})	8.4 (**)	15 (**)	8.6 (**)
Organic (OP)	6.7	6.8	6.1	14.7	11.7 (**)	8.4 (^{NC})	15 (^{NC})	8.6 (^{NC})
Fertilization								
with PK fertilizer (CF)	0.5	0.5	NC	0.6	0.9 (^{NS})	0.6 (^{NS})	0.6 (^{NS})	NC (^{NC})
without fetrtilizer (OF)	NC	NC	0.1	0.6	NC (^{NC})	NC (^{NC})	0.6 (^{NC})	0.2 (^{NS})
Variety								
Babylon	8.4	PD		PD	11.4 (^{NC})	PD		PD
Fuego	16.8	PD		PD	20.8 (**)	PD		PD
Nile	8.4	PD			11.4 (**)	PD		

^{NS}, not significant ($p > 0.05$); *, $p < 0.05$; **, $p < 0.01$. ^{NC}, F-value not computed; ^{NC}, *p*-value not computed. PD, variety included as a passive driver. [1], data from six years/growing seasons (2005, 2006, 2010, 2013, 2014, 2015) and variety were included as an "active" explanatory variable (see Figure 4); [2], data from six years/growing seasons (2005, 2006, 2010, 2013, 2014, 2015) and variety were included as a "passive" explanatory variable (see Supplementary Figure S1); [3], data from four years/growing seasons (2006, 2009, 2010, 2013) in which the variety Fuego was grown were used (see Supplementary Figure S5); [4], data from four years/growing seasons (2009, 2013, 2014, 2017) in which disease severity was assessed and variety were included as a "passive" explanatory variable were used (see Figure 5).

When variety was used a passive driver in RDA2, very similar associations between the climate, fertilization and crop protection drivers, and crop performance response variables were detected (Supplementary Figure S1).

RDA3 was based on data from the four years (2006, 2009, 2010, 2013) in which the variety Fuego was used, and designed to investigate associations between climatic, fertilization, and crop protection explanatory variables, and crop performance response variables without confounding effects of variety. Also, this RDA was based on data from two years (2006 and 2010) with relatively low (2.2 and 1.8 t/ha respectively) and two years (2009 and 2013) with relatively high (5.1 and 3.6 t/ha respectively) yields (Table 3). Seed/pod, grain protein content and TGW could not be included as response variables in RDA3, because they were not assessed in the 2009 growing season. In RDA3, the explanatory variables accounted for 31.2% of the total variation and temperature and crop protection were the only significant drivers identified, explaining 14.8% and 6.1% of variation, respectively (Table 4).

In the biplot resulting from RDA3, which was based on data from years in which the variety Fuego was used, grain and straw yield, pods/m^2 and harvest index were positively associated with temperature, precipitation, and conventional crop protection along (the positive axis 1), but negatively with radiation and organic crop protection (along the negative axis 1) (Supplementary Figure S2).

RDA4 was based on data from the four years (2009, 2013, 2014, 2017) in which foliar disease severity and crop performance parameters were assessed (Table 4, Figure 5). Since different varieties were used (Fuego in 2009 and 2013, and Babylon in 2014 and 2017), variety was included as a passive response variable in RDA4 (Table 4, Figure 5). As in RDA3, seed/pod, grain protein content, and TGW could not be included as response variables in RDA4, because they were not assessed in the 2009 growing season. In RDA4, the active explanatory variables accounted for 37.4% of the total variation and temperature and crop protection were identified as the strongest drivers, explaining 20.0% and 14.7% of the variation, respectively, although precipitation and radiation were also identified as significant drivers (Table 4, Figure 5).

In biplot resulting from RDA4 (which was based on data from the four years in which foliar disease severity was assessed in addition to crop performance), chocolate spot and rust severity were positively associated with precipitation along the negative axes 1 and 2 (Figure 5).

Similar to the trends observed in RDAs 1–3, the number of plant/m^2, pods/m^2 and both grain and straw yield were positively associated with temperature and conventional crop protection (along the positive axis 2) (Figure 5). The number of pods/m^2 and grain yield were also positively associated with precipitation (along the negative axis 1), while the number of plants/m^2 and straw yield were also positively associated with radiation along the positive axis 1 (Figure 5).

Continuous explanatory variables (△, climate drivers):
PRE, precipitation
TEMP, air temperature
RAD, radiation

Fixed explanatory variables (▲, agronomic drivers):
Crop protection
CP, conventional crop protection
OP, organic crop protection
Fertilization
CF, conventional fertilization
OF, organic fertilization

Passive fixed explanatory variable:
Variety **(□)**
Bab, variety Babylon
Fue, variety Fuego;

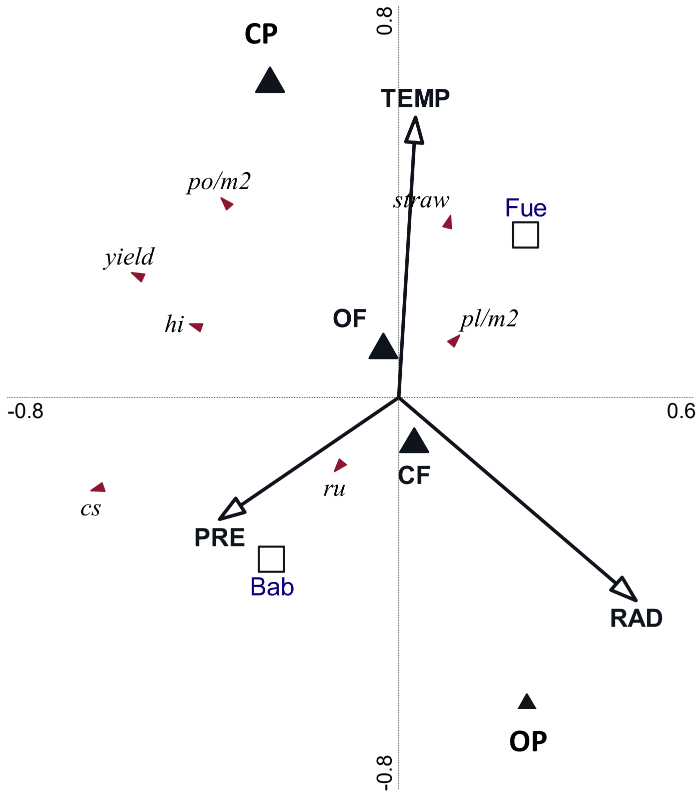


Figure 5. Biplot resulting from RDA4 showing the associations between climate and agronomic explanatory variables/drivers and crop performance response variables. Data included were from four growing seasons/years (2009, 2013, 2014, 2017). In the biplot, the horizontal axis 1 explains 27.0% of the variation and the vertical axis 2 a further 9.4% **Response variables (▲): Crop health parameters:** cs, chocolate spot severity (AUDPC); ru, rust severity (AUDPC); **Crop performance parameters:** pl/m^2, plants/m^2; po/m^2, pods/m^2; yield, grain yield; straw, straw yield; tgw, thousand seed/grain weight; hi, harvest index.

4. Discussion

This study, uniquely, compared faba bean health and performance in crops grown with different crop protection and fertilization regimes used in conventional and organic farming in a range of growing seasons with contrasting climatic background conditions. This allowed, for the first time, an estimate of the relative importance of agronomic parameters and climatic background conditions on foliar disease severity, grain yields, and other performance parameters in faba bean crop grown in Northern Britain.

4.1. Effect of Organic and Conventional Management Practices on Crop Health

For conventional faba bean crops, the use of fungicides to control chocolate spot and rust in faba beans is recommended, since some studies reported that this can significantly reduce disease severity and increase grain yield [16,37,38]. However, in this study, no significant effect of fungicides on disease severity could be detected. Also, there appeared to be no positive correlation between grain yield and disease severity (e.g., the comparison of grain yields in the four years in which disease severity was assessed found the highest grain yields in 2014, the year with the highest chocolate spot severity, while the lowest grain yields were recorded in 2017, the season with the lowest chocolate spot severity). In this context, it is important to note that several other studies reported no or only very small effects of fungicide application on disease severity and grain yields [39,40].

This suggests that the higher grain and straw yield in crops under conventional crop protection observed in this study were primarily due to differences in weed control (use of herbicides versus mechanical weed control). Faba beans and other grain legumes (e.g., lupins and soya beans) are known to be more susceptible to damage and plant losses from post-emergence mechanical weed control compared with other arable crops such as cereals and potato [41,42]. This and the lower plant densities (plants/m^2) in crops under organic crop protection also support the view that the use of herbicides instead of mechanical weed control was the main reason for the higher yields recorded with conventional crop protection regimes, as previously reported for soya beans [43]. Improvement of mechanical weed control (e.g., the use of sensor-guided mechanical weed control systems) may therefore have the potential to reduce crop damage and thereby increase grain yields in organic grain legume production [42], and this should be investigated in future studies.

The finding that the application of mineral P and K fertilizers had no significant effect on foliar disease severity was expected, because previous studies, which reported higher foliar disease severity in mineral NPK compared with manure-fertilized wheat, potato, cabbage, and lettuce crops, linked the higher disease severity to mineral N-fertilizer inputs [6,21,22,24,25], which were not used in the conventional faba bean fertilization regime in this study.

4.2. Effect of Organic and Conventional Management Practices on Crop Performance

Systematic reviews/meta-analyses reported that yields in organic farming systems are on average around 25–30% lower compared with conventional farming, although very few of the studies included in the meta-analyses reported data for grain legumes [44–46]. A recent Danish study reported a yield gap of ~20% between faba beans produced with conventional and organic production protocols [47]. Results from the NFSC trials reported here suggest that, similar to other field crops [6,21,22,24,25], both differences in crop protection and fertilization contributed to the yield gap between organic and conventional faba bean crops. However, the yield gap between organic and conventional crops reported in this study was smaller (~10–15%) than that reported for other crops (e.g., wheat, potato, and cabbage) in the NFSC trials and other field experiments [6,21,22,24,25,44–46].

Since N-fixation by symbiotic *Rhizobium* bacteria in root nodules of faba bean is known to be very efficient in Northern Europe [14,15,47], it is currently recommended to (i) only use mineral P and K fertilizers for conventional faba bean crops, and (ii) not apply manure before planting organic faba bean crops in the UK. The finding that the applications of mineral P and K fertilizer resulted in a small but significant increase in grain yields is therefore consistent with previous studies that reported that P and K (and in some region also S) are the main growth/yield limiting factors in legume crops [15].

However, the finding that ANOVA detected only a small increase (~8%) in grain and straw yield when mineral PK fertilizer was used may suggest that the application of P and K fertilizers to faba bean crops in diverse crop rotations is not economically viable, and this should be investigated in future studies. This could, for example, be based on a meta-analysis of faba bean yield data from contrasting regions in Northern Britain and cost/benefit analysis based on (i) faba bean prices and (ii) P&K fertilizer and application costs, which have increased rapidly over recent years [48].

4.3. Relative Effect of Climatic and Agronomic Variables on Faba Bean Performance

Grain legume yields are considered by farmers to be more variable than those of cereals, and yield fluctuations are one of the main reasons farmers give for not growing these crops [49]. However, a recent analysis of results from long-term field experiments across Northern Europe found that grain yields of spring-planted faba bean, lupin, and field pea crop yields are as stable as spring-sown cereal crops [12].

In the NFSC trials reported here, ANOVA detected large differences in grain yields (which varied between 2.1 and 6.3 t/ha) between seasons, and all four RDAs found that climatic drivers accounted for the largest proportion of the variation. This could suggest that climatic factors have had a larger impact on faba bean performance than the contrasting crop protection and fertilization protocols used in organic and conventional farming systems in the UK. However, when variety was included as an explanatory variable in RDA1, it also accounted for a substantial proportion of variation, which suggests that variety and/or climate x variety interactions may also have contributed to the differences in yields between growing seasons identified by ANOVA.

Climatic explanatory variables did, however, also explain the largest proportion of the variation in RDA3 (which was not confounded by variety, because it was based on data from the four years in which the variety Fuego was grown). RDA3 identified air temperature as the strongest driver for faba bean performance, and precipitation as the strongest driver for disease severity, although radiation and crop protection were also identified as significant drivers. Specifically, RDA3 was based on data from four years (two years, 2006 and 2010, with relatively low grain yields and two years, 2009 and 2013, with relatively high grain yields) identified temperature as the strongest positive driver for both grain and straw yield, which suggests that the low grain yields in 2006 and 2010 were primarily due to lower temperatures. However, 2006 and 2010 were also years with lower precipitation during the summer months and this may explain why grain and straw yields were also positively associated with precipitation in RDA3. These findings are consistent with previous reports that the main yield limiting factors in temperate regions such as Northern Europe are low temperature and excessive environmental moisture [50,51].

Results also indicate that disease severity and grain yields may have been affected by the distribution of rainfall and temperature over the growing season. For example, chocolate spot severity and grain yields recorded for the variety Babylon were substantially higher in 2014 than 2017, although the total rainfall and cumulative temperatures were similar. However, the substantially higher rainfall early in the growing season in 2014 (162 mm in April and May) compared with 2017 (35 mm in April and May) may explain the higher chocolate spot severity in 2014. This view is consistent with recent reports of higher chocolate spot severity in growing seasons with cool wet conditions in spring [52,53]. In contrast, the lower rainfall between June and August in combination with the higher temperatures and solar radiation in July in 2014 may explain the higher grain yields recorded in the 2014 compared with the 2017 season [50,51].

It is also important to consider that cumulative effects of different management practices on soil parameters may have had a confounding effect, since the soils/plots in which faba beans were grown in different years/growing seasons had been managed with the four contrasting agronomic protocols for between two (crops grown in 2005) and fourteen (crops grown in 2014) years prior to planting of faba beans.

The positive association between higher air temperatures and grain yields may indicate that the higher temperatures predicted as a result of global warming may increase faba bean yields in the UK. In contrast, the positive associations between precipitation and disease severity may suggests that, if climate change will also result in higher or more variable precipitation, this may increase disease pressure and thereby reduce yields and/or yield stability [54–56].

Variety was not included as a factor in the experimental design. However, the variety used in experiments changed over time, in line with the variety recommendation for Northeastern England [16]. As a result, three different varieties (Nile, Fuego, Babylon) were grown in the seven growing seasons in which faba beans were included in the NFSC trials. This allowed variety to be included as an additional agronomic explanatory variable in the RDA, and RDA1 identified variety as a significant driver that explained (i) a similar proportion of the variation in crop performance as climate and (ii) substantially more of the variation than crop protection.

However, the finding that precipitation accounted for a larger proportion of the variation in RDA2 (when variety was a passive driver) than RDA1 (when variety was an active driver) suggests that there may be interactions between climate and variety and that the RDA results should be interpreted with caution. Future studies should therefore include variety as a factor to enable potential effects of interactions between variety and

(i) climate, (ii) crop protection, and (iii) fertilization on faba bean health, yield, and yield stability to be identified/quantified.

In the experiments reported here, faba been seeds were not treated with *Rhizobium* inoculum, because soils in Northern Britain were thought to contain sufficiently high faba bean-specific *Rhizobium* populations for effective colonization and development of functional root nodules on bean plants [14]. However, a recent study that compared nodulation in clover swards established from *Rhizobium*-inoculated and non-inoculated clover seeds in Northern Britain reported that inoculation results in higher numbers and larger root nodules in the first year after sowing of clover swards in fields in which legume crops had not been grown for more than ten years [57]. Future studies should therefore also investigate whether, and to what extent, the use of *Rhizobium* inoculation of faba bean seeds may further increase crop yields and yield stability.

The inclusion of grain legume crops in arable crop rotations has also been shown to (i) improve soil structure, organic matter, and microbial activity, (ii) increase plant available N and P concentrations in soils and (iii) remediate negative effects of frequent tillage and mineral fertilizer use on a range of soil health parameters [57–60]. These long-term impacts on soil health and productivity should also be considered when estimating the overall benefits/gains from including grain legumes in cereal-dominated arable rotations.

4.4. Study Limitations

The main limitation of this study was that variety was not included as a factor in the experimental design. Potential impacts of variety could therefore only be investigated by RDA, which showed that variety accounted for a large proportion of the variation. Future studies should therefore include variety as a factor to allow interactions between variety and both (i) agronomic and (ii) seasons with contrasting climatic conditions to be investigated. Another limitation was the missing data for disease severity and some performance parameters in some of the growing seasons, which reduced the statistical power of both the ANOVA and RDA.

5. Conclusions

Results from this study showed that both conventional crop protection and fertilization regimes contribute to the higher grain yields in conventional compared with organic faba bean production in Northern Britain, although the effect of conventional crop protection may be primarily due to the use of herbicides instead of mechanical weed control. However, the yield gap between organic and conventional faba bean crops detected (~10–15%) was smaller than those recorded in wheat, potato, and field vegetable crops included in the crop rotations of the NFSC trials.

While this study confirmed results from a range of previous studies that reported lower faba bean yields in organic compared to conventional farming systems, it did not find evidence for greater yield stability in organic production systems as recently reported in a long-term field experiment carried out in Denmark [47]. Since agrochemical costs are predicted to rise more rapidly than agricultural commodity prices in the future [4,6] future, future research should investigate the economic viability of both fungicide and P and K fertilizer applications in conventional faba bean production and the potential to manage weeds in both conventional and organic faba bean crops by sensor-guided mechanical weed control technologies.

Results from both the ANOVA and RDA showed that climatic conditions during the growing season explain a larger proportion of the variation in faba bean performance in Northern Britain, compared with the agronomic variables included in the study. However, based on the data available, it is difficult to predict whether climate change will overall increase or decrease average faba bean yields in the UK. Results from the RDA suggest that (i) higher temperatures may increase faba bean yields, (ii) higher rainfall is likely to increase disease pressure.

Performing RDAs with and without inclusion of variety as an explanatory variable also indicates that variety may be a stronger driver than both fertilization and crop protection for faba bean performance. However, this needs to be confirmed in studies in which variety is included as a factor in the field experimental design. If confirmed, this would mean that breeding/selection for biotic and abiotic stress resistance is likely to be an important tool to mitigate negative impacts of climate change on faba bean yields and yield stability. In this context, it is important to consider that, in contrast to other arable crops, there has been relatively limited effort to develop improved faba bean genotypes [61].

It is important not to extrapolate results obtained for faba beans grown on a sandy clay loam soil in this study to other grain legume species grown in Northern Europe (i.e., lupins, peas), because they are usually grown on lighter soil with different nutrient and water content and availability profiles.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14030422/s1, Supplementary Table S1. Rotation/sequence of crops in the four replicate experiments of the Nafferton Factorial Systems Comparison (NFSC) trial between 2005 and 2017; Supplementary Table S2. Effects of year/growing season, crop protection and fertilization regimes on downy mildew (*Peronospora vicia*) and rust (*Uromyces faba*) disease severity (AUDPC) on faba bean leaves in the top, middle, and bottom third of crop canopy; Supplementary Table S3. Effects of year/growing season, crop protection, and fertilization regime on crop emergence, and the number of plants/m^2, pods/m^2 and seeds/pod, grain, and straw yield and thousand grain/seed weight (TGW) of faba bean crops at maturity grown in the Nafferton Factorial Systems Comparison (NEFG) trials between 2005 and 2017; Supplementary Figure S1. Biplot resulting from the RDA showing the associations between climate and agronomic explanatory variables/drivers and crop performance response variables; Supplementary Figure S2. Biplot resulting from the RDA showing the associations between climate and agronomic explanatory variables/drivers and crop performance response variables.

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Conflicts of Interest: Carlo Leifert and Nikos Volakakis own and manage organic farms in Greece and Volakakis's farming business is Geokomi plc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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