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Effect of Climatic Conditions, and Agronomic Practices Used in Organic and Conventional Crop Production on Yield and Nutritional Composition Parameters in Potato, Cabbage, Lettuce and Onion; Results from the Long-Term NFSC-Trials

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Abstract: Background: There is increasing evidence that the reliance on synthetic chemical pesticides and mineral fertilizers in agriculture has significant negative environmental and/or health impacts and poses a risk for future food security. Systematic reviews/meta-analyses showed that organic production systems, which omit the use of agrochemicals, produce crops with lower yields, but superior nutritional composition. However, the agronomic parameters responsible for differences in crop yields and nutritional quality are poorly understood. Methods: Here we report results for four field vegetable crops from the Nafferton Factorial Systems Comparison (NFSC) trial. This long-term factorial field experiment was designed to (i) identify effects of growing season/climatic variation, and contrasting rotational designs, crop protection protocols and fertilization regimes used in organic and conventional systems on crop health, yield and nutritional parameters and (ii) estimate the relative importance of climatic and agronomic drivers for crop health, yield and nutritionally relevant quality parameters. Quality parameters monitored in harvested products, included phenolic, glucosinolate, vitamin C, vitamin B_9, carotenoid, cadmium (Cd), nickel (Ni), lead (Pb) and glycoalkaloid concentrations. Results: Climatic conditions during the growing season were found to have a larger impact on crop yield and quality than the agronomic factors (pre-crop, crop protection, fertilization) studied. However, the (i) interactions between growing season with contrasting climatic conditions and agronomic factors identified by ANOVA for crop health, yield and quality parameters and (ii) the associations between the three climatic drivers (precipitation, temperature, radiation) and crop yield and quality parameters differed substantially between the four crop plant species. Among the agronomic factors, fertilization had a substantially larger impact compared with both pre-crop and crop protection. Specifically, crop yields were found to be significantly increased by the use of (i) conventional fertilization and crop protection methods in potato, (ii) conventional fertilization, but organic crop protection methods in cabbage, and (iii) conventional fertilization regimes in lettuce, while none of the agronomic factors had a significant effect on onion yields. When important crop pest and diseases were assessed, (i) conventional crop protection resulted in significantly lower late blight severity in potato, while (ii) organic crop protection resulted in lower bird damage and cabbage root fly (CRF) incidence in cabbages, and *Sclerotinia* incidence in lettuce and (iii) organic fertilization resulted in lower CRF and *Sclerotinia* incidence in cabbage and lettuce respectively. When concentrations of nutritionally relevant phytochemicals were compared, organic fertilization resulted in significantly higher phenolic concentrations in potato, cabbage and lettuce, higher glucosinolate and carotenoid concentrations in cabbage, higher vitamin C concentrations in potato and cabbage and higher vitamin B_9 concentrations in potato and lettuce—but lower concentrations of toxic glycoalkaloids in potato. Significant effects of crop protection protocols on phytochemical concentrations were only detected in cabbage with conventional crop protection resulting in higher glucosinolate and vitamin B_9 concentrations. When toxic metal concentrations were compared, organic fertilization resulted in significantly lower Cd concentrations in all four crops and lower Ni concentrations in potato, cabbage and onion. Significant effects of crop protection were only detected in cabbage, where organic crop protection resulted in lower Ni concentrations. Pb concentrations were not affected by any of the agronomic factors. The potential implications of results for improving (i) strategies to reduce the use of non-renewable resources and environmental impacts of vegetable production and (ii) the productivity of organic and other low-input vegetable production systems without compromising food quality are discussed. Conclusions: The study confirms that organic vegetable production protocols result in higher concentrations of phenolics and other nutritionally desirable phytochemicals, but lower concentrations of the toxic metals Cd and Ni in harvested products. It also demonstrates, for the first time, that this is primarily due to differences in fertilization regimes. The finding that in three of the four crops (cabbage, lettuce and onion) the application of synthetic chemical crop protection products had no measurable positive impact on crop health and yield should be considered in the context of the growing concern about health impacts of pesticide use in field vegetable crops.

Keywords: organic; conventional; nutritional quality; crop yield; fertilization; crop protection; phytochemicals; Cd; Ni; Pb

1. Introduction

There is growing awareness among scientists, government regulators and consumers about the need to reduce the (i) dependence on non-renewable resources and (ii) negative environmental impacts of agriculture to maintain future food security [1–8]. Specifically, there is a need to reduce the use of agrochemicals, in particular mineral nitrogen (N), phosphorus (P) and potassium (K) fertilizers and synthetic pesticides [1,5–8]. Mineral N-fertilizers are of concern because their manufacture via the Haber–Bosch process (i) requires large amounts of energy (the production of 1 kg mineral N requires approximately 1 kg of fossil fuel) and (ii) is associated with substantial quantities of greenhouse gas (GHG) emissions (the manufacture of N-fertilizers has been estimated to account for approximately 10% of total GHG emissions from agriculture) [8]. The use of mineral P and K-fertilizers is also of growing concern because they are produced from mined mineral deposits which are rapidly depleted (e.g., the currently known exploitable P-deposits have been estimated to be exhausted within the 21st century) [5–8]. Therefore, the current reliance on mineral N, P and K fertilizers in intensive conventional farming systems represents a substantial risk for future food security [8].

Mineral N and P-fertilizers also contribute significantly to the eutrophication of marine and fresh-water ecosystems and were linked to a reduction in the safety and nutritional quality (e.g., higher Cd and lower phenolic/antioxidant levels) of food and feed crops [8–10].

The manufacture of pesticides also requires substantial amounts of energy/fossil fuel and contributes significantly to the carbon footprint of conventional crop production [8]. The use of, and increasing dependence on, pesticides for crop protection in conventional agriculture was (i) shown to have negative environmental/biodiversity impacts (e.g., a reduction in natural enemy populations of invertebrate pests), (ii) described as a potential risk for yield stability (e.g., due to resistance development) and (iii) linked to potential negative human health impacts [2,4,8,11–16].

In addition, the reliance on agrochemicals in conventional farming systems is of increasing concern from an economic sustainability perspective, because the cost of mineral NPK fertilizers and many synthetic pesticides has been rising more rapidly than agricultural commodity prices [8,17–19]. In developed countries, this is thought to reduce the ability of farmers to increase/maintain current crop yield levels, and in developing countries this makes many agrochemicals unaffordable for farmers [8,17,19].

Recent systematic reviews and meta-analyses of published data from studies in which the crop yields in conventional and organic farming systems were compared, have estimated that organic crop production systems (which prohibit the use of most agrochemicals) produce, on average, 20–25% lower yields compared with intensive conventional systems [20,21]. In contrast, recent systematic reviews and meta-analyses of nutritionally relevant crop composition data suggest that organic crops have a superior nutritional composition (e.g., lower concentrations of pesticides and the toxic metal Cd, but higher concentrations of phenolics and other antioxidants) [22–25]. However, it is important to highlight that these meta-analyses also identified very high levels of variation between (i) years in which assessments were made, (ii) countries/regions in which studies were carried out and/or (iii) different crops/crop types [20–25]. For example, the average yield gap between organic and conventional crop yields was reported to be more than 30% for vegetable, ~25% for cereals and ~10% for legumes, while there was no yield gap in fruit crops [20]. Similarly, total phenolic concentrations were estimated to be around 10%, 25% and 60% higher in organic compared with conventional vegetables, fruits and cereal crops, respectively, while a significant difference in Cd concentrations could only be detected in cereal crops [23]. A major limitation of all studies included in recent meta-analyses is that they only compared crops from organic and conventional production, and therefore, cannot be used to identify the specific agronomic (e.g., differences in crop protection, fertilization regimes, tillage and rotation design) and/or climatic parameters responsible for (i) differences in crop yields and nutritional composition between organic and conventional crops and (ii) the large between-study/crop variation. However, this information is urgently required to (i) further improve organic and other low agrochemical input production systems (e.g., to increase crop yields/yield stability without negative impacts on crop health and nutritional quality) and (ii) identify potential impacts of climate change on different crop production systems.

The Nafferton Factorial Systems Comparison (NFSC) trials were established as part of the European Commission funded research project QualityLowInputFood (https://cordis.europa.eu/project/id/506358/ accessed on 1 March 2023) to address this knowledge gap. Specifically, the NFSC trials were designed to identify the relative effects of (i) the main agronomic parameters (rotation design, fertilization regimes, crop protection protocols) that differ between organic and conventional production systems and (ii) climatic parameters (radiation, temperature and precipitation) on the health, yields and nutritional composition of cereal and field vegetable crops. Some results from the NFSC-trials on cereal and potato performance have been published previously [26–28]. Here we report the results obtained for crop health, yield and nutritionally relevant composition parameters in the four contrasting field vegetable crops (potato, cabbage, lettuce and onion) included in the NFSC-trials.

The objectives of the study were to identify/quantify (i) the effects of growing season, rotational position/previous crop (winter barley versus spring beans), crop protection (standard organic versus conventional protocols recommended for the different crops) and fertilization (mineral NPK versus cattle manure) on selected crop health, yield and nutritional parameters in the four vegetable crops using ANOVA and (ii) the relative importance of climatic and agronomic explanatory variables/drivers on selected crop yield and nutritional quality parameters using redundancy analyses (RDA).

The four field vegetable species included in this study were chosen because they (i) belong to four different plant families (potato, *Solanum tuberosum* L., Solanaceae; white cabbage, *Brassica oleraceae* L., Brassicaceae; iceberg lettuce, *Lactuca sativa* L., Asteraceae; onion, *Allium cepa* L., Amaryllidaceae), (ii) have different requirements with respect to the pedoclimatic conditions, soil nutrient availability/fertilizer inputs and weed, pest and disease control interventions required for optimum crop performance and (iii) are commercially important vegetable crops grown in northern Britain.

2. Materials and Methods

2.1. Experimental Site and Experimental Design

2.1.1. Nafferton Factorial Systems Comparison Trials

The Nafferton Factorial Systems Comparison (NFSC) trials were established at Newcastle University's Nafferton Experimental Farm, Northumberland, UK (54°59′09″ N; 1° 43′56″ W). The soil in the 6 ha field used for the experiment is a uniform sandy loam formed in a slowly permeable glacial till deposit classified as a Cambic Stagnogley [29] or Stagnic Cambisol [30], which had a mean organic matter content of 3.3% at the beginning of the NFSC trials. The climatic conditions in the three growing seasons in which both crop yield and nutritional composition were assessed (2004, 2005 and 2007) and that were used for redundancy analyses (RDA) are shown in Supplementary Table S1.

Detailed descriptions of the experimental design were published previously [26–28]. Briefly, in the NFSC trials the effects of (i) crop rotation, (ii) crop protection protocols and (iii) fertilization regimes prescribed for organic and conventional production systems were studied using a split-split-split plot design with four replicate blocks and four replicate experiments. Supplementary Figure S1 shows the dimensions and principal arrangement of crop rotation main plots, crop protection subplots and fertilization sub-subplots. The two crop rotations main plots compared a (i) 8-year diverse, legume-rich rotation used/recommended for organic systems (organic rotation) with a (ii) 8-year arable crop-dominated rotation typical for conventional systems (conventional rotation) in the north of England. It should be noted that oil seed rape, which is the most widely used break crop in conventional crop rotations, was replaced with field vegetables as break crops in the conventional rotation. The 4 replicate experiments were each started at a different stage of the 8-year rotation, to allow each crop in the 2 rotations to be grown in two growing seasons within a 4-year period. Supplementary Table S2 provides detailed information on the crop rotation used in each replicate experiment in the first 8-year period of the experiment (2001 to 2008). In this study, the crop rotation effect is described as a previous crop or pre-crop (PC) effect. In 2005, the four vegetable crops were grown after PC winter wheat in the organic rotation only, while in 2006 and 2007 vegetables were grown after PC winter barley in the conventional rotation and after PC spring-beans in the organic rotation. This allowed the effect of two contrasting PCs to be compared in the same growing season.

Each rotation main plot was divided into 2 crop protection subplots (6 × 48 m) in which crop protection was carried out according to either (i) British farm assured conventional crop protection (CP) recommendations or (ii) Soil Association (www.soilassociation.org, accessed on 1 March 2023) organic crop protection (OP) standards [31]. Each of these subplots was divided into two fertility management sub-subplots (6 × 24 m) in which fertilization was carried out either according to (i) to conventional farming practice (mineral NPK fertilizer inputs; CF) or (ii) organic farming standards (cattle manure fertilizer inputs; OF).

The arrangement of crop protection subplots and fertilization sub-subplots was randomized in each of the four replicate experiments. In total, 10-meter unplanted separation strips were established between crop protection subplots and 5 m unplanted separation strips between fertilization sub-subplots (Supplementary Figure S1).

2.1.2. Supplementary Field Experiment with Onion

A supplementary field experiment was carried out in 2004 to investigate the effect of different organic fertilizer types and input levels on (i) pest and disease incidence/damage and (ii) yields in onion crops under organic crop protection (see Supplementary Materials and Figures S2 and S3 for details of the experimental design and methods used).

2.2. Crop Management and Yield Assessments

2.2.1. Potato

Potato seed tubers of the variety Santé were planted in ridges (distance between rows: 90 cm, distance between seed tubers within the row: 35 cm) using a semi-automatic 2-row potato planter (Reekie, Forfar, Scotland, UK). Potato seed tubers planted in conventional crop protection subplots (CON CP) were produced under conventional potato seed tuber production conditions, while seed tubers used in organic crop protection subplots (ORG CP) were produced to Soil Association organic seed tuber production standards. Both organic and conventional potato seeds tubers were supplied by Greenvale AP (Duns, UK). Conventional and organic crop protection and defoliation treatments used are described in Supplementary Table S3. After defoliation, tubers were left in the ground to allow skin maturation and then harvested using a single row potato harvester (Ransomes, Ipswich, UK). Organic and conventional fertilization regimes are described in Supplementary Table S3. All fertilizers were applied four weeks prior to planting of tubers. No irrigation was used. Potato crops were planted on the 2nd of May, 27th of April and 26th of April and harvested on the 13th of September, 26th of September and 13th of September in the 2005, 2006 and 2007 growing seasons, respectively.

Potato yields were assessed by harvesting the four middle rows of each plot. Fresh weights were determined by weighing tubers harvested in each plot immediately after harvesting.

2.2.2. Cabbage, Lettuce and Onion

Cabbage, lettuce and onion crops were established from organic seedlings/transplants (plots under organic crop protection) produced to Soil Association standards by Roger White nurseries (Boston, UK) or conventional transplants (plots under conventional crop protection) produced by TH Clements plc (Boston, UK). Cabbage crops were planted using a semi-automatic Sfoggia transplanter (Sfoggia Agriculture Division Srl, Montebelluna, Italy) on the 4th, 11th and 24th of May, and harvested by hand on the 10th of August, 8th of August and 10th of September in the 2005, 2006 and 2007 growing seasons, respectively. Lettuce crops were planted on the 5th, 12th and 25th of May and harvested by hand on the 13th of July, 20th of July and 7th of August in the 2005, 2006 and 2007 growing seasons, respectively. Onion crops were planted on the 5th, 11th, and 24th of May and harvested by hand on the 6th of October, 25th of September and 8th of October in the 2005, 2006 and 2007 growing seasons, respectively. Conventional and organic crop protection and fertilization regimes for cabbage, lettuce and onions are described in Supplementary Tables S4–S6.

Cabbage and lettuce head and onion bulb yields were assessed by harvesting the middle row of each of the three beds within a plot. Fresh weights were determined by weighing cabbage and lettuce heads and onion bulbs immediately after harvest.

2.3. Pest and Disease Assessments

2.3.1. Potato

Plots were examined weekly after plant emergence for symptoms of foliar diseases, until the first symptoms of late blight (*Phytophthora infestans*) were detected on potato leaves and twice a week thereafter. Significant foliar disease symptoms were only detected for late blight and foliar blight severity was assessed/recorded and the cumulated disease severity was calculated as the area under the disease progress curve (AUDPC) using a previously described protocol [27].

2.3.2. Cabbage

Plots were examined weekly for disease symptoms and pest damage. The only substantial pest damage detected was from birds (mainly crows) and cabbage root fly (*Delia radicum*) although some *Alternaria* symptoms on leaves were also detected.

Bird damage was assessed in the 2005 and 2006 season at the start of head formation in five randomly selected plants from the middle row of each of the three beds in each fertilization sub-subplot. Bird damage was recorded as percentage of damaged plant leaves.

Cabbage root fly incidence was assessed in 2004, 2005 and 2006. The incidence was assessed as the proportion of plants that had visible symptoms of cabbage root fly maggot damage on roots at harvest.

2.3.3. Lettuce

Plots were examined weekly for disease symptoms and pest damage. Only *Sclerotinia* symptoms were detected on lettuce heads in the 2005, 2006 and 2007 seasons and disease incidence was assessed by determining the percentage of infected plants in all three beds within a plot.

2.3.4. Onion

Plots were examined weekly for disease symptoms and pest damage. Although *Botrytis* was detected on a small number of plants no significant levels of disease and pest damage were detected in onion crops.

2.4. Nutritional Analyses

Samples of harvested potato tubers, cabbage and lettuce head leaves, and onion bulbs were freeze-dried immediately after harvest and then shipped to different specialist laboratories for mineral nutrient, toxic metal and phytochemical analyses. However, fresh potato tubers were used for glycoalkaloid analyses.

Nitrogen concentrations in harvested products were determined at Newcastle University by combustion using a LECO C & N analyzer (LECO corporation, St. Joseph, MI, USA) according to the application notes provided by the instrument's producer (Form No. 203-821-273). Analyses of toxic metal and mineral nutrient concentrations other than N were carried out by Sabanci University (Istanbul, Turkey) using previously described methods [26,27].

Phenolic concentrations were determined by the CECEA-Departamento de Fitotecnia e Engenharia Rural, Universidade de Trás-os-Montes e Alto Douro (UTAD; Vila Real, Portugal) using an optimized and validated multiphytochemical reverse-phase HPLC method [32].

Ascorbic acid/Vitamin C and carotenoid analyses were carried out by the Central Food Research Laboratory (Budapest, Hungary) using standard HPLC-based protocols [33,34].

Folate/Vitamin B_9 analyses were carried out by the Institute for Food Research (Norwich, UK) using a standard protocol based on a a chloramphenicol-resistant *Lactocaseibacillus rhamnosus* NCIMB 10463 microbiological assay [35].

Concentrations of the main potato glycoalkaloids (GA) α-chaconine and α-solanine were determined using a standard liquid chromatography/mass spectrometry (LC/MS) protocol [36].

2.5. Leaf Chlorophyll Analyses (SPAD)

Leaf chlorophyll concentrations were estimated based on measurements in a representative sample of 100 plants per plot in potato, and 10 plants from each of the 3 rows in each plot (=30/plot) in cabbage and lettuce crops. Chlorophyll assessments were carried out using a hand-held Konica Minolta chlorophyll meter SPAD-502 plus device (Konica Minolta Business solution UK Ltd., Basildon, UK) 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 [37]. Chlorophyll assessments were carried out (i) at growth stage IV (80% maturity) in potato, and (ii) in late July/early August in cabbage and lettuce crops.

2.6. Statistical Analyses

The effects of year, crop protection and fertility management on measured parameters were assessed using ANOVA derived from a linear mixed-effects model using the '*nlme*' package [38] in R [39]. 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 [40]. Another model with pre-crop, crop protection and fertility management as fixed effects was used for data analysis from years in which crops were grown following more than one species of pre-crop. The hierarchical nature of the split-split plot design was reflected in the random error structures that were specified as block/pre-crop/crop protection. In years when crops were grown after only one previous crop, the model only included crop protection and fertility management as fixed effects. This reduced model was also used when previous crop did not have a significant effect. The normality of the residuals of all models was tested using QQ-plots. Differences between the four crop management strategies used (FM × CP interaction means) and interactions between management strategies and pre-crop were tested using Tukey contrasts of the general linear hypothesis testing (glht) function of the '*multcomp*' package in R [41]. A linear mixed effects model was used, containing a treatment main effect, with four levels, with the random error term specified as described above. The standard error (SE) of mean was used in order to describe how precise the sample's mean is compared with the true mean of the population. Both means and SE were generated by using the '*t apply*' function in R.

The relationships between concentrations of biochemical compounds, macro–micro nutrients, heavy metals and environmental, agronomic factors were investigated using partial redundancy analysis (pRDA). In all cases, the pRDAs were carried out using CANOCO 5 [42]. Automatic forward selection of the environmental, agronomic, and phenolic factors within the RDAs was used and their significance in explaining additional variance calculated using Monte Carlo permutation tests.

3. Results

The agronomic factors studied were (i) crop protection (organic, based on mechanical weed control in all crops, insect proof crop covers in cabbage and Cu-fungicides in potato as the only intervention versus conventional, based on the application of synthetic chemical herbicide, insecticides fungicides and/or plant growth regulators), (ii) fertilizer input types (NPK versus FYM) and (iii) previous crop in the rotation (spring beans versus winter-barley).

When interpreting rotation effects, it is important to consider that previous crops in the rotation are known to affect (i) soil nutrient availability (e.g., higher N-availability after legume crops such as beans compared with non-legume crops such as barley) and may thereby confound the effect of contrasting fertilizer input types on crop yield and quality parameters, (ii) weed, disease and pest pressure and may thereby confound the effects of contrasting crop protection regimes on crop yield and quality parameters as previously described [8].

3.1. Effect of Contrasting Agronomic Protocols on Crop Health and Yield

Significant main effects of crop protection on yields were detected in potato and cabbage crops, but not lettuce and onion (Table 1).

Table 1. Effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) and pre-crop (spring beans versus winter barley) on the total yields [1], and severity of major pests and diseases of potato, cabbage, lettuce and onion crops. Values shown are main effect means ± SE and yields are expressed on a fresh weight basis; significantly higher means are highlighted in bold.

Parameter Assessed	Crop Protection (P)		Fertilizer Type (F)		Pre-Crop (PC)							
Crop Species	**CON**	**ORG**	**CON**	**ORG**	**Spring**	**Winter**	**Main Effects**			**2-Way Interactions**		
or Pest/Disease	**(CP)**	**(OP)**	**(NPK)**	**(FYM)**	**Beans**	**Barley**	**P**	**F**	**PC**	**P × F**	**P × PC**	**F × PC**
Total Yield (t/ha)												
Potato [1]	**42** ± 1	35 ± 1	**44** ± 1	33 ± 1	34 ± 1	34 ± 1	***	***	NS	** [6]	NS	T
Cabbage [2]	54 ± 1	**61** ± 3	**71** ± 2	45 ± 2	48 ± 3	46 ± 3	***	***	NS	** [6]	NS	NS
Lettuce [3]	38 ±1	36 ± 1	**39** ± 1	34 ± 1	42 ± 2	39 ± 2	NS	***	T	NS	NS	NS
Onion [3]	22 ± 1	21 ± 1	21 ± 1	22 ± 1	21 ± 2	20 ± 1	NS	NS	NS	NS	NS	NS
Crop health												
Potato—late blight (AUDPC) [1]	6 ±2	**18** ± 5	11 ± 3	14 ± 4	12 ± 3	18 ± 18	**	NS	NS	NS	NS	NS
Cabbage—root fly (%IP) [4]	**17.7** ± 2.6	1.2 ± 0.4	**11.6 ± 3.0**	7.2 ± 1.8	NA	NA	***	*	NA	T	NA	NA
Cabbage—bird damage (%LD) [5]	**7.8** ± 1.1	0.4 ± 0.1	4.2 ± 0.9	4.1 ± 1.0	NA	NA	***	NS	NA	NS	NA	NA
Lettuce—*Sclerotinia* (%IP) [3]	**19.2** ± 2.4	16.9 ± 1.9	**21.6** ± 2.3	14.5 ± 1.9	**21.9** ±1.4	14.4 ± 1.2	*	***	**	NS	NS	NS
Onion—*Botrytis* (%IP) [4]	2.1 ± 0.4	2.2 ± 0.4	2.0 ± 0.4	2.2 ± 0.4	NA	NA	NS	NS	NA	NS	NA	NA

CON, conventional; ORG, organic; NS, not significant; T, trend (0.1 > p > 0.05); *, 0.05 > p > 0.01; **, 0.01 > p > 0.001; ***, p < 0.001; NA, not available; AUDPC, area under the disease progress curve; %IP, % infested plants; %LD, % leaf damage; [1], data for main effect means and the P × F interaction are from 9 growing seasons/years (2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011 and 2012) while data for main effects of PC, and the P × PC and F × PC interactions are from 4 growing seasons (2006, 2007, 2010 and 2011); [2], data for main effects means of P and F and the P × F interactions are from 6 growing seasons (2004, 2005, 2006, 2007, 2008 and 2009) while data for the main effect of PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [3], data for the main effects of P and F and the P × F interaction are from 4 growing seasons (2004, 2005, 2006 and 2007), while data for PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [4], data for the main effects of P and F and the P × F interaction are from 2 growing seasons (2005 and 2006); [5], data for the main effects of P and F and the P × F interaction are from 3 growing seasons (2004, 2005 and 2006); [6], see Table 2 for interaction means ± SE.

Table 2. Interaction means for the effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) on potato tuber and cabbage head yields.

			Factor 2. Fertilizer Type	
Crop Species	**Parameter Assessed**	**Factor 1. Crop Protection**	**Conventional (NPK)**	**Organic (FYM)**
Potato	Yield (t/ha)	Conventional	48 ± 2 a A	36 ± 2 a B
		Organic	39 ± 2 b A	31 ± 1 b B
Cabbage	Yield (t/ha)	Conventional	69 ± 3 a A	44 ± 2 a B
		Organic	74 ± 3 a A	45 ± 3 a B

For each crop species means labelled with the same lower-case letter within the same column and capital letter within the same row are not significantly different according to Tukey's Honestly Significant Difference Test (HSDT) ($p < 0.05$).

In potato the use of conventional crop protection protocols (CP) based on application of synthetic chemical herbicides, insecticides/nematicides and fungicides, resulted in higher yields compared with organic crop protection protocols (OP) based on mechanical/hand weeding and Cu-fungicide applications only (Table 1). In contrast, in cabbage crops the use of CP based on the application of synthetic chemical herbicides, insecticides and fungicides resulted in lower yields compared with OP based on mechanical/hand weeding and application of insect-proof crop covers only (Table 1).

Significant main effects of fertilizer type were detected for potato, cabbage and lettuce, with yields being higher in crops fertilized with mineral NPK-fertilizer (NPK), compared with crops fertilized with composted farmyard cattle manure (FYM) applied at the same total N-input level (Table 1).

ANOVA detected no significant main effects of pre-crop (PC; spring beans vs. winter barley), although there was a trend ($0.1 > p > 0.05$) towards significantly higher yield of lettuce crops grown after spring beans compared with winter barley as the PC (Table 1).

ANOVA also detected significant interactions between crop protection and fertilizer type in potato and cabbage (Table 1). When these interactions were further investigated the yield difference between crop protection regimes in both crops was larger when NPK was used as fertilizer, although the differences in yield between crop protection regimes were only significant in potato (Table 2).

The only crop pests and diseases that caused substantial levels of crop damage in the experiments were late blight (*Phytophtora infestans*) in potato, birds (mainly crows) and cabbage root fly (CRF, *Delia radicum*) in cabbage, and *Sclerotinia* in lettuce (Table 1).

Significant main effects of crop protection were detected in potato, cabbage and lettuce, but not onion crops (Table 1). In potato, the use of CP resulted in substantially lower late blight severity compared with OP (Table 1). In contrast, in cabbage CP resulted in higher crow and CRF damage compared with OP and in lettuce CP, based on the use of synthetic chemical herbicides and fungicides, resulted in slightly, but significantly, higher *Sclerotinia* severity compared with OP which was based on mechanical and hand weeding only (Table 1).

Significant main effects of fertilizer type were only detected for CRF damage in cabbage and *Scerotinia* severity in lettuce, which were both higher in crops fertilized with NPK compared with FYM applied at the same total N-input level (Table 1).

A significant main effect of pre-crop was only detected for lettuce, with *Sclerotinia* disease severity found to be higher in lettuce grown after spring beans compared with winter barley as the pre-crop (Table 1). It is important to note that both (i) spring beans (an N-fixing legume crop) as pre-crop and (ii) mineral NPK fertilizer (which is known to result in higher N-availability in soil compared with FYM applied at the same N-input level) resulted in higher *Sclerotinia* disease severity when compared with barley as pre-crop and FYM as fertilizer, respectively (Table 1).

3.2. Effect of Contrasting Fertilization Regimes on Onion Health and Yield; Results from a Supplementary Field Experiment

A supplementary field experiment was carried out in the 2004 growing season to compare the effect of 3 different organic fertilizer types (chicken manure pellets, CMP; fresh farmyard manure, fFYM; composted farmyard manure, cFYM) applied at 3 input levels (equivalent with 85, 170 and 250 kg N/ha) on pest and disease damage, and yields of onion crops (see Supplementary Materials for a detailed description of the material and methods used). Results showed that (i) pest and disease losses were significantly higher, while (ii) total and marketable yields were significantly lower with CMP (the fertilizer type with the highest available N-content) compared with both fFYM and cFYM (Supplementary Table S9). In addition, crop losses due to bean seed fly damage increased while yields decreased with increasing fertilizer input levels when crops were fertilized with CMP (Supplementary Table S10). In contrast, there was no significant effect of fertilizer input level when fFYM or cFYM were used as fertilizer and only an application of cFYM at a rate equivalent to 85 kg N/ha resulted in numerically higher yields when compared with un-fertilized control plots (Supplementary Table S10). However, it is important to note that the difference in yield between unfertilized control plots and plots fertilized with cFYM at a rate equivalent to 85 kg N/ha was not significant (Supplementary Table S10).

3.3. Effect of Agronomic Protocols on Leaf Chlorophyll and N Concentration in Harvested Crops

Leaf chlorophyll (SPAD) levels and N-concentrations in harvested crops were assessed to detect differences in N availability/supply to crops grown with contrasting agronomic protocols (Table 3).

Significant main effects of crop protection were detected for (i) cabbage leaf chlorophyll levels and N concentration in cabbage heads, which were both higher with CP and (ii) N concentrations in potato tubers, which were higher with OP (Table 3).

Significant main effects of fertilization on leaf chlorophyll and N concentration were detected for potato, cabbage and lettuce, which were all higher with NPK compared with FYM applied at the same total N-input level (Table 3).

A significant main effect of pre-crop was only detected for the N concentrations in potato tubers, which was found to be higher after spring beans compared with winter barley as the pre-crop (Table 3).

It is important to note that both spring beans (a N-fixing legume crop) and mineral NPK fertilizer (which is known to result in higher N-availability in soil compared with FYM applied at the same N-input level) resulted in higher N concentrations in potato tubers (Table 3).

It is also important to consider that for lettuce ANOVA detected (i) significantly higher *Sclerotinia* severity (Table 1) and (ii) trends towards both, lower yields (Table 1) and higher N concentrations (Table 3) in crops grown after winter barley compared with spring bean as pre-crop.

ANOVA also detected a significant interaction between crop protection and pre-crop for chlorophyll (SPAD) levels in potato leaves (Table 3). When the interaction was further investigated (Table 4), OP resulted in higher chlorophyll levels when spring beans were the pre-crop, while CP resulted in higher leaf chlorophyll levels when winter barley was the pre-crop (Table 4). However, no significant differences could be detected when individual interaction means were compared (Table 4).

Table 3. Effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) and pre-crop (spring beans versus winter barley) on leaf chlorophyll levels (SPAD) and concentrations of nitrogen (N) in potato tubers, cabbage and lettuce heads and onion bulbs. Values shown are main effect means ± SE and are expressed on a fresh weight basis; significantly higher means are highlighted in bold.

Parameter	**Crop Protection (P)**		**Fertilizer Type (F)**		**Pre-Crop (PC)**							
Assessed	**CON**	**ORG**	**CON**	**ORG**	**Spring**	**Winter**	**Main Effects**			**2-Way Interactions**		
Crop Species	**(CP)**	**(OP)**	**(NPK)**	**(FYM)**	**Beans**	**Barley**	**P**	**F**	**PC**	**P × F**	**P × PC**	**F × PC**
Chlorophyll Levels (SPAD)												
Potato [1]	41.7 ± 0.4	41.7 ± 0.5	**44.9** ± 0.4	38.5 ± 0.5	43.8 ± 0.6	43.1 ± 0.6	NS	***	NS	NS	*[4]	T
Cabbage [2]	**64.5** ± 0.7	62.9 ± 0.8	**69.1** ± 0.4	58.3 ± 0.4	64.2 ± 1.3	64.0 ± 1.2	***	***	NS	T	NS	NS
Lettuce [3]	41.3 ± 0.3	41.3 ± 0.2	**41.8** ± 0.2	40.8 ± 0.3	41.3 ± 0.3	41.3 ± 0.3	NS	**	NS	NS	NS	NS
N (mg/kg)												
Potato [1]	2.32 ± 0.06	**2.46** ± 0.06	**2.68** ± 0.59	2.09 ± 0.46	**2.33** ± 0.88	2.17 ± 0.09	**	***	*	NS	NS	NS
Cabbage [2]	**2.21** ± 0.05	2.11 ± 0.06	**2.52** ± 0.04	1.81 ± 0.03	2.39 ± 0.08	2.43 ± 0.08	***	***	NS	T	NS	NS
Lettuce [3]	1.16 ± 0.03	1.17 ± 0.02	**1.22** ± 0.02	1.12 ± 0.02	1.17 ± 0.02	1.21 ± 0.02	NS	***	T	NS	NS	NS
Onion [3]	2.02 ± 0.06	1.98 ± 0.06	2.04 ± 0.06	1.96 ± 0.06	2.18 ± 0.07	2.23 ± 0.04	NS	NS	NS	NS	NS	NS

CON, conventional; ORG, organic; CP, conventional crop protection protocols used; OP, organic crop protection protocols used; NPK, mineral NPK used as fertilizer; FYM, cattle farm yard manure used as fertilizer; NS, not significant; T, trend ($0.1 > p > 0.05$); *, $0.05 > p > 0.01$; **, $0.01 > p > 0.001$; ***, $p < 0.001$; [1], data for main effect means and the P × F interaction are from 9 growing seasons/years (2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011 and 2012) while data for main effects of PC, and the P × PC and F × PC interactions are from 4 growing seasons (2006, 2007, 2010 and 2011); [2], data for main effects means of P and F and the P × F interactions are from 6 growing seasons (2004, 2005, 2006, 2007, 2008 and 2009) while data for the main effect of PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [3], data for the main effects of P and F and the P × F interaction are from 4 growing seasons (2004, 2005, 2006 and 2007), while data for PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [4], see Table 4 for interaction means ± SE.

Table 4. Interaction means for the effect of crop protection protocols (organic versus conventional) and fertilization (mineral NPK versus farmyard manure) on leaf chlorophyll (SPAD) levels in potato.

			Factor 2. Pre-Crop	
Crop Species	**Parameter Assessed**	**Factor 1. Crop Protection**	**Spring Beans**	**Winter Barley**
Potato	Leaf chlorophyll (SPAD)	Conventional	43.4 ± 0.8 [1]	43.7 ± 0.9 [1]
		Organic	44.2 ± 0.8 [1]	42.5 ± 1.0 [1]

[1] No significant differences between interaction means were detected using Tukey's HSDT ($p < 0.05$).

3.4. Effect of Contrasting Agronomic Protocols on P, K and S Concentration in Hharvested Crops

P-, K- and S-concentrations in harvested crops were assessed to detect differences in P, K, and S availability/supply to crops grown with contrasting agronomic protocols.

Significant main effects of crop protection were only detected for cabbage, with CP resulting in higher P and K concentration in cabbage heads (Table 5).

Significant main effects of fertilization were detected for all four crops. When FYM was used as fertilizer, concentrations of (i) P were higher in potato, cabbage and lettuce, (ii) K were higher in potato and cabbage and (iii) S concentrations were higher in potato and onion, when compared with NPK-fertilized crops. In contrast, in lettuce, S concentrations were lower when FYM was used as the fertilizer (Table 5).

Significant main effects of pre-crop were detected for P concentrations in cabbage (higher after winter barley), K concentrations in cabbage (higher after spring beans), and K and S concentrations in lettuce (higher after spring beans) (Table 5).

ANOVA also detected significant interactions between (i) crop protection and pre crop for P concentrations in onions and (ii) fertilizer type and pre-crop for S concentrations in lettuce (Table 5).

When the interaction between crop protection and pre-crops for P-concentrations in onion was further investigated, P-concentrations were found to be higher with conventional crop protection in crops grown after spring beans, but higher with organic crop protection in crops grown after winter barley (Table 6).

When the interaction between fertilizer type and pre-crop for S concentrations in lettuce was further investigated, S concentrations were higher in lettuce crops grown after spring beans when FYM was used as fertilizer, but higher in lettuce grown after winter barley when NPK was used as fertilizer (Table 7), although it should be noted that the differences between pre-crops were not significant in both NPK and FYM fertilized crops.

Table 5. Effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) and pre-crop (spring beans versus winter barley) on phosphorus (P), potassium and sulphur (S) in potato tubers, cabbage and lettuce heads and onion bulbs. Values shown are main effect means ± SE and are expressed on a fresh weight basis; significantly higher means are highlighted in bold.

Parameter	**Crop Protection (P)**		**Fertilizer Type (F)**		**Pre-Crop (PC)**							
Assessed	**CON**	**ORG**	**CON**	**ORG**	**Spring**	**Winter**	**Main Effects**			**2-Way Interactions**		
Crop Species	**(CP)**	**(OP)**	**(NPK)**	**(FYM)**	**Beans**	**Barley**	**P**	**F**	**PC**	**P × F**	**P × PC**	**F × PC**
P (μg/kg)												
Potato [1]	373 ± 6	380 ± 6	362 ± 6	**391** ± 5	373 ± 7	361 ± 9	NS	***	NS	NS	NS	T
Cabbage [2]	**326** ± 5	294 ± 5	293 ± 4	**327** ± 5	329 ± 7	**341** ± 6	***	***	*	T	NS	NS
Lettuce [3]	154 ± 3	153 ± 3	148 ± 3	**159** ± 3	164 ± 3	166 ± 3	NS	***	NS	NS	NS	NS
Onion [3]	261 ± 6	260 ± 8	258 ± 7	263 ± 7	282 ± 4	281 ± 5	NS	NS	NS	NS	** [4]	NS
K (mg/kg)												
Potato [1]	3.17 ± 0.06	3.15 ± 0.06	3.01 ± 0.05	**3.30** ± 0.06	2.9 ± 0.1	2.9 ± 0.1	NS	***	NS	NS	NS	T
Cabbage [2]	**1.98** ± 0.03	1.89 ± 0.03	1.80 ± 0.02	**2.08** ± 0.02	1.84 ± 0.04	**1.92** ± 0.05	***	***	**	NS	NS	NS
Lettuce [3]	1.17 ± 0.03	1.17 ± 0.03	1.16 ± 0.03	1.18 ± 0.03	0.94 ± 0.02	**1.07** ± 0.04	NS	NS	**	NS	NS	NS
Onion [3]	1.53 ± 0.03	1.55 ± 0.03	1.54 ± 0.03	1.54 ± 0.04	1.35 ± 0.03	1.41 ± 0.02	NS	NS	T	NS	NS	NS
S (μg/kg)												
Potato [1]	257 ± 3	257 ± 3	252 ± 3	**262** ± 3	256 ± 4	247 ± 5	NS	**	T	NS	NS	NS
Cabbage [2]	440 ± 13	420 ± 14	379 ± 13	481 ± 12	515 ± 14	515 ± 17	**	***	NS	NS	NS	** [4]
Lettuce [3]	67 ± 1	67 ± 1	**67** ± 1	66 ± 1	65 ± 1	**70** ± 1	NS	*	** [5]	NS	NS	NS
Onion [3]	339 ± 8	334 ± 10	316 ± 7	**357** ± 9	354 ± 10	342 ± 12	NS	***	NS	NS	NS	NS

CON, conventional; ORG, organic; CP, conventional crop protection protocols used; OP, organic crop protection protocols used; NPK, mineral NPK used as fertilizer; FYM, cattle farm yard manure used as fertilizer; NS, not significant; T, trend (0.1 > p > 0.05); *, 0.05 > p > 0.01; **, 0.01 > p > 0.001; ***, p < 0.001; [1], data for main effect means and the P × F interaction are from 9 growing seasons/years (2004, 2005, 2006, 2007,2008, 2009, 2010, 2011, 2012) while data for main effects of PC, and the P × PC and F × PC interactions are from 4 growing seasons (2006, 2007, 2010 and 2011); [2], data for main effects means of P and F and the P × F interactions are from 6 growing seasons (2004, 2005, 2006, 2007, 2008 and 2009) while data for the main effect of PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [3], data for the main effects of P and F and the P × F interaction are from 4 growing seasons (2004, 2005, 2006 and 2007), while data for PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [4], see Table 6 for interaction means ± SE; [5], see Table 7 for interaction means ± SE.

Table 6. Interaction means for the effect of crop protection protocols (organic versus conventional) and previous crop on phosphorus (P) concentrations in onion.

			Factor 2. Pre-Crop	
Crop Species	**Parameter Assessed**	**Factor 1. Crop Protection**	**Spring Beans**	**Winter Barley**
Onion	P (µg/kg)	Conventional	0.29 ± 0.01 a A	0.27 ± 0.01 b B
		Organic	0.28 ± 0.01 a B	0.29 ± 0.01 a A

Means labelled with the same lower-case letter within the same column and capital letter within the same row are not significantly different according to Tukey's HSDT ($p < 0.05$).

Table 7. Interaction means for the effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus cattle FYM) on sulphur (S) concentrations in cabbage.

			Factor 2. Pre-Crop	
Crop Species	**Parameter Assessed**	**Factor 1. Fertilizer Type**	**Spring Beans**	**Winter Barley**
Cabbage	Leaf S (µg/kg)	Cattle FYM	0.48 ±0.02 b A	0.46 ±0.03 b A
		Mineral NPK	0.55 ±0.01 a A	0.58 ±0.01 a A

Means labelled with the same lower-case letter within the same column and capital letter within the same row are not significantly different according to Tukey's HSDT, ($p < 0.05$).

3.5. Effect of Contrasting Agronomic Protocols on Nutritionally Relevant Phytochemicals

Significant main effects of crop protection were only detected for cabbage, with CP resulting in higher glucosinolate and vitamin B_9 concentrations in cabbage heads compared with OP (Table 8).

Significant main effects of fertilizer type were detected in potato, cabbage and lettuce, but not onion crops (Table 8). Specifically, the use of NPK resulted in significantly lower concentrations of (i) total phenolics in potato, cabbage and lettuce, (ii) glucosinolates in cabbage, (iii) carotenoids in cabbage, (iv) vitamin C in potato and cabbage, and (iv) vitamin B_9 concentrations in potato and lettuce when compared with concentrations in crops fertilized with FYM applied at the same total N-input level (Table 8).

A significant main effect of pre-crop was only detected for vitamin C concentrations in cabbage which were higher after winter barley compared with spring beans as pre-crop (Table 8). It is important to note that both spring beans (a N-fixing legume crop) and mineral NPK fertilizer (which is known to result in higher N-availability in soil compared with FYM applied at the same N-input level) resulted in lower vitamin C concentrations in cabbage.

ANOVA also detected a significant interaction between crop protection and fertilizer type for carotenoid concentrations in potato tubers (Table 8). OP resulted in significantly higher carotenoid concentrations when FYM was used as fertilizer, while there was no significant difference between the two crop protection regimes when NPK was used as the fertilizer (Table 9).

No other interactions were detected for nutritionally relevant phytochemicals assessed in harvested crops (Table 8).

Table 8. Effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) and pre-crop (spring beans versus winter barley) on the concentrations of (a) total phenolics (b) carotenoids, (c) vitamin C and (d) vitamin B_9 in potato tubers, cabbage and lettuce heads and onion bulbs, and (e) glucosinolates in cabbage heads. Values shown are main effect means ± SE and are expressed on a fresh weight basis; significantly higher means are highlighted in bold.

Parameter	Crop Protection (P)		Fertilizer Type (F)		Pre-Crop (PC)							
Assessed	CON	ORG	CON	ORG	Spring	Winter	Main Effects			2-Way Interactions		
Crop Species	(CP)	(OP)	(NPK)	(FYM)	Beans	Barley	P	F	PC	P × F	P × PC	F × PC
Phenolics (μg/g)												
Potato [1]	285 ± 14	293 ± 14	277 ± 13	**301** ± 14	253 ± 10	259 ± 8	NS	*	NS	NS	NS	NS
Cabbage [1,2]	11 ± 1	9 ± 1	9 ± 1	**12 ± 1**	9 ± 1	12 ± 1	T	**	NS	NS	NS	NS
Lettuce [1]	104 ± 9	109 ± 10	101 ± 8	**112** ± 10	89	99	NS	*	T	NS	NS	NS
Onion [1,3]	725 ± 50	721 ± 40	740 ± 46	706 ± 45	640 ± 40	641 ± 31	NS	NS	NS	NS	NS	NS
Glucosinolates (μg/g)												
Cabbage [1]	**1374** ± 108	1233 ± 104	1128 ± 92	**1479** ± 113	1432 ± 53	1670 ± 110	*	***	NS	NS	NS	NS
Carotenoids (μg/g)												
Potato [1]	0.70 ± 0.04	0.77 ± 0.05	0.73 ± 0.04	0.75 ± 0.04	0.78 ± 0.05	0.75 ± 0.04	T	NS	NS	* [4]	NS	NS
Cabbage [1]	3.5 ± 0.4	3.2 ± 0.4	3.0 ± 0.4	**3.7** ± 0.4	4.3 ± 0.4	4.8 ± 0.4	NS	**	NS	T	NS	NS
Lettuce [1]	4.4 ± 0.3	5.0 ± 0.4	4.5 ± 0.4	4.8 ± 0.3	4.10 ± 0.3	4.64 ± 0.3	T	NS	NS	NS	NS	NS
Onion [1]	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	NS	NS	NS	T	NS	T
Vitamin C (μg/g)												
Potato [1]	95 ± 4	97 ± 4	91 ± 4	**101** ± 4	105 ± 3	105 ± 3	NS	***	NS	NS	NS	NS
Cabbage [1]	224 ± 19	223 ± 19	211 ± 18	**236** ± 20	318 ± 14	**337** ± 14	NS	**	*	NS	NS	NS
Lettuce [1]	7 ± 1	7 ± 1	7 ± 1	7 ± 1	6 ± 1	6 ± 1	NS	NS	NS	NS	NS	NS
Onion [3]	100 ± 21	93 ± 13	86 ± 12	107 ± 22	115 ± 26	94 ± 15	NS	NS	NS	NS	NS	NS
Vitamin B_9 (μg/g)												
Potato [1]	0.17 ± 0.01	0.18 ± 0.01	0.17 ± 0.01	**0.18** ± 0.01	0.19 ± 0.01	0.19 ± 0.01	NS	***	NS	NS	NS	NS
Cabbage [1]	**0.44** ± 0.02	0.39 ± 0.02	0.41 ± 0.01	0.43 ± 0.02	0.426 ± 0.01	0.436 ± 0.02	**	T	NS	NS	NS	NS
Lettuce [1]	0.32 ± 0.38	0.35 ± 0.02	0.32 ± 0.02	**0.35** ± 0.02	0.33 ± 0.03	0.33 ± 0.03	T	*	NS	NS	NS	NS
Onion [1]	0.42 ± 0.05	0.44 ± 0.05	0.44 ± 0.05	0.42 ± 0.05	0.45 ± 0.06	0.45 ± 0.05	NS	NS	NS	NS	NS	NS

CON, conventional; ORG, organic; CP, conventional crop protection protocols used; OP, organic crop protection protocols used; NPK, mineral NPK used as fertilizer; FYM, cattle farm yard manure used as fertilizer; NS, not significant; T, trend ($0.1 > p > 0.05$); *, $0.05 > p > 0.01$; **, $0.01 > p > 0.001$; ***, $p < 0.001$; [1], data for main effect means and the P × F interaction are from 3 growing seasons/years (2005, 2006 and 2007), while data for main effects of PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007); [2], total hydroxycinnamic acid derivatives; [3], flavonoids; [4], see Table 9 for interaction means ± SE.

Table 9. Interaction means for the effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) on tuber carotenoid concentrations in potato.

			Factor 2. Fertilizer Type	
Crop Species	**Parameter Assessed**	**Factor 1. Crop Protection**	**Conventional (Mineral NPK)**	**Organic (Cattle FYM)**
Potato	Tuber carotenoids (μg/g)	Conventional	0.73 ± 0.06 a A	0.67 ± 0.04 b A
		Organic	0.72 ± 0.05 a A	0.83 ± 0.07 a A

Means labelled with the same lower-case letter within the same column and capital letter within the same row are not significantly different according to Tukey's HSDT ($p < 0.05$).

3.6. Effect of Contrasting Agronomic Protocols on Concentrations of Toxic Metals (Cd, Ni, Pb) and Glycoalkaloids

A significant main effects of crop protection was only detected for Ni in cabbage, which was found to be higher with CP compared with OP (Table 10).

Significant main effects of fertilization were detected for Cd in all crops and Ni in potato, cabbage and onion, and for glycoalkaloids in potato, with concentrations found to be higher with NPK compared with FYM applied at the same total N-input level (Table 10).

It is interesting to note that the relative effect of fertilization on Cd concentrations differed between crops (Table 10). Specifically, Cd concentrations were 50, 46, 25 and 17% higher in mineral NPK-fertilized crops of potato, onion, lettuce and cabbage, respectively.

Significant main effects of pre-crop were only detected for Cd in lettuce, which was found to be higher with winter barley compared with spring beans as the pre-crop (Table 10), although trends towards significance for higher Cd concentrations in crops grown after winter barley were also detected for potato and onion (Table 10). It is important to note that winter barley pre-crops were fertilized (mineral NPK or FYM) while no fertilizers were applied to spring bean pre-crops.

ANOVA detected no significant interactions between factors for the 3 toxic metals monitored in the study (Table 10).

It is also important to highlight that Pb-concentrations in harvested crops were not affected by any of the agronomic factors (crop protection, fertilizer type, pre-crop) (Table 10).

Table 10. Effect of crop protection protocols (organic versus conventional), fertilization (mineral NPK versus farmyard manure) and pre-crop (spring beans versus winter barley) on the concentrations of the toxic metals cadmium (Cd), nickel (Ni) and lead (Pb) in potato tubers, cabbage and lettuce heads and onion bulbs, and glycoalkaloids in potato tubers. Values shown are main effect means ± SE and are expressed on a fresh weight basis; significantly higher means are highlighted in bold.

Parameter	Crop Protection (P)		Fertilizer Type (F)		Pre-Crop (PC)							
Assessed	CON	ORG	CON	ORG	Spring	Winter	Main Effects			2-Way Interactions		
Crop Species	(CP)	(OP)	(NPK)	(FYM)	Beans	Barley	P	F	PC	P × F	P × PC	F × PC
Cd (μg/kg)												
Potato [1]	31 ± 2	32 ± 3	**39** ± 3	24 ± 1	29 ± 1	38 ± 5	NS	***	T	NS	NS	NS
Cabbage [2]	5.2 ± 0.2	4.8 ± 0.2	**5.4** ± 0.2	4.6 ± 0.2	5.5 ± 0.2	5.9 ± 0.2	T	***	NS	T	NS	NS
Lettuce [3]	12.6 ± 0.5	13.1 ± 0.5	**14.2** ± 0.5	11.4 ± 0.4	12.4 ± 0.4	**13.1** ± 0.4	NS	***	*	NS	NS	NS
Onion [3]	16 ± 1	16 ± 1	**19** ± 1	13 ± 1	14 ± 1	17 ± 1	NS	***	T	NS	NS	NS
Ni (μg/kg)												
Potato [1]	52 ± 4	53 ± 4	**59** ± 4	46 ± 4	55.6 ± 4.9	54.5 ± 4.9	NS	**	NS	NS	NS	NS
Cabbage [2]	**21** ± 1	19 ± 1	**23** ± 1	17 ± 1	27 ± 1	27 ± 1	*	***	NS	NS	NS	NS
Lettuce [3]	19 ± 1	20 ± 1	20 ± 1	19 ± 1	19 ± 1	19 ± 1	NS	NS	NS	T	NS	NS
Onion [3]	37 ± 2	35 ± 2	**38** ± 2	34 ± 2	34 ± 3	34 ± 3	NS	*	NS	NS	NS	NS
Pb (μg/kg)												
Potato [1]	21 ± 2	31 ± 10	23 ± 2	30 ± 11	14 ± 1	15 ± 1	NS	NS	NS	NS	NS	NS
Cabbage [2]	6.0 ± 0.6	5.2 ± 0.5	5.4 ± 0.5	5.8 ± 0.6	7.1 ± 0.8	7.5 ± 1.1	NS	NS	NS	NS	NS	NS
Lettuce [3]	8.0 ± 0.9	9.3 ± 1.2	8.0 ± 0.9	9.3 ± 1.2	4.8 ± 0.5	5.7 ± 0.8	NS	NS	NS	NS	NS	NS
Onion [3]	13.5 ± 1.8	14.3 ± 2.6	14.5 ± 2.5	13.4 ± 2.0	7.0 ± 0.9	8.2 ± 1.1	NS	NS	NS	NS	NS	NS
Glycoalka- loids (μg/g)												
Potato [1]	42 ± 2	40 ± 1	**45** ± 2	37 ± 1	37 ± 2	37 ± 2	NS	***	NS	NS	NS	NS

CON, conventional; ORG, organic; CP, conventional crop protection protocols used; OP, organic crop protection protocols used; NPK, mineral NPK used as fertilizer; FYM, cattle farm yard manure used as fertilizer; NS, not significant; T, trend (0.1 > p > 0.05); *, 0.05 > p > 0.01; **, 0.01 > p > 0.001; ***, p < 0.001; [1], data for main effect means and the P × F interaction are from 7 growing seasons/years (2004, 2005, 2006, 2007, 2010, 2011 and 2012) while data for main effects of PC, and the P × PC and F × PC interactions are from 4 growing seasons (2006, 2007, 2010 and 2011); [2], data for main effect means and the P × F interaction are from 6 growing seasons/years (2004, 2005, 2006, 2007, 2008 and 2009) while data for main effects of PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006, 2007); [3], data for main effect means and the P × F interaction are from 4 growing seasons/years (2004, 2005, 2006 and 2007) while data for main effects of PC, and the P × PC and F × PC interactions are from 2 growing seasons (2006 and 2007).

3.7. Associations between Environmental and Agronomic Parameters and Crop Yield and Selected Nutritional Quality Parameters

The unique design of the NFSC-trials allowed the associations between environmental and agronomic explanatory variables/drivers and crop yield and quality to be compared for four crop species under the same climatic conditions in three growing seasons.

A sequence of redundancy analyses (RDAs) was carried out to estimate and compare the relative importance of environmental (radiation, temperature and precipitation) and agronomic (crop protection, fertilization) explanatory variables/drivers for yields and nutritional composition in the four different vegetable crops. Previous crop could not be included as an explanatory variable in the RDAs, because only two years of data were available for pre-crop effects.

The initial "exploratory" RDAs used organic and conventional fertilization and crop protection protocols as the agronomic explanatory variables/drivers, and (a) crop yield and selected (b) toxic metals (Cd, Ni, Pb) and (c) phytochemicals (total phenolics and/or flavonoids, vitamin C and folate for all four crops, for cabbage also total glucosinolates, and for potato also total glycoalkaloids) as response variables (Supplementary Table S7).

The initial RDAs showed that (i) only environmental factors and fertilization protocols were significant ($p < 0.05$) explanatory variables/drivers, (ii) climatic background conditions explain a substantially larger proportion of the total variation in crop yield and the nutritional composition than fertilization protocols in all crops, (iii) the environmental driver which explained the largest amount of variation differed between crops, and (iv) the proportion of variation explained by fertilization differed between crops (Supplementary Table S7). Specifically, precipitation was the strongest driver in potato, lettuce and onion crops, while radiation and temperature were the strongest drivers in cabbage crops. Additionally, the amount of variation explained by fertilization was higher in potato than cabbage and lowest in lettuce and onion (Supplementary Table S7).

Since the exploratory RDAs identified the contrasting fertilizer types as significant ($p < 0.05$) explanatory variables, we subsequently carried out additional RDAs in which we used the N, P, and K supply/availability from either mineral NPK or cattle manure (estimated from the nutrient concentrations in harvested crop tissues) and crop protection protocols as the agronomic explanatory variables/drivers (Supplementary Table S8).

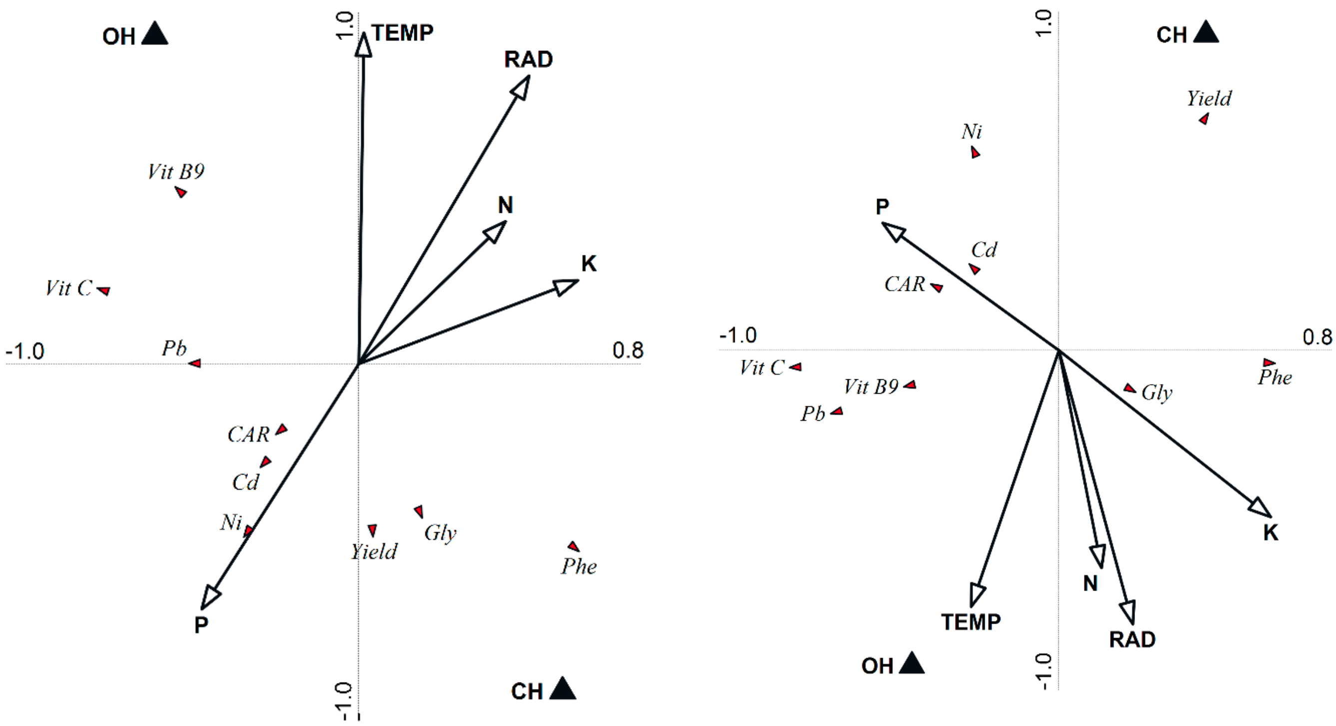
When data from NPK and FYM fertilized crops were analyzed separately by RDA, the explanatory variables that explained most of the variation and were identified as significant ($p < 0.05$), differed (i) between crops and (ii) for crops or the same vegetable species produced with different fertilizer types (Supplementary Table S8). The results of RDAs for different crops are therefore described in separate sections below.

3.7.1. Potato

Radiation, K-availability, temperature and crop protection were identified as significant explanatory variables in both NPK and FYM fertilized crops, with radiation and K-availability explaining the largest amount of variation (Supplementary Table S8; Figure 1). There was also a trend ($p = 0.09$) towards N-availability being a significant driver in FYM, but not NPK-fertilized crops (Supplementary Table S8; Figure 1).

For potato the overall trends for associations between explanatory and response variables shown in bi-plots resulting from the RDA were similar in NPK and FYM-fertilized crops (Figure 1).

Potato was also the only crop in which crop protection was identified as a significant driver (Table 10). Tuber yield was positively associated with conventional crop protection along axes 1 and 2 in both NPK and FYM-fertilized potato crops. In contrast, concentrations of vitamin C and B_9 were positively associated with organic crop protection protocols along axis 1 in both NPK and FYM-fertilized crops (Figure 1).



Potato—mineral NPK-fertilizer Potato—composted cattle manure

Figure 1. Biplots derived from the redundancy analysis showing the relationship between environmental (radiation, air temperature, precipitation) and agronomic (N, P and K availability/supply, crop protection protocols) explanatory variables/drivers, and total tuber yield (yield), and concentrations of the toxic metals cadmium (Cd), Nickel (Ni) and lead (Pb), total phenolics (Phe), total carotenoids (CAR), Vitamin C (Vit C), Vitamin B_9 (Vit B_9), and toxic glycoalkaloids (Gly) in potato tubers harvested in experimental plots fertilized with either (a) mineral NPK fertilizer or (b) composted cattle manure applied at the same N-level. **Fixed explanatory variables** are shown as black triangles (▲) and were (a) conventional crop protection protocols (CH) and (b) organic crop protection protocols (OH). **Continuous explanatory variables** are shown as black arrows and were: (a) radiation (RAD), (b) air temperature (TEMP), precipitation (PRE, not computed), (d) N-availability (N), (e) P-availability (P), and K-availability (K). See Supplementary Table S8 for the % variation explained by, and F-values and p-values of the explanatory variables/drivers. In the biplot based on data from mineral NPK-fertilized crops 30% of variation is explained by the horizonal axis 1 and a further 8% by the vertical axis 2. In the biplot based on data from composted cattle manure-fertilized crops 41% of variation is explained by the horizontal axis 1 and a further 9% by the vertical axis 2.

Tuber yield and phenolic and glycoalkaloid concentrations were positively associated with radiation and both K and N availability along axis 1 (Figure 1). In contrast, concentrations of vitamin C, vitamin B_9, carotenoids, Cd, Ni and Pb were negatively associated with radiation, and both K and N-availability along axis 1 (Figure 1).

Concentrations of Cd and Ni in potato tubers were positively associated with P-availability along axes 1 and 2, although it should be noted that P-availability was not identified as a significant driver (Figure 1).

It should be noted that ANOVA found that late blight severity was lower when crops were grown with conventional crop protection (Table 1) and this may have confounded the associations with both climatic and agronomic explanatory variables identified by RDA.

3.7.2. Cabbage

In NPK-fertilized cabbage crops temperature and precipitation were the only significant ($p < 0.05$) explanatory variables identified by RDA and explained most of the variation

(Supplementary Table S8; Figure 2). In contrast, in FYM-fertilized crops radiation, precipitation and K-availability were identified as significant explanatory variables by RDA and K-availability explained the largest amount of the variation (Supplementary Table S8; Figure 2).

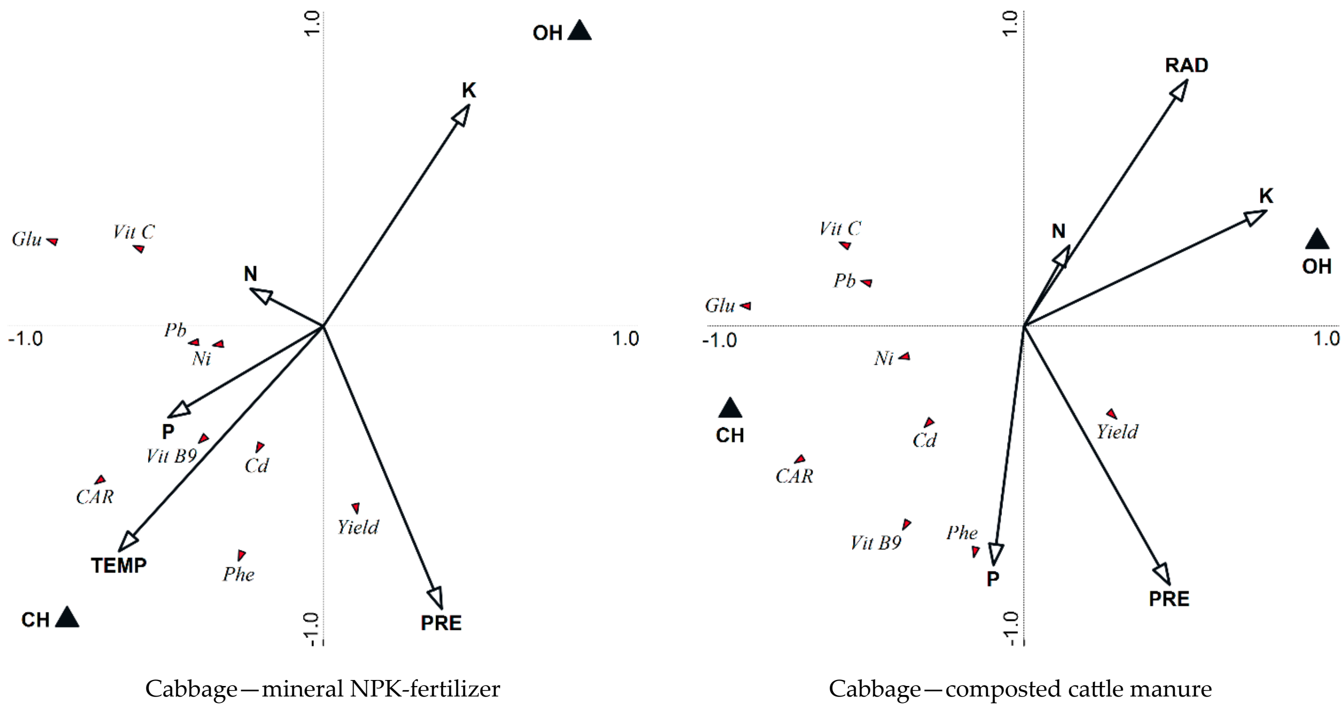


Figure 2. Biplot derived from the redundancy analysis showing the relationship between environmental (radiation, air temperature, precipitation) and agronomic (N, P and K availability/supply, crop protection protocols) explanatory variables/drivers, and total cabbage yield and concentrations of the toxic metals cadmium (Cd), Nickel (Ni) and lead (Pb), total phenolics (Phe), total carotenoids (CAR), glucosinolates (Glu), vitamin C (Vit C), Vitamin B_9 (Vit B_9) in cabbage heads harvested in experimental plots fertilized with either (a) mineral NPK fertilizer or (b) composted cattle manure applied at the same N-level. **Fixed explanatory variables** are shown as black triangles (▲) and were (a) conventional crop protection protocols (CH) and (b) organic crop protection protocols (OH). **Continuous explanatory variables** are shown as black arrows and were: (a) radiation (RAD), (b) air temperature (TEMP), precipitation (PRE), (d) N-availability (N), (e) P-availability (P), and K-availability (K). See Supplementary Table S8 for the % variation explained by, and F-values and *p*-values of the explanatory variables/drivers. In the biplot based on data from mineral NPK-fertilized crops 39% of variation is explained by the horizonal axis 1 and a further 13% by the vertical axis 2. In the biplot based on data from composted cattle manure-fertilized crops 41% of variation is explained by the horizontal axis 1 and a further 10% by the vertical axis 2.

Cabbage head yield was closely positively associated with (a) precipitation along both axes 1 and 2 and (b) K-availability along axis 1 in both NPK and FYM-fertilized crops (Figure 2). However, in FYM-fertilized crops, yield was also positively associated with radiation along axis 1, whereas in NPK-fertilized crops, yield was also negatively associated with temperature along axis 1 (Figure 2).

In NPK-fertilized crops, Cd, Ni and Pb concentrations were positively associated with temperature along axis 1 (Figure 2). In contrast, in FYM-fertilized crops toxic metal concentrations were negatively associated with radiation and precipitation along axis 1 (Figure 2).

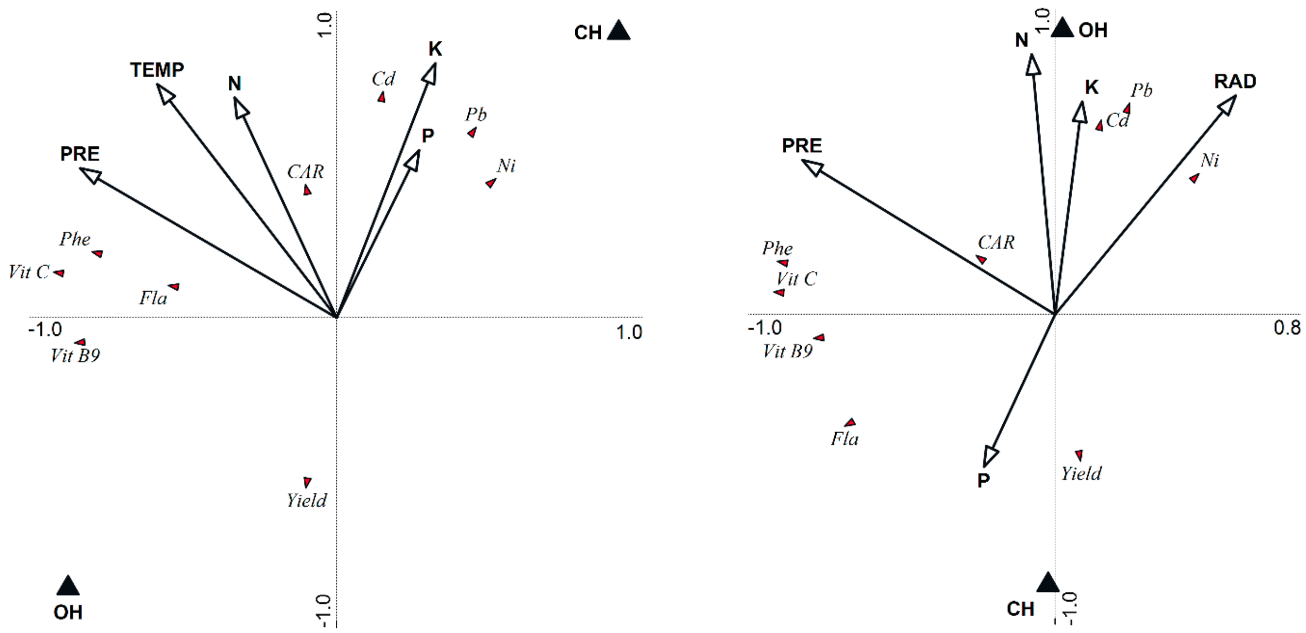
Concentrations of Cd and Ni in cabbage heads were also positively associated with P-availability along both axes 1 and 2 in both NPK and FYM-fertilized crops, although it should be noted that P-availability was not identified as a significant driver (Figure 2).

In NPK-fertilized crops concentrations of total phenolics, glucosinolates, carotenoids, vitamin C and vitamin B_9 were positively associated with temperature, but negatively associated with precipitation along axis 1 (Figure 2). In contrast, in FYM-fertilized crops, concentrations of these secondary plant metabolites were negatively associated with radiation, precipitation and K-availability (Figure 2).

It should be noted that ANOVA found that cabbage root fly infestation was lower when crops were grown with organic crop protection (which was based on applying insect proof crop covers) and FYM as fertilizer (Table 1) and that this may have confounded the associations with both climatic and agronomic explanatory variables identified by RDA.

3.7.3. Lettuce

In NPK-fertilized lettuce crops temperature and precipitation were the only significant ($p < 0.05$) explanatory variables identified by RDA and explained most of the variation (Supplementary Table S10; Figure 3). In contrast, in FYM-fertilized crops radiation, precipitation and both P and N-availability were identified as significant explanatory variables by RDA, although the two environmental drivers explained the largest amount of variation (Supplementary Table S8; Figure 3).



Lettuce—mineral NPK-fertilizer Lettuce—composted cattle manure

Figure 3. Biplot derived from the redundancy analysis showing the relationship between environmental (radiation, air temperature, precipitation) and agronomic (N, P and K availability/supply, crop protection protocols) explanatory variables/drivers, and total lettuce yield and concentrations of the toxic metals cadmium (Cd), Nickel (Ni) and lead (Pb), total phenolics (Phe), total flavonoids (Fla), total carotenoids (CAR), vitamin C (Vit C), Vitamin B_9 (Vit B_9) in lettuce heads harvested in experimental plots fertilized with either (a) mineral NPK-fertilizer or (b) composted cattle manure applied at the same N-level. **Fixed explanatory variables** are shown as black triangles (▲) and were (a) conventional crop protection protocols (CH) and (b) organic crop protection protocols (OH). **Continuous explanatory variables** are shown as black arrows and were: (a) radiation (RAD), (b) air temperature (DD), precipitation (PRE), (d) N-availability (N), (e) P-availability (P), and K-availability (K). See Supplementary Table S8 for the % variation explained by, and F-values and *p*-values of the explanatory variables/drivers. In the biplot based on data from mineral NPK-fertilized crops 30% of variation is explained by the horizonal axis 1 and a further 8% by the vertical axis 2.

In NPK-fertilized crops, lettuce head yield was weakly positively associated with temperature and precipitation along the negative axis 1 (which explained 30% of variation), while there was a negative association between the 2 environmental drives and yield along axis 2 (which explained 8% of the variation) (Figure 3).

In contrast, in FYM-fertilized crops, yield was negatively associated with precipitation and N-availability along both axis 1 and 2. Additionally, yield was positively associated with radiation along the axis 1 (which explained 56% of variation), but negatively along axis 2 (which explained 15% of variation) (Figure 3). Yield was negatively associated with P-availability along axis 1, but positively along axis 2.

In the biplot based on data from composted cattle manure-fertilized crops 56% of variation is explained by the horizontal axis 1 and a further 15% by the vertical axis 2.

In NPK-fertilized crops, phenolic, carotenoid, vitamin C and vitamin B_9 concentrations were positively associated, while Cd, Pb and Ni concentrations were negatively associated with temperature and precipitation along axis 1. In contrast, in FYM-fertilized crops, phenolic, carotenoid, vitamin C and vitamin B_9 concentrations were positively associated with precipitation, but negatively associated with radiation along axis 1, while toxic metal concentrations were positively associated with radiation and negatively associated with precipitation along axis 1 (Figure 3).

Concentrations of Cd, Ni and Pb in cabbage heads were positively associated with P-availability in mineral NPK, but negatively in FYM-fertilized crops along axis 1, although it should be noted that P-availability was only identified as a significant driver in cattle manure fertilized crops (Figure 3).

It should be noted that ANOVA found that *Sclerotinia* incidence was lower when crops were grown with organic crop protection, FYM as fertilizer and with winter barley as the preceding crop (Table 1) and this may have confounded the associations with both climatic and agronomic explanatory variables identified by RDA.

3.7.4. Onion

In NPK-fertilized onion crops, temperature, precipitation and K-availability were identified as significant explanatory variables, but only temperature and precipitation explained a large amount of variation (Table 10). In contrast, in FYM-fertilized onion crops only radiation and precipitation were identified as significant drivers and explained most of the variation (Table 10).

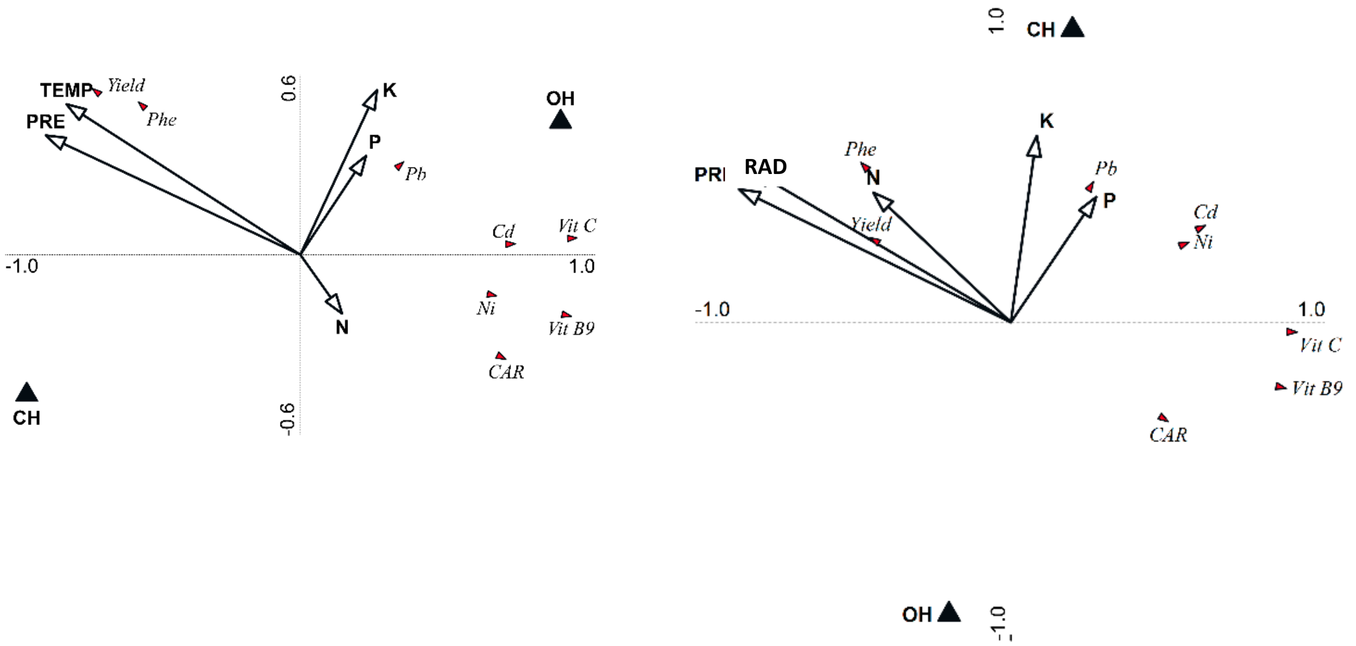
Onion bulb yields were positively associated with (a) precipitation and temperature in NPK-fertilized and (b) precipitation and irradiation in FYM-fertilized crops along axis 1 (Figure 4). In NPK-fertilized crops yields were also negatively associated with K-availability (Figure 4).

Although N and P-availability were not identified as significant drivers, it should be noted that N-availability was negatively associated with yield in NPK-fertilized, but positively in FYM-fertilized crops (Figure 4), while yield was negatively associated with K and P-availability in both NPK and FYM-fertilized crops (Figure 4).

Phenolic concentrations were positively associated with (a) precipitation and temperature in NPK-fertilized and (b) precipitation and irradiation in FYM-fertilized crops along axis 1, while the reverse was found for carotenoid, vitamin C and vitamin B_9 concentrations (Figure 4).

Cd, Ni and Pb concentrations in onion bulbs were negatively associated with (a) precipitation and temperature in NPK-fertilized and (b) precipitation and irradiation in FYM-fertilized crops along axis 1 (Figure 4). In both NPK and FYM-fertilized crops, toxic metal concentrations were positively associated with P and K-availability, although it should be noted that (a) P-availability was not identified as a significant driver and (b) K-availability was only found to be a significant driver in NPK-fertilized crops (Figure 4).

It should be noted that in onion crops, disease and pest incidence was very low, and not affected by crop protection, fertilizer type and previous crop (Table 10). This allowed associations between climatic and agronomic explanatory variables and crop yield and quality to be assessed without confounding effects of differences in crop health.



Onion—mineral NPK-fertilizer Onion—composted cattle manure

Figure 4. Biplot derived from the redundancy analysis showing the relationship between environmental (radiation, air temperature, precipitation) and agronomic (N, P and K availability/supply, crop protection protocols) explanatory variables/drivers, and total onion yield and concentrations of the toxic metals cadmium (Cd), Nickel (Ni) and lead (Pb), total phenolics (Phe), total carotenoids (CAR), Vitamin C (Vit C), Vitamin B_9 (Vit B_9) in onion bulbs harvested in experimental plots fertilized with either (a) mineral NPK fertilizer or (b) composted cattle manure applied at the same N-level. **Fixed explanatory variables** are shown as black triangles (▲) and were (a) conventional crop protection protocols (CH) and (b) organic crop protection protocols (OH). **Continuous explanatory variables** are shown as black arrows and were: (a) radiation (RAD), (b) air temperature (TEMP), precipitation (PRE), (d) N-availability (N), (e) P-availability (P), and K-availability (K). See Supplementary Table S8 for the % variation explained by, and F-values and *p*-values of the explanatory variables/drivers. In the biplot based on data from mineral NPK-fertilized crops 67% of variation is explained by the horizonal axis 1 and a further 5% by the vertical axis 2. In the biplot based on data from composted cattle manure-fertilized plot 60% of variation is explained by the horizontal axis 1 and a further 7% by the vertical axis 2.

4. Discussion

The long-term Nafferton Factorial Systems Comparison (NFSC) trials were designed to allow the simultaneous comparison of crop health, yield and nutritionally relevant composition parameters in (a) arable crops (cereals, faba beans, grass/clover) and (b) four important field vegetable crops under contrasting agronomic and climatic background conditions. The long-term, factorial design of the experiment also allowed, for the first time, a comparison of the relative effects of (i) agronomic practices (rotation design, crop protection, and fertilization) used and (ii) climatic parameters on crop performance in conventional and organic farming systems.

The initial redundancy analyses (RDA) showed that the environmental/climatic conditions explained a larger proportion of the variability in crop yields and nutritional composition than the fertilizer input types and crop protection protocols compared in the NFSC trials. This suggests that the climate changes predicted due to global warming may have a larger impact on crop yields and quality than the changes to agronomic practices designed to (i) reduce the use of non-renewable resources and (ii) minimize the negative environmental impacts resulting from agrochemical use in field vegetable production. For example, precipitation explains the largest proportion of variation in potato crops (a staple food crop in the UK) in this study; this supports a previously published prediction that changes in precipitation pattern in the UK resulting from global climate change may reduce potato yields and/or increase the need for supplementary irrigation in the UK [43].

Detailed studies into the potential effects of global climate change on (i) cabbage, onion and lettuce yields and (ii) the nutritional quality in all four crops in the UK are not currently available. However, in this study precipitation also explained the largest amount of variation in the (i) initial RDA for lettuce and onion and (ii) separate RDA for NPK and FYM-fertilized cabbage crops. This suggests that the changing and more extreme precipitation pattern predicted for the UK may have similar impacts in cabbage, lettuce and onion production.

It is also important to consider that results from both the ANOVA and RDA demonstrated that the effects of both climatic and agronomic factors/variables on the crop health, yield and nutritional composition parameters differed substantially between crops.

Results for (i) crop yield and health and (ii) phytochemicals and (iii) toxic metal composition parameters are discussed in detail in Sections 4.1–4.3, respectively, below, followed by a discussion of potential reasons for contrasting associations between climatic drivers and crop performance in (iv) different crops species (Section 4.4) and (v) the same vegetable species produced using FYM or mineral NPK fertilizer (Section 4.5). Study limitations are described in Section 4.6.

4.1. Crop Health and Yield

4.1.1. Potato

Most previous studies that compared potato yields in conventional and organic production systems generally reported substantially lower yields in organic systems [44]. Additionally, previously published results from the NFSC trial demonstrated that the yield gap between conventional and organic farming systems was due to both less efficient crop protection and fertilization in organic systems [27], and this was confirmed by the analysis reported here.

The higher late blight incidence in crops grown under organic crop protection found in this study is consistent with previous published results from the NFSC trial [27] and other studies carried out as part of the EU projects Blight-MOP, QualityLowInputFood and NUE-crops [45–50]. In this study, (i) late blight severity was three times higher with organic compared with conventional crop protection regimes and (ii) there was a strong positive association between conventional crop protection and tuber yields. This suggests that the yield gap associated with crop protection was primarily due to the use of more effective, synthetic chemical fungicides for blight control in conventional production; late blight control in organic systems is based on crop protection products (e.g., Cu-fungicide, clay or compost extract sprays) that are known to be less efficient [27,45,46].

Previous studies concluded that the yield gap associated with fertilization is mainly due to lower supply/availability of N from FYM compared with NPK [27,47,48], which is supported by the finding of lower leaf chlorophyll and tuber N content in FYM-fertilized potato crops in this study, although RDA results suggest that K was the main macronutrient limiting yield in both NPK and FYM-fertilized crops.

There is published evidence that the yield gap between organic and conventional potato production may be narrowed via a range of approaches [44,48–50]. Most importantly, studies in both temperate and semi-arid regions have demonstrated the potential to increase organic potato yields via the use of more blight-resistant potato varieties [45,49,50]. However, it should be noted that these studies also reported that most currently available highly blight resistant potato varieties (i) are late-maturing and only suitable for long-season, main-crop potato production and (ii) may not always satisfy sensory and processing quality expected by consumers [45,49,50]. It is also interesting to note that high levels of blight resistance in some varieties were shown to be associated with lower levels of potato beetle infestation damage, which, similar to late blight, is more challenging to control in organic systems [50]. Pre-sprouting of seed tubers, optimization of planting dates and density was also shown to reduce late blight pressure and/or improve yields in organic potato production [51].

It is more difficult to envisage approaches/strategies that may close the yield gap associated with fertilization, because (i) FYM inputs used for organic crops were equivalent to 250 kg N/ha which is the maximum manure input allowed in a given year under EU environmental legislation for nitrate sensitive zones [8] and (ii) research efforts focused on breeding more nutrient use efficient potato varieties have only recently started [46,47]. Additionally, although previous studies showed that growing potato directly after grass clover leys to further increase N-availability may increase total tuber yields in organic production systems, it also increases the risk of tuber damage by soil pests such as wireworms, which reduces marketable tuber yields [27].

However, it should also be noted that the yield gap may also narrow due to (i) regulatory restrictions on the use of pesticides in conventional production (e.g., the recent prohibition of aldicarb for nematode/soil pest control) and (ii) the development of resistance against commonly used pesticides (e.g., fungicides used for late blight control) [52–54].

4.1.2. Cabbage, Lettuce and Onion

Different to potato, most previous studies comparing cabbage, lettuce and onion yields in organic and conventional production reported no or only small (~10%) yield differences between the two production systems [44,55,56], which is consistent with the results reported in this study. However, this is, to our knowledge, the first study in which the specific effects of (i) rotation designs (ii), crop protection protocols and (iii) fertilization regimes used in organic and conventional production on crop health and yields was investigated for these vegetable species.

The results of both the crop health and yield assessments were particularly surprising, since they identified no significant benefit of using conventional crop protection on pest and disease severity or crop yields, although it is widely assumed that the use of synthetic chemical pesticides is essential to maintain current crop health and yield levels [57,58].

The finding that conventional crop protection resulted in higher pest damage in cabbage and *Sclerotinia* incidence in lettuce was particularly surprising, because it suggests that the organic, prevention-focused crop protection protocols were more efficient. The use of insect-proof crop covers is increasingly recognized to be a very effective method to prevent bird and invertebrate pest damage in brassicas and other field vegetables. For example, insect-proof crop covers are now not only widely used in organic, but also conventional production of *Brassica* crops for which supermarkets have set a very low threshold for CRF damage or no off-license pesticides are registered/available for CRF control (e.g., swedes/rutabaga) [59]. The reasons for the higher incidence of *Sclerotinia* in lettuce crops under conventional crop protection (which included fungicide applications) remains unclear, but may have been due to fungicide resistance development within the local *Sclerotinia* population; fungicides are widely used for *Sclerotinia* control in oil seed rape, which is the main break crop in arable rotation in northern Britain [8–10].

In contrast, the finding that the use of mineral NPK fertilizer resulted in higher yields compared with FYM applied at the same N-input level in cabbage and lettuce was not surprising, since similar results were previously reported for both wheat and potato [8,9,27], and also, found for potato in this study. Results from the RDA may indicate that insufficient K-supply from FYM was the main explanatory variable in cabbage, while an imbalance in N and P supply from FYM was responsible for lower yield in lettuce, but these hypotheses will have to be confirmed in future studies.

The finding of higher levels of CRF infestation in cabbage and *Sclerotinia* disease incidence in lettuce in mineral NPK compared with FYM-fertilized crops is consistent with previous studies which reported that high mineral N fertilizer inputs result in higher disease severity and/or an inhibition of plant resistance responses to biotrophic diseases/pests [8–10,27,60].

However, in cabbage the lower CRF damage in FYM compared with NPK-fertilized plots may also have been due to higher levels of competition/predation of CRF eggs/maggots in FYM-fertilized soils. This view is supported by a previous study, which reported that the population density of predatory ground beetles is significantly higher in FYM compared with NPK-fertilized plots in the NFSC trial [61,62].

The finding that growing lettuce after a legume pre-crop (spring beans) resulted higher *Sclerotinia* incidence compared with lettuce grown after a cereal (winter barley) may have also been due to higher N-availability (due to N-fixation by spring beans crops). However, this may also have been, at least partially, due to a higher *Sclerotinia* inoculum being present in soil after beans, since *Sclerotinia* is known to be an important pathogen in both beans and lettuce, but not barley [63]. However, the trend towards higher lettuce yields with spring beans as pre-crop, suggests that the positive effects of higher N-availability from a legume pre-crop outweighed negative impacts of higher disease severity.

The finding that in onion no effects of preceding crop and fertilizer input type were detected for (i) bulb yields and N-concentrations and (ii) phytochemical concentrations suggests that both (i) the organic (cattle FYM equivalent to 170 kg N/ha) and (ii) conventional (150 kg N/ha, 100 kg P_2O_5/ha and 150 kg K_2O/ha) fertilization regime allowed optimum yields and quality to be achieved.

This view is supported by the results from a supplementary experiment which investigated the effect of different organic fertilizer types and input levels on onion yields, because the study showed that in onion crops grown in a fertile soil after a one-year clover ley, additional FYM inputs will not significantly increase crop yields. Results from the experiments reported here are also broadly consistent with a recent Polish study which compared onion yields and quality achieved by (i) a standards mineral N-fertilizer treatment (100 kg N/ha) and (ii) two organic fertilizer input types (red clover pellets, alfalfa pellets) applied at 3 total N-input levels (120, 180 and 240 kg N/ha) [64]. Specifically, this study found (i) no significant yield differences between the mineral N-control and organic fertilizers applied at the lowest input level, (ii) no significant yield difference between organic fertilizers applied at different N-input levels, and (iii) slightly, but significantly lower yields in mineral N-fertilized crops compared with the two higher organic fertilizer input levels [64].

4.2. Phytochemicals

This is to our knowledge the first study that investigated the effects of contrasting pre-crops, crop protection and fertilization regimes (typically used in organic and conventional production) on the nutritionally relevant phytochemical and toxic metal concentrations in field vegetable crops.

The finding that significant effects of crop protection were only detected in cabbage crops (which had significantly lower concentrations of glucosinolates (the dominant group of phenolics found in cabbages) and vitamin B_9 when produced with organic crop protection protocols) was interesting because cabbage was also the only crop in which (i) organic crop protection resulted in significantly lower leaf nitrogen and chlorophyll concentrations and (ii) insect-proof crop covers were used as part of the organic, but not the conventional crop protection protocol. This may suggest that the reduction in glucosinolate and vitamin B_9 concentrations was part of the physiological response of cabbage plants to the well-documented changes in solar radiation, temperature, air velocity and/or relative humidity that result from the application of crop covers [65]. It is also important to note that a previous study with wheat reported that organic crop protection (which did not include the applications of crop covers) resulted in significantly higher total leaf phenolic acids concentrations (the dominant phenolics found in wheat) compared with conventional crop protection [10].

However, the finding that the use of NPK as fertilizer resulted in (i) higher N concentrations in potato tubers and cabbage and lettuce heads, but (ii) lower phenolic concentrations in potato, cabbage and lettuce, (iii) lower glucosinolate concentrations in cabbage, (iv) lower vitamin C concentrations in potato and cabbage, and (v) lower vitamin B_9 concentrations in potato and lettuce, was not surprising, since there has been mounting evidence that high mineral N-fertilizer inputs result in a down-regulation of the synthesis of certain secondary metabolites in plants and especially phytochemicals (e.g., phenolics) that are part of constitutive and inducible resistance responses to biotic or abiotic stress factors [8–10,60,66]. The finding that glucosinolate concentrations were significantly lower in cabbages grown after spring beans compared with winter barley also supports the conclusion that high N-availability was the main driver for lower phytochemical phenolic concentrations. These results also provide further evidence for the hypothesis that the higher phenolic concentrations and total antioxidant activity found in organic crops is mainly due to the non-use of mineral N-fertilizer [8–10,22–25].

It is important to point out that except for glucosinolate concentrations in cabbage (which were 31% higher in FYM-fertilized crops) the significant differences in phenolic, carotenoid and other phytochemical concentrations between NPK and FYM-fertilized crops were between 6 and 23%, which is consistent with many previous studies which reported significantly higher phenolic and vitamin concentrations, and/or antioxidant activity in organic compared with conventional vegetable crops [8,22–25,67]. Additionally, when comparing the composition of cabbages from organic versus conventional production systems, it is important to consider that the 31% higher glucosinolate concentrations resulting from organic, FYM-based fertilization regimes were partially offset by the 11% lower glucosinolate concentrations resulting from organic crop protection protocols (that included the application of insect-proof crop covers) in this study.

Different to the nutritionally desirable phytochemicals discussed above, concentrations of toxic glycoalkaloids in potato tubers were 22% higher in NPK compared with FYM-fertilized crops, which is consistent with previous studies which reported that glycoalkaloid concentrations increase with increasing N-fertilizer input levels [68]. However, it should be noted that studies which compared glycoalkaloid concentrations in organic and conventional potato crops reported variable results [25,27,68–73].

The finding of no significant differences in phytochemical concentrations in onion is consistent with the results of a recent Polish study which found no substantial differences in total flavonoids and vitamin C concentrations in onion crops fertilized with mineral N and organic fertilizers [64].

4.3. Toxic Metals

This is to our knowledge the first study that investigated the effects of contrasting pre-crops, crop protection and fertilization regimes (typically used in organic and conventional production) on the nutritionally relevant toxic metal concentrations in field vegetable crops.

ANOVA results for toxic metals were very similar for all four crops, with (i) Cd and Ni concentrations found to be higher in NPK compared with FYM-fertilized crops (although the difference was not significant for Ni in lettuce), (ii) no significant effect of crop protection on Cd and Ni concentrations being detected (except for a slightly, but significantly higher Ni concentration in cabbage crops grown under conventional crop protection) and (iii) no significant effect of both crop protection and fertilization on Pb concentrations being detected in all four crops. These finding are consistent with those obtained for wheat crops grown in the NFSC trial [26], where NPK fertilizer use n increased Cd and Ni concentrations but had no effect on Pb concentrations in cereal grain, while there was no significant effect of crop protection on toxic metal concentrations in grain. Results are also consistent with meta-analyses that compared the Cd concentrations in organic and conventional crops, which reported higher concentrations in conventional compared with organic crops [8,23–26]. As suggested in previous studies the higher concentrations of Cd and Ni in crops from NPK-fertilized crops were most likely due to the use on mineral P fertilizers which contain Cd and Ni as contaminants [8,23–26].

RDA identified negative associations between the three toxic metals and precipitation in cabbage, lettuce and onions, which is consistent with previous studies which reported that drought results in an accumulation of toxic metals in crop plants [74].

4.4. Associations between Climatic Drivers and Crop Performance Differ between Vegetable Species

The vegetable crops compared in this study belong to four different plant families and are known to differ significantly in terms of morphology, physiology and nutrient, water, temperature and light requirements for optimum growth and yields [75]. The RDA results showing differences in the pattern of associations between NPK-availability and environmental drivers and yields of different vegetable species was therefore expected. However, there was very limited information on the effects of climatic parameters on phytochemical concentrations in different vegetable crops. The finding of different and often contrasting associations pattern for different vegetables species was therefore unexpected. For example, precipitation was (i) negatively associated with phenolic, carotenoid, vitamin C and vitamin B_9 concentrations in cabbage, (ii) positively associated with the same phytochemicals in lettuce and (iii) positively associated with phenolic concentrations, but negatively associated carotenoid, vitamin C and vitamin B_9 in onion crops. Similarly, in potato, RDA identified positive associations between radiation and phenolic and glycolalkaloid concentrations in potato tubers, which is consistent with one previous study [67]. In contrast, radiation was negatively associated with phenolic, carotenoid, vitamin C and vitamin B_9 concentrations in FYM-fertilized cabbages and lettuce crops. The reasons for these differences remain unclear, but results suggest that climate change resulting from global warming may (i) not only affect crop yields, but also nutritionally relevant phytochemical concentrations in vegetables, and may (ii) have contrasting impacts in different vegetable species.

4.5. Associations between Climatic Drivers and Crop Performance Are Affected by Fertilizer Type

To our knowledge, this is the first study which demonstrated that associations between climatic drivers and crop yield and quality are affected by fertilizer type (mineral NPK versus FYM applied at the same total N-input level). For example, the strongest climatic drivers identified by RDA were temperature and precipitation in mineral NPK, but radiation and precipitation in FYM-fertilized cabbage, lettuce and onion crops. In contrast, radiation explained the largest proportion of variation in mineral NPK-fertilized, but temperature in FYM-fertilized potato crops.

When contemplating potential explanations for these differences, it is important to consider that the (i) total available N, P and K and (ii) the nutrient release/availability pattern of N, P and K differ considerably between NPK and FYM when applied at the same N-input level. Most importantly, the mineral fertilizers used (ammonium nitrate, superphosphate and potassium chlorite) in trials provided water-soluble, readily plant-available forms of N, P and K to crops [8–10]. As a result, the plant-available N, P and K in soil is highest at the beginning of the growing period and then decreases due to plant uptake and losses from soil (e.g., leaching down the soil profile or surface run-off especially during periods of high precipitation) [8–10]. In contrast, in FYM only a small proportion of total N is present as readily plant-available NH_4-N or NO_3-N; most N in FYM is part of organic compounds and only becomes plant-available after mineralization by the soil biota [8–10]. In temperate climates, mineralization is known to increase with increasing soil temperature during the growing period but decreases when insufficient oxygen (water logging conditions) or water (drought conditions) availability reduces soil biological activity [8–10]. Additionally, previous studies showed that only around 50% of total N applied with FYM becomes plant-available in the first year after application [8–10].

Contrasting effects of climatic parameters on the soil processes that affect nutrient availability may therefore at least partially explain the different pattern of associations between climatic drivers and crop performance observed in NPK and FYM-fertilized crops.

For example, precipitation early in the growing season may have a greater effect on crop yield and quality in NPK-fertilized crops, because this could be predicted to result in larger nutrient losses from leaching and run-off from NPK than FYM inputs. In contrast, high precipitation and lower temperatures (which may inhibit both mineralization and nutrient uptake by roots) later in the growing season may be predicted to have a greater effect on crop yield and phytochemical composition in FYM-fertilized crops.

However, interactions between climate and fertilizer type that affect pest and disease pressure and/or crop resistance—and thereby, crop yield and quality—may also contribute to the contrasting association pattern between crops grown with mineral NPK and FYM. For example, in cabbage, the use of manure resulted in significantly lower levels of CRF root infestation and higher yields. It is likely that lower CRF damage resulted in greater nutrient uptake capacity in FYM compared with mineral NPK-fertilized plants, resulting in solar radiation becoming a more important limiting factor for crop yield. This view is supported by the finding that irradiation was identified as a strong positive driver for crop yield in FYM, but not mineral NPK-fertilized crops. Similarly, in lettuce the lower incidence of *Sclerotinia* in FYM-fertilized crops may partially explain why radiation was identified as a significant driver in FYM, but not mineral NPK-fertilized lettuce crops.

Future studies should focus on gaining a more detailed mechanistic understanding of the complex fertilization × climate interactions identified in this study, because this may provide important information for the development of strategies to (i) improve the sustainability and (ii) mitigate negative impacts of climate change on food production.

4.6. Study Limitations

The main limitations of the study presented here are that (i) phytochemical concentration data were only available for three growing seasons and (ii) crop health assessment data were only available for two growing seasons for cabbage, lettuce and onion crops. This limited the statistical power available for the ANOVA and prevented crop health assessments from being included as an explanatory variable in the RDA. Similarly, since data for crops grown after different previous crops (spring beans versus winter barley) were only available for two growing seasons, previous crops could not be included in the RDA as an explanatory variable.

Another limitation is that weed density was not monitored simultaneously in the three seasons in which nutritional composition data were collected. However, a previously published study of weed density and diversity in the NFSC trials showed that organic and conventional weed management protocols in the experiment achieved similar levels of weed control [76].

5. Conclusions

The study confirms results of previously published systematic reviews and meta-analyses which reported that organic production methods result in higher concentrations of phenolics and other nutritionally desirable phytochemicals, but lower concentrations of the toxic metals Cd and Ni [23–26]. It also demonstrates, for the first time, that in potato, cabbage, lettuce and onion this is primarily due to differences in fertilization regimes, while crop protection and pre-crop had a more limited impact on these nutritional composition parameters.

The interactions between climatic variables and agronomic practices used in organic and conventional vegetable production systems identified in this study may also explain the large variation found between studies that compared the nutritional composition of organic and conventional crops in different countries/climatic regions [23–26].

Pesticide residue levels were not compared in this study, and in this context, it needs to be considered that (i) organic vegetables were shown to contain significantly lower levels of pesticides compared with conventional products, (iii) that there is increasing concern about negative health impacts of dietary pesticide exposure and (ii) changing to organic food consumption was recently shown to reduce total pesticide exposure by more than 90% [8,13–15,23–25].

If confirmed in future studies, the finding that in cabbage, lettuce, and onion the application of synthetic chemical crop protection products had no measurable positive impact on crop health and yield, would raise the question whether pesticides should be continued to be permitted for use in these crops, given of the growing concern about both negative environmental and health impacts of pesticide use in field vegetables [8,13–15,23–25]. Additionally, no significant yield difference could be detected when cabbage, lettuce and onion crops grown in plots under organic and conventionally management were compared. This suggests that mineral NPK fertilizer inputs are also not essential to maintain current yield levels in these crops.

In contrast, this study confirmed the outcomes of other studies which showed that the use of synthetic, chemical fungicides in conventional potato production results significantly lower late blight severity and higher tuber yields compared with late blight control protocols used in organic production [27]. Moreover, similar to winter wheat [8–10], the yield gap between organic and conventional potato production was found to be due to both less efficient crop protection and fertilization regimes. Recent pilot studies suggest that there is potential to narrow the yield gap in potato by focusing on the breeding/selection of new potato varieties which combine (i) high levels of blight resistance with (ii) increased nutrient uptake efficiency from organic fertilizer inputs and (iii) the sensory and processing quality attributes desired by consumers [49,50].

By showing that climatic parameters account for a substantially larger proportion of the total variation than major agronomic factors, this study also confirms the urgent need to develop strategies/infrastructure that can mitigate the likely impacts of climate change on field vegetable yields and quality [43].

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy13051225/s1: Figure S1. Principle layout of rotation main plots, crop protection subplots and fertilization sub-subplots in each of the four-replicate experiment; Figure S2. Layout of the supplementary onion experiment; Figure S3. Maximum and minimum daily temperatures (°C), daily rainfall (mm) and total monthly sunshine hours (Sun hrs) during the 2004 onion growing season at the Stockbridge Technology Centre (STC) site; Table S1. Rotation/sequence of crops in the four replicate experiments of the Nafferton Factorial Systems Comparison (NFSC) trial between the start of the experiment in 2001 and 2008; Table S2. Climatic conditions during the three growing seasons in which phytochemical analyses were carried out; Table S3. Crop protection/defoliation protocols and fertilization regimes used in potato crops; Table S4. Crop protection protocols and fertilization regimes used in cabbage crops; Table S5. Crop protection protocols and fertilization regimes used in lettuce crops; Table S6. Crop protection protocols and fertilization regimes used in onion crops; Table S7. Proportion of variation explained, F-values and p-values of explanatory variables of a redundancy analysis (RDA) with radiation (RAD), air temperature (TEMP), precipitation (PRE) as environmental explanatory variables, and fertilizer types (organic [OF] vs. mineral NPK [CF]), and crop protection protocols (organic [OP] vs. conventional [CP]) as agronomic explanatory variables, and crop yield and selected nutritional quality parameters[1] as response variables; Table S8. Proportion of variation explained, F-values and p-values of explanatory variables of a redundancy analysis (RDA) with radiation (RAD), temperature (TEMP), precipitation (PRE) as environmental explanatory variables, and nitrogen (N), phosphorus (P) and potassium (K) availability/supply (estimated from N, P, K concentrations in harvested potato tubers, cabbages and lettuce heads and onion bulb) and crop protection protocols (organic [OP] vs. conventional [CP]) as agronomic explanatory variables, and crop yield and selected nutritional quality parameters[1] as response variables; Table S9. Effect of fertilizer input types and input level on total and marketable bulb yields, bulb N-content, bean seed fly damage and onion neck rot incidence in onion; Table S10. Effect of fertilizer input level on total and marketable bulb yields, bean seed fly damage and onion neck rot incidence in onion crops fertilized with different organic fertilizer types. Values shown are main effect means and are expressed on a fresh weight basis.

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