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Performance of Modern and Traditional Spelt Wheat (*Triticum spelta*) Varieties in Rain-Fed and Irrigated, Organic and Conventional Production Systems in a Semi-Arid Environment; Results from Exploratory Field Experiments in Crete, Greece

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Abstract: Background: Consumer demand for organic spelt wheat has increased rapidly and production has expanded into semi-arid regions, where it was not traditionally grown. Methods: Here, we report the results of a factorial field experiment designed to compare the performance of four spelt varieties grown in rain-fed and irrigated, conventional and organic production systems in a semi-arid environment. Results: Irrigation resulted in 2.5-fold higher grain yields, a reduction in grain protein, taller plants and an increase in stem lodging. While yields of all varieties were similar and low in rain-fed production, the variety Züricher Oberländer Rotkorn (ZOR) produced the highest, Filderstolz and Oberkulmer intermediate and the variety Rubiota the lowest grain yields in irrigated systems. Organic production with chicken or sheep manure as fertilizer resulted in 15% higher yields that mineral NPK fertilizer-based conventional production protocols. Conclusions: Rain-fed spelt production results in very low yields and is therefore unlikely to be commercially viable. Results suggest that organic fertilization regimes and the variety ZOR will result in the highest yields in irrigated systems, while the two traditional spelt varieties Filderstolz and Oberkulmer will more reliably produce grain protein levels that comply with bread-making quality standards.

Keywords: spelt wheat; variety choice; organic production; yield; protein content; lodging; irrigation; composted manures; semi-arid; minor cereals

1. Introduction

Spelt (*Triticum spelta* L., syn. *T. aestivum* ssp. *spelta* (L.) Thell.) is an ancient hulled, hexaploid wheat, which was cultivated as far back as 7000–8000 BC [1,2]. Spelt was a major food crop in many regions of Europe from the Bronze age to medieval times, but production decreased after the introduction of potato into Europe; and over the last 150 years, spelt wheat was gradually replaced by high-yielding, common wheat (*Triticum aestivum* L., syn. *T. aestivum* ssp. *aestivum* (L.) Thell.) varieties which have no husks and are therefore easier/cheaper to process [1,2]. However, spelt has remained as a staple food and minor cereal crop in some regions of central Europe and northern Spain [1].

Over the last 20 years, the demand for spelt wheat has rapidly increased and is predicted to continue to increase by ~5% annually. Demand is driven, at least partially, by consumer perceptions and increasing scientific evidence showing that spelt wheat (a) has a higher nutritional value than common wheat and (b) is a robust crop with high levels of disease resistance suitable for organic farming, which is also expanding globally [3–5]. The increase in demand has led to an expansion of conventional and, in particular, organic spelt wheat production into regions where it was not previously grown, including regions with semi-arid Mediterranean climates [4,6].

European spelt wheat varieties arose through the introgression of cultivated emmer wheat (*T. dicoccum* L.) into free-threshing *T. aestivum* and traditional spelt varieties have very long stems/straw (150–200 cm) [1,2]. Recent spelt breeding efforts have focused primarily on yield and yield-related traits (e.g., shorter stems to increase harvest index and lodging resistance) [1,2]. Spelt can easily be crossed with "modern" short-straw common wheat varieties and several commercially grown, shorter-straw spelt varieties have been developed from *T. aestivum* × *T. spelta* crosses [1,2]. However, traditional, "pure" *T. spelta* varieties (which have not originated from recent crosses with *T. aestivum*), are also grown commercially in Europe (e.g., the "Ur-Dinkel" varieties grown in many German speaking regions of Europe). The breeding and selection of new spelt varieties for commercial production has primarily focused on the needs of the traditional spelt growing regions in central and northern Europe [1,2,7], while there is very limited information on the performance of different spelt varieties/genotypes in semi-arid wheat production regions of southern Europe [6,8].

Factorial field trials with common wheat (*T. aestivum*) in northern Europe have demonstrated that both different fertilization (use of organic instead of mineral NPK fertilizer) and crop protection (non-use of pesticides) methods used in organic production contribute to the significantly lower grain yields achieved in organic compared to conventional production systems [9,10]. In contrast, lower protein levels in organic wheat grain were linked primarily to lower N availability associated with the use of organic (e.g., animal and green manures) instead of mineral N fertilizer [9,10]. However, there is limited information on the relative performance of spelt wheat in organic and conventional production systems in semi-arid wheat production regions in Europe. One previous study in Greece compared the performance of three long-straw spelt and one short-straw common wheat cultivar in plots receiving no or standard mineral N input (100 kg ha^{-1}) [6] and reported (a) high levels of lodging (>50% in fertilized plots) in all three spelt, but not the common wheat cultivar and (b) that mineral N inputs increased lodging levels in spelt. These results suggest that, given the higher disease resistance, grain protein content and weed competitiveness in spelt compared to common wheat, the breeding/selection of more lodging resistant cultivars should be the main focus of research aimed at improving spelt wheat production systems in semi-arid regions.

In semi-arid regions with unpredictable precipitation, supplementary irrigation is often commercially viable and used to increase wheat yields/yield stability [11–13]. Supplementary irrigation is also thought to improve mineral nutrient availability in production systems (e.g., organic farming) that rely on animal and green manures as fertilizer; most mineral nutrients (especially N) in manure only become available for uptake following microbial mineralization in the soil, which is significantly reduced at low soil water/drought conditions [10].

The overall aim of this study was to compare the performance of four contrasting spelt varieties that are commercially grown in Central Europe in rain-fed and irrigated plots fertilized with manure or mineral NPK fertilizer in southern Crete, in order to identify varieties suitable for organic and conventional production systems in semi-arid regions of Europe.

The specific objectives of this study were to assess the effect of, and interactions between, (i) irrigation (with and without supplementary irrigation), (ii) fertilization regimes used in organic and conventional wheat production in Crete (sheep manure vs. chicken manure vs. conventional mineral NPK fertilizers applied at a similar total N-input level of 100 kg ha^{-1}) and (iii) contrasting spelt varieties (two traditional pure, long-straw spelt varieties, one long straw variety developed specifically for organic and low-input production systems and one modern short straw variety originating from a *T. spelta* × *T. aestivum* cross) on grain yield, protein content and yield-related growth parameters of spelt wheat.

The three fertilizer inputs represent the main fertilizers used by organic (sheep and chicken manure) and conventional (mineral NPK) farmers and also represent the main agronomic difference between organic and conventional production systems in Greece [14,15]. However, some conventional farmers in Crete also use manure as fertilizer and apply synthetic chemical pesticides in some seasons (Dr Manolis Kabourakis, Mediterranean University, Crete, Greece pers. comm.). Experiments with all four varieties were carried out in two consecutive growing seasons. However, one variety (Rubiota) was assessed in three consecutive winter production seasons, which allowed a more accurate estimate of potential confounding effects of climatic background conditions on grain yield and protein content and yield-related growth parameters of spelt.

2. Materials and Methods

2.1. Field Experimental Design

Spelt was grown in an established, long-term factorial field experiment (Livadopa 2; semi-arid arable cropping systems comparison trial) which was established near Sivas in Messara Valley, in southern Crete, Greece. The area has an average annual rainfall of ~300 mm and the soil at the field site is sandy-loam, with a slightly alkaline pH of 8.0. The experiment was established in 2012 and had 4 replicate blocks with two factors: (i) fertilizer type (main plot 6 × 12 m; mineral NPK, chicken manure and sheep manure applied at the same total N-input level) and (ii) irrigation (sub-plots 3 × 12 m; with and without supplementary drip irrigation). In the first 3 years (2012, 2013, 2014), spring potato crops were grown in the experimental plots. In the 2014/2015 cereal growing season, only one spelt variety (Rubiota) was planted (generating 24 individual 12 × 3 m plots), while in the 2015/2016 and 2016/2017 growing seasons, four varieties were planted (generating 96 individual 3 × 3 m plots) in the experimental plots.

In the fertilizer input type main plots, three fertilizers/fertilization regimes were compared, namely (i) composted chicken manure (2.74% total N w/w; 2.92% total P; w/w; 3.90% total K w/w; 491 mg NH_4-N/kg; 2373 mg NO_3-N/kg), (ii) composted sheep manure (2.45% total N w/w; 0.43% total P w/w; 3.10% total K w/w; 130 mg NH_4-N/kg; 120 mg NO_3-N/kg) and (iii) mineral NPK applied at a total N-input level equivalent to 100 kg ha^{-1} for spelt wheat and 200 kg^{-1} N ha for the preceding potato crops. For the mineral NPK treatment, ammonium sulphate- (21-0-0; Yara, www.yara.com, accessed on 1 March 2021), superphosphate- (0-20-0, Gavriel, http://gavriel.gr/, accessed on 1 March 2021) and K_2SO_4- (0-0-50 Evergrow, (http://global-evergrow.com/, accessed on 1 March 2021) based fertilizers were used and P and K were applied at a rate of 40 kg P_2O_5 and 40 kg K_2O ha^{-1} for each crop (spelt and the preceding potato crops). Manure was sourced from local sheep and poultry producers. No supplementary mineral phosphorus and potassium fertilizers were applied in the manure-fertilized plots.

Supplementary irrigation was applied weekly during March and April at a rate of 280 m^3 ha^{-1} in all three growing seasons (2014/2015, 2015/2016 and 2016/2017) using a standard drip irrigation system to minimize the risk of foliar disease development. In total, the amount of water applied to plots via drip irrigation was equivalent by to 220 mm of precipitation.

The four spelt varieties included in the experiment were (i) Filderstolz, a short straw variety based on a cross between spelt and a high-yielding UK common wheat variety (Maris Huntsman) developed by Hohenheim University (https://lsa-weizen.uni-hohenheim.de/en/111466, accessed on 1 March 2021); (ii) Oberkulmer Rotkorn, a long-straw traditional Swiss landrace marketed as a "true" or "pure" spelt containing no common wheat genetics; (iii) Rubiota, a long straw, traditional Czech variety; and (iv) Züricher Oberländer Rotkorn (ZOR), a Sativa variety (http://www.sativa-rheinau.ch,/, accessed on 1 March 2021) bred/selected under organic farming conditions and registered in 2012.

The Messara plain has very low weed, disease and pest pressure and both organic and conventional producers used mechanical weed control. As a result, synthetic chemical pesticides are rarely used by conventional producers in this region. Since preliminary trials with spelt confirmed that there is very low disease and pest pressure and that weeds can be managed efficiently by mechanical weed control before sowing (soil cultivation after the first rains in autumn to prepare a 'stale' seedbed results in a significant reduction in weeds) and supplementary hand weeding, "crop protection" was excluded as a factor in the experimental design.

2.2. Agronomic Protocols and Assessments

Spelt wheat was sown in mid-November (2014, 2015 and 2016) by using a Super Sow-Lite drill (www.jordanATVeng.com, accessed on 1 March 2021).

Data on air temperature and precipitation during the growing period were obtained from the government weather station at Petrokefali (http://penteli.meteo.gr/stations/moires/, accessed on 1 March 2021) which is located 3 km from the trial site (Figure 1). Total precipitation was 800, 297 and 291 mm and mean temperatures were 16, 17.2 and 16 °C during the 2014/2015, 2015/2016 and 2016/2017 growing season, respectively. The average maximum day time temperatures during the grain filling period were 26.6, 27.4 and 26.9 °C in the 2014/2015, 2015/2016 and 2016/2017 growing season, respectively.

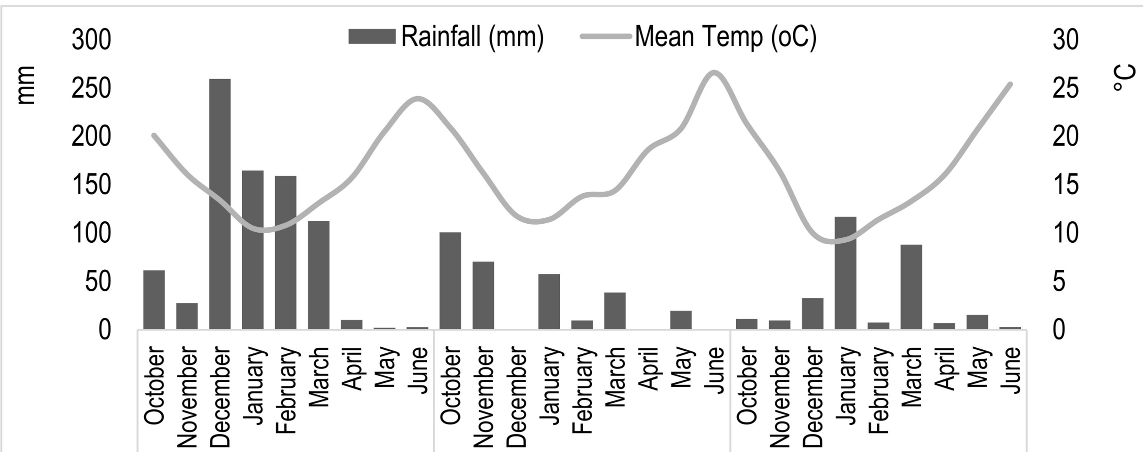

Figure 1. Precipitation and air temperature in the three growing seasons/harvest years (2014/2015, 2015/2016 and 2016/2017).

No pesticides were used, which reflects commercial practice in both conventional and organic cereal production in Crete, which are both low input/extensive. Weeds were controlled mechanically by cultivation before planting and supplementary hand-weeding. Supplementary hand weeding was only necessary and used in the 2014/2015 season which had exceptionally high rainfall.

The stems and leaves of plants in all plots were assessed weekly for visible pest and disease symptoms between emergence and the onset of leaf senescence. Total pest damage and disease symptoms remained below 1% in all plots. Lodging was assessed visually in each plot and recorded as the percentage of cereal tillers/stems being bent over at an angle of $\geq 45^{\circ}$ or lying on the ground.

Indirect measurements of leaf chlorophyll concentration were taken with a SPAD (Soil-Plant Analysis Development) hand-held chlorophyll meter (SPAD 502 Plus, Konica-Minolta, Tokyo, Japan) and used as an estimate for relative N availability to crops. Ten plants were selected randomly on each sampling date in each plot and flag leaf values were recorded.

Yields were assessed by harvesting four 0.5 m^2 quadrats by hand from each plot. Plant height in each quadrat was measured prior to harvest, and tillers and ears from each quadrat were counted to determine the number of tillers and ears per m^2. Ears were separated from straw and grains were separated and de-hulled by using a Wintersteiger LD350 laboratory thresher (Weinsteiger AG, Ried, Austria; www.wintersteiger.com, accessed on 1 March 2021). The grain/hull ratio was determined by weighing the dehulled grain and hulls from each harvested grain sample. A subsample of grain samples was dried at 70 °C in an oven to determine the dry matter content. The thousand grain weight (TGW) was determined by using an electronic seed counter (Elmor C3, Elmor Ltd. Schwyz, Switzerland: https://elmor.com, accessed on 1 March 2021). Harvest index (HI) was calculated as the ratio (%) between grain yield and above-ground biomass. Samples of grain (about 300 g) were then milled into fine powder (<1 mm) using a Retsch centrifuge mill (Retsch. GmbH, Haan, Germany; www.retsch.com, accessed on 1 March 2021) and flour was stored in aliquots in −80 °C until further analysis. Milled flour N content was determined with the Dumas combustion method by using a vario MACRO cube C/N Analyzer (Elementar LTD, Langenselbold, Germany; www.elementar.com, accessed on 1 March 2021). Grain crude protein concentration was estimated by multiplying N with 6.25 [16].

2.3. Statistical Analysis

Non-linear mixed-effects models [17] were used to produce ANOVA *p*-values for main effects and all interactions using the nlme (non-linear mixed effects) package in R software [18]. Data for four varieties from two growing seasons were analyzed by four-factor analysis (ANOVA) with season, fertilizer type, irrigation and variety as fixed effects. The hierarchical nature of the split–split plot design was reflected in the random error structures that were specified as block/season/fertilizer type/irrigation.

Data for the variety Rubiota from three growing seasons were analyzed by three-factor analysis (ANOVA) with season, fertilizer type and irrigation as fixed effects while random error structures were specified as block/season/fertilizer type. The normality of the residuals of all models was tested using QQ-plots.

Differences between fertilizer types, varieties as well as the interaction between factors were tested by using "*Tukey*" contrasts in the general linear hypothesis testing (glht) function of the multcomp package in R [19]. A linear mixed effects model was used for the "*Tukey*" contrasts, containing a treatment main effect, with the random error term specified as described above. Means and standard errors of means for the main effects and the interaction effect tables were generated using the '*tapply*' function in R.

The relationship between weather (air temperature, precipitation), fertilizer type, variety and grain yield and yield components was assessed using partial redundancy analysis (RDA), with trial blocks (replicates) as covariables. The RDAs were carried out using the CANOCO 5 software [20].

3. Results

The specific objective of this study was to identify effects of, and interactions between, (a) irrigation, (b) fertilizer type and (c) variety on grain yield, protein content, lodging and yield-related growth parameters in two seasons (2015/2016 and 2016/2017) with low

(~300) precipitation typical for many semi-arid regions of the Mediterranean. However, as shown in Figure 1 in the 2015/2016 season most rainfall was recorded early in the growing season (October and November), while in 2016/2017 most rainfall was recorded later in the growing season (January and March). For the variety Rubiota, the experiment was performed in one additional season (2014/2015) with unusually high rainfall (800 mm) for the region (Figure 1 and Table 1).

Table 1. Effects of growing season (2014/2015, 2015/2016 and 2016/2017), supplementary irrigation (with or without) and fertilizer type (chicken manure, mineral NPK, sheep manure) on spelt wheat (variety Rubiota) grain yield, crude protein content, stem lodging and plant height. Values shown are the means ± standard errors.

Factor	Grain Yield	Crude Protein	Stem Lodging	Plant Height (GS62)
	t ha^{-1} DW	%	%	cm
Season (n = 24)				
2014/2015	3.7 ± 0.2 **a**	13.4 ± 0.2	15 ± 4	176 ± 1 **a**
2015/2016	0.9 ± 0.1 **c**	13.5 ± 0.4	13 ± 3	94 ± 3 **c**
2016/2017	2.1 ± 0.2 **b**	13.9 ± 0.5	7 ± 2	117 ± 4 **b**
Fertilizer Type (n = 24)				
Chicken manure	2.2 ± 0.3	13.2 ± 0.3 **b**	10 ± 2	127 ± 8
Mineral NPK	2.3 ± 0.4	14.6 ± 0.4 **a**	14 ± 3	132 ± 8
Sheep manure	2.3 ± 0.3	13.1 ± 0.3 **b**	11 ± 3	127 ± 7
Irrigation (n = 36)				
With	2.7 ± 0.2	12.9 ± 0.2	19 ± 2	136 ± 5
Without	1.8 ± 0.2	14.4 ± 0.3	5 ± 1	122 ± 7
ANOVA *p*-values				
Main Effects				
Season (YR)	**0.0001**	**0.0152**	0.0525	**<0.0001**
Fertilizer type (FT)	ns	**0.0112**	Ns	ns
Irrigation (IR)	**<0.0001**	**0.0001**	**<0.0001**	**<0.0001**
Interactions [1]	ns	ns	Ns	ns
YR × FT	ns	**0.0047** [3]	Ns	**0.0124** [3]
YR × IR	**0.0108** [2]	0.0809	**0.0024** [2]	**<0.0001** [2]
FT × IR	ns	ns	Ns	0.0716
YR × FT × IR	ns	ns	Ns	ns

Means that are followed by the same letter within each column are not significantly different (general linear hypothesis test $p < 0.05$); [1] only interactions for which significant results or trends ($0.1 < p < 0.05$) towards significant results were detected for at least one parameter are shown; [2] see Table 2 for interaction means ±SE; [3] see Table 3 for interaction means ± SE.

It should be noted that plants remained free of symptoms of foliar, stem and soil-borne disease throughout the growing period in all three growing seasons and no symptoms of soil-borne diseases were detected on roots at harvest.

3.1. Effect of Harvest Year/Season

When results for the variety Rubiota from three seasons (2014/2015, 2015/2016 and 2016/2017 harvest years) were analyzed by three-factor ANOVA, grain yield, and most yield-related growth performance parameters were highest in 2014/2015 (the season with high rainfall) and lowest in 2015/2016 (the season with average, but early rainfall) (Table 1 and Table S1; Figure 1). However, there was no significant main effect of season on lodging and protein content (Table 1). A range of interactions between harvest year and other experimental factors were also detected and are described in the subsections on the effects of irrigation (Section 3.2), fertilization (Section 3.3) and/or variety (Section 3.4) below.

3.2. Effect of Supplementary Irrigation

When results for the variety Rubiota from three seasons were analyzed by three-factor ANOVA, significant main effects of irrigation were detected for grain yield, protein content and all yield-related growth parameters except harvest index (Table 1 and Table S1). Supplementary irrigation resulted in 50% higher yields and 4-fold higher lodging, and significantly increased plant height, tillers per m^2, ears per m^2, grain/hull ratio and TGW (by 11%, 15%, 15%, 15% and 7%, respectively Table 1 and Table S1). In contrast, irrigation significantly reduced leaf chlorophyll (SPAD) and grain protein levels by 4% and 12%, respectively (Table 1 and Table S1). However, ANOVA also detected significant 2-way interactions between year and irrigation for yield, lodging, plant height, HI, tillers per m^2 and leaf chlorophyll (Tables 1 and 2).

Table 2. Interaction means ± SE for the effects of growing season (2014/2015, 2015/2016 and 2016/2017) and supplementary irrigation (with or without) on spelt wheat (variety Rubiota) grain yield and yield-related growth parameters.

	Factor 1	Factor 2. Supplementary Irrigation			
Parameter Assessed	Season	With (n = 12)		Without (n = 12)	
Grain Yield (t ha^{-1} DW)	2014/2015	4.0 ± 0.3	A a	3.5 ±0.3	A a
	2015/2016	1.2 ± 0.2	A c	0.6 ±0.1	B c
	2016/2017	3.0 ± 0.2	A b	1.3 ±0.2	B b
Stem Lodging (%)	2014/2015	28 ± 4	A a	2 ± 1	B a
	2015/2016	19 ± 4	A b	8 ± 3	B a
	2016/2017	9 ± 2	A c	4 ± 2	A a
Plant Height GS62	2014/2015	175 ± 1	A a	176 ± 1	A a
	2015/2016	101 ± 3	A c	86 ± 4	B c
	2016/2017	131 ± 5	A b	103 ± 3	B b
Tillers (per m^2)	2014/2015	438 ± 14	A a	431 ± 13	A a
	2015/2016	366 ± 23	A b	248 ± 22	B c
	2016/2017	345 ± 20	A b	319 ± 14	A b
SPAD GS50	2014/2015	41.9 ± 0.3	A a	41.7 ± 0.4	A a
	2015/2016	36.0 ± 1.3	B b	40.9 ± 1.2	A a
	2016/2017	42.6 ± 0.9	A a	43.0 ± 0.9	A a
SPAD GS62	2014/2015	40.1 ± 0.4	A a	38.7 ± 0.3	A b
	2015/2016	ND		ND	
	2016/2017	42.0 ± 1.0	B a	45.2 ±1.2	A a

For each parameter assessed, means labelled with capital letter within the same row or the same-lower case letter within the same column are not significantly different (general linear hypothesis test $p < 0.05$).

Irrigation was shown to increase grain yield only in the two seasons with average total rainfall (2015/2016 and 2016/2017), but not the season with unusually high rainfall (2014/2015), and a similar trend was also observed for stem height (Table 2).

In contrast, irrigation significantly increased lodging points only in 2014/2015 (the season with unusually high rainfall) and 2016/2017 (the season with average and late rainfall), by 26 percentage points (p.p.) and 11 p.p., respectively (Table 2). Additionally, lower leaf chlorophyll levels in irrigated plots were only detected in the two years with average rainfall (2015/2016 and 2016/2017) (Table 2).

3.3. Effect of Fertilizer Type

When results for the variety Rubiota from three seasons were analyzed by three-factor ANOVA no significant main effect of fertilizer type could be detected for grain yield, lodging, plant height, tiller and ear numbers (Table 1 and Table S1). However, significant main effects were detected for (a) protein and chlorophyll content (SPAD at GS 39, 50 and 62), which were higher with NPK than organic fertilizers, (b) harvest index and grain to hull ratio which were lower with NPK than organic fertilizers and (c) thousand grain weight which was higher with sheep manure than chicken manure and NPK (Table 1 and Table S1). Significant 2-way interactions between season and fertilizer type were detected for protein content and most yield-related growth parameters, but not grain yield (Tables 1 and 3 and Table S1).

Table 3. Interaction means ± SE for the effects of growing season (2014/2015, 2015/2016 and 2016/2017) and fertilizer type (chicken manure, mineral NPK and sheep manure) on spelt wheat (variety Rubiota) grain crude protein content and yield-related growth parameters.

	Factor 1	**Factor 2. Fertilizer Type**					
Parameters	**Year**	**Chicken Manure (n = 8)**		**Mineral NPK (n = 8)**		**Sheep Manure (n = 8)**	
Crude Protein %	**2014/2015**	13.3 ± 0.3	**A a**	13.2 ± 0.3	**A c**	13.8 ± 0.3	**A a**
	2015/2016	13.1 ± 0.5	**B a**	14.5 ± 0.7	**A b**	12.8 ± 0.5	**B a**
	2016/2017	13.2 ± 0.7	**B a**	16.0 ± 0.6	**A a**	12.7 ± 0.6	**B a**
Plant Height GS62 Cm	**2014/2015**	17 ± 1	**A a**	175 ± 1	**A a**	175 ± 1	**A a**
	2015/2016	90 ± 6	**A c**	94 ± 5	**A c**	97 ± 3	**A c**
	2016/2017	115 ± 7	**B b**	127 ± 9	**A b**	109 ± 5	**B b**
Tillers (per m^2)	**2014/2015**	437 ± 20	**A a**	443 ± 20	**A a**	423 ± 9	**A a**
	2015/2016	297 ± 44	**AB b**	269 ± 29	**B c**	356 ± 23	**A b**
	2016/2017	331 ± 17	**AB b**	378 ± 20	**A b**	287 ± 14	**B c**
Ears (per m^2)	**2014/2015**	351 ± 15	**A a**	358 ± 19	**A a**	308 ± 17	**A a**
	2015/2016	175 ± 27	**AB b**	127 ± 14	**B c**	216 ± 12	**A b**
	2016/2017	274 ± 25	**A c**	270 ± 29	**A b**	247 ± 20	**A b**
Grain to Hull Ratio	**2014/2015**	2.28 ± 0.04	**A a**	2.35 ± 0.11	**A a**	2.43 ± 0.07	**A a**
	2015/2016	1.43 ± 0.20	**B b**	1.26 ± 0.16	**B c**	1.87 ± 0.13	**A b**
	2016/2017	2.12 ± 0.06	**A a**	1.99 ± 0.13	**A b**	2.04 ± 0.04	**A b**
SPAD GS39	**2014/2015**	41.9 ± 0.5	**A a**	42.5 ± 0.5	**A a**	41.5 ± 0.4	**A a**
	2015/2016	ND		ND		ND	
	2016/2017	37.8 ± 1.4	**B b**	44.3 ± 1.3	**A a**	37.3 ± 1.0	**B b**
SPAD GS50	**2014/2015**	41.7 ± 0.3	**A a**	42.4 ± 0.5	**A b**	41.4 ± 0.4	**A a**
	2015/2016	38.5 ± 0.9	**AB b**	41.1 ± 1.3	**A b**	35.9 ± 2.3	**B b**
	2016/2017	41.7 ± 0.7	**B a**	45.8 ± 0.9	**A a**	40.9 ± 0.6	**B a**
SPAD GS62	**2014/2015**	39.9 ± 0.5	**A b**	38.8 ± 0.3	**A b**	39.5 ± 0.5	**A b**
	2015/2016	ND		ND		ND	
	2016/2017	41.8 ± 1.4	**B a**	46.9 ± 1.2	**A a**	42.1 ± 1.2	**B a**

For each parameter assessed, means labelled with capital letter within the same row or the same lower-case letter within the same column are not significant different (general linear hypothesis test $p < 0.05$).

For all parameters significant differences between fertilizer types were only detected in the two seasons with average rainfall (2015/2016 and 2016/2017), but not the season with unusually high rainfall (2014/2015) (Table 3).

3.4. Associations between Agronomic and Climatic Variables and Spelt Wheat Performance

Redundancy analyses (RDAs) were carried out for data collected for the variety Rubiota in three contrasting growing seasons (2014/2015, 2015/2016 and 2016/2017) to identify the relative strength of associations between climatic (temperature and rainfall in different harvest years/seasons) and agronomic (irrigation, fertilization) explanatory variables/drivers, and grain yield, lodging and yield-related growth parameters (Figure 2).

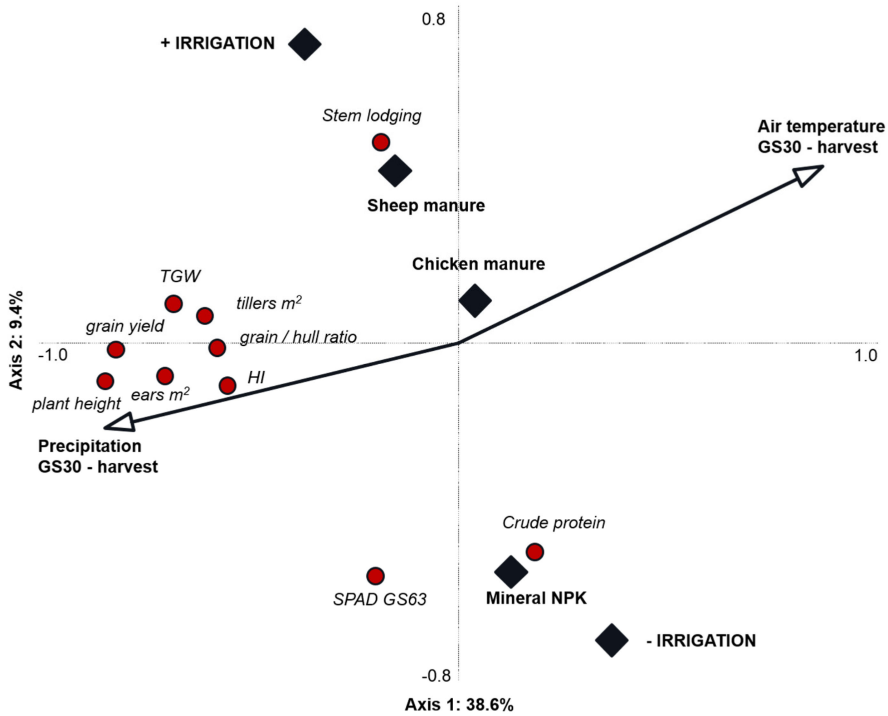

Figure 2. Biplot derived from the redundancy analysis showing the relationship between environmental (air temperature, precipitation) and agronomic (fertilizer type and supplementary irrigation) explanatory variables/drivers and grain yield, stem lodging, crude protein content and yield-related growth parameters (harvest index [HI], plant height, tillers per m^2, ears per m^2, thousand grain weight [TGW], grain/hull ratio and chlorophyll content [SPAD] at GS63) in spelt wheat variety Rubiota. Fixed explanatory variables are shown as black diamonds (⧫) and were: (a) irrigation (without irrigation F = 13.7, p = 0.002; with irrigation F = 13.7, p = 0.002) and (b) fertilizer type (mineral NPK F = 5.4, p = 0.002; sheep manure F = 1.4, p = 0.242). Continuous explanatory variables are shown as arrows and were (c) air temperature between GS30 and harvest (F = 34.2, p = 0.002) and (d) precipitation (F = 6.0, p = 0.002).

In the bi-plot derived from RDA shown in Figure 2, a total of 38.6% of variation in the data obtained for the variety Rubiota is explained by the horizontal axis 1 and a further 9.4% by the vertical axis 2. Air temperature between GS30 and harvest (F = 34.2, p = 0.002) and irrigation (without irrigation F = 13.7, p = 0.002; with irrigation F = 13.7, p = 0.002) were identified as the strongest drivers, but fertilizer type (mineral NPK F = 5.4, p = 0.002; sheep manure F = 1.4, p = 0.242) and precipitation between GS30 and harvest (F = 6.0, p = 0.002) also explained significant amounts of the additional variation. Grain yield and all yield-related growth parameters recorded for the variety Rubiota were positively associated with precipitation and to a lesser extent supplementary irrigation along the negative axis 1 and negatively associated with air temperature and to a lesser extent non-use of irrigation (Figure 2). In contrast, stem lodging was positively associated with the use of supplementary irrigation along the negative axis 1 and positive axis 2, while chlorophyll content (SPAD at GS63) and grain protein levels were positively associated with the use of mineral NPK fertilizer and non-use of irrigation (Figure 2).

3.5. Effect of Variety

The performance of four different spelt varieties under contrasting irrigation and fertilization regimes was only compared in the two average rainfall seasons (2015/2016 and 2016/2017) (Table 4, Figure 1).

The main effects of season/harvest year, irrigation and fertilizer type (and interactions between these 3 factors) identified by four-factor ANOVA of data from four varieties collected in two seasons (Table 4, Tables S2–S6), were broadly similar to those identified by three-factor ANOVA of data obtained in three seasons for the variety Rubiota (see sections on harvest year, irrigation and fertilizer type above). However, in addition, the four-factor ANOVA also identified significant main effects of fertilizer type on grain yield and lodging, with grain yield found to be significantly (15%) lower and lodging 2-fold higher with mineral NPK fertilizer than chicken and sheep manure (Table 4).

Table 4. Effects of growing season (2015/2016 and 2016/2017), supplementary irrigation (with or without), fertilizer type (chicken manure, mineral NPK, sheep manure) and variety (Filderstolz, Oberkulmer, Rubiota and ZOR) on spelt wheat grain yield, crude protein content, stem lodging and plant height.

	Grain	**Crude**	**Stem**	**Plant Height**
	Yield	**Protein**	**Lodging**	**at GS 62**
Factor	**t ha^{-1} DW**	**%**	**%**	**cm**
Season (n = 96)				
2015/2016	1.1 ± 0.1	12.5 ± 0.2	9.2 ± 1.1	84 ± 2
2016/2017	2.7 ± 0.2	13.0 ± 0.3	4.1 ± 0.6	107 ± 2
Fertility Type (n = 64)				
Chicken manure	2.0 ± 0.2 **a**	12.0 ± 0.2 **b**	4.9 ± 1.0 **b**	94 ± 3
Mineral NPK	1.7 ± 0.2 **b**	14.2 ± 0.4 **a**	10.3 ± 1.4 **a**	98 ± 3
Sheep manure	2.0 ± 0.2 **a**	12.1 ± 0.2 **b**	4.8 ± 0.9 **b**	94 ± 2
Irrigation (n = 96)				
With	2.7 ± 0.2	11.7 ± 0.2	8.6 ± 1.0	108 ± 2
Without	1.1 ± 0.1	13.9 ± 0.3	4.8 ± 0.8	84 ± 2
Variety (n = 48)				
Filderstolz	2.0 ± 0.2 **b**	11.4 ± 0.3 **c**	3.1 ± 0.8 **b**	80 ± 3 **c**
Oberkulmer	1.7 ± 0.2 **bc**	13.4 ± 0.3 **ab**	7.3 ± 1.5 **a**	94 ± 3 **b**
Rubiota	1.5 ± 0.2 **c**	13.7 ± 0.3 **a**	9.9 ± 1.6 **a**	105 ± 3 **a**
ZOR	2.4 ± 0.3 **a**	12.5 ± 0.6 **b**	6.4 ± 0.9 **ab**	103 ± 3 **a**
ANOVA *p*-values Main Effects				
Season (YR)	**0.001**	ns	**0.0412**	**0.0016**
Fertility type (FT)	**<0.0001**	**<0.0001**	**0.0023**	**<0.0001**
Irrigation (IR)	**<0.0001**	**<0.0001**	**0.0002**	**<0.0001**
Variety (SV)	**0.041**	**<0.0001**	**0.0147**	ns
Interactions [1]				
YR × FT	ns	0.0578	Ns	**0.0252** [2]
YR × IR	**<0.0001** [3]	ns	Ns	ns
FT × IR	ns	ns	Ns	ns
YR × SV	**<0.0001** [4]	ns	**0.0182** [4]	ns
FT × SV	ns	0.0858	Ns	ns
IR × SV	**0.0015** [5]	ns	Ns	ns
YR × FT × IR	0.0781	ns	Ns	ns

Means that are followed by the same letter within each column are not significantly different (general linear hypothesis test $p < 0.05$); [1] only interactions for which significant results or trends ($0.1 < p < 0.05$) towards significant results were detected for at least one parameter are shown; [2] see Table S4 for interaction means ±SE; [3] see Table S3 for interaction means ±SE; [4] see Table 5 for interaction means ±SE; [5] see Table 6 for interaction means ± SE.

Significant main effects of variety were detected for grain yield, lodging and a range of yield-related growth parameters (Table 4 and Table S2). Specifically, the variety Rubiota (a traditional Czech spelt variety) had the longest straw, highest lodging and protein levels, and the lowest grain yield. The variety Oberkulmer (a traditional Swiss spelt variety) had the highest TGW and produced similar yields, stem lodging, protein levels, HI, ears per m^2 grain to hull ratios and leaf chlorophyll content (SPAD), but significantly shorter straw when compared to Rubiota (Table 4 and Table S2). The variety ZOR (a variety more recently developed in Switzerland for the organic farming sector) had the highest grain to hull ratio and significantly higher grain yields than the other three varieties. ZOR also had a similar straw length, but significantly lower lodging levels than Rubiota, but also lower protein levels than both Rubiota and Oberkulmer (Table 4 and Table S2).

The variety Filberstolz (developed from a *T. spelta* x *T. aestivum* cross) had the shortest straw, highest harvest index and ears per m^2, lowest grain to hull ratio and TGW. Filderstolz also had the lowest lodging and protein levels, but the highest estimated chlorophyll content (SPAD) and second highest yields (Table 4 and Table S2).

Significant 2-way interactions between (a) variety and season were detected for a range of performance parameters and (b) variety and irrigation for grain yield only (Table 4 and Table S2). When the interactions between variety and season (Table 5) were further investigated significant differences in grain yield and grain/hull ratio between varieties were only detected in the season with late rainfall (2016/2017), with ZOR found to have the highest yield and grain/hull ratio.

In contrast, significant differences in stem lodging were only detected in the season with early rainfall (2015/2016), when Rubiota had the highest (13%) and Filderstolz the lowest (2.9%) lodging levels (Table 5). For harvest index and ears per m^2, significant differences between varieties were detected in both seasons, but the highest harvest index and ears per m^2 were recorded for Filderstolz in the season with late rainfall (2015/2016), but ZOR in the season with early rainfall (2016/2017).

Table 5. Interaction means ± SE for the effects of growing season (2015/2016 and 2016/2017) and variety (Filderstolz, Oberkulmer, Rubiota and ZOR) on spelt wheat grain yield, yield-related growth parameters,).

	Factor 1.	**Factor 2. Spelt Variety**							
Parameters	**Season**	**Filderstolz (n = 24)**		**Oberkulmer (n = 24)**		**Rubiota (n = 24)**		**ZOR (n = 24)**	
Grain Yield t ha^{-1} DW	**2015/2016**	1.3 ± 0.2	**A b**	1.0 ± 0.1	**A b**	0.9 ± 0.1	**A b**	1.1 ± 0.2	**A b**
	2016/2017	2.7 ± 0.3	**B a**	2.4 ± 0.3	**BC a**	2.1 ± 0.2	**C a**	3.6 ± 0.3	**A a**
Stem Lodging %	**2015/2016**	2.9 ± 1.05	**C a**	11.9 ± 2.5	**AB a**	13.1 ± 2.7	**A a**	8.8 ± 1.4	**B a**
	2016/2017	3.2 ± 1.31	**A a**	2.6 ± 1.1	**A b**	6.7 ± 1.5	**A b**	4.0 ± 1.1	**A b**
Harvest Index %	**2015/2016**	13.3 ± 1.3	**A b**	10.2 ± 1.3	**B b**	10.9 ± 0.9	**B b**	9.0 ± 1.3	**B b**
	2016/2017	24.1 ± 1.4	**AB a**	20.6 ± 1.6	**C a**	21.8 ± 1.4	**BC a**	25.6 ± 1.3	**A a**
Ears per m^2	**2015/2016**	235 ± 13	**A b**	191 ± 17	**B b**	173 ± 13	**BC b**	155 ± 17	**C b**
	2016/2017	281 ± 17	**B a**	266 ± 19	**B a**	264 ± 14	**B a**	326 ± 15	**A a**
Grain/Hull Ratio	**2015/2016**	1.3 ± 0.09	**A b**	1.4 ± 0.11	**A b**	1.5 ± 0.11	**A b**	1.4 ± 0.13	**A b**
	2016/2017	1.9 ± 0.05	**B a**	1.9 ± 0.06	**B a**	2.1 ± 0.05	**B a**	2.4 ± 0.04	**A a**

For each parameter assessed, means labelled with capital letter within the same row or the same lower-case letter within the same column are not significantly different (general linear hypothesis test $p < 0.05$).

When the interaction between variety and irrigation (Table 6) was further investigated significant differences in grain yield between varieties were only detected in irrigated plots, while yields of all varieties were similar in non-irrigated plots. With irrigation the variety ZOR produced the highest and the varieties Oberkulmer and Rubiota the lowest grain yields.

Table 6. Interaction means ± SE for the effects of supplementary irrigation (with or without) and variety (Filderstolz, Oberkulmer, Rubiota and ZOR) on spelt wheat grain yield.

	Factor 1.	**Factor 2. Spelt Variety**			
Parameter	**Irrigation**	**Filderstolz (n = 24)**	**Oberkulmer (n = 24)**	**Rubiota (n = 24)**	**ZOR (n = 24)**
Grain Yield t ha^{-1}	Irrigation +	2.9 ± 0.3 **B a**	2.6 ± 0.2 **B a**	2.1 ± 0.2 **C a**	3.4 ± 0.4 **A a**
	Irrigation −	1.1 ± 0.1 **A b**	0.9 ± 0.2 **A b**	1.0 ± 0.1 **A b**	1.3 ± 0.2 **A b**

For each parameter assessed, means labelled with capital letter within the same row or the same lower-case letter within the same column are not significantly different (general linear hypothesis test $p < 0.05$).

A weak, but significant (p = 0.039) 4-way interaction between season, irrigation, fertilization and variety was detected only for the grain to hull ratio (GHR) (Tables S2 and S6). Although there was no 4-way interaction for crude protein, mean grain protein levels for each treatment combination (season × irrigation × fertilization × variety) were also compared (Table S6) to identify whether different varieties can produce grain with crude protein concentrations above 11.5%, 13% and 14%, which represents (a) the minimum level accepted by UK millers for organic high-quality milling spelt wheat, (b) the level specified by the National Association of British and Irish Millers for high-quality milling wheat (common and spelt) and (c) the highest level demanded by some millers for conventional high-quality milling spelt wheat, respectively.

In irrigated, mineral NPK-fertilized plots only the variety Rubiota produced protein levels above 13% in both and 14% in one year (2016/2017) (Table S6). In irrigated, manure-fertilized plots none of the four variety produced protein levels ≥ 13% and only the varieties Oberkulmer and Rubiota produced protein levels ≥ 11.5% in both years (except for Oberkulmer in chicken manure-fertilized plots in 2015/2016). In contrast, in non-irrigated mineral NPK-fertilized plots, all varieties produced protein levels above 13% in both years, but only Oberkulmer, Rubiota and ZOR had protein contents above 14% in both years. In non-irrigated, manure-fertilized plots all four varieties produced protein levels ≥ 11.5%, but only Oberkulmer and Rubiota produced levels ≥ 13% in both years (Table S6).

3.6. Associations between Variety, Fertilizer Type, and Water and N Availability, and Spelt Wheat Performance Parameters

Redundancy analyses (RDAs) were carried out for data collected for all four varieties in two low-rainfall (~300 mm) growing seasons (2015/2016 and 2016/2017) to identify the relative strength of associations between variety, fertilizer type, water availability (total water input from precipitation and rainfall between January and June) and N availability (estimated from chlorophyll levels [SPAD] at GS 50) explanatory variables/drivers and grain yield, lodging and yield-related growth parameters (Figure 3).

In the bi-plot derived from RDA shown in Figure 3, a total of 18.6% of variation is explained by the horizontal axis 1 and a further 11.7% by the vertical axis 2. Water availability (F = 34.2, p = 0.002) was the strongest explanatory variable and variety (Filderstolz: F = 4.77, p = 0.002; Rubiota: F = 3.4, p = 0.046; ZOR: F = 2.1, p = 0.124; Oberkulmer: F = 2.1, p = 0.124) and fertilizer type (mineral NPK F = 16.2, p = 0.002; chicken manure F = 0.3, p = 0.802) were also identified as significant drivers, while estimated N availability (F = 2.6, p = 0.054) explained only a small amount of the additional variation.

Grain yield and all yield-related growth parameters were positively associated with water availability/precipitation along the negative axis 1 (Figure 3). In contrast, protein content was negatively associated with water availability and positively associated with mineral NPK fertilizer use along the positive axis 1 (Figure 3). Stem lodging was positively associated with mineral NPK fertilizer and the varieties ZOR and Rubiota, along the negative axis 2, but negatively associated with manure and use of the variety Filderstolz along the positive axis 1 (Figure 3).

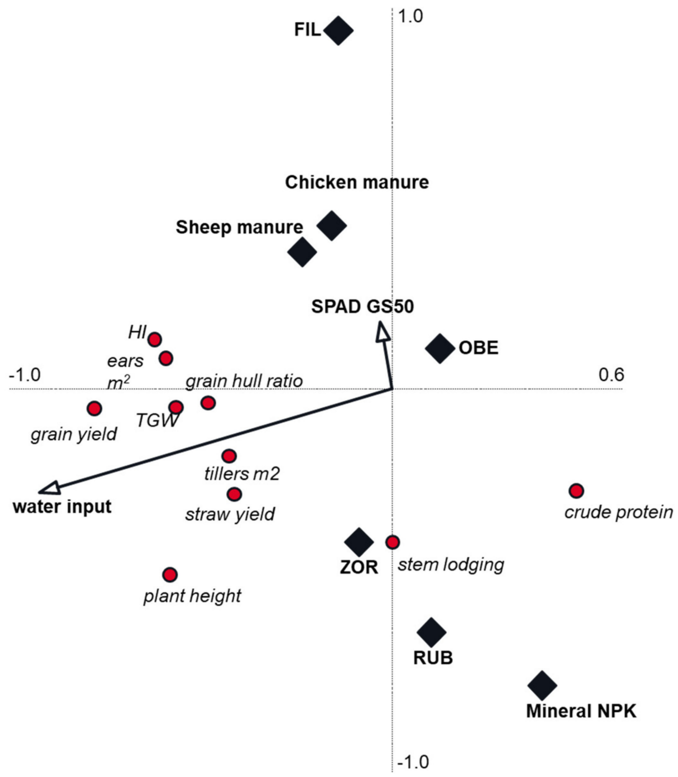

Figure 3. Biplot derived from the redundancy analysis showing the relationship between variety choice, fertilizer type, water availability [1] and N availability [2] explanatory variables/drivers and grain yield, stem lodging, crude protein content and yield-related growth parameters (harvest index [HI], plant height, tillers per m^2, ears per m^2, thousand grain weight [TGW], grain/hull ratio in spelt wheat. Fixed explanatory variables are shown as black diamonds (⧫) and were: (a) variety (Filderstolz [FIL]: F = 4.77, p = 0.002; Rubiota [RUB]: F = 3.4, p = 0.046; Züricher Oberländer Rotkorn [ZOR]: F = 2.1, p = 0.124; Oberkulmer [OBE]: F = 2.1, p = 0.124), (b) fertilizer type (mineral NPK [MIN]: F = 16.2, p = 0.002; chicken manure [CHI] F = 0.3, p = 0.802; Sheep manure [SHE]: F and p unknown). Continuous explanatory variables are shown as arrows and were (c) water availability [1] (F = 39.0, p = 0.002) and air temperature (F = 34.2, p = 0.002) and (b) N availability [2] (F = 2.6, p = 0.054). [1] total water input from precipitation and irrigation between January and June; [2] N availability was estimated from chlorophyll assessments [SPAD] at GS50.

4. Discussion

Since spelt production was until recently restricted to temperate regions, most previous agronomic research and breeding efforts to improve spelt production systems were carried out in the traditional spelt production regions in central and northern Europe [2–4]. The series of factorial field trials reported here is, to our knowledge, the first study into the effects of (i) irrigation, (ii) fertilizer type and (iii) variety on grain yield, protein content, lodging and yield-related growth parameters in spelt grown under semi-arid pedoclimatic conditions.

Overall, this study demonstrated that spelt wheat performance in semi-arid regions is determined by complex interactions between environmental parameters (rainfall and temperature), agronomic practices and spelt genotype. The effects of (i) climatic background condition and supplementary irrigation, (ii) fertilization regimes used in conventional and organic production and (iii) contrasting varieties on spelt performance are discussed in separate sections below.

4.1. Effect of Season/Climatic Conditions and Supplementary Irrigation

Results suggest that climatic conditions (rainfall and temperature) and supplementary irrigation had the largest relative effect on crop yield, stem lodging and growth parameters. The finding that irrigation substantially increased lodging and most growth parameters (including straw length, tiller and ear number, harvest index, thousand grain weight) in all three seasons, but grain yield only in the two seasons with low (~300 mm) precipitation is consistent with previous studies on common and Durum wheat in semi-arid environments [11,12,21].

In contrast, supplementary irrigation reduced chlorophyll (SPAD) (a known indicator for N availability/uptake) and grain protein levels, which indicates that crop growth/biomass production increased to a greater extent than N availability and/or uptake in irrigated crops resulting in a dilution effect for N-levels in leaves and lower grain N/crude protein concentrations [11,13]. On average, over the four varieties, grain from irrigated plots had 11.7% protein which is below the level specified/expected for high-quality milling wheat (12.5%–13%) in many European countries [22], while mean protein levels in grain from non-irrigated plots were well above the threshold at 14.2%. However, there was substantial variation for protein content between varieties (see Section 3.5 above and Section 4.4 below).

Results obtained for the variety Rubiota suggest that, in seasons with unusually high rainfall, supplementary irrigation will not significantly affect grain yield, but substantially increase the risk of stem lodging, which is known to have negative impacts on grain quality (e.g., higher mycotoxin and lower Hageberg falling number levels). Supplementary irrigation should therefore be managed carefully and only applied when monitoring of soil moisture levels and weather forecasts predict that it will be beneficial for crop growth, as previously recommended for common wheat [23].

The negative association between air temperature, grain yield and yield-related growth parameters identified by RDA is consistent with previous studies with common wheat in other semi-arid regions, which reported that temperatures above 30 °C during grain filling reduce yield [24,25].

4.2. Effect of Season/Climatic Conditions and Supplementary Irrigation

The three fertilizers compared in this study are the main inputs available and used for conventional (mineral NPK) and organic (chicken and sheep manure) crop production in Greece and other semi-arid regions of Europe [14,15,26]. Manure and mineral N fertilizer were applied at a total N-input level (100 kg N ha^{-1}) as recommended for spelt, which is considered to be more nutrient-use efficient than common wheat [27]. In contrast, N-input levels recommended for common wheat production in Europe are between 170 and 200 kg N ha^{-1} [9,10] and factorial field experiments with common wheat in the UK reported significantly higher grain yields and protein content with mineral NPK than cattle manure fertilizer when applied at the same N-input level of 170 kg N ha^{-1} in a northern temperate climate [9,10].

The finding of lower grain yields in mineral NPK compared to manure-fertilized plots (in the 2015/2016 and 2016/2017 seasons) in this study was therefore surprising, especially since both the high leaf chlorophyll (SPAD) and grain N/crude protein levels suggested that N availability to crops was, as expected, higher in mineral NPK than manure-fertilized plots.

The most feasible explanation for contrasting relative yield response of wheat in semi-arid and temperate regions is that soil water is the primary yield limiting factor and that repeated organic matter inputs improved soil water retention and availability to plants, and thereby grain yield as previously described [28]. This view is supported by the trends of the interaction between seasons, irrigation and fertilizer type for grain yield detected when data from four varieties in the two seasons with low (~300 mm) rainfall were analyzed/compared. This analysis showed that NPK fertilizer resulted in lower yields only in the three environments with lower water availability later in the season (early rainfall season with and without irrigation and late rainfall season without irrigation), while in the environment with the highest soil water availability (late rainfall season with irrigation), yield with mineral NPK were the same as with chicken manure and numerically higher than sheep manure. The lack of significant differences in grain yield between both irrigation and fertilization treatments found for the variety Rubiota in the season with unusually high (~800 mm) rainfall also supports this conclusion.

Results for Rubiota in the high rainfall season are consistent with those of an extensive factorial study carried out in Apulia (a semi-arid region in southern Italy with ~600 mm rainfall during the growing season), which also reported no significant difference in spelt yields between plots fertilized with organic and mineral NPK fertilizers (Fares et al., 2012).

The use of animal manure instead of mineral NPK fertilizer was also shown to reduce soil-borne fungal and nematode disease severity in crops such as tomato and melon and this was linked to higher microbial activity in soil [29–31]. Although no visible disease symptoms were detected in any of the experimental plots, no detailed microbiological root assessments were carried out in this study and suppression of latent soil-borne diseases cannot be excluded as potential explanatory variable/driver for the higher yield observed in manure-fertilized crops. Additional studies should therefore be carried out to provide a more detailed mechanistic understanding of the complex interaction between production season (and associated rainfall pattern), supplementary irrigation and fertilizer type identified for grain yield in this study.

Similar to previous studies with common wheat in northern temperate climates [9,10] manure use resulted in lower leaf chlorophyll (SPAD) and grain protein levels than mineral NPK fertilizer, and protein concentrations for several varieties remained below the minimum concentrations demanded by millers for high-quality organic (11.5%) and conventional (13%) milling spelt with manure as fertilizer (see Section 3.5 above and Section 4.4 below).

4.3. Effect of Variety—Yield/Yield Stability

The main aim of this study was to compare the performance of four contrasting spelt varieties (that are commercially grown in Central Europe) in rain-fed and irrigated plots fertilized with manure or mineral NPK fertilizers, in order to identify varieties suitable for organic and conventional production systems in semi-arid regions of Europe.

There have been, to our knowledge, only two previous studies which compared the performance of different spelt varieties under semi-arid conditions [6,8]. Only the study by Koutroubas, Fotiadis and Damalas [6] reported results for individual varieties and compared performance in plots fertilized with mineral N fertilizer inputs recommended for conventional spelt production (100 kg N ha^{-1}) in two consecutive growing seasons. Although no supplementary irrigation was used, the study identified lodging as the main challenge for spelt wheat production in Greece; all three spelt varieties showed lodging levels of more than 50%, while there was no lodging in the common wheat variety that was included as a control [6].

The four varieties included in this study (Filderstolz, Oberkulmer, Rubiota and ZOR) had substantially lower lodging rates in both rain-fed (≤8%) and irrigated (≤28%) production systems when grown with chicken manure, sheep manure or mineral NPK fertilizer applied at the same total N-input level of 100 kg N ha^{-1}. In the two low rainfall seasons typical for semi-arid Mediterranean regions, the two varieties (Filderstolz and ZOR) which produced the highest yields in irrigated plots (2.9 and 3.4 t ha$^{-1\text{, respectively}}$) also had the lowest lodging levels (3% and 6%). From a yield and yield stability perspective, these two varieties are therefore thought to be the most suitable candidate spelt varieties for production in semi-arid environments.

4.4. Effect of Variety—Bread-Making Quality

The National Association of British and Irish Millers' (NABIM 2019) specification for the protein content of high-quality organic and conventional milling/bread-making wheat is ≥13% and similar protein levels (12.5%–13%) are specified/expected for milling wheat in other European countries [22]. However, for conventional milling, spelt wheat European millers often only pay "high-quality" price premiums if the protein content is $\geq$14%, while the minimum protein concentration specified by millers for organic "high-quality" milling spelt wheat can be as low as 11.5%.

The finding that mean protein concentrations in irrigated plots were below 13% in mineral NPK and below 11.5% in compost-fertilized plots suggests that the two highest-yielding varieties (Filderstolz and ZOR) are unsuitable for high-quality milling wheat production in both organic (manure fertilized) and conventional (mineral NPK-fertilized) irrigated systems. In contrast, the finding that Rubiota produced protein levels >11.5% with both sheep and chicken manure and levels >13% in all three seasons and >14% in two out of three seasons with mineral NPK fertilizers suggests that Rubiota has potential for high-quality milling wheat production in both organic and conventional irrigated systems. Similarly, a recent study by Magistrali, Vavera, Janovska, Rempelos, Cakmak, Leifert, Grausgruber, Butler, Wilkinson and Bilsborrow [7] confirmed the potential of the variety Rubiota to produce high grain protein content under both conventional (mineral N) and manure-based (FYM and cattle slurry) fertilizer sources in both the UK and the Czech Republic with 15.2% and 16.3 %, respectively when averaged across the 2 years of study (2015 and 2016) and the 4 N sources (mineral N, biogas digestate, FYM and cattle slurry) used. Magistrali, Vavera, Janovska, Rempelos, Cakmak, Leifert, Grausgruber, Butler, Wilkinson and Bilsborrow [7] also studied the effect on other grain quality parameters, i.e., hectolitre weight and HFN and observed that while the variety Rubiota had the highest protein content, the variety ZOR had the highest hectolitre weight and HFN and was the only variety to achieve the NBIM quality threshold of >13% protein, >76 kg hL^{-1} hectolitre weight and >250 s HFN in both the UK and CZ.

In contrast, the finding that mean protein concentrations in non-irrigated plots were above 13% for all four varieties in mineral NPK-fertilized plots suggests that all four varieties may be suitable for high-quality conventional milling spelt wheat production in rain-fed systems. However, it should be pointed out that only Oberkulmer, Rubiota and ZOR had mean protein levels of above 14% in mineral NPK-fertilized plots that are needed to obtain a price premium from some millers for conventional milling spelt wheat. In non-irrigated plots fertilized with manure, all varieties produced mean protein levels above 11.5%, but only Rubiota and Oberkulmer had levels above 13% and are therefore considered to have a greater potential for organic, high-quality, milling spelt wheat production.

4.5. Limitations of This Study

The main limitation of this study is that crude protein was the only bread-making quality parameter assessed. Since it is not possible to accurately assess differences in bread-making quality based on crude protein alone, future studies should investigate a wider range of processing quality parameters (e.g., Hagberg falling number, gluten protein profiles, grain hardness) before recommendations are made to millers/processors.

5. Conclusions

Overall results suggest that spelt wheat can be reliably produced in semi-arid regions using varieties developed in central Europe (Germany, Switzerland and Czech Republic), but satisfactory yields and yield stability can only be achieved with supplementary irrigation.

Irrigation regimes and water input levels will require further optimisation and the two varieties that were more recently developed for conventional (Filderstolz) and organic (ZOR) farming produced higher yields in irrigated production than the two traditional varieties (Rubiota and Oberkulmer) and may have higher yield stability due to greater lodging resistance.

In contrast, grain protein comparisons suggest that Rubiota is the most suitable variety for high quality milling spelt wheat production, especially in irrigated production systems. However, since crude protein was the only bread-making quality parameter assessed this needs to be confirmed in future studies that assess a wider range of processing quality parameters and/or carry out baking tests with flour from all 4 varieties. Baking tests should include standard and long-fermentation-based sourdough bread making methods, since the later are becoming increasingly popular.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11050890/s1, Table S1. Effects of growing season, irrigation and fertilizer type on spelt wheat (variety Rubiota) harvest index (HI), tillers and ears per m2, grain to hull ratio, thousand grain weight (TGW) and estimated leaf chlorophyll content (SPAD-meter readings); Table S2. Effects of growing season, irrigation, fertilizer type and variety choice on spelt wheat harvest index (HI), tillers and ears per m2, grain to hull ratio, thousand grain weight (TGW) and estimated leaf chlorophyll content (SPAD-meter readings); Table S3. Interaction means ± SE for the effects of growing season (2015/16, 2016/17) and supplementary irrigation (with and without) on spelt wheat grain yield and yield related growth parameters; Table S4. Interaction means ± SE for the effects of growing season (2015/16, 2016/17) and fertilizer type (chicken manure, mineral NPK, sheep manure) on spelt wheat grain crude protein content and yield related growth parameters; Table S5. Interaction means ± SE for the effects of growing season (2015/16, 2016/17), supplementary irrigation (with or without) and fertilizer type (chicken manure, mineral NPK, sheep manure) on spelt wheat grain yield and harvest index; Table S6. Interaction means ± SE for the effects of growing season (2015/16, 2016/17), supplementary irrigation (with or without) and fertilizer type (chicken manure, mineral NPK, sheep manure) and variety choice (Filderstolz, Oberkulmer, Rubiota, ZOR) on spelt wheat grain/hull ratio and crude protein content.

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