agriculture

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Comparison of Hybrid Rye and Wheat for Grain Yield and Other Agronomic Traits Under Less Favourable Environmental Conditions and Two Input Levels

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Abstract: Agriculture in the European Union is constantly the subject of public debate, particularly concerning reduced mineral fertilisation and reduced chemical plant protection. Hybrid rye could play a special role in this context, as it usually requires less fertiliser and pesticides than winter wheat and has a high yield potential. In Germany, both crops can be grown on most sites. To test whether hybrid rye is competitive with winter wheat, a trial was conducted with 10 hybrid rye and 20 wheat varieties of all quality levels. The trial was grown for three years (2021, 2022, 2023) on three conventionally managed farms with 40–64 soil points (on a scale of 1–100) in south-west Germany. It was conducted with two input levels: I1, fertilisation (100–120 kg N/ha for hybrid rye; 140–180 kg N/ha for winter wheat), and chemical plant protection including growth regulators; I2, no chemical plant protection, and 20% reduced N fertilisation, one to three harrows. In eight out of nine location × year combinations, hybrid rye was significantly ($p < 0.001$) superior to winter wheat in terms of grain yield under these conditions. On average, hybrid rye yielded 9.1 and 7.8 t ha^{-1} for I1 and I2, respectively, compared to 8.0 and 6.8 t ha^{-1} for wheat, respectively. A close correlation of the cultivar's grain yield between I1 and I2 for both crops showed a missing cultivar × input level interaction. Under these conditions, hybrid rye produced higher grain yields and better baking quality than wheat in both input regimes, contributing to a more sustainable cropping system.

Keywords: grain yield; nitrogen; pesticides; *Secale cereale*; *Triticum aestivum*

Academic Editor: Daniel Tan

Received: 24 July 2024
Revised: 8 January 2025
Accepted: 8 January 2025
Published: 13 January 2025

Citation: Miedaner, T.; Lauenstein, S.; Lieberherr, B. Comparison of Hybrid Rye and Wheat for Grain Yield and Other Agronomic Traits Under Less Favourable Environmental Conditions and Two Input Levels. *Agriculture* **2025**, *15*, 163. https://doi.org/10.3390/agriculture15020163

1. Introduction

Winter rye (*Secale cereale* L.) has long been considered an inferior crop and relegated to the poorest, sandy, and dry soils, because it is more tolerant to abiotic stress factors than other cereals. The main reason for this poor reputation was the inferior grain yield of population rye cultivars compared to self-pollinating wheat. Today, however, hybrid rye cultivars yield much more than traditional population rye according to the German VCU (value of cultivation and use) trials [1]. Over 26 years, this difference increased from 13% in 1989 to 18% in 2014 compared to the yield level of population varieties. Hybrid breeding started at the University of Hohenheim in the 1970s and resulted in the first varieties in 1985 [2]. In 2023, 83.8% of the total rye area of 629.000 hectares in Germany was cultivated with hybrid cultivars [3]. Hybrid rye is also available in countries like Spain, France, the UK, Austria, Poland, Denmark, Sweden, Finland, the Baltic States, the Czech Republic, Slovakia, Hungary, Belarus, Ukraine, and Russia, although the market penetration is much lower in these countries (except for Denmark, the UK, and the Czech Republic) [4]. In the European Union (EU), rye was grown on 1.9 million hectares, producing 7.4 million tons in

2023, with the main producers being Germany and Poland. In contrast, winter wheat is still the largest crop in the EU, which is grown on 21.8 million hectares [5].

In Germany, rye and wheat can be grown in the same regions, soil types, weather conditions, and even in the same field sites. In 1950, population rye was the most widely grown cereal in Germany with 1.36 million hectares, compared to wheat with 1.01 million hectares [6]. This changed in the 1960s with the success of wheat breeding, which led to high-yielding semi-dwarf varieties. Even today, the breeding success for grain yield in self-pollinating wheat is 2.3 times higher than in cross-pollinating population rye (0.48 dt/ha yr vs. 0.21 dt/ha yr) [7]. This situation has changed with the introduction of hybrid rye, which can now match winter wheat yields in many locations. This raises the question of whether, and under what conditions, hybrid rye can compete with wheat.

Population rye outcompetes hybrid rye, wheat, and triticale only on the least productive sites. Wheat is clearly the best yielding small-grain cereal on the most productive sites, according to analyses of the 2011–2020 state variety trials with 159 location–year combinations, where these cereals were grown on the same location in Germany [8]. This accounts, however, for only 25% of the soils in Germany. In between, there is a wide range of production conditions that make up the majority of agricultural land in Germany, which could be used for both hybrid rye and wheat. In the EU, there is an ongoing public debate about sustainability and lower inputs in agriculture. The high-input conventional agriculture of recent decades is largely responsible for soil degradation, loss of biodiversity, groundwater contaminated with nitrogen and pesticides, increasing resistance of pests and weeds to pesticides, and a declining consumer confidence in food quality [9]. The European Commission's 'farm to fork' strategy aims to reduce chemical pesticides by 50% and fertilisers by at least 20% [9]. Hybrid rye could play a special role in this scenario, as it typically requires less fertiliser and pesticides than winter wheat and has high yield potential even on low or medium productive soils.

The primary objective of this study was to compare hybrid rye and wheat under less favourable environmental conditions and two input regimes. In particular, we aimed to (1) compare the performance of hybrid rye and wheat for grain yield and other agronomic traits under two input regimes in three locations over 3 years, and (2) compare the response of individual genotypes within each cereal species to the two input regimes. It should be emphasised that we did not aim for low-input conditions, as this is not an option in high-yielding regions such as north-west Europe.

2. Materials and Methods

2.1. Cultivars and Site Description

The study consisted of 10 commercial hybrid rye cultivars and 20 commercial wheat cultivars, both of winter type (Table S1). The cultivars were selected for their multiplication area, baking quality, and resistance characteristics to the main diseases, which make them representative of commercial cultivars grown in Germany. The experiments were conducted in south-western Germany at Stuttgart-Hohenheim (48.71° N, 9.19° E, HOH), Eckartsweier near Willstätt (48.52° N, 7.87° E, EWE), and Oberer Lindenhof near Eningen (48.47° N, 9.31° E, OLI) in the years 2021, 2022, and 2023, thus comprising nine location × year combinations. The three locations have different eco-climatic characteristics (Table 1). EWE in the upper Rhine valley was, in all three years, the warmest site, while OLI on the Swabian Alb was the coolest and wettest site, and HOH lies in between. In 2021, there was more rain than in the other years; in particular, 2022 was rather dry during the growth period.

Hybrid rye and wheat were sown on the same dates in early October and harvested at the end of the following July. In OLI, the harvest was in mid-August because of the higher altitude. The soil value (Bodenzahl) was determined using the German Soil Taxation

Framework [10,11] by the Land Evaluation Act of 16 October 1934. Soil values were assigned according to soil type, geological age of the parent rock, and soil development stage. Only the natural yield conditions (soil structure up to 1 metre below the surface, terrain, climatic conditions, and water conditions) were taken into account and evaluated. The best soil quality was given a soil value of 100 (e.g., Chernozems of the Magdeburger Börde), and the worst was given a value of 1 (e.g., diluvial sandy soil, very shallow with a maximum topsoil of 15 cm). Compared to this range, all three sites in all three years represent moderately productive sites with soil values ranging from 40 to 64.

Table 1. Description of the experiment sites Hohenheim (HOH), Eckartsweier (EWE), and Oberer Lindenhof (OLI) in the three experimental years.

Parameter	HOH	EWE	OLI
Elevation (above sea level)	390 m	140 m	720 m
Region	Filder plain	Upper Rhine valley	Schwabian Alb
Sum of precipitation (mm) [1]			
2021	583	823	945
2022	546	420	645
2023	514	584	705
Mean temperature (°C) [2]			
2021	13.8	15.4	11.7
2022	15.7	18.1	13.9
2023	15.6	17.0	13.3
Soil value (1–100)			
2021	60	62	49
2022	60	40	64
2023	64	63	55

[1] The period of 1 October–31 July; [2] the period of 1 April–31 July.

2.2. Experimental Design and Field Management

The genotypes were treated with two input variants: I1, N fertilisation of 100–120 kg ha^{-1} for hybrid rye and 140–180 kg ha^{-1} for wheat (including soil mineral N) in two to three doses, chemical pesticides and growth regulators applied according to local practices; I2, 20% reduced N fertilisation, no pesticides, no growth regulators, and one to three weed harrows in autumn and/or spring. All details are given in Tables S2–S5. The cultivars were sown using a GPS-controlled seeding machine in a fully randomised block design with two replicates (hybrid rye) or a 5 × 4 lattice design with two replicates (wheat), and each plot was 6 m^2 in area. Each crop was surrounded by border plots of the same crop. Both crops were sown in adjacent plots at all locations. The seeding rate for hybrid rye was 200 grains m^{-2} and for wheat 320 grains m^{-2} in I1. In I2, 10% more seed was used for both crops to compensate for possible losses due to harrowing.

2.3. Measurements

Weed density (WD) was analysed at BBCH 25–29 on a scale of 1–9, where 1 = no weed and 9 = full weed cover. The date of heading (HD) and flowering date (FD) were measured on days after Jan 1. Plant height (PH) was measured after flowering in centimetres from the soil surface to the top of the ear (without awns in hybrid rye). Leaf blight (LB) was rated on a scale of 1–9, where 1 = no spots, 5 = 20% of leaf area covered, and 9 = 40% of leaf area covered. Lodging (LOD) was scored on a 1–9 scale with 1 = entire plot standing upright and 9 = entire plot lying on the ground. LB and LOD were not observed in all trials. OLI 2023 erroneously failed to collect harvest samples; therefore, no TGW and PC could be measured. Plots were harvested with a combine harvester for experimental plots with an integrated scale. Water content was measured at harvest for each plot using a near-infrared spectrometer (NIRS) and adjusted to 14% moisture before statistical analyses of grain yield (GY). The protein content (PC) of wheat was determined by NIRS using a Spectra

Star instrument from Unity Scientific, Inc. (Brookfield, CT, USA). The measurement was performed using short-wave infrared light with wavelengths between 1175 and 2425 nm. An existing calibration for wheat was used. Thousand-grain weight (TGW) was measured by using Seed Analyser MARViN (MARViTECH GmbH, 19243 Wittenburg, Germany).

2.4. Statistical Analyses

All calculations were made on a plot basis. It was not the intention of this study to compare individual rye varieties with individual wheat varieties. For the first objective, the comparison of hybrid rye and wheat on three locations in three years, we used exact *p* values from the respective ANOVA. For the second objective, the analysis of cultivars within the cereals, another ANOVA was calculated using a factorial design model. In both analyses, the adjusted means of each trait per crop, input level, location and year, and their interactions (fixed effects) were calculated based on best linear unbiased estimation (BLUE) while variance components were estimated for genotypes and their interactions (random effects) based on best linear unbiased prediction (BLUP). For fixed effects, the Wald statistics in the ASReml R-package was used to establish statistical significance, and the significance of variance components for random effects was determined using the likelihood ratio test. Exact *p* values were given for both analyses. All calculations of the multi-factorial experiment were analysed in the statistical program R [12] using the ASReml package (version 4.1.0.160) [13,14]. The relationships between the two input levels and between the traits were analysed by Pearson's correlation using R-Studio software (version 2023.03.0-386) [15]. Principal component analysis (PCA) was performed using the R-package 'stats', version 4.3.0, within the R-package. The R-package 'factoextra' version 1.0.7 [16] was used for visualisation.

3. Results

3.1. Comparison Between Hybrid Rye and Wheat

In eight out of nine environments, hybrid rye was significantly superior to winter wheat in grain yield in both I1 and I2 (Tables 2 and 3). On average, hybrid rye yielded 1.1 and 1.0 t/ha more grain than wheat in I1 and I2, respectively, with both differences being highly significant ($p < 0.001$). This was only not the case in EWE 2023, where a hail storm shortly before harvest caused lodging and grain losses in rye. Under these conditions, wheat yielded significantly more in I1, but the difference was not significant in I2. As rye as a crop is earlier in development and much taller than wheat, HD, FD, and PH were consistently different between both crops ($p < 0.001$). Rye showed a significantly ($p < 0.001$) higher value for LOD in all location–year combinations where lodging occurred. This was particularly evident in I2, where no growth regulators were applied. Rye is known to have smaller grains despite intensive selection efforts by breeders, so TGW was significantly ($p < 0.001$) lower in rye than in wheat in all cases. Protein content (PC) was only measured in wheat, as in rye, it does not play a role in baking quality.

Table 2. Comparison of grain yield and other agronomic traits for input level I1 calculated across 10 hybrid rye and 20 wheat cultivars in each location and study year; *p* value from the Wald Statistic for detecting differences between cereals.

Year	Loc	Cereal	GY (t/ha)	WD (1–9)	HD (d)	FD (d)	PH (cm)	LB (1–9)	LOD (1–9)	TGW (g)	PC (%)
2021	HOH	Rye	9.9	1.20	143.35	155.80	135.50	3.20	3.90	29.84	-
		Wheat	9.6	1.05	159.08	162.93	85.70	-	1.00	42.28	10.15
		p value	0.003	ns	<0.001	<0.001	<0.001	-	<0.001	<0.001	-
	EWE	Rye	9.9	1.35	136.50	150.55	158.75	2.60	2.40	33.40	-
		Wheat	8.0	1.40	156.05	159.93	95.13	4.94	1.00	40.47	12.69
		p value	<0.001	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	-

Table 2. *Cont.*

Year	Loc	Cereal	GY (t/ha)	WD (1–9)	HD (d)	FD (d)	PH (cm)	LB (1–9)	LOD (1–9)	TGW (g)	PC (%)
	OLI	Rye	7.3	1.00	154.10	164.90	157.00	5.45	5.90	30.86	-
		Wheat	5.8	1.00	170.43	173.45	87.88	5.85	1.00	35.09	13.57
		p value	<0.001	ns	<0.001	<0.001	<0.001	ns	<0.001	0.001	-
2022	HOH	Rye	9.0	2.00	-	-	139.05	1.40	1.00	38.32	-
		Wheat	8.4	1.18	-	-	82.75	1.18	1.00	46.17	8.89
		p value	0.028	<0.001	-	-	<0.001	ns	ns	<0.001	-
	EWE	Rye	8.3	1.25	131.60	137.95	119.50	3.68	1.00	34.06	-
		Wheat	6.5	1.13	142.85	147.30	71.75	4.00	1.00	38.73	11.09
		p value	<0.001	ns	<0.001	<0.001	<0.001	ns	ns	<0.001	-
	OLI	Rye	9.8	1.00	140.25	150.30	126.50	4.30	1.00	35.72	-
		Wheat	8.6	1.00	159.58	164.25	88.12		1.00	44.94	11.12
		p value	<0.001	ns	<0.001	<0.001	<0.001		ns	<0.001	-
2023	HOH	Rye	8.2	1.00	134.80	145.85	147.05	2.20	1.00	35.28	-
		Wheat	7.8	1.00	148.90	151.90	87.40	2.40	1.00	46.84	8.55
		p value	0.014	ns	<0.001	<0.001	<0.001	ns	ns	<0.001	-
	EWE	Rye	8.3	1.00	127.20	140.35	157.00	1.18	3.90	28.83	-
		Wheat	9.5	1.00	143.55	148.48	98.63	1.31	1.95	43.33	10.75
		p value	<0.001	ns	<0.001	<0.001	<0.001	ns	<0.001	<0.001	-
	OLI	Rye	10.9	1.00	147.95	153.35	130.40	1.78	1.00	-	-
		Wheat	8.5	1.00	160.98	163.88	78.80	-	1.00	-	-
		p value	<0.001	ns	<0.001	<0.001	<0.001		ns	-	-
Mean		Rye	9.1	1.20	138.39	149.88	141.19	2.87	2.34	33.29	
		Wheat	8.0	1.08	153.85	159.01	86.24	3.28	1.11	42.23	10.85
		p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.031	<0.001	<0.001	-

Abbreviations: Loc—location; GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LB—leaf blotch; LOD—lodging at harvest; TGW—thousand-grain weight; PC—protein content; 1—lowest; 9—highest; d—days since 1 January; ns indicates no significant relationship. HOH = Hohenheim; EWE = Eckartsweier; OLI = Oberer Lindenhof.

Table 3. Comparison of grain yield and other agronomic traits for the low input level I2 calculated across 10 hybrid rye and 20 wheat cultivars in each location and study year; *p* value from the Wald Statistic for detecting differences between cereals.

Year	Loc	Cereal	GY (t/ha)	WD (1–9)	HD (d)	FD (d)	PH (cm)	LB (1–9)	LOD (1–9)	TGW (g)	PC (%)
2021	HOH	Rye	8.9	2.10	140.00	154.30	163.75	4.65	7.25	29.48	-
		Wheat	8.2	2.35	156.35	161.00	96.75	-	1.00	43.88	9.26
		p value	0.003	ns	<0.001	<0.001	<0.001	-	<0.001	<0.001	-
	EWE	Rye	8.8	1.50	134.20	148.95	171.50	4.20	3.00	30.76	-
		Wheat	7.4	2.63	155.17	158.95	99.00	5.82	1.00	40.42	11.93
		p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	-
	OLI	Rye	7.7	2.50	154.20	164.85	158.25	6.05	4.10	31.66	-
		Wheat	5.4	2.78	170.98	173.93	90.75	5.05	1.00	37.52	11.82
		p value	<0.001	ns	<0.001	<0.001	<0.001	ns	<0.001	<0.001	-
2022	HOH	Rye	7.1	2.95	-	-	147.25	2.60	1.00	37.20	-
		Wheat	6.3	3.95	-	-	86.02	1.25	1.00	44.03	8.05
		p value	<0.001	<0.001	-	-	<0.001	<0.001	ns	<0.001	-
	EWE	Rye	6.9	2.75	129.15	137.70	139.75	2.90	2.05	31.23	-
		Wheat	5.8	3.28	141.82	147.28	75.94	4.63	1.00	41.35	9.39
		p value	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	-
	OLI	Rye	8.5	2.00	138.00	150.75	142.00	5.70	1.00	36.45	-
		Wheat	7.5	2.15	159.25	164.10	92.75	-	1.00	46.56	9.79
		p value	<0.001	ns	<0.001	<0.001	<0.001	-	ns	<0.001	-
2023	HOH	Rye	6.7	1.80	134.70	146.15	150.30	6.45	1.00	35.27	-
		Wheat	5.8	1.33	149.03	152.00	85.13	2.82	1.00	47.46	8.43
		p value	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	ns	<0.001	-
	EWE	Rye	6.8	1.15	126.30	139.80	167.45	2.84	6.35	27.85	-
		Wheat	7.2	1.23	142.80	147.73	104.37	2.20	3.48	39.90	10.08
		p value	ns	ns	<0.001	<0.001	<0.001	ns	<0.001	<0.001	-
	OLI	Rye	9.0	4.00	145.85	153.75	159.15	1.61	1.00	-	-
		Wheat	7.5	4.00	160.15	163.05	91.77	-	1.00	-	-
		p value	<0.001	ns	<0.001	<0.001	<0.001	-	ns	-	-
Mean		Rye	7.8	2.31	136.94	149.53	155.49	4.11	2.97	32.49	
		Wheat	6.8	2.63	153.16	158.50	91.39	3.63	1.28	42.64	9.84
		p value	<0.001	<0.001	<0.001	<0.001	<0.001	ns	<0.001	<0.001	

Abbreviations: LOC—location; GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LF—lodging at flowering; LH—lodging at harvest; TGW—thousand-grain weight; PC—protein content; 1—lowest; 9—highest; d—days; ns indicates no significant relationship. HOH = Hohenheim; EWE = Eckartsweier; OLI = Oberer Lindenhof.

3.2. Comparison Between Input Levels

The largest differences between input levels were found for grain yield (Table 4). On average, I1 yielded 16 % (hybrid rye) and 18 % (wheat) more than I2. Differences in WD, PH, and PC were expected due to the missing pesticides and growth regulators, and reduced nitrogen. LB and LOD were observed only on some of the sites. Hybrid rye was much taller than wheat, and in I2, the difference was even greater because no growth regulator was applied. Overall, both weed and disease pressure were low in the trials. LB was only present in some locations, mainly caused by *Zymoseptoria tritici* in wheat and *Rhynchosporium secalis* in rye.

Table 4. Comparison of input levels for grain yield and other agronomic traits across 10 cultivars of hybrid rye and 20 cultivars of wheat and 3 locations in 3 years.

Crop	Input Level	GY (t/ha)	WD (1–9)	HD (Days)	FD (Days)	PH (cm)	LB (1–9)	LOD (1–9)	TGW (g)	PC (%)
Rye	I1	9.06 a	1.2 a	138 a	150 a	141 a	2.9 a	2.3 a	33.3 a	NA
	I2	7.82 b	2.3 b	137 b	150 a	156 b	4.1 b	3.0 a	33.0 a	NA
Wheat	I1	8.01 a	1.1 a	154 a	159 a	86 a	3.3 a	1.1 a	42.2 a	10.9 a
	I2	6.77 b	2.7 b	153 b	159 a	91 b	3.6 b	1.3 a	42.6 a	9.8 b

Abbreviations: GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LF—lodging at flowering; LH—lodging at harvest; TGW—thousand-grain weight; PC—protein content; 1—lowest; 9—highest; d—days; NA—not assigned. Note: different lowercase letters represent significant differences between different treatments at $p < 0.05$.

3.3. Within-Crop Variation

The ANOVA for grain yield showed highly significant ($p < 0.001$) differences for I, Y, L, and all interactions across most traits (Tables 5 and 6). Interestingly, the difference between cultivars was not significant in hybrid rye, but was significant in wheat, mainly due to the highly differing classes of baking quality related to grain yield. Most interactions with the cultivar showed no significance for GY in both crops. Similar results were obtained for the other traits. Only LOD showed no significance for the main effects and most of the interactions, because LOD occurred in wheat only in EWE23 in I1 and I2, and in rye, only in four and five location–year combinations in I1 and I2, respectively. Similarly, WD was not significant for Y and L, but was highly significant ($p < 0.001$) for all their interactions. C × I was only significant for HD, FD, PH in hybrid rye and wheat. Interestingly, cultivar-specific differences between the two input levels were very similar in both crops, ranging from 0.93 to 1.53 t ha^{-1} in rye and from 0.67 to 1.59 t ha^{-1} in wheat.

Table 5. *p* values from ANOVA of grain yield and other agronomic traits of hybrid rye for detecting differences among two input levels and 10 cultivars in 3 locations and 3 study years.

	GY		WD		HD		FD		PH		LB		LOD		TGW	
	df	*p* Value	df	*P* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value
Location (L)	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	ns	2	<0.001
Year (Y)	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001
L × Y	4	<0.001	4	<0.001	3	<0.001	3	<0.001	4	<0.001	4	<0.001	4	<0.001	3	<0.001
Input level (I)	1	<0.001	1	<0.001	1	<0.001	1	ns	1	<0.001	1	<0.001	1	ns	1	0.032
I × L	2	<0.001	2	<0.001	2	ns	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001
I × Y	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	0.012	2	0.005
I × L × Y	4	<0.001	4	<0.001	3	<0.001	3	0.037	4	<0.001	4	<0.001	4	<0.001	3	ns
Cultivar (C)	9	ns	9	ns	9	<0.001	9	<0.001	9	0.020	9	ns	9	ns	9	0.019
C × L	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns	18	<0.001	18	ns
C × Y	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns	18	0.019
C × L × Y	36	ns	36	ns	27	ns	27	<0.001	36	0.039	36	ns	36	ns	27	ns
C × I	9	ns	9	ns	9	ns	9	ns	9	<0.001	9	ns	9	ns	9	ns
C × I × L	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns	18	<0.001	18	ns

Table 5. *Cont.*

	GY		WD		HD		FD		PH		LB		LOD		TGW	
	df	*p* Value	df	*P* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value
C × I × Y	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns	18	ns
C × I × Y × L	36	ns	36	ns	27	ns	27	ns	36	ns	36	ns	36	0.001	27	0.030

Abbreviations: GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LB—leaf blight; LOD—lodging at harvest; TGW—thousand-grain weight; df = degrees of freedom; ns indicates no significant relationship.

Table 6. *p* values from ANOVA of grain yield and other agronomic traits of wheat for detecting differences among two input levels and 20 cultivars in 3 locations and 3 study years.

	GY		WD		HD		FD		PH		LB		LOD		TGW		PC	
	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value	df	*p* Value
Location (L)	2	<0.001	2	ns	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	ns	2	<0.001	2	<0.001
Year (Y)	2	<0.001	2	ns	2	<0.001	2	<0.001	2	<0.001	2	<0.001	2	ns	2	<0.001	2	<0.001
L × Y	4	<0.001	4	<0.001	4	<0.001	3	<0.001	4	<0.001	1	<0.001	4	<0.001	3	<0.001	3	<0.001
Input level (I)	1	<0.001	1	<0.001	1	<0.001	1	<0.001	1	<0.001	1	<0.001	1	ns	1	ns	1	<0.001
I × L	2	<0.001	2	<0.001	2	<0.001	2	ns	2	0.001	2	<0.001	2	ns	2	<0.001	2	<0.001
I × Y	2	<0.001	2	<0.001	2	<0.001	2	0.003	2	<0.001	2	<0.001	2	ns	2	<0.001	2	<0.001
I × L × Y	4	0.002	4	<0.001	4	<0.001	3	<0.001	4	<0.001	1	ns	4	0.003	3	<0.001	3	ns
Cultivar (C)	19	<0.001	19	ns	19	<0.001	19	<0.001	19	<0.001	19	0.006	19	ns	19	<0.001	19	<0.001
C × L	38	ns	38	ns	38	ns	38	<0.001	38	ns	38	ns	38	ns	38	0.049	38	ns
C × Y	38	ns	38	ns	38	0.003	38	ns	38	0.036	38	0.009	38	ns	38	0.033	38	0.029
C × L × Y	76	<0.001	76	ns	76	<0.001	57	<0.001	76	<0.001	19	<0.001	76	ns	57	<0.001	57	<0.001
C × I	19	ns	19	ns	19	<0.001	19	0.018	19	<0.001	19	ns	19	ns	19	ns	19	ns
C × I × L	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns
C × I × Y	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns	38	ns
C × I × Y × L	76	ns	76	ns	76	ns	57	0.026	76	ns	19	ns	76	ns	57	<0.001	57	ns

Abbreviations: GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LB—leaf blight; LOD—lodging at harvest; TGW—thousand-grain weight; PC—protein content; ns indicates no significant relationship.

Correlations among traits were significant only in some instances. For hybrid rye, the correlations between GY and LB, as well as between FD and LB, were significant in I1; in I2, the correlations between FD and HD, as well as between FD and LB, were significant (Table 7). LOD and TGW were only weakly correlated.

Table 7. Correlations among grain yield and other agronomic traits across 10 hybrid rye cultivars and nine location × year combinations; I1 is above and I2 is below the diagonal.

	GY	WD	HD	FD	PH	LB	LOD	TGW
GY		0.48	−0.07	0.47	0.34	−0.76 **	0.18	−0.02
WD	−0.08		0.05	0.04	0.11	−0.05	0.45	−0.46
HD	−0.40	0.05		0.50	−0.48	0.06	−0.11	−0.18
FD	0.04	0.06	0.85 **		0.81	−0.67 *	−0.19	0.09
PH	0.19	0.32	−0.34	0.33		−0.34	−0.25	0.23
LB	−0.21	−0.25	−0.51	−0.81 **	0.29		0.04	−0.20
LOD	0.40	−0.30	0.07	0.11	0.21	0.29		−0.63
TGW	0.05	0.59	−0.10	−0.01	0.18	−0.42	−0.72 *	

Abbreviations: GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LB—leaf blight; LOD—lodging at harvest; TGW—thousand-grain weight. Note: * represents $p < 0.05$; ** represents $p < 0.01$ and indicates significant relationships.

More significant correlations among traits were observed for wheat caused by the higher number of genotypes (Table 8). GY showed the well-known negative correlation with PC in both I1 and I2. Also, the correlations between HD and FD, HD/FD and LB, and HD/FD and LOD were significant in both input variants. Also, LB and LOD were significantly correlated.

Table 8. Correlations among grain yield and other agronomic traits across 20 wheat cultivars and nine location × year combinations; I1 is above and I2 is below the diagonal.

	GY	WD	HD	FD	PH	LB	LOD	TGW	PC
GY		0.25	−0.23	−0.10	−0.25	−0.17	0.04	−0.02	−0.83 ***
WD	−0.33		0.09	−0.01	0.03	−0.35	−0.10	0.03	−0.42
HD	−0.10	0.02		0.91 ***	−0.21	−0.63 **	−0.78 ***	0.10	0.13
FD	−0.07	−0.04	0.92 ***		0.62	−0.62 **	−0.71 ***	0.15	0.07
PH	−0.30	−0.05	−0.33	0.09		0.33	0.34	0.34	0.02
LB	−0.16	−0.11	−0.74 ***	−0.70 ***	0.41		0.64 **	−0.13	0.10
LOD	−0.06	0.19	−0.77 ***	−0.69 ***	0.36	0.68 ***		−0.01	−0.03
TGW	0.12	−0.09	0.05	0.00	0.31	−0.10	−0.15		−0.01
PC	−0.73 ***	0.26	−0.05	0.02	0.07	0.17	0.28	−0.12	

Abbreviations: GY—grain yield; WD—weed density; HD—heading date; FD—flowering date; PH—plant height; LB—leaf blight; LOD—lodging at harvest; TGW—thousand-grain weight; PC—protein content; Note: ** represents $p < 0.01$; *** represents $p < 0.001$ and indicates significant relationships.

The PCA explained in the first two dimensions 49.9% of the total variance for hybrid rye and 66.6% for wheat. Input levels and location–year combinations were clustered in hybrid rye, illustrating their correlation (Figure 1). Only EWE23 for I1 had the weakest correlation and clearly deviated due to the fact that this was the only location–year combination where wheat yielded significantly more than hybrid rye (Table 3). For wheat, I1 and I2 have the largest angle between their vectors at OLI21 and EW 21. As the PCA gives an indication of the discriminating power of each test environment based on the vector length, these input–environment combinations were the most discriminating for the cultivars tested. The PCA also shows the distribution of cultivars. In hybrid rye, four out of ten genotypes are located on the left side: KWS Binntto, KWS Eterno, Piano, and KWS Trebiano. For wheat, the deviation in the cultivars was greater, corresponding to the significant variation among cultivars.

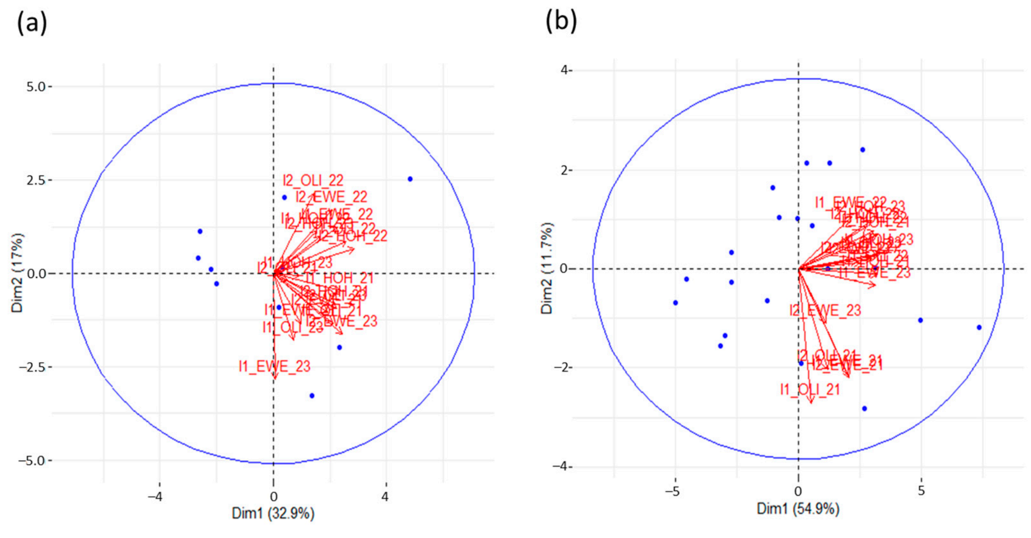

Figure 1. Principal component analysis (PCA) of grain yield (GY) for 2 input levels (I1 = high; I2 = low) and 9 location–year combinations for (**a**) 10 hybrid rye cultivars and (**b**) 20 wheat cultivars; blue dots are individual cultivars.

Figure 2 shows a clear correlation between I1 and I2 for 10 cultivars of hybrid rye and 20 cultivars of wheat and illustrates the low importance of the genotype × input level interaction. The best cultivar for I1 was regularly also the best for I2 in hybrid rye and wheat. The correlation between I1 and I2 was r = 0.60 ($p > 0.1$) for hybrid rye, and r = 0.75 ($p < 0.05$) without the cultivars KWS Trebiano and Piano. For wheat, the correlation was r = 0.80 ($p < 0.001$). There are only a few genotypes that deviate significantly from the regression. Most of these deviating cultivars had a higher grain yield on the low input level than the mean. The wheat cultivar 'Ritter', however, had a somewhat higher deviation between I1 and I2. The differences in yield between the wheat varieties according to their baking quality level are obvious. The highest yields were achieved by the two C varieties (feed quality), which were placed among the hybrid rye cultivars.

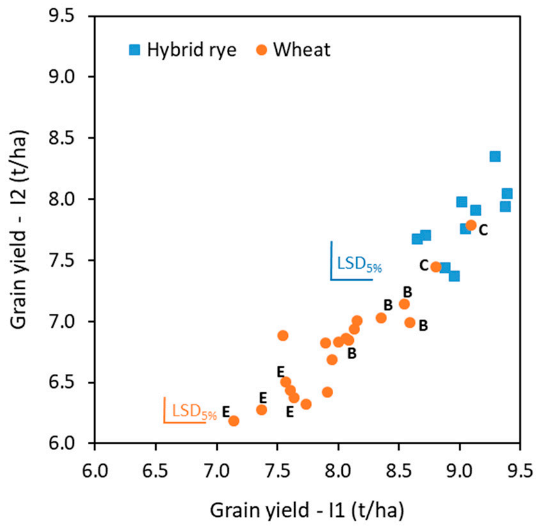

Figure 2. Grain yield in I1 vs. I2 for 10 cultivars of hybrid rye and 20 cultivars of wheat across 9 location × year combinations; uppercase letters indicate the grain quality of wheat: E (=excellent), B (=good), and C (=feed quality) are indicated, the remainder are in class A (=very good); $LSD_{5\%}$ indicates the least significant difference at $p < 0.05$ for wheat and hybrid rye, respectively.

4. Discussion

The main objective of this study was to compare hybrid rye and wheat in terms of grain yield when grown in less favourable environments and at two input levels. For this purpose, 10 hybrid rye and 20 wheat cultivars representative for German commercial cultivars were grown on three ecologically different locations in 3 years.

4.1. Effects of Locations and Years

Weather conditions are very variable in the humid climate zone. We therefore conducted our experiments at three ecologically different sites in south-western Germany over three consecutive years. The ANOVAs showed significant effects for both main factors for most traits. Where this was not the case, the L × Y interaction was significant. Accordingly, the means of all the traits varied considerably between sites, years, and crops. For example, GY varied between 6.5 and 10.9 t/ha in I1 and between 5.4 and 9.0 t/ha in I2. As phenological data depend mainly on temperature and humidity, HD and FD also varied widely. LB and LOD were particularly variable because conditions were not favourable for fungal diseases or lodging at all sites and in all years. This is of course more pronounced in I2 where no fungicides and growth regulators were used. The years had a strong effect on PC in wheat. Here, 2021 yielded higher values than the following two years due to higher moisture and thus better nitrogen availability from the soil. The high effects of locations and years illustrate the necessity of multi-environmental trials.

Given the German soil taxation with values from 1 to 100 [10,11], we consider all test sites of this study as less favourable because their soil value varied from 40 to 64. This represents the majority of German agricultural sites. The soil number for arable land illustrates the differences in yield caused by soil conditions (soil types, geological origin, state levels) [17]. Very good to good soils for agricultural land have soil numbers above 60. A moderately productive site has a soil number between 40 and 60, and a less productive site has a value of 20 to 40. A soil number below 20 is considered unsuitable for agricultural production (except for grassland). According to the results of the long-term state variety trials, it is undisputed that wheat has an advantage on the very good soils and population rye on the sites with very low productivity [8]. The question we want to examine here concerns the relative competitiveness of wheat and hybrid rye on the majority of field sites with soil numbers between 40 and 60, which are covered by our trial sites.

4.2. Effects of Input Level

In addition to the soil quality, the input level determines the productivity of a field site and a crop. We followed a good agricultural practice in I1 and reduced the input in terms of nitrogen fertilisation (−20%), pesticides, and growth regulators (none) in I2. The input level had a significant ($p < 0.001$) effect in hybrid rye and wheat on grain yield and most other traits as shown by the ANOVAs. Also, the interactions of input level with locations and years were mostly significant, illustrating that inferior soil fertility on some sites could be compensated for by a higher input level. In fact, the reduced input level reduced the grain yield by 1.3 t/ha in hybrid rye and 1.2 t/ha in wheat. Significant differences between input levels could be expected for WD, LB, and LOD, because these are directly dependent on the use of pesticides and growth regulators. Comparisons for LB and LOD, however, are difficult, because both traits could not be recorded on every location–year combination.

For wheat, the difference in protein content (PC, 9.84 vs. 10.85%) is especially important, because payments for farmers are still often based on protein content. In I2, PC ranged, on average, between 8.1% and 11.9% for the location–year combinations. Only two out of eight environments achieved B (good) quality, with the rest being feed quality (<11%). In I1, between 8.6% and 13.6% PC were achieved, resulting in B quality in three out of eight location–year combinations and A (very good) quality in one. This shows that even in I1, nitrogen supply was not high enough to support excellent PC. This is an environmental problem, because N fertilisation is the main contributor to agricultural greenhouse gas emissions [18].

4.3. Effects of the Crop

The present experiment clearly demonstrated the superiority of hybrid rye over wheat in terms of grain yield when the crops are grown on soils with moderate fertility and the input of fertiliser and pesticides is only moderate or even reduced. In I1 and I2, hybrid rye consistently yielded more than wheat in eight out of nine location–year combinations. The only exception was EWE23 in I1, where lodging in rye occurred and a hail storm hit a few days before harvest. Rye is more susceptible to hail than wheat because its grains are open in the husk and lodging can be a problem with long-strawed rye in adverse weather conditions.

In contrast to the self-pollinating wheat, hybrid rye utilises heterotic vigour to a great extent. Hybrid varieties with improved agronomic and physiological traits are known to yield better even under low N input conditions, as shown in rice [19]. However, it should be noted that, in our experiments, minimal disease and lodging pressure (except EWE23) occurred over the three years.

The differences between the crops were not limited to grain yield. Some differences were based on the different physiology of the crops. Rye flowers and matures earlier than wheat, so HD and FD are clearly different. This earlier development helps farmers manage work peaks, because planting and harvest are one to two weeks earlier. Rye is also a much taller crop, with a difference from wheat of 55 cm and 65 cm in I1 and I2, respectively, and is more susceptible to LOD. The shortness of wheat is due to the use of a height-reducing (*Rht*) gene in most commercial wheat cultivars. And rye has a much lower TGW, despite this being a high breeding priority. However, these crop-specific differences can be managed by the farmer through agronomic or chemical measures. So, the main issue in deciding which crop to grow on moderately productive soil is still grain yield. And this clearly favours hybrid rye, especially in less favourable environments.

Rye and wheat have completely different baking properties. In the case of wheat, this is mainly based on protein content and, to some extent, protein quality (see below). Rye, on the other hand, contains no gluten proteins and its baking ability is based on pentosane content and an intact starch (i.e., low alpha-amylase activity). Pentosans belong to the hemicelluloses and are mixtures of polysaccharides. Therefore, the protein content of rye, usually 9–11%, does not play a role in its baking ability and it is baked after sourdough fermentation, whereas yeast fermentation is the rule for wheat. As a result, all rye samples in our study were suitable for baking in all location–year combinations, whereas wheat was only suitable in some location–year combinations due to the lower protein content resulting from less nitrogen availability.

Rye releases about 20% less greenhouse gas (GHG) emissions and has an 8% lower carbon footprint than wheat, according to a new analysis of VCU (value for cultivation and use) trials in Germany spanning the period from 1983 to 2019 [18]. This difference is essentially due to the fact that rye requires 25% less nitrogen than wheat. Due to the larger root system and especially the longer root length, rye has a higher nitrogen utilisation efficiency and a lower risk of N leaching than wheat. Although the higher yields of hybrid rye compared to population rye led to 4% higher GHG emissions, this was more than compensated for by the 13% higher yields of hybrid rye in this study [18].

From an economic point of view, the biggest difference between wheat and rye is the cost of seed, which is for hybrid rye around twice that of wheat due to higher production costs of hybrid seed. This higher price, however, is compensated for by the high grain yield in most instances. Additionally, hybrid rye is sown in a lower seed density than wheat to compensate for the higher seed price. In addition, rye is unfortunately valued less than wheat in the market, which is not always offset by the higher grain yields and the lower input levels. For the years 2021 to 2023, the price difference between wheat and rye was between EUR 11.50 and EUR 30.50 per ton of grain.

The breeding of new and site-adapted varieties will become even more important in the future. In the face of climate change, crops like rye, with increased drought stress tolerance [20], good yield, and water use efficiency even in dry years, are needed. (Hybrid) rye has inherent advantages over wheat, especially under lower input conditions. This is additionally favoured by breeders' selection in the respective regions over the years. Due to the effectiveness of hybrid breeding, hybrid rye had the highest absolute long-term breeding progress among five winter cereals, with 1.88 and 1.80 t ha^{-1} in the low and high input level across 30 years, respectively [7]. This is considerably higher than that of winter wheat with 1.43 and 1.30 t ha^{-1}, respectively.

4.4. Effects of Cultivars Within Crops

Hybrid rye showed no differences among cultivars for grain yield and most other traits. The only exceptions were HD and FD and, to a lesser extent, PH and TGW, as shown by the p values of the ANOVA. These traits are strongly influenced by breeders' selection. This is also true for grain yield, but here, we have selected the actual most widely grown top cultivars, so no large differences were achieved. Since hybrid rye is produced in the form of a top cross hybrid that contains up to four genetic components [2], the commercial varieties are heterogeneous, and accordingly, the genetic variance between hybrid cultivars is lower than between cultivars of wheat.

No significant cultivar × input level interaction was obtained in hybrid rye, except for PH, because some cultivars are more responsive to growth regulators than others. This result from the ANOVA is confirmed by the high level of agreement between I1 and I2 (Figure 2), which is a result of the missing interaction. Accordingly, the PCA shows no different grouping of grain yield from I1 and I2.

Similarly, no cultivar × input level interaction for GY was found for wheat, although the GY differences between cultivars were significant. This result is consistent with the results of a long-term breeding evaluation of winter wheat: breeding under a high-input regime improves cultivar performance even under low inputs [21]. The significant correlation for grain yield between I1 and I2 that we achieved for both crops supports this observation. Clearly, breeders did not select special cultivars for low-input conditions. However, this may also be due to the fact that the differences between I1 and I2 were not strong enough to show specific cultivar differences.

The significant variance among wheat cultivars for GY was mainly due to the different baking quality classes included in our study that correspond to different GY levels. The well-known negative correlation between GY and PC in wheat, which was also detected in our study (Table 8), is caused by genomic regions that affect both traits. In a study with 1739 wheat genotypes, four of the five detected putative QTLs underlying both traits showed an antagonistic effect with a positive effect on one trait and a negative effect on the other [22]. However, variation in PC does not correlate well with baking quality (loaf volume) in wheat [23]. There are cultivars that are less dependent on PC to obtain a good baking quality due to improved protein functionality [23]. Because about 45% of wheat in the EU is used solely for feeding [24], it is cheaper and better to add soy protein to the feed than to produce high-protein wheat with a high N input. This is important in view of the European Union's agricultural policy objective of reducing the nitrogen fertiliser surplus by around 20%, as we did in our study. In addition, the production of nitrogen fertilisers is a highly energy-intensive process, and nitrogen losses may pollute the groundwater. Therefore, a lower-nitrogen-demanding crop like hybrid rye is advantageous. A lower protein content is no problem for hybrid rye, because its baking quality is not based on PC, but on the content of complex carbohydrates, like pentosanes. Farms with their own feed production will undoubtedly benefit from cheaper rye if they observe the known restrictions on its use in feeding, especially for young animals.

5. Conclusions

Hybrid rye could be promoted to be grown on a larger area than at present, as shown by the high GY potential in this study. Indeed, hybrid rye in I2 yielded about the same level as wheat in the intensive variant under less favourable conditions. Thus, hybrid rye is set to be a game-changer for rye-producing countries, especially when fertilisation and chemical plant protection are reduced due to environmental constraints, as is currently being discussed in the European Commission [9]. Its high nutrient and water use efficiency will also be a key factor in future climate change strategies. Since in rye, it is not the protein but the pentosane content that plays the main role in baking ability, all rye cultivars in all location–year combinations were suitable for baking. For wheat, on average, this was the case for only four out of eight (I1) and two out of eight (I2) combinations, respectively.

Taking into account the objectives of the European Green Deal, both crops require cultivars that deliver good yields and quality with reduced use of pesticides and mineral fertilisers. Our experiment showed that this is not very common at the moment, as the cultivars tested responded quite similarly to input reduction. On the other hand, there is a need for rye varieties with high lodging tolerance, even with reduced or no use of growth regulators. The forthcoming introduction of short-straw varieties could make a significant contribution to this in hybrid rye.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture15020163/s1. Table S1: Tested wheat and hybrid rye varieties with wheat quality, year of registration, and breeding company; Table S2: Applied pesticides in I1 and date and growth stage (EC) of application; Table S3: Date of mechanical harrowing; Table S4: Applied N fertilisation (kg N/ha): I1; Table S5: Applied N fertilisation (kg N/ha): I2.

Author Contributions: Conceptualisation and writing, T.M.; formal analysis, S.L.; investigation in 2022, S.L.; investigation in 2021 and 2023, B.L.; responsibility for all field trials, B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: All relevant data are given within the manuscript or the Supplementary Materials. The datasets used during the present experiments are available from the corresponding author upon reasonable request.

Acknowledgments: The authors gratefully acknowledge the excellent technical support of Christian Metzke and Mohsen Sadeghi (HOH), Christine Maus (EWE), and Heralt Pöschel (OLI).

Conflicts of Interest: The authors declare no conflicts of interest.

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