Hybrid Cultivar and Crop Protection to Support Winter Rye Yield in Continuous Cropping

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Supplementary information

Table S1. Chemical properties of the soil in the experiment in 2016, after harvesting of crops (mean ± standard error).

Year	Soil layer (cm)	C_{org} (g kg^{-1}) [1]	N_{tot} (g kg^{-1}) [2]	Available (mg kg^{-1})			pH [5]
				P [3]	K [3]	Mg [4]	
For the entire experimental area							
2016	0-25	9.96±0.21	0.734±0.011	108.9±2.45	192.2±4.55	53.3±0.73	5.51±0.04
For the winter rye fields							
2016	0-25	10.9±0.60	0.852±0.024	105.5±3.42	232.7±7.48	62.8±1.56	5.62±0.05

[1] C_{org} – organic carbon content determined by calorimetry via oxidation with a solution of $K_2Cr_2O_7 + H_2SO_4$ and measuring the absorption on a spectrophotometer; [2] N_{tot} – total N content, Kjeldahl method; [3] Egner–Riehm method; [4] Schachtschabel method; [5] in 1 M KCl, potentiometric method; all analyses were performed at the accredited laboratory of the Chemical and Agricultural Station in Olsztyn, Poland (Accreditation Certificate No. AB 277 issued by the Polish Center for Accreditation in Warsaw).

Table S2. Atmospheric precipitation and daily air temperature during the study periods according to the Meteorological Station in Bałcyny, Poland.

	Month												Sum/mean
	IX	**X**	**XI**	**XII**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX - VIII**
	Precipitation, mm												
2016/2017	17.1	96.3	78.2	77.8	15.8	40.5	53.0	52.1	34.0	109.9	106.1	54.8	735.6
2017/2018	211.1	160.3	49.0	53.8	37.6	2.0	25.0	28.1	41.0	64.7	140.7	31.2	844.5
2018/2019	29.1	46.9	24.5	57.2	43.0	33.8	30.2	0.0	97.8	92.0	85.8	64.8	605.1
2019/2020	84.4	38.1	20.1	17.6	28.6	44.9	25.4	1.1	64.0	99.3	39.7	107.2	570.4
2020/2021	32.1	81.2	10.9	25.1	34.7	13.6	23.6	36.4	109.0	31.3	128.4	147.4	673.7
2021/2022	23.5	27.9	47.1	22.1	40.7	57.6	0.2	20.0	47.7	89.6	63.3	134.2	573.9
1991-2020	58.0	56.2	43.4	43.6	34.2	26.4	30.9	29.0	62.4	72.5	91.9	66.1	614.6
	Air temperature, °C												
2016/2017	14.7	6.9	2.5	1.0	–3.2	–1.2	5.1	6.7	13.1	16.7	17.3	18.7	8.2
2017/2018	13.5	9.4	4.3	1.9	0.0	–4.1	–0.5	11.9	16.5	17.9	20.0	20.4	9.3
2018/2019	15.3	9.8	4.1	1.1	–2.5	2.0	4.9	8.6	12.2	21.4	17.6	19.5	9.5
2019/2020	13.7	9.9	5.6	2.8	2.3	3.1	3.3	6.9	10.1	17.9	17.7	19.2	9.4
2020/2021	14.7	10.1	5.6	1.5	–2.5	–4.5	2.4	5.7	11.6	19.4	21.1	16.7	8.5
2021/2022	12.9	8.9	4.7	–2.2	0.6	2.3	1.9	6.2	12.1	17.9	18.1	20.8	8.7
1991-2020	13.4	8.1	3.4	–0.4	–2.2	–1.2	2.1	8.1	13.1	16.4	18.5	18.3	8.1

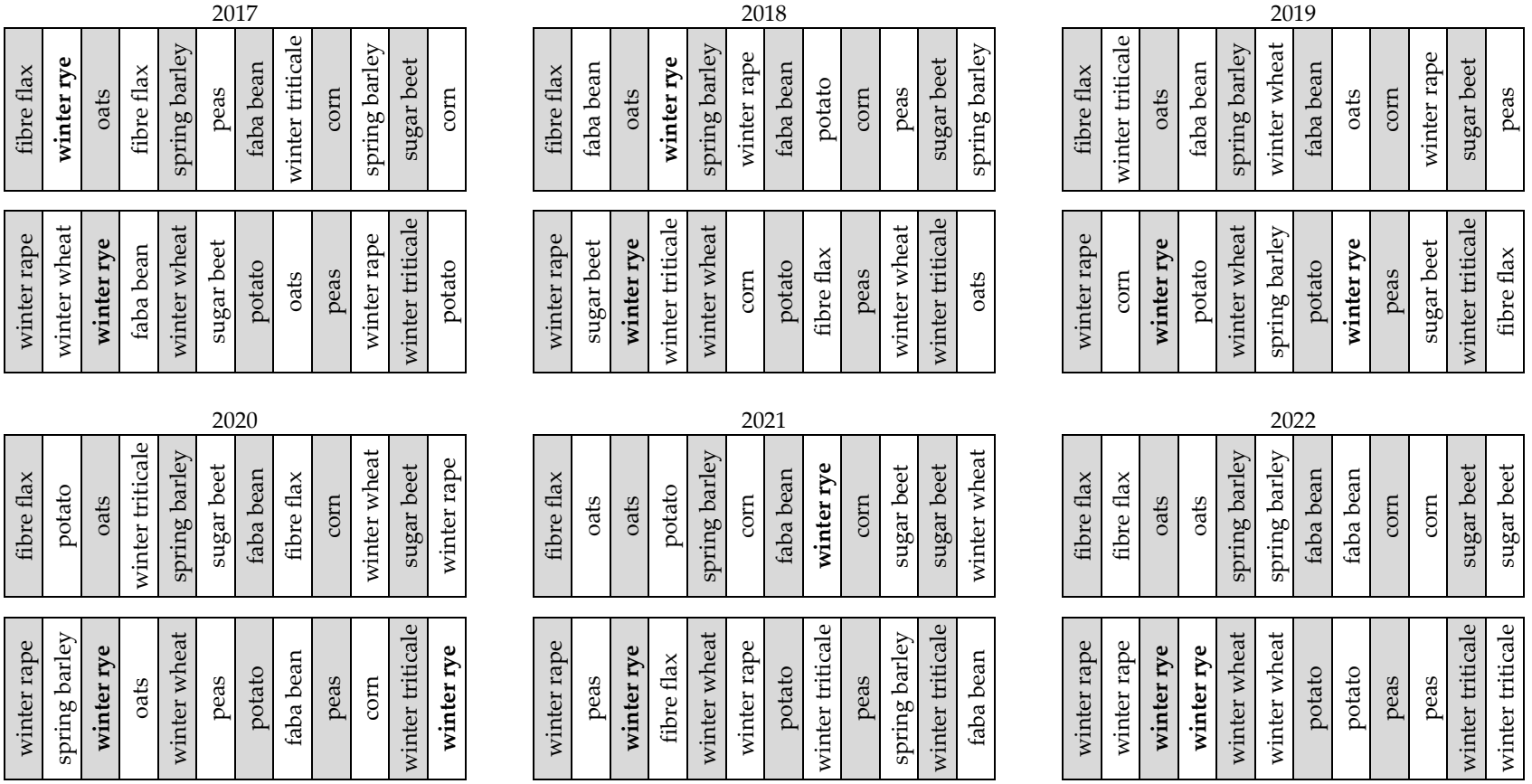

Figure S1. The arrangement of continuous cropping (gray plots; CC) and crop rotation (white plots; CR) fields in the Bałcyny experiment in the following years during 2017-2022. The fields of winter rye under the present study are marked in bold red.

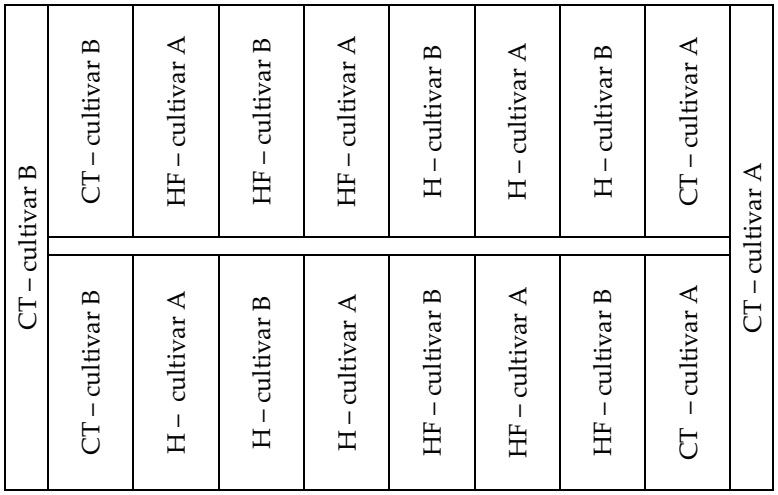

Figure S2. The arrangement of cultivars and plant protection levels on each single field of continuous crops (CC) or crop rotation (CR) shown in Figure S1. CT—plots with no herbicide or fungicide treatments; H—plots with herbicide application; HF—plots with the application of herbicide and fungicide. In the fields of winter rye: cultivar A – KWS Binntto, cultivar B – Dańkowskie Diament.

Table S3. Pesticide treatments applied to winter rye plots in the growing seasons under study.

Year (growing season)	Trade name	Producer / supplier	Active ingredient (g · dm^{-3})	Dose, dm^3 ha^{-1}	Application time
Herbicides [1]					
2016/17	Trinity 590 SC	ADAMA Polska Sp. z o.o., Warsaw, Poland	chlorotoluron (250) + diflufenican (40) + pendimethalin (300)	2	27.10
2017/18	Trinity 590 SC	ADAMA Polska Sp. z o.o., Warsaw, Poland	chlorotoluron (250) + diflufenican (40) + pendimethalin (300)	2	07.11
2018/19	Trinity 590 SC	ADAMA Polska Sp. z o.o., Warsaw, Poland	chlorotoluron (250) + diflufenican (40) + pendimethalin (300)	2	10.10
2019/20	Bizon	Dow Agrosciences Polska Sp.z.o.o., Warsaw, Poland	diflufenican (100) + florasulam (3.75) + penoxulam (15)	2	14.10
2020/21	Bizon	Dow Agrosciences Polska Sp.z.o.o., Warsaw, Poland	diflufenican (100) + florasulam (3.75) + penoxulam (15)	2	14.10
2021/22	Bizon	Dow Agrosciences Polska Sp.z.o.o., Warsaw, Poland	diflufenican (100) + florasulam (3.75) + penoxulam (15)	2	13.10
Fungicides [2]					
2016/17	Artea 330 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	propiconazole (250) + cyproconazole (80)	0.4	11.05
	Amistar 250 SC	Syngenta Polska Sp. z o.o., Warsaw, Poland	azoxystrobin (250)	0.6	11.05
2017/18	Fandango 200 EC	Bayer Sp. z o.o., Warsaw, Poland	fluoxastrobin (100) + prothioconazole (100)	1	02.05
	Artea 330 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	propiconazole (250) + cyproconazole (80)	0.4	21.05
	Amistar 250 SC	Syngenta Polska Sp. z o.o., Warsaw, Poland	azoxystrobin (250)	0.6	25.05
2018/19	Capalo 337.5 SE	BASF Polska Sp. z o.o., Warsaw, Poland	fenpropimorph (200) + epoxiconazole (62.5) + metrafenone (75)	1.5	26.04
	Artea 330 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	propiconazole (250) + cyproconazole (80)	0.4	20.05
	Amistar 250 SC	Syngenta Polska Sp. z o.o., Warsaw, Poland	azoxystrobin (250)	0.6	20.05
2019/20	Capalo 337.5 SE	BASF Polska Sp. z o.o., Warsaw, Poland	fenpropimorph (200) + epoxiconazole (62.5) + metrafenone (75)	1.5	24.04
2020/21	Capalo 337.5 SE	BASF Polska Sp. z o.o., Warsaw, Poland	fenpropimorph (200) + epoxiconazole (62.5) + metrafenone (75)	1.5	10.04
	Artea 330 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	propiconazole (250) + cyproconazole (80)	0.4	21.05
	Amistar 250 SC	Syngenta Polska Sp. z o.o., Warsaw, Poland	azoxystrobin (250)	0.6	21.05
	Osiris 65 EC	BASF Polska Sp. z o.o., Warsaw, Poland	epoxiconazole (37.5) + metconazole (27.5)	1.5	18.06
2021/22	Capalo 337.5 SE	BASF Polska Sp. z o.o., Warsaw, Poland	fenpropimorph (200) + epoxiconazole (62.5) + metrafenone (75)	1.5	09.04
	Artea 330 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	propiconazole (250) + cyproconazole (80)	0.4	16.05
	Amistar 250 SC	Syngenta Polska Sp. z o.o., Warsaw, Poland	azoxystrobin (250)	0.6	16.05
	Osiris 65 EC	BASF Polska Sp. z o.o., Warsaw, Poland	epoxiconazole (37.5) + metconazole (27.5)	1.5	15.06
Insecticides [3]					
2020/21	Decis Mega 50 EW	Bayer Sp. z o.o., Warsaw, Poland	deltamethrin (50)	0.1	31.05
2021/22	Decis Mega 50 EW	Bayer Sp. z o.o., Warsaw, Poland	deltamethrin (50)	0.1	26.05
Growth regulators [3]					
2016/17	Moddus 250 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	ethyl trinexapac (250)	0.4	11.05
2017/18	Moddus 250 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	ethyl trinexapac (250)	0.3	02.05
2018/19	Moddus 250 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	ethyl trinexapac (250)	0.4	26.04
2020/21	Moddus 250 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	ethyl trinexapac (250)	0.4	10.04
2021/22	Moddus 250 EC	Syngenta Polska Sp. z o.o., Warsaw, Poland	ethyl trinexapac (250)	0.3	09.04

[1] applied in the plots with herbicide (H) and herbicide and fungicide (HF) protection; [2] applied in the plots with herbicide and fungicide (HF) protection; [3] applied in all plots.

Table S4. Basic agricultural data for winter rye in the growing seasons under study.

Item	Year (growing season)					
	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022
Soil tillage system	plowing system	plowing system	plowing system	plowing system	plowing system	plowing system
Expected plant density at emergence, No. m^{-2}	400	400	400	400	400	400
Farmyard manure (FYM), t ha^{-1}	15 *			15 *		
Mineral fertilization						
-P_2O_5, kg ha^{-1}	70 [1]	70 [1]	70 [1]	70 [1]	70 [1]	70 [1]
-K_2O, kg ha^{-1}	100 [1]	100 [1]	100 [1]	100 [1]	100 [1]	100 [1]
-N, kg ha^{-1}	70 (50 [2] + 20 [3])	70 (50 [2] + 20 [3])	70 (50 [2] + 20 [3])	70 (50 [2] + 20 [3])	70 (50 [2] + 20 [3])	70 (50 [2] + 20 [3])
Plant protection						
- herbicides	– / +	– / +	– / +	– / +	– / +	– / +
- fungicides	– / +	– / +	– / +	– / +	– / +	– / +
- insecticides	–	–	–	–	+	+
- growth regulators	+	+	+	–	+	+
Sowing date	19.09	02.10	18.09	12.09	12.09	21.09
Harvest date	04.08	23.07	29.07	02.08	27.07	28.07

* FYM applied only in rye continuous cropping; [1] before sowing; [2] after vegetation re-start in spring; [3] at rye stem elongation stage; + applied; – not applied.

Table S5. Effect of the interaction of cropping system × cultivar × plant protection × year on winter rye yield, t ha^{-1} (means and standard errors) [1].

Cropping system (CS)	Cultivar (Cv)	Plant protection (PP)	Year (Yr)					
			2017	2018	2019	2020	2021	2022
CC	KWS Binntto	CT	6.31 ± 0.62	3.94 ± 0.30	6.81 ± 0.09	7.14 ± 0.07	5.35 ± 0.03	3.57 ± 0.26
		H	6.61 ± 0.29	5.21 ± 0.49	7.48 ± 0.12	7.27 ± 0.21	7.56 ± 0.53	7.50 ± 0.31
		HF	7.21 ± 0.18	5.41 ± 0.33	8.28 ± 0.18	8.34 ± 0.12	7.98 ± 0.33	7.74 ± 0.19
	Dańkowskie Diament	CT	4.12 ± 0.12	1.56 ± 0.13	5.48 ± 0.03	3.46 ± 0.10	4.91 ± 0.22	3.86 ± 0.03
		H	4.76 ± 0.19	4.06 ± 0.10	5.77 ±0.15	4.53 ± 0.32	6.82 ± 0.38	6.34 ± 0.28
		HF	4.53 ± 0.16	3.84 ± 0.29	6.31 ± 0.09	5.31 ± 0.06	6.74 ± 0.30	6.26 ± 0.35
CR	KWS Binntto	CT	10.41 ± 0.09	7.29 ± 0.29	9.34 ± 0.17	8.99 ± 0.58	8.37 ± 0.16	7.95 ± 0.10
		H	9.18 ± 0.26	6.25 ± 0.52	8.50 ± 0.45	9.13 ± 0.04	8.00 ± 0.19	9.16 ± 0.10
		HF	9.47 ± 0.18	6.89 ± 0.10	9.29 ± 0.18	10.37 ± 0.47	8.04 ± 0.30	9.50 ± 0.39
	Dańkowskie Diament	CT	7.08 ± 0.02	5.60 ± 0.05	7.60 ± 0.31	6.68 ± 0.42	5.66 ± 0.26	6.52 ± 0.13
		H	6.70 ± 0.19	5.36 ± 0.67	7.01 ± 0.21	6.14 ± 0.13	6.07 ± 0.13	7.11 ± 0.62
		HF	6.31 ± 0.12	3.94 ± 0.19	6.81 ± 0.12	7.14 ± 0.31	5.35 ± 0.20	3.57 ± 0.40

[1] interaction not significant at $p < 0.05$; CC – continuous cropping system; CR – crop rotation system; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.

The effects of the identified interactions between the experimental factors on the individual yield components of winter rye

An analysis of the CS × PP interaction revealed that the spike density of winter rye under the CT treatment was lower in the CC system than in the CR system. However, in rye protected by the H and HF treatments, the differences between the CC and CR systems were not significant (Table S6). In the years 2017 and 2019-2021, no differences in spike density were observed between the CC and CR systems (Table S7). However, in 2018 and 2022, a decrease in spike density was observed in the CC system compared to the CR system. From 2017 to 2020, a greater spike densities were observed in the cultivar KWS Binntto than in the cultivar Dańkowskie Diament whereas in 2021 to 2022 there were no differences between cultivars in this regards (Table S8). The effect of PP level on spike density exhibited variability across the study years. Specifically, in the years 2017, 2020, and 2021, the PP factor did not demonstrate any significant differences in spike density (Table S9). Conversely, in 2018 and 2022, the H treatment increased spike density to the same extent as the HF treatment compared to the CR treatment. In 2019, the H treatment tended to increase spike density, but only the HF treatment contributed to a significant increase compared to the CT treatment. Details on the effect of the Cv × PP × Yr interaction on spike density of winter rye are shown in Table S10.

Table S6. Effect of the interaction of cropping system × plant protection on the spike density of winter rye, No. m^{-2} (means and standard errors).

Cropping system (CS)	Plant protecion (PP)		
	CT	H	HF
CC	378 ± 16 $^{b\,1}$	443 ± 13 ^{a}	457 ± 15 ^{a}
CR	439 ± 12 ^{a}	462 ± 10 ^{a}	460 ± 13 ^{a}

[1] different letters indicate significant differences at $p < 0.05$; CC – continuous cropping system; CR – crop rotation system; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application

Table S7. Effect of the interaction of cropping system × year on the spike density of winter rye, No. m^{-2} (means and standard errors).

Cropping system (CS)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
CC	413 ± 19 $^{c\,1}$	317 ± 21 ^{d}	481 ± 19 ^{a}	481 ± 11 ^{a}	456 ± 11 ^{ab}	407 ± 25 ^{c}
CR	446 ± 22 $^{a\text{-}c}$	432 ± 13 ^{bc}	457 ± 18 ^{ab}	457 ± 20 ^{ab}	458 ± 12 ^{ab}	473 ± 15 ^{ab}

[1] different letters indicate significant differences at $p < 0.05$; CC – continuous cropping system; CR – crop rotation system.

Table S8. Effect of the interaction of cultivar × year on the spike density of winter rye, No. m^{-2} (means and standard errors).

Cultivar (Cv)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
KWS Binntto	461 ± 23 bc [1]	409 ± 20 de	520 ± 13 a	513 ± 8 a	466 ± 12 b	452 ± 24 b-d
Dańkowskie Diament	397 ± 15 e	339 ± 22 f	419 ± 15 c-e	425 ± 15 b-e	448 ± 11 b-d	428 ± 19 b-e

[1] different letters indicate significant differences at $p < 0.05$.

Table S9. Effect of the interaction of plant protection × year on the spike density of winter rye, No. m^{-2} (means and standard errors).

Plant protection (PP)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
CT	411 ± 19 e-g [1]	332 ± 29 h	428 ± 25 c-g	442 ± 22 b-f	467 ± 18 a-d	374 ± 29 g-h
H	416 ± 24 d-g	406 ± 24 fg	471 ± 13 a-d	485 ± 17 ab	456 ± 15 a-f	481 ± 16 a-c
HF	462 ± 30 a-e	384 ± 24 g	510 ± 23 a	481 ± 19 a-c	450 ± 10 b-f	465 ± 24 a-e

[1] different letters indicate significant differences at $p < 0.05$; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.

Table S10. Effect of the interaction of cultivar × plant protection × year on the spike density of winter rye, No. m^{-2} (means and standard errors).

Cultivar (Cv)	Plant protection (PP)	Year (Yr)					
		2017	2018	2019	2020	2021	2022
KWS Binntto	CT	424 ± 28 e-l [1]	363 ± 43 j-m	503 ± 12 b-e	502 ± 13 b-e	476 ± 31 b-g	385 ± 53 h-l
	H	426 ± 37 e-l	451 ± 29 c-i	478 ± 18 b-g	512 ± 20 a-d	482 ± 8 b-f	483 ± 28 b-f
	HF	534 ± 42 ab	413 ± 22 f-l	579 ± 12 a	525 ± 6 a-c	441 ± 14 d-j	486 ± 32 b-f
Dańkowskie Diament	CT	398 ± 28 g-l	301 ± 39 m	352 ± 18 lm	381 ± 23 i-l	457 ± 20 b-i	363 ± 29 j-m
	H	405 ± 35 f-l	362 ± 31 j-m	464 ± 21 b-h	457 ± 23 b-i	429 ± 25 d-l	479 ± 19 b-g
	HF	389 ± 15 h-l	355 ± 43 k-m	441 ± 17 d-j	436 ± 28 d-k	459 ± 14 b-i	443 ± 36 c-j

[1] different letters indicate significant differences at $p < 0.05$; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.

The grain number per spike of winter rye exhibited variation depending on the CS factor during the study period (Table S11). In 2017, 2019, and 2022, a lower number of grains per spike was observed in rye cultivated in the CC system compared to the CR system. Conversely, in 2021, the opposite outcome was recorded. In 2018 and 2020, no significant differences were detected between the CC and CR systems in this regard. The effects of the Cv × PP × Yr interaction on grain number per spike of winter rye are detailed in Table S12.

Table S11. Effect of the interaction of cropping system × year on the grain number per spike of winter rye, No. (means and standard errors).

Cropping system (CS)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
CC	46.0 ± 1.0$^{de\ 1}$	42.6 ± 1.9^{ef}	39.9 ± 1.7^{f}	46.7 ± 1.7^{cd}	54.3 ± 1.3^{a}	45.4 ± 1.5^{de}
CR	50.0 ± 1.1^{bc}	45.0 ± 1.0^{de}	44.4 ± 1.1^{de}	50.3 ± 1.4^{bc}	50.6 ± 1.2^{b}	50.0 ± 1.6^{bc}

[1] different letters indicate significant differences at $p < 0.05$; CC – continuous cropping system; CR – crop rotation system.

Table S12. Effect of the interaction of cultivar × plant protection × year on the grain number per spike of winter rye, No. (means and standard errors).

Cultivar (Cv)	Plant protection (PP)	Year (Yr)					
		2017	2018	2019	2020	2021	2022
KWS Binntto	CT	49.5 ± 2.0 $^{c-i\ 1}$	38.6 ± 3.7 ^{mn}	40.2 ± 3.0 ^{lmn}	47.6 ± 2.9 $^{d-k}$	54.6 ± 1.6 ^{abc}	44.9 ± 1.4 $^{f-m}$
	H	51.9 ± 1.3 $^{a-f}$	46.4 ± 2.3 $^{e-l}$	46.7 ± 1.4 $^{e-l}$	51.0 ± 1.5 $^{a-h}$	56.7 ± 1.9 ^{ab}	53.9 ± 1.5 $^{a-d}$
	HF	49.8 ± 1.8 $^{b-i}$	46.8 ± 2.1 $^{e-l}$	45.6 ± 1.7 $^{f-l}$	51.7± 3.0 $^{a-g}$	57.2 ± 2.3 ^{a}	52.8 ± 2.2 $^{a-e}$
Dańkowskie Diament	CT	44.3 ± 1.6 $^{h-m}$	46.6 ± 1.4 $^{e-l}$	35.9 ± 3.9 ^{n}	40.3 ± 2.9 ^{lmn}	46.6 ± 2.0 $^{e-l}$	44.4 ± 2.1 $^{h-m}$
	H	44.7 ± 2.0 $^{g-m}$	41.1 ± 2.4 $^{k-n}$	42.0 ± 0.8 $^{j-n}$	50.5 ± 1.4 $^{a-h}$	51.2 ± 1.1 $^{a-h}$	48.3 ± 2.8 $^{c-j}$
	HF	47.6 ± 2.1 $^{d-k}$	43.2 ± 2.3 $^{i-m}$	42.3 ± 1.8 $^{j-n}$	50.0 ± 2.5 $^{b-i}$	48.4 ± 0.7 $^{c-j}$	40.9 ± 2.6 $^{k-n}$

[1] different letters indicate significant differences at $p < 0.05$; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.

The analysis of variance demonstrated that the 1000-grain weight of the Dańkowskie Diament cultivar under CT treatment conditions exhibited higher values in comparison to those of the KWS Binntto cultivar. Conversely, under H and HF treatment conditions, no significant differences were observed between the cultivars in terms of this trait (Table S13). Over the study period, in 2017, 2018, 2020, and 2021, the 1000-grain weight of winter rye was lower in the CC system than in the CR system (Table S14). In 2019, the CS factor did not differentiate the 1000-grain weight. In 2022, the 1000-grain weight of rye grown in the

CC system was higher than that of rye grown in the CR system. A significant difference in 1000-grain weight volume was only documented in 2019, with the KWS Binntto cultivar showing superiority. In the other years, no such differences were observed between the cultivars (Table S15). The effect of PP level on 1000-grain weight exhibited variability across the study years. In 2017, 2018, 2019, and 2021, the PP factor was found to be statistically insignificant (Table S16). In 2018, the H treatment did not alter 1000-grain weight compared to the CT treatment; however, the HF protection did enhance this attribute. Conversely, in 2020, the H and HF treatments both increased the 1000-grain weight of rye to the same extent compared to the CT treatment. Table S17 details the effects of the interaction of cropping system × plant protection × year on the 1000-grain weight of winter rye.

Table S13. Effect of the interaction of cultivar × plant protection on the 1000-grain weight of winter rye, g (means and standard errors).

Cultivar (Cv)	Plant protection (PP)		
	CT	H	HF
KWS Binntto	31.06 ± 0.70 b [1]	31.56 ± 0.62 ab	32.08 ± 0.60 a
Dańkowskie Diament	32.03 ± 0.58 a	31.21 ± 0.60 b	31.83 ± 0.59 a

[1] different letters indicate significant differences at $p < 0.05$; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.

Table S14. Effect of the interaction of cropping system × year on the 1000-grain weight of winter rye, g (means and standard errors).

Cropping system (CS)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
CC	29.79 ± 0.30 d [1]	27.10 ± 0.27 f	36.63 ± 0.28 a	28.29 ± 0.50 e	26.94 ± 0.20 f	32.26 ± 0.25 c
CR	36.24 ± 0.23 a	32.42 ± 0.20 c	36.55 ± 0.36 a	33.84 ± 0.38 b	29.52 ± 0.31 d	29.96 ± 0.49 d

[1] different letters indicate significant differences at $p < 0.05$; CC – continuous cropping system; CR – crop rotation system.

Table S15. Effect of the interaction of cultivar × year on the 1000-grain weight of winter rye, g (means and standard errors).

Cultivar (Cv)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
KWS Binntto	32.67 ± 0.77 c [1]	29.73 ± 0.74 e	37.08 ± 0.28 a	31.29 ± 0.80 d	27.87 ± 0.36 f	30.78 ± 0.55 d
Dańkowskie Diament	33.36 ± 0.87 c	29.78 ± 0.62 e	36.11 ± 0.32 b	30.83 ± 0.80 d	28.60 ± 0.43 f	31.45 ± 0.38 d

[1] different letters indicate significant differences at $p < 0.05$.

Table S16. Effect of the interaction of plant protection × year on the 1000-grain weight of winter rye, g (means and standard errors).

Plant protection (PP)	Year (Yr)					
	2017	2018	2019	2020	2021	2022
CT	33.28 ± 0.87 $^{b\,1}$	30.14 ± 0.89 ^{de}	36.90 ± 0.30 ^{a}	30.79 ± 1.07 ^{d}	28.46 ± 0.72 ^{fg}	29.70 ± 0.67 ^{e}
H	32.45 ± 1.07 ^{bc}	29.35 ± 0.84 ^{ef}	36.35 ± 0.39 ^{a}	30.32 ± 1.02 ^{de}	28.01 ± 0.35 ^{g}	31.84 ± 0.40 ^{c}
HF	33.31 ± 1.10 ^{b}	29.79 ± 0.80 ^{de}	36.53 ± 0.47 ^{a}	32.08 ± 0.82 ^{c}	28.22 ± 0.33 ^{g}	31.80 ± 0.43 ^{c}

[1] different letters indicate significant differences at $p < 0.05$; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.

Table S17. Effect of the interaction of cropping system × plant protection × year on the 1000-grain weight of winter rye, g (means and standard errors).

Cropping system (CS)	Plant protection (PP)	Year (Yr)					
		2017	2018	2019	2020	2021	2022
CC	CT	30.59 ± 0.57 $^{fgh\,1}$	27.26 ± 0.35 ^{kl}	36.60 ± 0.19 ^{a}	27.44 ± 0.60 ^{jkl}	26.16 ± 0.26 ^{l}	31.63 ± 0.38 ^{def}
	H	28.98 ± 0.42 ^{ij}	26.77 ± 0.58 ^{kl}	36.58 ± 0.31 ^{a}	27.75 ± 1.13 ^{jk}	27.15 ± 0.24 ^{kl}	32.84 ± 0.33 ^{cd}
	HF	29.80 ± 0.42 ^{ghi}	27.27 ± 0.48 ^{kl}	36.72 ± 0.82 ^{a}	29.67± 0.57 ^{hi}	27.51 ± 0.27 ^{jkl}	32.33 ± 0.49 ^{de}
CR	CT	35.97 ± 0.38 ^{a}	33.02 ± 0.25 ^{cd}	37.21 ± 0.58 ^{a}	34.15 ± 0.44 ^{bc}	30.75 ± 0.38 ^{fgh}	27.78 ± 0.62 ^{jk}
	H	35.91 ± 0.29 ^{a}	31.93 ± 0.37 ^{def}	36.11 ± 0.74 ^{a}	32.88 ± 0.84 ^{cd}	28.88 ± 0.41 ^{ij}	30.84 ± 0.43 $^{e-h}$
	HF	36.82 ± 0.45 ^{a}	32.31 ± 0.30 ^{de}	36.34 ± 0.53 ^{a}	34.49 ± 0.55 ^{b}	28.93 ± 0.45 ^{ij}	31.27 ± 0.67 ^{efg}

[1] different letters indicate significant differences at $p < 0.05$; CC – continuous cropping system; CR – crop rotation system; CT – no herbicide or fungicide treatments; H – herbicide application; HF – herbicide and fungicide application.