Is Diversified Crop Rotation an Effective Non-chemical Strategy for Protecting Triticale Yield and Weed Diversity?

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Table S1. Air temperature and atmospheric precipitation during the study periods according to the Meteorological Station in Bałcyny.

Growing season	Month											
	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII
Air temperature, °C												
2016/17	14.7	6.9	2.5	1.0	-3.2	-1.2	5.1	6.7	13.1	16.7	17.3	18.7
2017/18	13.5	9.4	4.3	1.9	0.0	-4.1	-0.5	11.9	16.5	17.9	20.0	20.4
2018/19	15.3	9.8	4.1	1.1	-2.5	2.0	4.9	8.6	12.2	21.4	17.6	19.5
2019/20	13.7	9.9	5.6	2.8	2.3	3.1	3.3	6.9	10.1	17.9	17.7	19.2
2020/21	14.7	10.1	5.6	1.5	-2.5	-4.5	2.4	5.7	11.6	19.4	21.1	16.7
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
Atmospheric precipitation, mm												
2016/17	17.1	96.3	78.2	77.8	15.8	40.5	53.0	52.1	34.0	109.9	106.1	54.8
2017/18	211.1	160.3	49.0	53.8	37.6	2.0	25.0	28.1	41.0	64.7	140.7	31.2
2018/19	29.1	46.9	24.5	57.2	43.0	33.8	30.2	0.0	97.8	92.0	85.8	64.8
2019/20	84.4	38.1	30.1	17.6	28.6	44.9	25.4	1.1	64.0	99.3	39.7	107.2
2020/21	32.1	81.2	10.9	25.1	34.7	13.6	23.6	36.4	109.0	31.3	128.4	147.4
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

no PP – cultivar B	no PP – cultivar B	HF – cultivar A	HF – cultivar B	HF – cultivar A	H – cultivar B	H – cultivar A	H – cultivar B	no PP – cultivar A	
	no PP – cultivar B	H – cultivar A	H – cultivar B	H – cultivar A	HF – cultivar B	HF – cultivar A	HF – cultivar B	no PP – cultivar A	no PP – cultivar A

no PP – plots with no plant protection treatments; H – plots with herbicide application; HF – plots with the application of herbicide and fungicide

Figure S1. The arrangement of plant protection levels and cultivars in a single field of crop rotation or continuous cropping in the experiment in Bałcyny.

DCR – Borowik	DCR – Borowik	DCR+HF – Trapero	DCR+HF – Borowik	DCR+HF – Trapero	DCR+H – Borowik	DCR+H – Trapero	DCR+H – Borowik	DCR – Trapero	
	DCR – Borowik	DCR+H – Trapero	DCR+H – Borowik	DCR+H – Trapero	DCR+HF – Borowik	DCR+HF – Trapero	DCR+HF – Borowik	DCR – Trapero	DCR – Trapero

DCR – plots of diversified crop rotation with no plant protection treatments; DCR+H – plots of diversified crop rotation in which herbicide was additionally applied;
DCR+HF – plots of diversified crop rotation in which herbicide and fungicide were additionally applied. Plots in grey are excluded from the study presented in the article.

Figure S2. The arrangement of the tested factors on winter triticale field under the study.

Table S2. Hierarchical taxonomic classification of weed species observed in the experiment (according to Mirek et al. [1]) – adopted to calculate taxonomic distinctness index (*Δ+*).

Weed species	Genus	Family	Order	Class	Division	Kingdom
Equisetum arvense L.	*Equisetum*	*Equisetaceae*	*Equisetales*	*Equisetopsida*	*Pteridophyta*	*Plantae*
Agropyron repens (L.) P. Beauv.	*Agropyron*	*Poaceae*	*Poales*	*Liliopsida*	*Spermatophyta*	*Plantae*
Apera spica-venti (L.) P. Beauv.	*Apera*	*Poaceae*	*Poales*	*Liliopsida*	*Spermatophyta*	*Plantae*
Avena fatua L.	*Avena*	*Poaceae*	*Poales*	*Liliopsida*	*Spermatophyta*	*Plantae*
Poa annua L.	*Poa*	*Poaceae*	*Poales*	*Liliopsida*	*Spermatophyta*	*Plantae*
Centaurea cyanus L.	*Centaurea*	*Asteraceae*	*Asterales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Cirsium arvense (L.) Scop.	*Cirsium*	*Asteraceae*	*Asterales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Chamomilla suaveolens (Pursh) Rydb.	*Chamomilla*	*Asteraceae*	*Asterales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Matricaria maritima ssp. *inodora* (L.) Dostál	*Matricaria*	*Asteraceae*	*Asterales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Sonchus arvensis L.	*Sonchus*	*Asteraceae*	*Asterales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Anchusa arvensis (L.) M. Bieb.	*Anchusa*	*Boraginaceae*	*Boraginales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Myosotis arvensis (L.) Hill	*Myosotis*	*Boraginaceae*	*Boraginales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Capsella bursa-pastoris (L.) Medik.	*Capsella*	*Brassicaceae*	*Capparales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Thlaspi arvense L.	*Thlaspi*	*Brassicaceae*	*Capparales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Atriplex patula L.	*Atriplex*	*Amaranthaceae*	*Caryophyllales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Arenaria serpyllifolia L.	*Arenaria*	*Caryophyllaceae*	*Caryophyllales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Stellaria media (L.) Vill.	*Stellaria*	*Caryophyllaceae*	*Caryophyllales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Chenopodium album L.	*Chenopodium*	*Chenopodiaceae*	*Caryophyllales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Vicia hirsuta (L.) Gray	*Vicia*	*Fabaceae*	*Fabales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Galium aparine L.	*Galium*	*Rubiaceae*	*Gentianales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Erodium cicutarium (L.) L'Hér.	*Erodium*	*Geraniaceae*	*Geraniales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Geranium pusillum Burm. F. ex L.	*Geranium*	*Geraniaceae*	*Geraniales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Galeopsis tetrahit L.	*Galeopsis*	*Lamiaceae*	*Lamiales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Lamium amplexicaule L.	*Lamium*	*Lamiaceae*	*Lamiales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Mentha arvensis L.	*Mentha*	*Lamiaceae*	*Lamiales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Fumaria officinalis L.	*Fumaria*	*Fumariaceae*	*Papaverales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Fallopia convolvulus (L.) Á. Löve	*Fallopia*	*Polygonaceae*	*Polygonales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Polygonum aviculare L.	*Polygonum*	*Polygonaceae*	*Polygonales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Polygonum laphathifolium L. ssp. *laphathifolium*	*Polygonum*	*Polygonaceae*	*Polygonales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Veronica arvensis L.	*Veronica*	*Scrophulariaceae*	*Scrophulariales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Veronica persica Poir.	*Veronica*	*Scrophulariaceae*	*Scrophulariales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*
Viola arvensis Murray	*Viola*	*Violaceae*	*Violales*	*Magnoliopsida*	*Spermatophyta*	*Plantae*

Table S3. Weed functional traits used to calculate functional diversity index (Q).

Plant trait	Trait characteristics	Rationale	Data source
Maximum plant height	Quantitative, m	light and water acquisition, competition ability	[2,3]
Growth habit	Qualitative: erect, prostrate, climbing	resource acquisition, space use, competition ability	[2], own observations
Specific leaf area (SLA)	Quantitative, mm²/mg	resource acquisition, stress tolerance, competition ability	[2] [1]
Season of emergence	Qualitative: spring, autumn or spring	competition start time	[3], own observations
Seed number	Quantitative, No./shoot: no seeds, <100; 100–1,000; 1,000–10,000; 10,000–100,000; >100,000	propagation, colonization capacity, future weed density	[2], own observations
Ecological trophic indicator value (Tr)	Quantitative, 1-5 scale [2]	trophic requirements, competition ability	[4,5] [3]

[1] average from available data; [2] 1 – soil extremely oligotrophic, 5 – soil extremely fertile; [3] [5] was used only for *Chamomilla suaveolens* (Pursh) Rydb. = *Matricaria discoidea* DC. (N value was used after scale converting).

Table S4. Weed species and their functional trait values adopted to calculate functional diversity index (Q) in the experiment.

Weed species	Height, m	Growth habit	SLA, mm² mg⁻¹	Season of emergence	Seed No. shoot⁻¹	Tr value
Equisetum arvense L.	0.5	erect	10.4	spring	*no seeds*	3.5
Agropyron repens (L.) P. Beauv.	1.5	erect	23.8	spring	100 - 1000	3.5
Apera spica-venti (L.) P. Beauv.	1.5	erect	19.1	autumn or spring	1000 - 10,000	3
Avena fatua L.	1.3	erect	21.8	spring	100 - 1000	3
Poa annua L.	0.3	erect	36.4	autumn or spring	100 - 1000	4
Centaurea cyanus L.	1	erect	26.0	autumn or spring	1000 - 10,000	3
Cirsium arvense (L.) Scop.	1.5	erect	15.4	spring	1000 - 10,000	3.5
Chamomilla suaveolens (Pursh) Rydb.	0.5	erect	23.3	spring	1000 - 10,000	4.5 [1]
Matricaria maritima ssp. *inodora* (L.) Dostál	1	erect	19.7	autumn or spring	10,000 - 100,000	4
Sonchus arvensis L.	1.5	erect	21.7	spring	10,000 - 100,000	3.5
Anchusa arvensis (L.) M. Bieb.	1	erect	16.5	spring	100 - 1000	3
Myosotis arvensis (L.) Hill	0.5	erect	29.4	autumn or spring	100 - 1000	3.5
Capsella bursa-pastoris (L.) Medik.	0.7	erect	30.0	autumn or spring	1000 - 10,000	4
Thlaspi arvense L.	0.5	erect	24.6	autumn or spring	1000 - 10,000	4
Atriplex patula L.	1.5	erect	17.4	spring	100 - 1000	4
Arenaria serpyllifolia L.	0.3	prostrate	20.1	autumn or spring	100 - 1000	2
Stellaria media (L.) Vill.	0.6	prostrate	53.7	autumn or spring	10,000 - 100,000	4.5
Chenopodium album L.	1.4	erect	22.2	spring	10,000 - 100,000	4.5
Vicia hirsuta (L.) Gray	0.6	climbing	22.1	autumn or spring	100 - 1000	3.5
Galium aparine L.	2 [2]	climbing	34.7	autumn or spring	100 - 1000	4.5
Erodium cicutarium (L.) L'Hér.	0.6	erect	25.7	autumn or spring	100 - 1000	3
Geranium pusillum Burm. F. ex L.	0.5	prostrate	25.5	autumn or spring	100 - 1000	4
Galeopsis tetrahit L.	1	erect	31.0	spring	100 - 1000	3.5
Lamium amplexicaule L.	0.3	erect	19.7	autumn or spring	100 - 1000	3.5
Mentha arvensis L.	0.6	erect	41.4	spring	100 - 1000	3.5
Fumaria officinalis L.	0.5	erect	28.5	spring	100 - 1000	4
Fallopia convolvulus (L.) Á. Löve	2	climbing	23.9	spring	100 - 1000	3.5
Polygonum aviculare L.	0.6	prostrate	28.9	spring	100 - 1000	3.5
Polygonum laphathifolium L. ssp. *laphathifolium*	1	erect	22.7	spring	100 - 1000	4.5
Veronica arvensis L.	0.5	erect	25.4	autumn or spring	100 - 1000	3.5
Veronica persica Poir.	0.5	prostrate	39.6	autumn or spring	100 - 1000	4.5
Viola arvensis Murray	0.5	erect	24.3	autumn or spring	100 - 1000	3.5

[1] N value by Ellenberg [5] was used after scale converting; [2] stem length was shown.

Table S5. Average proportion (%) of weed species biomass in the experiment.

Weed species	CR										CR+H									
	Trapero					Borowik					Trapero					Borowik				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Equisetum arvense L.	9.4	6.8	5.8	0.5	3.2	81.9	-	-	-	2.7	-	-	-	-	7.8	-	-	23.6	-	90.9
Agropyron repens (L.) P. Beauv.	6.2	0.2	-	-	-	0.6	-	-	-	-	85.4	-	28.0	50.0	-	56.8	-	-	-	5.4
Apera spica-venti (L.) P. Beauv.	5.1	44.8	69.4	46.7	27.0	-	27.6	46.2	4.0	-	-	-	15.3	-	-	3.3	17.1	-	-	-
Avena fatua L.	9.1	-	-	-	-	-	-	-	-	0.4	0.0	-	-	-	-	2.7	-	-	-	-
Poa annua L.	-	-	-	0.0	0.1	-	0.0	-	1.6	0.3	-	-	-	13.6	-	-	-	-	-	-
Centaurea cyanus L.	-	20.8	-	-	9.8	-	51.4	-	27.2	-	-	-	-	-	64.7	29.5	82.9	72.4	-	-
Cirsium arvense (L.) Scop.	-	1.1	-	-	-	-	-	-	-	-	-	-	13.6	-	10.9	-	-	-	-	-
Chamomilla suaveolens (Pursh) Rydb.	-	3.1	-	0.5	0.9	0.2	-	-	0.7	3.7	-	-	-	-	-	-	-	-	-	0.4
Matricaria maritima ssp. *inodora* (L.) Dostál	-	22.8	-	11.1	43.4	-	21.0	7.4	-	21.7	-	-	-	-	-	-	-	-	-	-
Sonchus arvensis L.	-	-	7.4	-	-	-	-	-	0.1	-	7.7	-	-	-	-	0.8	-	-	-	-
Anchusa arvensis (L.) M. Bieb.	-	-	-	3.5	0.4	-	-	-	2.4	-	-	-	-	-	-	-	-	-	-	-
Myosotis arvensis (L.) Hill	-	-	-	1.5	0.7	3.4	-	8.5	-	-	-	-	-	-	-	-	-	-	-	-
Capsella bursa-pastoris (L.) Medik.	4.5	0.0	0.7	7.7	5.3	3.9	-	2.9	4.0	3.7	-	-	-	-	-	-	-	-	-	-
Thlaspi arvense L.	0.6	-	-	1.9	0.7	2.8	-	-	1.9	0.2	-	-	-	-	-	-	-	-	-	-
Atriplex patula L.	-	-	1.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Arenaria serpyllifolia L.	-	-	0.1	3.4	0.2	-	-	1.3	0.3	-	-	-	-	-	-	-	-	-	-	-
Stellaria media (L.) Vill.	-	0.2	3.5	3.5	3.1	-	-	29.1	7.6	40.4	-	-	-	-	-	-	-	-	-	-
Chenopodium album L.	-	0.1	-	-	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	-	0.2
Vicia hirsuta (L.) Gray	-	-	2.1	13.6	-	-	-	1.5	40.6	-	-	-	-	-	-	-	-	-	-	-
Galium aparine L.	60.1	-	2.3	-	0.3	-	0.0	-	-	4.1	6.8	-	38.1	-	-	6.9	-	3.2	-	-
Erodium cicutarium (L.) L'Hér.	-	-	-	-	-	-	-	-	-	7.9	-	-	-	-	-	-	-	-	-	-
Geranium pusillum Burm. F. ex L.	-	-	-	-	1.1	-	-	1.0	-	0.6	-	-	-	-	-	-	-	-	-	-
Galeopsis tetrahit L.	-	-	-	0.1	0.0	-	-	-	0.8	-	-	22.2	-	18.2	6.5	-	-	-	75.0	1.6
Lamium amplexicaule L.	0.5	-	-	0.2	0.1	4.8	-	-	0.1	1.9	-	-	-	-	-	-	-	-	-	-
Mentha arvensis L.	-	-	-	-	-	0.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fumaria officinalis L.	0.8	-	1.8	-	0.4	-	-	-	-	0.7	-	-	-	-	7.1	-	-	-	-	-
Fallopia convolvulus (L.) Á. Löve	1.4	-	0.1	0.2	-	-	-	-	1.1	-	0.0	-	5.1	18.2	2.2	-	-	0.8	25.0	1.4
Polygonum aviculare L.	-	0.0	-	-	0.0	0.5	-	-	-	-	0.0	-	77.8	-	-	-	-	-	-	-
Polygonum laphathifolium L. ssp. *laphathifolium*	-	-	-	0.0	-	-	-	-	-	0.1	-	-	-	-	-	0.7	-	-	-	-
Veronica arvensis L.	-	-	-	0.5	0.9	-	-	1.3	3.7	0.1	-	-	-	-	-	-	-	-	-	-
Veronica persica Poir.	-	-	0.1	2.1	1.6	-	-	-	1.0	11.2	-	-	-	-	-	-	-	-	-	-
Viola arvensis Murray	2.2	-	5.1	2.9	0.8	0.9	-	0.9	2.6	0.3	-	-	-	-	-	-	-	-	-	-
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Formulas for diversity indices and their explanations

- Renyi diversity profiles (H_α) [6]:

$$H_\alpha = \left(\ln \sum_{i=0}^{S} p_i^\alpha \right)(1-\alpha)^{-1} \tag{1}$$

where:
p_i – proportion of i–species biomass to the community biomass; ln – natural logarithm; S – species richness; α – diversity levels assuming that $\alpha \geq 0$, $\alpha \neq 1$.
For $\alpha = 1$ Shannon-Wiener index (H') [7]:

$$H' = -\sum_{i=1}^{S} (p_i \ln p_i) \tag{2}$$

- Taxonomic distinctness indices (Δ^+) [8]:

$$\Delta^+ = \frac{\sum \sum_{i<j} w_{ij} x_i x_j}{\sum \sum_{i<j} x_i x_j} \tag{3}$$

where:
w_{ij} – the 'distinctness weight' of the i-th and j-th species according to the hierarchical taxonomic classification: $w = 0$ for biomass of individuals within the same species; $w = 1$ for different species within the same genus; $w = 2$ for species within the same family but different genera; $w = 3$ for species within the same order but different family; $w = 4$ for species within the same class but in different order; $w = 5$ for species within the same division but different class; $w = 6$ for species in different divisions of the plant kingdom; the basic taxonomic categories in the plant kingdom as well as systematic positions of individual species followed Mirek et al. [1] (see also Table S2); x_i – biomass of the i-th species in the community; x_j – biomass of the j-th species in the community.

- Rao's quadratic entropy (Q) [9]:

$$Q = \sum_{i=1}^{S-1} \sum_{j=i+1}^{S} d_{ij} p_i p_j \tag{4}$$

where:
p_i – proportion of i–species biomass to the community biomass; p_j – proportion of j–species biomass to the community biomass; d_{ij} – dissimilarity between species i and j, measured by the Euclidean distance based on six arbitrarily chosen functional traits: maximum plant height, growth habit, specific leaf area (SLA), season of emergence, seed number, and ecological trophic indicator value (Tr) (see also Table S3 for trait characteristics and rationale, and Table S4 for the list of weed species and their functional trait values adopted to calculate functional diversity index).
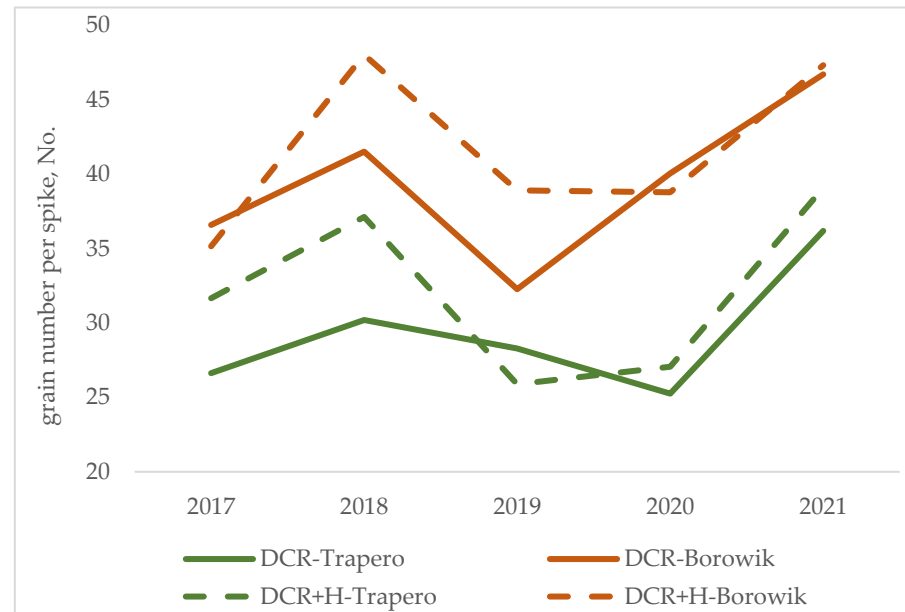
(a)
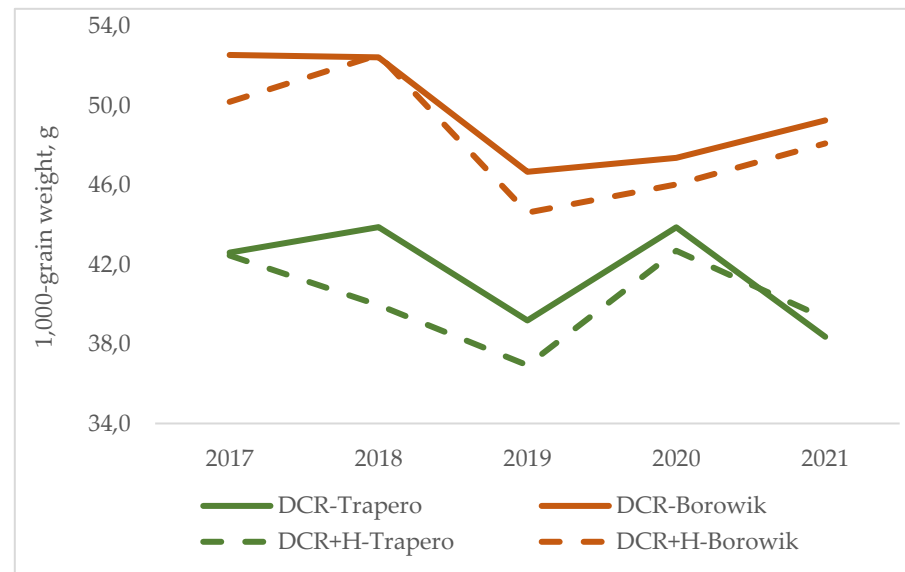
(b)

Figure S3. Effects of the interaction of weed management strategy × cultivar × year on grain number per spike (a) and 1,000-grain weight (b) of winter triticale.

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