Supplementary Material

Plant traits, growth stage and ash mass load control the vulnerability of potato, corn and wheat crops to volcanic ashfall

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Soil analyses

Since the plots used for growing potato, corn and wheat plants were used previously for other agronomical experiments, we conducted several analyses to confirm the homogeneity of key soil properties, including pH, nutrient status (P, K, Ca, Mg and total N contents) and organic carbon content (Table S1). Composite soil samples were collected in late May 2020, one month after fertilising the potato and corn crops. Soils were again sampled in late April 2021 after fertilisation of the wheat plot.

Climatic conditions

Prevailing winds during the 2020 (potatoes and corn) and 2021 (wheat) experiments predominantly blew from the south-south-east and south-south-west directions, reaching maximum average speeds of 1.1 and 1.5 m s^{-1} (Figure S1a). We recorded daily minimum, maximum and average air temperatures from hourly data collected by a weather station installed in one of the high tunnels. The recorded temperature extremes occurred during specific periods, with the lowest and highest temperatures reaching -9.5 and 37.9 °C, respectively. Coolest nights were recorded in May 2020 and February 2021, and the warmest days in August 2020 and June 2021 (Figure S1b). For the potato and corn crops in 2020, the average daily relative humidity was 71±12%. In 2021, during wheat cultivation, the daily relative humidity averaged 70±16% (Figure S1c). The daily solar intensity varied from 176 to 7079 W m^{-2} during the potato and corn cultivation, and from 264 to 5481 W m^{-2} during the wheat cultivation, with an average of 5022±1791 W m^{-2} and 2632±1027 W m^{-2}, respectively (Figure S1d).

Plant growth homogeneity

For the potato cultivation, we monitored leaf development, inflorescence appearance and number of plants and stems to assess growth homogeneity (Hack et al., 1993). Leaf development (86–96% of plants with ≥12 unfolded leaves) and inflorescence appearance (58–79% of plants with flowers visible) stages were homogenous between subplots (Figure S2). The number of potato plants and stems varied between 62 (ash mass load of 1 kg m^{-2} / with mitigation) and 65 (ash mass load of 2 kg m^{-2} / without mitigation) and between 199 (ash mass load of 1 kg m^{-2} / without mitigation) and 260 (control plants), respectively (Table S2).

Corn growth homogeneity between subplots was assessed with the leaf development and stem elongation stages evaluated 11 weeks after sowing (Lancashire et al. 1991), the male and female blooming evaluated between 12 and 16 weeks after sowing, and the insertion height of the first ear and last leaf (measured with a graduated pole) and the ear row number and length evaluated at harvest. Good homogeneity between subplots was observed in corn leaf development (22–52% of plants with ≥14 unfolded leaves) and stem elongation (19–53% of plants with ≥7 nodes visible) stages (Figure S3). There was a minimum delay of five days in male and female blooming of the control plants compared to ash-treated plants (Figure S4). Moreover, control plants had the lowest last leaf and first ear insertion height (Tukey HSD test, p-value<0.05) (Table S3). This suggests that control plants were more stressed than the ash-treated plants during their growth, potentially leading to suboptimal yield conditions. Thus, the *YL* calculated for the different ash treatments might be regarded as minimum values. On average and for all treatments, the corn ears were 18±3 cm long and were composed of 14±3 rows, indicating that ear formation was homogeneous between subplots (Table S3). Wheat growth homogeneity was difficult to assess plant by plant due to the high plant density. Instead, we carried up a visual follow-up, aided by systematically photographing each plot every fortnight, of the wheat plant growth.

Ash treatments

The ash material used in our experiments was generated by crushing a fresh volcanic rock of phonolitic composition (Table S4) obtained from a quarry near the Laacher See volcano, Germany (Van den Bogaard and Schmincke 1984). Since grain size influences ash retention on crop foliage (Ligot et al. 2023), we adjusted the grinding process of the phonolitic rock to approximate the grain size distribution (*GSD*) of the ash surrogate to that of ashfall from a subPlinian/Plinian eruption. For comparison, we referenced the *GSD* reported for the ash fallout from the 1982 eruption of El Chichón volcano, Mexico (Volcanic Explosivity Index (*VEI*) of 5, Rose and Durant 2009). The GSD of the ground phonolite (Figure S5) was measured by laser diffraction (Beckman Coulter LS13 320) in the range 0.04–2000 µm. Since the shape of a particle might influence its retention on crop foliage (Silva et al. 2013), we examined the surrogate ash morphology using scanning electron microscopy (*SEM*). The *SEM* images revealed that most particles had a blocky shape, although rounded and platy shapes were also observed (Figure S6). Similar particle shapes have been commonly documented for ash particles generated by explosive eruptions (e.g. Wohletz

1983; Coltelli et al. 2008; Nurfiani and Bouvet de Maisonneuve 2017). The vesicular ash type, typically associated with the fragmentation of gas-rich magmas, is absent in our experimental ash material as it cannot be generated through mechanical grinding of a solid rock. The colour of the phonolite is white-grey (N9 in the Munsell colour system (Munsell 1912)) and soluble salts are not present on the surface of the ash surrogate.

Table S1: Results of the soil analyses for the potato, corn and wheat plots. pH_{KCl}, P: phosphorus content, K: potassium content, Mg: magnesium content, Ca: calcium content, N: total nitrogen content, C_{org}: organic carbon content, NO_3^-: nitrate content at three soil depths (0–30, 30–60 and 60–90 cm).

sampling month	repetition	pH_{KCl}	P (mg 100 g_{soil}^{-1})	K (mg 100 g_{soil}^{-1})	Mg (mg 100 g_{soil}^{-1})	Ca (mg 100 g_{soil}^{-1})	N (mg 100 g_{soil}^{-1})	C_{org} (g kg_{soil}^{-1})	NO_3^- (0-30 cm) (g ha^{-1})	NO_3^- (30-60 cm) (g ha^{-1})	NO_3^- (60-90 cm) (g ha^{-1})
May 2020	2	5.87 ± 0.01	5.11 ± 0.41	14.09 ± 0.02	21.3 ± 0.46	188 ± 10.3	0.103 ± 0.0078	9.58 ± 1	59.5 ± 26.8	20.8 ± 13.2	25,15
May 2020	2	5.84 ± 0.06	5.18 ± 0.14	14.53 ± 0.76	21.3 ± 0.87	187 ± 1.94	0.109 ± 0.0007	9.94 ± 0.76	101 ± 19.6	52.1 ± 2.83	42,1
May 2020	2	5.77 ± 0.13	4.81 ± 0.27	15.88 ± 0.18	21.3 ± 1.01	188 ± 0.07	0.106 ± 0.0049	10.1 ± 1.04	138 ± 26.6	49.4 ± 1.48	26,07
May 2020	2	5.88 ± 0.18	5.5 ± 1.19	15.42 ± 0.61	21.3 ± 1.84	187 ± 8.94	0.106 ± 0.0057	9.66 ± 0.29	83.0 ± 27.8	28.4 ± 5.9	33,46
May 2020	2	5.95 ± 0.1	5.85 ± 1.06	15.75 ± 1.28	21.4 ± 0.71	189 ± 3.24	0.109± 0.0014	9.28 ± 0.06	98.4 ± 2.82	28 ± 3.85	24,37
May 2020	2	5.81 ± 0.02	5.19 ± 0.66	13.97 ± 0.91	21.4 ± 0.73	188 ± 9.94	0.104 ± 0.0064	9.46 ± 0.5	65.4 ± 20.2	32.8 ± 14.9	32,17
May 2020	2	5.95 ± 0.13	5.46 ± 0.36	16.36 ± 0.09	22.6 ± 1.98	198 ± 10.7	0.1 ± 0.0014	10.5 ± 1.13	104 ± 10.9	48.2 ± 9.91	69,99
May 2020	2	5.83 ± 0.15	5.17 ± 0.76	13.89 ± 1.37	20.5 ± 0.74	190 ± 13.58	0.102 ± 0.007	9 ± 0.28	99.4 ± 19.4	33.1 ± 18.1	47,3
April 2021	0	6,36	5,53	18,4	21,4	203	0,0930	10,1	7,75	22,4	52,4
April 2021	0	6,09	5,86	17,6	22,0	189	0,0974	9,64	9,03	40,6	81,8
April 2021	0	6,11	5,39	17,0	22,1	188	0,0929	9,21	6,60	22,2	67,8
April 2021	0	5,99	5,67	19,2	21,6	189	0,1010	10,1	6,57	22,8	62,7
April 2021	0	5,97	5,76	15,7	22,5	194	0,0934	9,03	7,79	26,4	57,5
April 2021	0	5,98	6,41	15,6	22,6	187	0,0961	9,73	5,22	21,7	56,1
April 2021	0	5,87	7,14	16,2	22,0	190	0,0988	10,4	6,12	14,2	36,6
April 2021	0	5,90	4,97	15,7	19,9	180	0,0994	9,34	8,79	17,8	32,8
April 2021	0	6,04	5,42	15,4	22,2	188	0,0954	9,39	5,11	13,8	39,9
April 2021	0	6,10	5,52	17,7	22,7	191	0,0950	9,51	6,66	19,2	43,7
April 2021	0	5,84	5,54	17,6	21,4	184	0,0957	9,24	6,29	24,7	49,8
April 2021	0	5,93	5,67	15,2	22,9	195	0,0982	10,1	7,55	21,2	42,3
April 2021	0	5,93	5,97	15,3	22,6	191	0,0947	9,19	6,50	15,7	45,5
April 2021	0	5,89	4,44	13,8	18,5	181	0,0740	7,18	8,48	21,7	39,0

Table S2: Number of potato plants and stems in the control and ash-treated plots 11 weeks after planting.

ash mass load (kg m^{-2})	mitigation	plant number	stem number
control	without	64	260
1	without	64	199
1	with	62	212
2	without	63	230
2	with	65	232
5	without	63	227
5	with	65	222

Table S3: Insertion heights (mean ± sd) of the first ear and the last leaf of corn plants measured at harvest, and ear row number and length. As the mean values for the different treatments were statistically different (*p*-value <0.05) and a post-hoc Tukey *HSD* test was performed. In cases where similar letters are used, it indicates that means are not significantly different (Tukey *HSD* test at a 95% family-wise confidence level).

		ash mass load (kg m^{-2})					
	control	1	2	5	1	2	5
		with mitigation			without mitigation		
first ear height (cm)	114 ± 26^{a}	126 ± 22^{b}	131 ± 21^{b}	125 ± 21^{ab}	128 ± 20^{b}	121 ± 22^{ab}	115 ± 23^{a}
last leaf height (cm)	213 ± 47^{b}	232 ± 42^{abc}	247 ± 35^{c}	235 ± 35^{ac}	246 ± 30^{c}	236 ± 38^{ac}	219 ± 49^{ab}
ear row number	14 ± 2^{a}	14 ± 3^{a}	14 ± 4^{a}	14 ± 3^{a}	14 ± 3^{a}	14 ± 3^{a}	14 ± 3^{a}
ear length	18 ± 3^{a}	18 ± 3^{a}	17 ± 2^{a}	17 ± 3^{a}	18 ± 3^{a}	17 ± 4^{a}	16 ± 2^{a}

Table S4: Bulk composition (oxide-basis) of the phonolite rock used for producing the ash surrogate.

major element	weight %
SiO_2	52.5
Al_2O_3	21.8
K_2O	9.6
Na_2O	7.8
Fe_2O_3	2.9
CaO	1.5
TiO_2	0.3
MgO	0.2

Table S5: Spatial homogeneity of the ash deposit formed by using the ash spreader. Eight plastic trays with an opening of 104 cm^2 were placed randomly on the ground to cover a surface area of ~4.5 m^2. *sd*: standard deviation.

ash load in the tray (g)	**ash mass load (kg m^{-2})**
3.05	0.10
3.22	0.12
3.18	0.12
3.37	0.13
3.01	0.09
3.72	0.19
3.15	0.11
3.35	0.14
mean	0.13
sd	0.03

Table S6: Number of lodged corn stalks after exposure to 1, 2 and 5 kg m^{-2} of ash. The stalk is considered broken if the angle with the vertical position is >45° and bent if <45°.

		ash mass load (kg m^{-2})					
	control	1	2	5	1	2	5
		with mitigation			**without mitigation**		
broken stalk	0	0	0	17	0	0	13
bent stalk	0	0	3	17	0	1	12

Table S7: Potato (tuber), corn (whole plant, stalk+leaves, grains and total) and wheat (grains and straw) production before (control) and after treatment with various ash mass loads at the "growth", "flowering" and "maturation" stages. The effect of ash removal *via* manual shaking (mitigation) on potato and corn *Y* is also included. For wheat, four and eight subplots were used for the ash treatment and control group, respectively, allowing the calculation of mean and standard deviation values. *Y*: yield; *YL*: yield loss; Y_{std}: standardised grain yield; YL_{std}: standardised grain yield loss.

crop type	plant part	ash mass load	mitigation	growth stage	*Y*	*YL*	Y_{std}	YL_{std}	number of filled ears	unfertilised ear lenght
		kg m^{-2}			t ha^{-1}	%	t ha^{-1}	%		%
potato	tuber	0	without	control	42	0	/	/	/	/
potato	tuber	1	without	flowering	39	8	/	/	/	/
potato	tuber	1	with	flowering	37	13	/	/	/	/
potato	tuber	2	without	flowering	34	20	/	/	/	/
potato	tuber	2	with	flowering	32	24	/	/	/	/
potato	tuber	5	without	flowering	32	25	/	/	/	/
potato	tuber	5	with	flowering	35	18	/	/	/	/
corn	whole plant	0	without	control	62	0	/	/	/	/
corn	whole plant	1	without	flowering	57	8	/	/	/	/
corn	whole plant	1	with	flowering	55	10	/	/	/	/
corn	whole plant	2	without	flowering	50	19	/	/	/	/
corn	whole plant	2	with	flowering	60	3	/	/	/	/
corn	whole plant	5	without	flowering	44	28	/	/	/	/
corn	whole plant	5	with	flowering	51	17	/	/	/	/
corn	stalk+leaves	0	without	control	29	0	/	/	/	/
corn	stalk+leaves	1	without	flowering	31	-9	/	/	/	/
corn	stalk+leaves	1	with	flowering	30	-5	/	/	/	/
corn	stalk+leaves	2	without	flowering	28	2	/	/	/	/
corn	stalk+leaves	2	with	flowering	28	2	/	/	/	/
corn	stalk+leaves	5	without	flowering	24	18	/	/	/	/
corn	stalk+leaves	5	with	flowering	23	20	/	/	/	/
corn	grain	0	without	control	19	0	9	0	44	14
corn	grain	1	without	flowering	18	4	8	13	39	13
corn	grain	1	with	flowering	17	10	7	16	41	17
corn	grain	2	without	flowering	14	29	6	34	39	17
corn	grain	2	with	flowering	16	16	7	21	42	19
corn	grain	5	without	flowering	12	36	5	41	36	20
corn	grain	5	with	flowering	13	33	5	39	38	21
corn	total	0	without	control	59	0	/	/	/	/
corn	total	1	without	flowering	57	3	/	/	/	/
corn	total	1	with	flowering	56	6	/	/	/	/
corn	total	2	without	flowering	49	17	/	/	/	/
corn	total	2	with	flowering	56	6	/	/	/	/
corn	total	5	without	flowering	43	27	/	/	/	/
corn	total	5	with	flowering	47	21	/	/	/	/
wheat	grain	0	without	control	7.3±1.6	-0.5±12.7	7,2±1,5	-0.5±12.3	/	/
wheat	grain	0.5	without	growth	7.8±1.7	-8.3±13.8	7.8±1.7	-8.3±13.6	/	/
wheat	grain	2	without	growth	7.4±1.8	-2.9±13.8	7.4±1.7	-3.4±13.5	/	/
wheat	grain	5	without	growth	7±2	3.1±14.8	7±2	3±14.6	/	/
wheat	grain	9	without	growth	7±0.8	2.5±9	7±0.9	2.2±9	/	/
wheat	grain	0.5	without	flowering	7.2±1.8	0.9±14.1	7.1±1.8	1.3±13.8	/	/
wheat	grain	2	without	flowering	7±1.3	3.6±11.3	7±1.3	3±11.1	/	/
wheat	grain	5	without	flowering	6.4±1.4	11±11	6.4±1.3	11.3±10.7	/	/
wheat	grain	9	without	flowering	5.6±0.3	22.3±6.1	5.6±0.3	22.2±6	/	/
wheat	grain	0.5	without	maturation	8.2±1.8	-13.9±14.7	8.1±1.8	-13.6±14.4	/	/
wheat	grain	2	without	maturation	7±1.6	3.4±12.6	6.9±1.6	3.6±12.5	/	/
wheat	grain	5	without	maturation	7.6±1.9	-5.8±14.9	7.5±1.9	-5.1±14.5	/	/
wheat	grain	9	without	maturation	7.4±1.3	-3±11.2	7.4±1.3	-2.7±11	/	/
wheat	straw	0	without	control	8.9±2.1	-0.6±14	/	/	/	/
wheat	straw	0.5	without	growth	8±1.5	9.4±10.8	/	/	/	/
wheat	straw	2	without	growth	7.1±1.5	20.1±10.2	/	/	/	/
wheat	straw	5	without	growth	8.2±1.4	7.5±10.5	/	/	/	/
wheat	straw	9	without	growth	8.1±0.5	8.1±7.9	/	/	/	/
wheat	straw	0.5	without	flowering	7.9±1.2	10.6±9.7	/	/	/	/
wheat	straw	2	without	flowering	8.6±2.2	3.1±14	/	/	/	/
wheat	straw	5	without	flowering	8.3±1.7	6.2±12	/	/	/	/
wheat	straw	9	without	flowering	7.1±0.9	19.4±8.2	/	/	/	/
wheat	straw	0.5	without	maturation	8.8±1.5	0.6±11.5	/	/	/	/
wheat	straw	2	without	maturation	8.4±1.1	4.4±9.6	/	/	/	/
wheat	straw	5	without	maturation	9.1±1.9	-2.5±13.1	/	/	/	/
wheat	straw	9	without	maturation	9.2±1.3	-4.4±11	/	/	/	/

Table S8: Crop yield loss (*YL*) estimates (mean, median, *q2.5*: 2.5th quantile, *q97.5*: 97.5th quantile, *q34.1*: 34.1th quantile and *q68.2*: 68.2th quantile) for wheat grain and straw of control plants and ash-treated plants. The input parameters used for their calculations (Equation 2a in main text) are also reported. *n*: number of observations; *sd*: standard deviation.

				production (t ha^{-1})		*YL (%)*					
plant part	**growth stage**	**ash mass load (kg m^{-2})**	***n***	**mean**	***sd***	**mean**	**median**	***q2.5***	***q97.5***	***q34.1***	***q68.2***
wheat grain	control	0	8	7.2	1.5	-2.2	0.0	-27.8	23.4	-12.8	11.8
wheat grain	growth	0.5	4	7.8	1.7	-10.1	-7.8	-38.4	18.2	-21.9	5.3
wheat grain	growth	2	4	7.4	1.7	-5.2	-2.9	-33.4	23.0	-16.9	10.1
wheat grain	growth	5	4	7.0	2.0	1.5	3.5	-29.0	31.9	-11.6	17.7
wheat grain	growth	9	4	7.0	0.9	0.5	2.7	-18.3	19.4	-6.8	11.2
wheat grain	flowering	0.5	4	7.1	7.1	-0.4	1.8	-29.1	28.4	-12.5	15.1
wheat grain	flowering	2	4	7.0	7.0	1.4	3.5	-21.8	24.6	-8.1	14.1
wheat grain	flowering	5	4	6.4	6.4	9.8	11.7	-12.4	32.0	0.6	22.0
wheat grain	flowering	9	4	5.6	5.6	20.9	22.6	8.5	33.4	16.3	28.2
wheat grain	maturation	0.5	4	8.1	1.8	-15.5	-13.0	-45.5	14.6	-28.0	0.9
wheat grain	maturation	2	4	6.9	1.6	1.9	4.1	-24.1	27.9	-8.9	16.1
wheat grain	maturation	5	4	7.5	1.9	-6.9	-4.6	-36.9	23.2	-19.5	9.4
wheat grain	maturation	9	4	7.4	1.3	-4.4	-2.2	-27.3	18.6	-13.7	8.3
wheat straw	control	0	8	8.9	2.1	-2.8	0.0	-32.0	26.3	-14.6	13.3
wheat straw	growth	0.5	4	8.0	1.5	7.5	10.0	-15.1	30.0	-1.4	20.2
wheat straw	growth	2	4	7.1	1.5	18.4	20.6	-2.9	39.7	9.9	30.3
wheat straw	growth	5	4	8.2	1.4	5.6	8.1	-16.3	27.4	-2.9	18.0
wheat straw	growth	9	4	8.1	0.5	6.2	8.7	-10.4	22.7	0.2	16.0
wheat straw	flowering	0.5	4	7.9	1.2	8.7	11.2	-11.5	29.0	1.0	20.3
wheat straw	flowering	2	4	8.6	2.2	1.1	3.7	-28.2	30.3	-10.9	17.1
wheat straw	flowering	5	4	8.3	1.7	4.2	6.8	-20.8	29.2	-5.8	18.2
wheat straw	flowering	9	4	7.1	0.9	17.7	20.0	0.6	34.9	11.3	27.6
wheat straw	maturation	0.5	4	8.8	1.5	-1.6	1.2	-25.6	22.4	-10.9	12.1
wheat straw	maturation	2	4	8.5	1.1	2.3	5.0	-17.8	22.4	-5.2	14.0
wheat straw	maturation	5	4	9.1	1.9	-4.7	-1.9	-32.0	22.5	-15.6	10.5
wheat straw	maturation	9	4	9.2	1.3	-6.6	-3.7	-29.5	16.3	-15.4	6.5

Table S9: The Dunnett's test results, which include the mean difference with the control group, the lower (lwr.ci) and upper (upr.ci) bounds of the confidence interval for the mean difference, and the *p*-value, are used to compare the quality analyses of the ash treatment of corn whole plants and the stalk+leaves with those of the control group.

ash treatment	difference	*lwr.ci*	*upr.ci*	*p* -value	
whole plant protein content					
1 kg m^{-2} - without mitigation	-0.06	-0.36	0.23	0.9829	
1 kg m^{-2} - with mitigation	-0.29	-0.58	0.01	0.0569	.
2 kg m^{-2} - without mitigation	0.32	0.03	0.62	0.0247	*
2 kg m^{-2} - with mitigation	0.22	-0.07	0.51	0.2047	
5 kg m^{-2} - without mitigation	0.43	0.13	0.72	0.0017	**
5 kg m^{-2} - with mitigation	-0.04	-0.33	0.26	0.9991	
whole plant cellulose content					
1 kg m^{-2} - without mitigation	0.76	-0.22	1.74	0.1860	
1 kg m^{-2} - with mitigation	2.18	1.20	3.16	0.0000	***
2 kg m^{-2} - without mitigation	0.82	-0.16	1.81	0.1305	
2 kg m^{-2} - with mitigation	0.81	-0.17	1.79	0.1434	
5 kg m^{-2} - without mitigation	2.93	1.95	3.91	0.0000	***
5 kg m^{-2} - with mitigation	3.08	2.09	4.06	0.0000	***
whole plant mineral content					
1 kg m^{-2} - without mitigation	-0.08	-0.36	0.21	0.9481	
1 kg m^{-2} - with mitigation	0.14	-0.14	0.42	0.6149	
2 kg m^{-2} - without mitigation	0.37	0.08	0.65	0.0062	**
2 kg m^{-2} - with mitigation	0.05	-0.24	0.33	0.9958	
5 kg m^{-2} - without mitigation	0.37	0.09	0.66	0.0049	**
5 kg m^{-2} - with mitigation	0.68	0.40	0.96	0.0000	***
whole plant organic matter digestibility					
1 kg m^{-2} - without mitigation	-2.00	-3.80	-0.20	0.0235	*
1 kg m^{-2} - with mitigation	-3.16	-4.96	-1.37	0.0001	***
2 kg m^{-2} - without mitigation	-2.03	-3.82	-0.23	0.0211	*
2 kg m^{-2} - with mitigation	-1.72	-3.51	0.08	0.0664	.
5 kg m^{-2} - without mitigation	-5.57	-7.37	-3.78	0.0000	***
5 kg m^{-2} - with mitigation	-4.12	-5.92	-2.33	0.0000	***
whole plant starch content					
1 kg m^{-2} - without mitigation	0.48	-1.41	2.38	0.9627	
1 kg m^{-2} - with mitigation	-2.29	-4.18	-0.39	0.0118	*
2 kg m^{-2} - without mitigation	1.71	-0.18	3.61	0.0897	.
2 kg m^{-2} - with mitigation	1.25	-0.64	3.15	0.3201	
5 kg m^{-2} - without mitigation	-3.39	-5.28	-1.50	0.0001	***
5 kg m^{-2} - with mitigation	-3.54	-5.44	-1.65	0.0000	***

Table S9 (continued)

ash treatment	difference	*lwr.ci*	*upr.ci*	*p*-value	
stalk+leaves protein content					
1 kg m^{-2} - without mitigation	0.43	-0.22	1.08	0.3213	
1 kg m^{-2} - with mitigation	0.15	-0.50	0.81	0.9745	
2 kg m^{-2} - without mitigation	0.38	-0.27	1.03	0.4423	
2 kg m^{-2} - with mitigation	0.20	-0.46	0.85	0.9230	
5 kg m^{-2} - without mitigation	-0.34	-1.00	0.31	0.5470	
5 kg m^{-2} - with mitigation	0.53	-0.12	1.19	0.1477	
stalk+leaves cellulose content					
1 kg m^{-2} - without mitigation	2.63	1.54	3.72	0.0000	***
1 kg m^{-2} - with mitigation	1.99	0.90	3.08	0.0001	***
2 kg m^{-2} - without mitigation	1.70	0.61	2.79	0.0007	***
2 kg m^{-2} - with mitigation	5.11	4.02	6.20	0.0000	***
5 kg m^{-2} - without mitigation	5.89	4.80	6.98	0.0000	***
5 kg m^{-2} - with mitigation	6.96	5.87	8.05	0.0000	***
stalk+leaves mineral content					
1 kg m^{-2} - without mitigation	1.64	0.71	2.57	0.0001	***
1 kg m^{-2} - with mitigation	1.45	0.52	2.38	0.0007	***
2 kg m^{-2} - without mitigation	3.42	2.49	4.35	0.0000	***
2 kg m^{-2} - with mitigation	1.82	0.89	2.75	0.0000	***
5 kg m^{-2} - without mitigation	2.25	1.32	3.18	0.0000	***
5 kg m^{-2} - with mitigation	2.89	1.96	3.82	0.0000	***
stalk+leaves matter digestibility					
1 kg m^{-2} - without mitigation	-13.32	-16.41	-10.22	0.0000	***
1 kg m^{-2} - with mitigation	-9.15	-12.24	-6.06	0.0000	***
2 kg m^{-2} - without mitigation	-18.65	-21.74	-15.56	0.0000	***
2 kg m^{-2} - with mitigation	-19.62	-22.71	-16.52	0.0000	***
5 kg m^{-2} - without mitigation	-26.63	-29.72	-23.54	0.0000	***
5 kg m^{-2} - with mitigation	-21.28	-24.37	-18.19	0.0000	***

Table S10: The Dunnett's test results, which include the mean difference with the control group, the lower (lwr.ci) and upper (upr.ci) bounds of the confidence interval for the mean difference, and the p-value, are used to compare the wheat grain quality analyses of ash-treated plants with those of the control group.

growth stage	ash mass load (kg m^{-2})	difference	*lwr.ci*	*upr.ci*	*p* -value	
hectoliter weight						
growth	0.5	1.150	-0.516	2.816	0.355	
growth	2	1.100	-0.566	2.766	0.410	
growth	5	0.250	-1.416	1.916	1.000	
growth	9	0.075	-1.591	1.741	1.000	
flowering	0.5	-0.375	-2.041	1.291	0.999	
flowering	2	-0.525	-2.191	1.141	0.983	
flowering	5	-1.350	-3.016	0.316	0.181	
flowering	9	-1.550	-3.216	0.116	0.083	.
maturation	0.5	-0.450	-2.116	1.216	0.995	
maturation	2	-1.775	-3.441	0.109	0.030	*
maturation	5	-3.425	-5.091	1.759	0.000	***
maturation	9	-2.325	-3.991	0.659	0.002	**
protein content						
growth	0.5	0.150	-1.387	1.687	1.000	
growth	2	0.425	-1.112	1.962	0.994	
growth	5	0.350	-1.187	1.887	0.999	
growth	9	0.150	-1.387	1.687	1.000	
flowering	0.5	0.200	-1.337	1.737	1.000	
flowering	2	0.475	-1.062	2.012	0.986	
flowering	5	0.250	-1.787	1.287	1.000	
flowering	9	0.225	-1.312	1.762	1.000	
maturation	0.5	0.200	-1.337	1.737	1.000	
maturation	2	0.300	-1.237	1.837	1.000	
maturation	5	0.450	-1.087	1.987	0.991	
maturation	9	0.275	-1.262	1.812	1.000	
Zeleny number						
growth	0.5	0.875	-3.284	5.034	1.000	
growth	2	1.375	-2.784	5.534	0.976	
growth	5	2.125	-2.034	6.284	0.729	
growth	9	1.625	-2.534	5.784	0.928	
flowering	0.5	1.125	-5.284	3.034	0.995	
flowering	2	1.375	-2.784	5.534	0.976	
flowering	5	0.125	-4.284	4.034	1.000	
flowering	9	1.625	-2.534	5.784	0.928	
maturation	0.5	1.375	-2.784	5.534	0.976	
maturation	2	1.625	-2.534	5.784	0.928	
maturation	5	1.625	-2.534	5.784	0.928	
maturation	9	1.375	-2.784	5.534	0.976	
Hagberg falling number						
growth	0.5	1.000	-44.334	89.334	0.973	
growth	2	0.976	-56.084	77.584	1.000	
growth	5	0.729	-55.084	78.584	1.000	
growth	9	0.928	-63.334	70.334	1.000	
flowering	0.5	0.995	-62.584	71.084	1.000	
flowering	2	0.976	-47.834	85.834	0.993	
flowering	5	1.000	-37.584	96.084	0.865	
flowering	9	0.928	-44.834	88.834	0.977	
maturation	0.5	0.976	-40.834	92.834	0.930	
maturation	2	0.928	-49.584	84.084	0.997	
maturation	5	0.928	-51.584	82.084	0.999	
maturation	9	0.976	-33.834	99.834	0.764	
grain hardness						
growth	0.5	0.973	-12.077	20.327	0.997	
growth	2	1.000	-14.577	17.827	1.000	
growth	5	1.000	-12.577	19.827	0.999	
growth	9	1.000	-14.827	17.577	1.000	
flowering	0.5	1.000	-14.327	18.077	1.000	
flowering	2	0.993	-17.327	15.077	1.000	
flowering	5	0.865	-13.827	18.577	1.000	
flowering	9	0.977	-11.577	20.827	0.992	
maturation	0.5	0.930	-10.077	22.327	0.941	
maturation	2	0.997	-14.077	18.327	1.000	
maturation	5	0.999	-12.577	19.827	0.999	
maturation	9	0.764	-18.327	14.077	1.000	

Table S10 (continued)

growth stage	ash mass load (kg m^{-2})	difference	*lwr.ci*	*upr.ci*	*p* -value
brightness of wheat flour					
growth	0.5	0.075	-1.149	1.299	1.000
growth	2	0.600	-0.624	1.824	0.771
growth	5	-0.275	-1.499	0.949	0.999
growth	9	-0.600	-1.824	0.624	0.771
flowering	0.5	-0.075	-1.299	1.149	1.000
flowering	2	-0.350	-1.574	0.874	0.992
flowering	5	-0.725	-1.949	0.499	0.551
flowering	9	-0.625	-1.849	0.599	0.729
maturation	0.5	-0.325	-1.549	0.899	0.996
maturation	2	-0.550	-1.774	0.674	0.846
maturation	5	-0.750	-1.974	0.474	0.507
maturation	9	-1.100	-2.324	0.124	0.102
color green-red of wheat flour					
growth	0.5	0.050	0.050	0.457	1.000
growth	2	-0.100	-0.100	0.307	0.998
growth	5	0.125	0.125	0.532	0.986
growth	9	0.175	0.175	0.582	0.877
flowering	0.5	-0.025	-0.025	0.382	1.000
flowering	2	0.125	0.125	0.532	0.986
flowering	5	0.100	0.100	0.507	0.998
flowering	9	0.050	0.050	0.457	1.000
maturation	0.5	0.000	0.000	0.407	1.000
maturation	2	0.000	0.000	0.407	1.000
maturation	5	0.000	0.000	0.407	1.000
maturation	9	0.075	0.075	0.482	1.000
color blue-yellow of wheat flour					
growth	0.5	0.100	-0.426	0.626	1.000
growth	2	-0.125	-0.651	0.401	0.998
growth	5	0.125	-0.401	0.651	0.998
growth	9	0.250	-0.276	0.776	0.799
flowering	0.5	0.150	-0.376	0.676	0.992
flowering	2	0.125	-0.401	0.651	0.998
flowering	5	0.350	-0.176	0.876	0.399
flowering	9	0.175	-0.351	0.701	0.975
maturation	0.5	-0.100	-0.626	0.426	1.000
maturation	2	0.025	-0.501	0.551	1.000
maturation	5	0.050	-0.476	0.576	1.000
maturation	9	-0.050	-0.576	0.476	1.000
shine index					
growth	0.5	0.000	-1.260	1.260	1.000
growth	2	0.575	-0.685	1.835	0.834
growth	5	-0.325	-1.585	0.935	0.997
growth	9	-0.650	-1.910	0.610	0.718
flowering	0.5	-0.150	-1.410	1.110	1.000
flowering	2	-0.375	-1.635	0.885	0.989
flowering	5	-0.775	-2.035	0.485	0.502
flowering	9	-0.625	-1.885	0.635	0.759
maturation	0.5	-0.225	-1.485	1.035	1.000
maturation	2	-0.450	-1.710	0.810	0.959
maturation	5	-0.625	-1.885	0.635	0.759
maturation	9	-0.875	-2.135	0.385	0.347

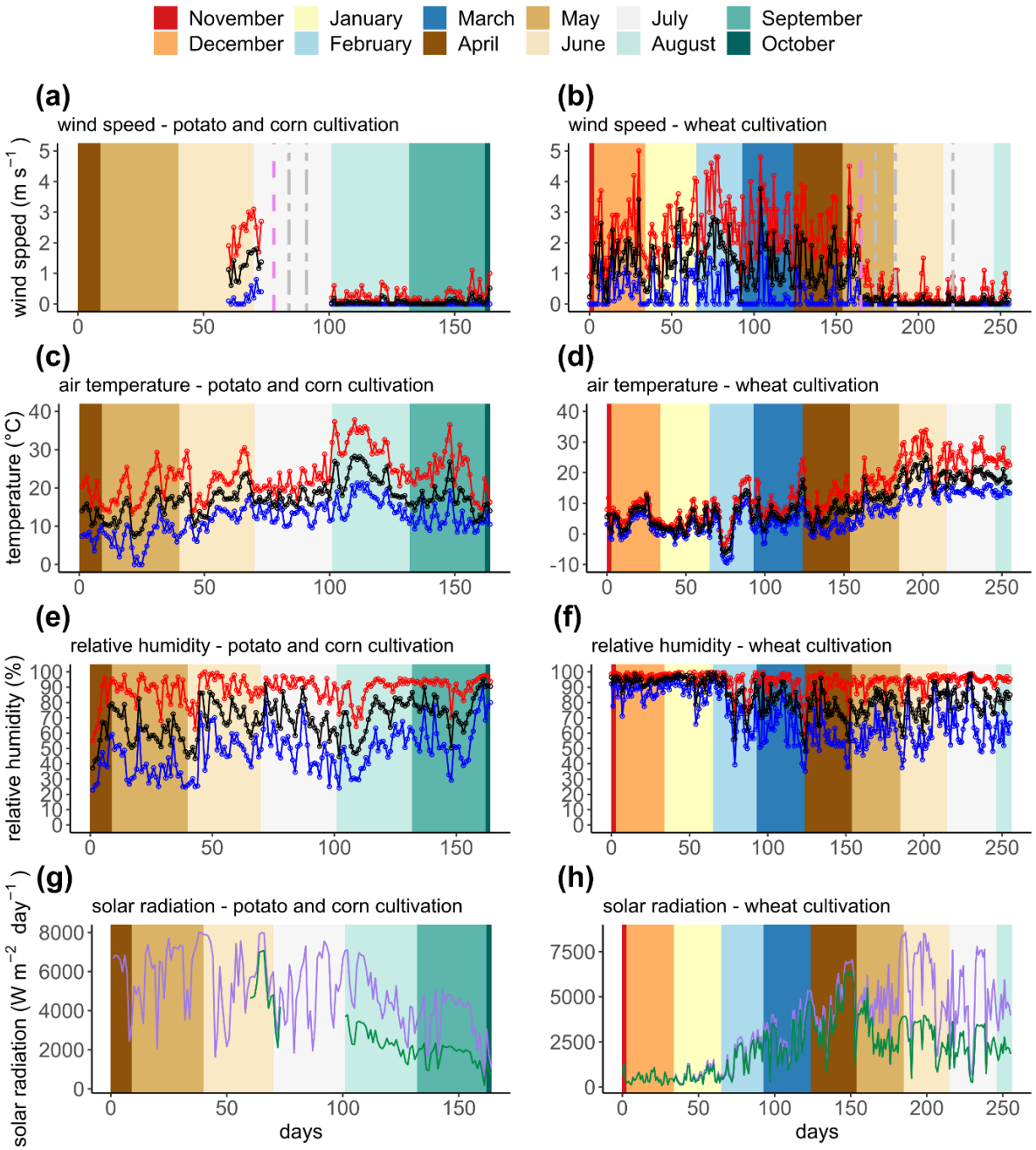

Figure S1: Wind speed (a, b), air temperature (c, d), relative humidity (e, f) and solar radiation (g, h) as recorded in 2020 (potatoes and corn) and 2021 (wheat) by a weather station installed ~2-m above the ground in the high tunnel. The purple and grey vertical dashed lines indicate the date of tarpaulin installation and ash application (potato and corn cultivation: the first grey line for ash application to potato plants and the second for ash application to corn plants; wheat cultivation: from left to right, the three grey lines for ash application to plants when at "growth", "flowering" and "maturation"), respectively. For comparison with a reference sensor, solar radiation measured outside the high tunnel (green curve line) were sourced from a sensor within the PAMSEB network (https://agromet.be/en/pages/home/) located ~500 meters from the experimental plots.

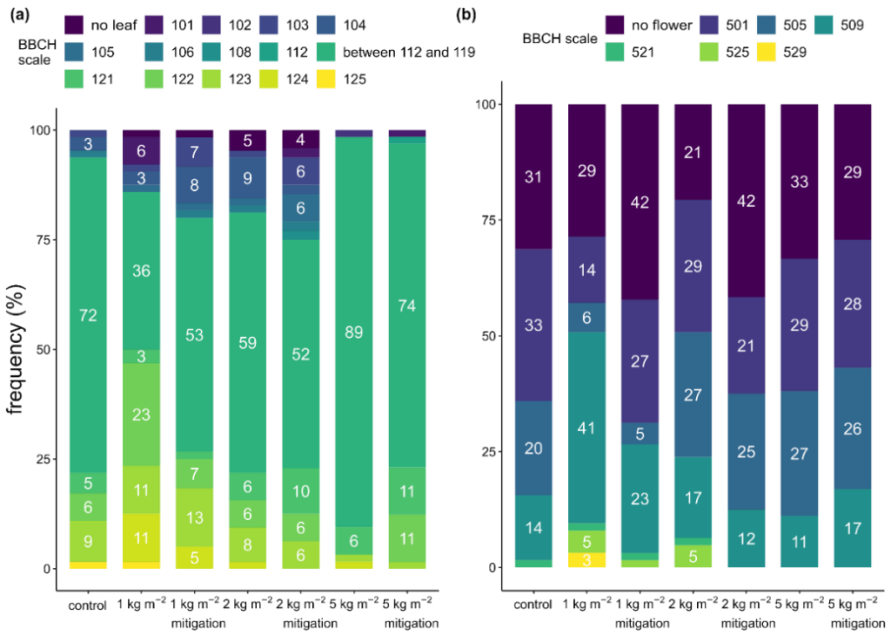

Figure S2: Visual evaluation of the potato plant growth stage in the control and ash-treated plots. The BBCH scale (Hack et al. 1993) was used: leaf development stage nine weeks after planting (legend code: 1NX indicates that the Xth leaf, from 1 to 19, of the Nth order branch, 0 for main stem and 2 for second stem, is unfold) (a) and inflorescence appearance stage 11 weeks after planting (legend code: 5NX indicates that the Nth inflorescence, 0 for the first and 2 for the second, has the buds visible (1), the buds 5 mm long (3) or the flower petals visible (9)) (b).

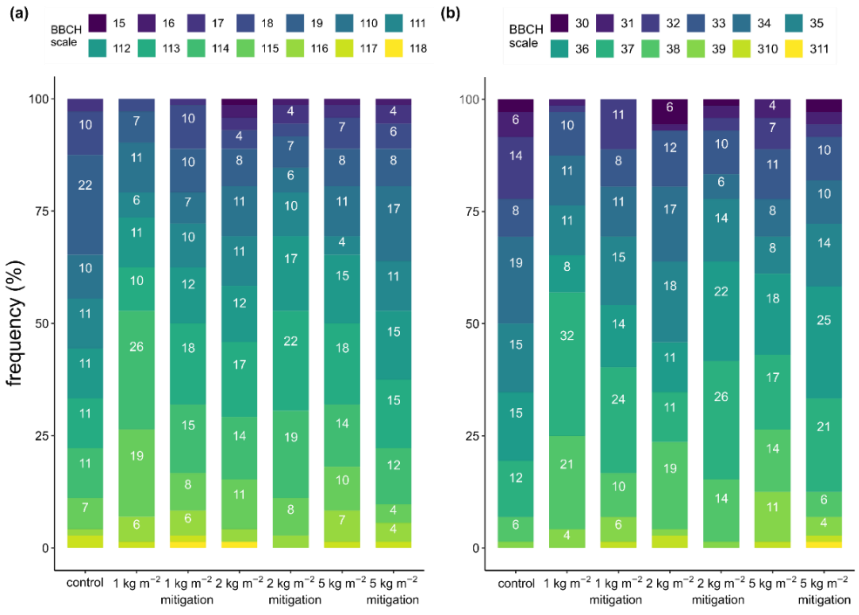

Figure S3: Visual evaluation of the corn plant growth stage in the control and ash-treated plots 11 weeks after sowing. The BBCH scale (Lancashire et al. 1991) was used: leaf development stage (legend code: 1X indicates that the Xth leaf is unfolded) (a) and stem elongation stage (legend code: 3X indicates that X nodes are identifiable) (b).

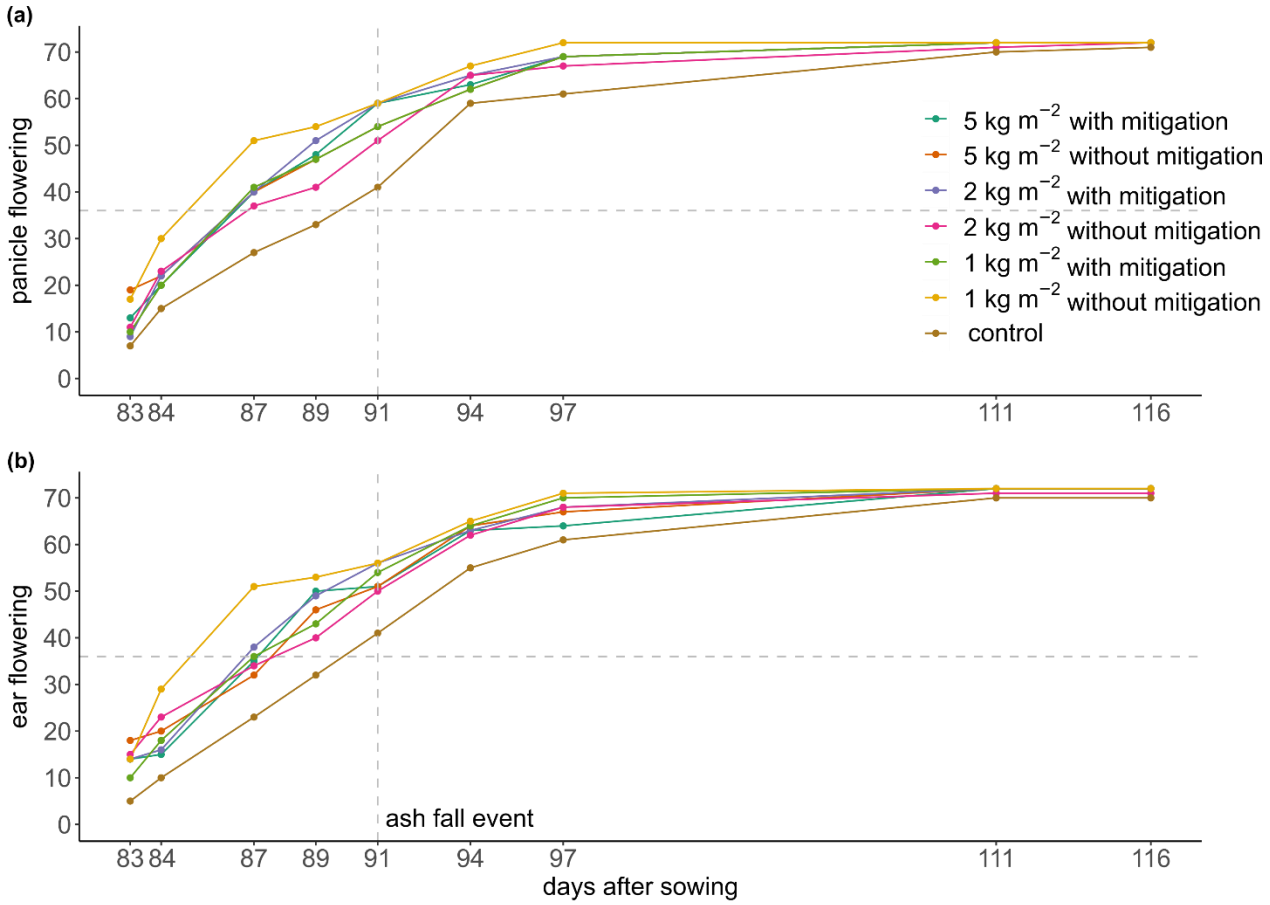

Figure S4: The number of corn plants in male (a) and female (b) blooming, characterised by the presence of visible silk and spikelets, respectively, in the control and ash-treated plots as measured between 12 to 16 weeks after sowing. The vertical and horizontal dashed lines mark the day of ash application and half of the corn plant population, respectively.

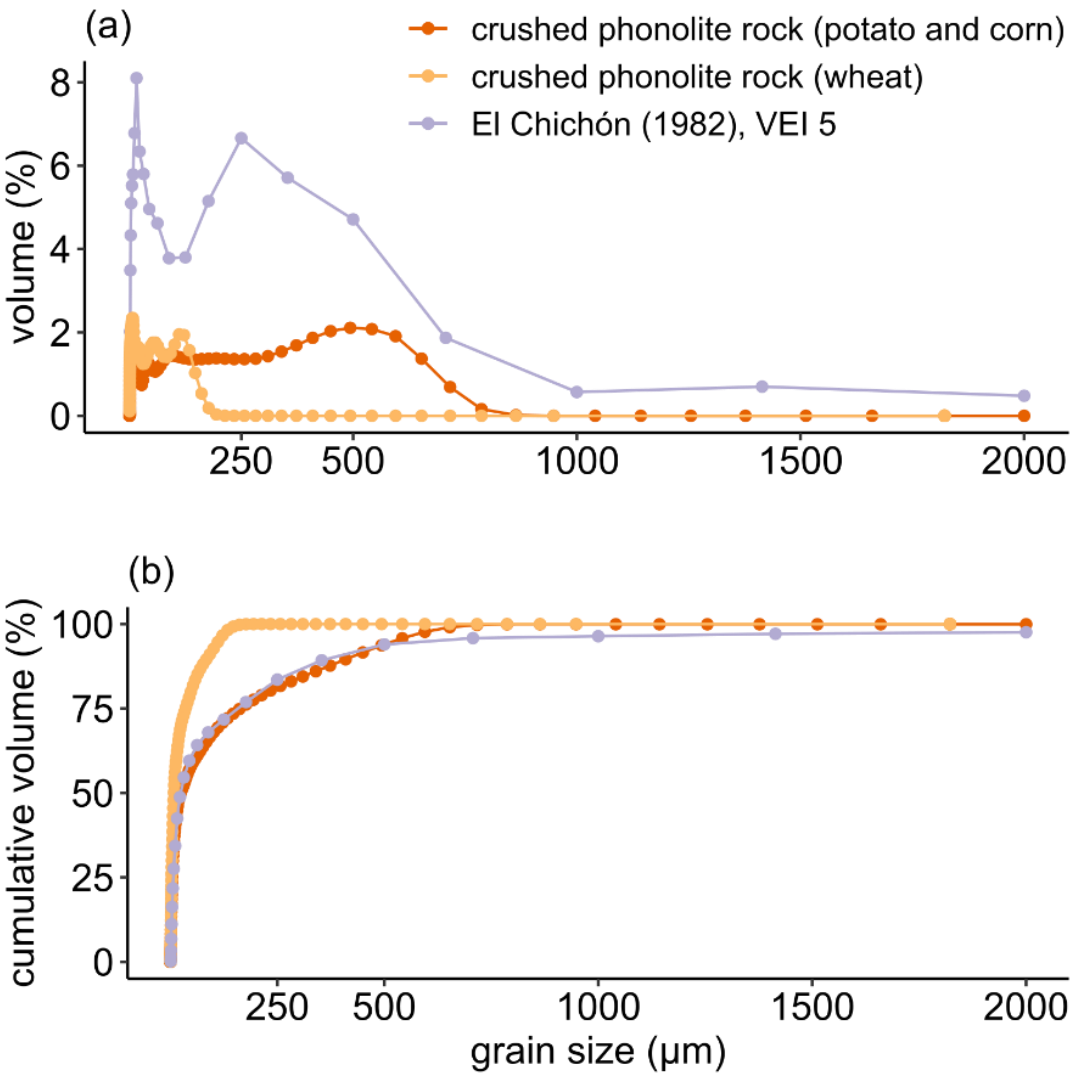

Figure S5: Grain size distribution (*GSD*) of the ash surrogate: volume (a) and cumulative volume (b). The *GSD* of the ash from the *VEI* 5 eruption of El Chichón volcano, Mexico, in 1982, is shown for comparison (Rose and Durant 2009).

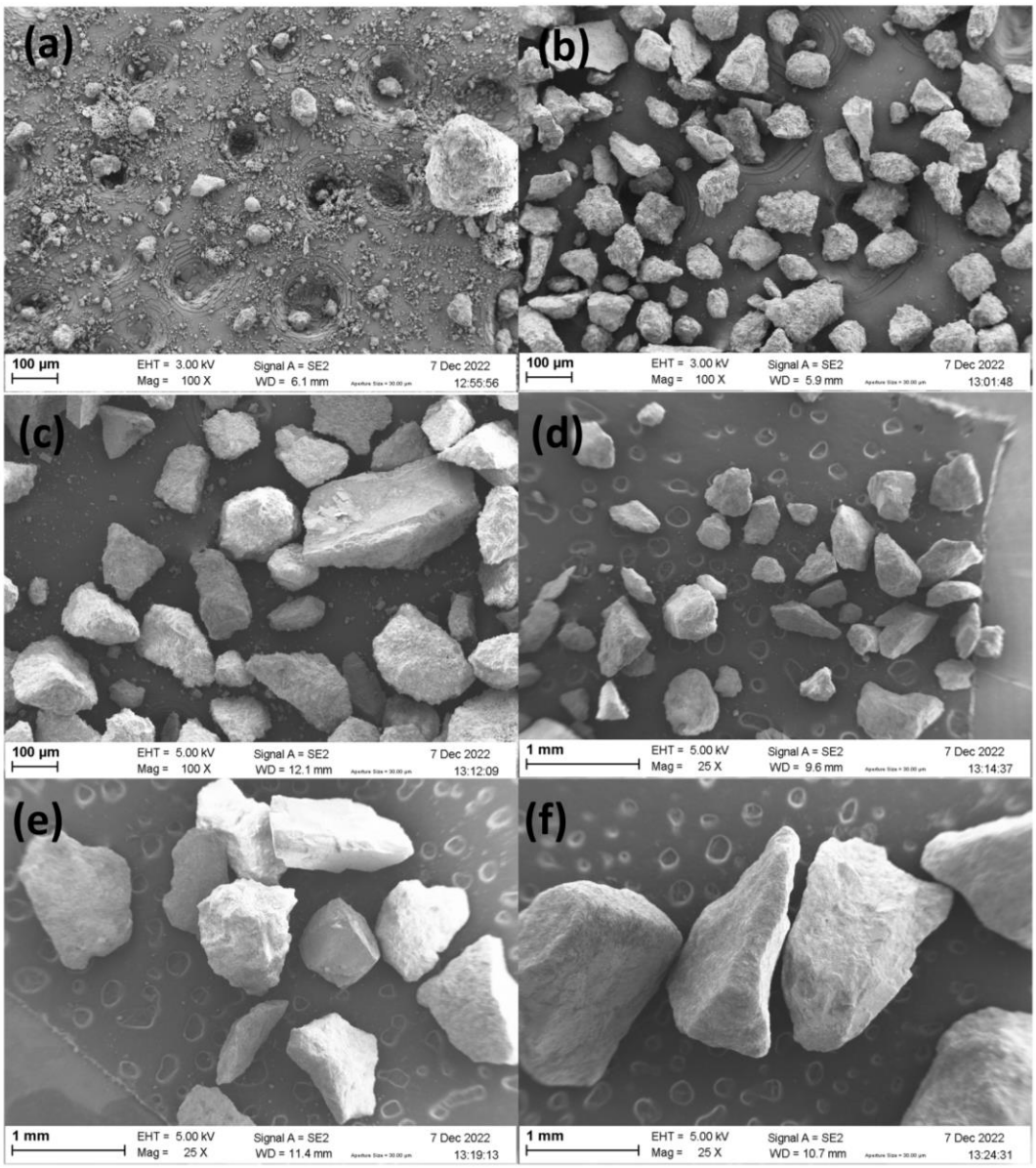

Figure S6: Scanning electron microscope (*SEM*) images of the ash surrogate obtained by crushing a phonolite rock. Particles were sieved in six size ranges to facilitate observations: ≤90 (a), 90–125 (b), 125–250 (c), 250–500 (d), 500–1000 (e) and 1000–2000 µm (f).

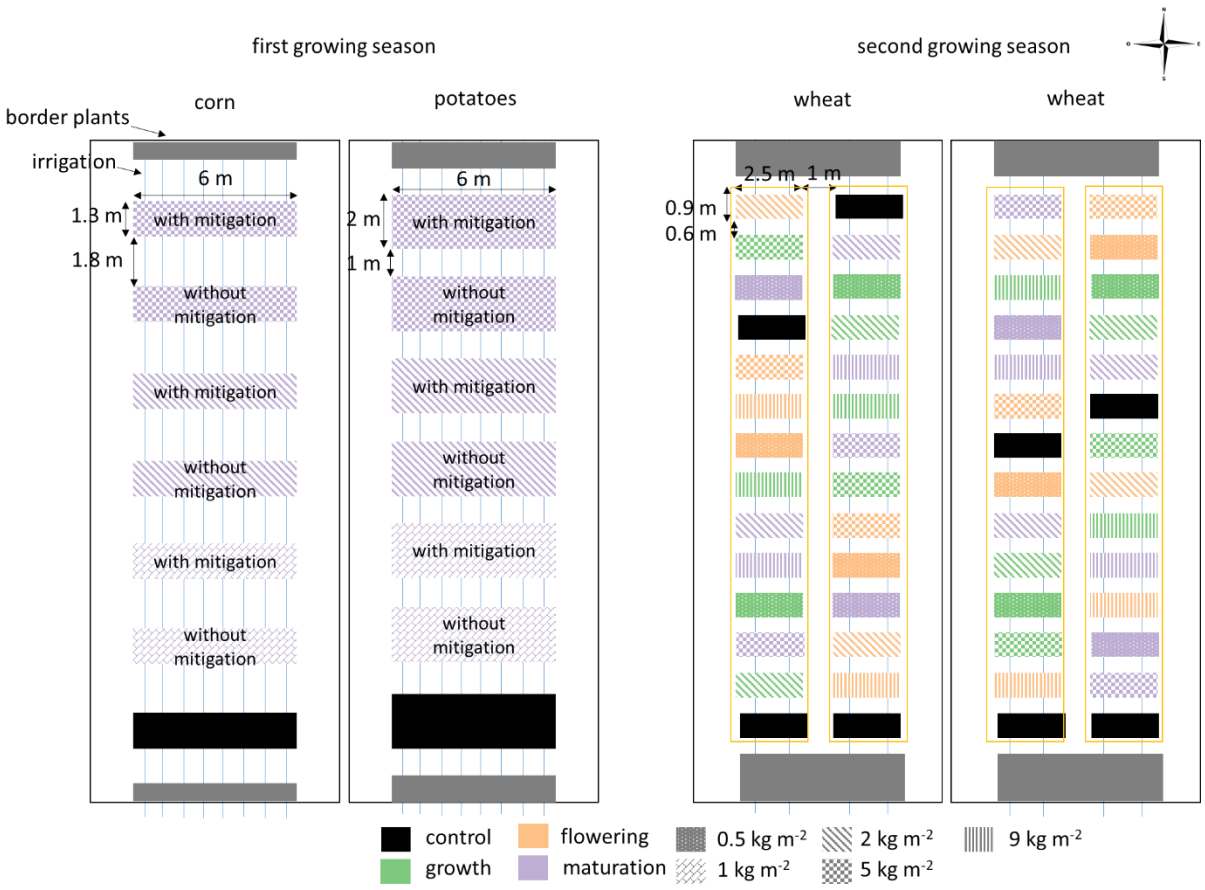

Figure S7: Spatial arrangement of the subplots in the high tunnels for potato and corn cultivation in April and May 2020, and for wheat cultivation in November 2020. The dimensions and spacing of the subplots and the irrigation system are depicted. Border plants were intentionally maintained along the subplot sides to ensure a consistent border effect across all subplots. Additionally, the control subplots were placed on the southern side of the high tunnel to serve as a windbreak. For wheat, the subplots were randomly distributed across the two marked orange blocks within each high tunnel.

Figure S8: Visual impacts of ash on potato plants: straight and bent stems before and immediately after application of 5 kg ash m^{-2} (a, b), yellowish to brownish leaves six days after application of 2 kg ash m^{-2} (c), and curled and yellowish ash-covered basal leaves 27 days after application of 5 kg ash m^{-2} (d).

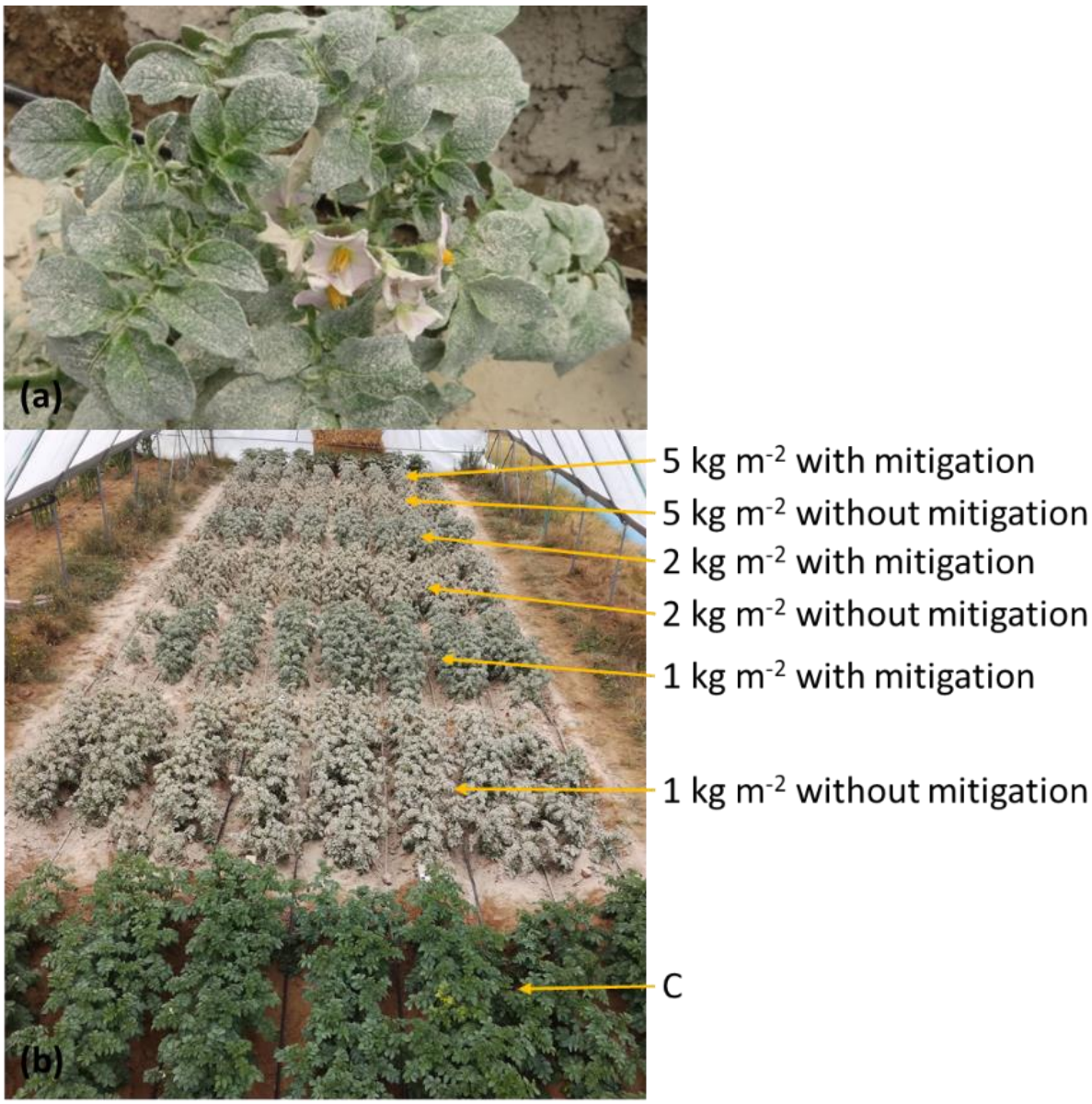

Figure S9: Visual effect of mitigation (plant shaking with a wooden stick the day after ash application) on potato leaves exposed to 2 kg m^{-2} of ash (a) and potato plant foliage exposed to 1, 2 and 5 kg m^{-2} of ash (b). C indicates the control plants.

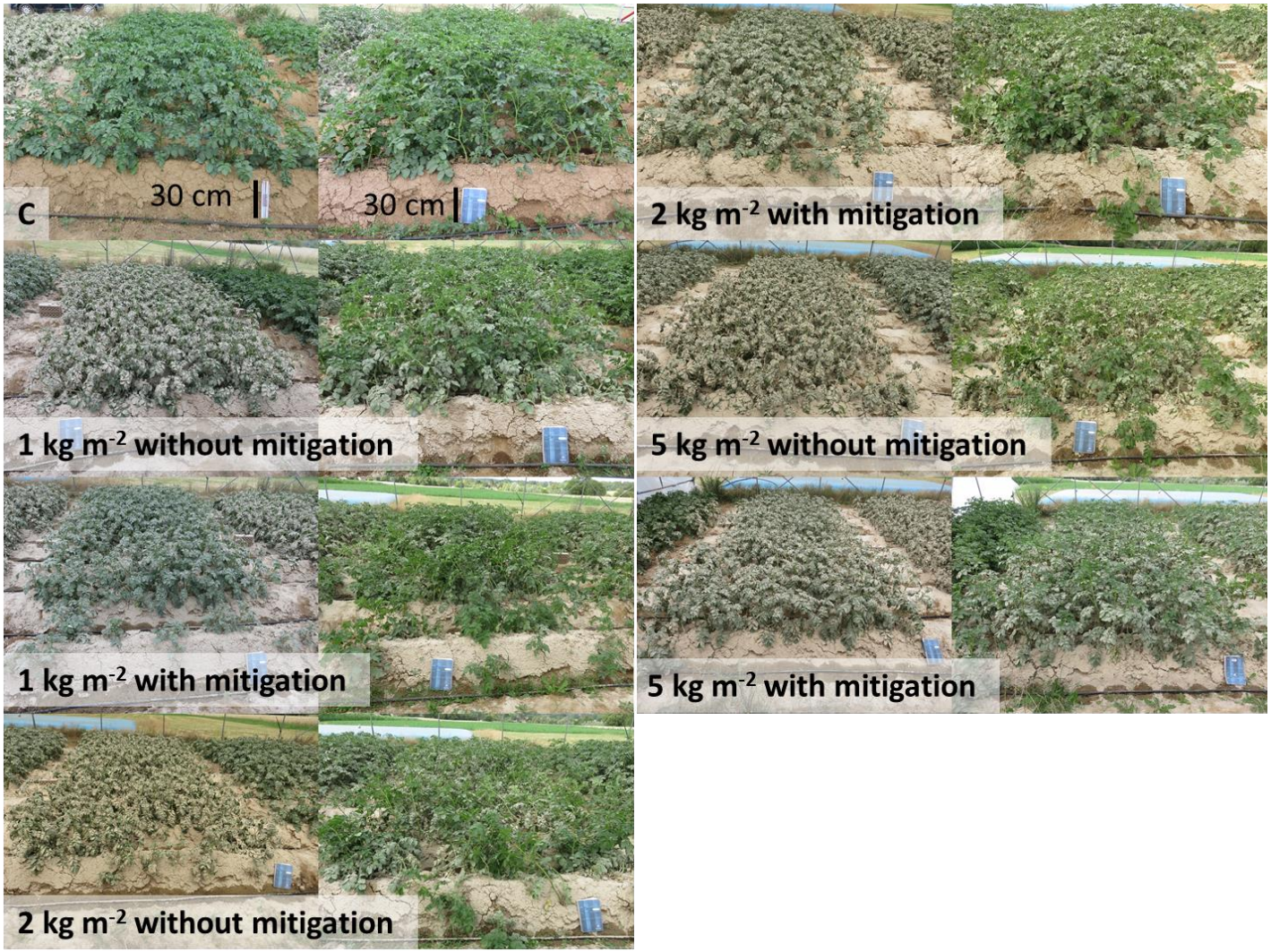

Figure S10: Photos of the potato plants one day (left) and 13 days (right) after treatment with 1, 2 and 5 kg ash m^{-2}, and with or without mitigation. C indicates the control plants. The blue notebook (length of 30 cm) is shown for scale.

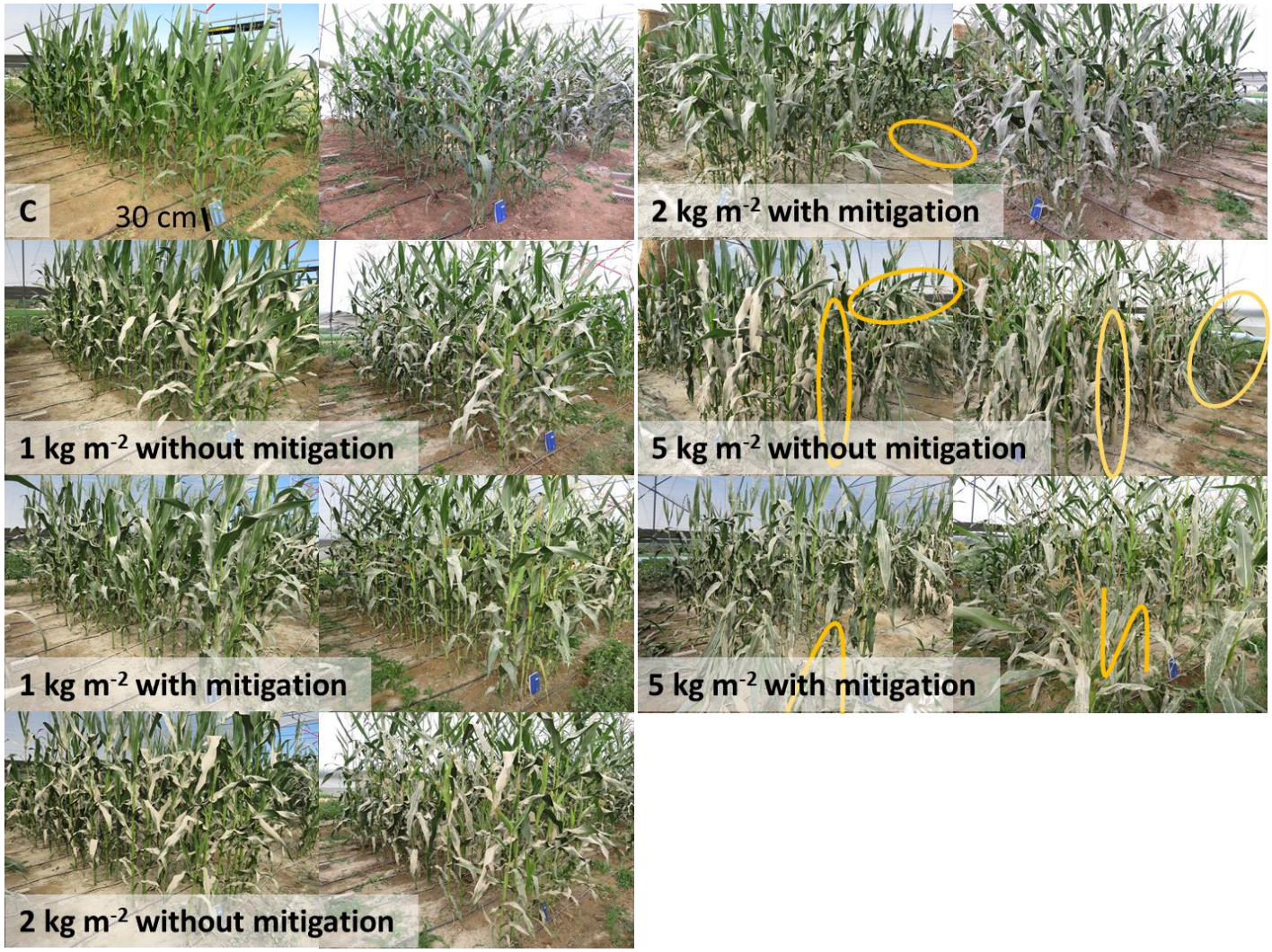

Figure S11: Photos of the corn plants one day (left) and 15 days (right) after treatment with 1, 2 and 5 kg ash m^{-2}, and with or without mitigation. C indicates the control plants. The circles indicate the bend and broken stalks. The blue notebook (length of 30 cm) is shown for scale.

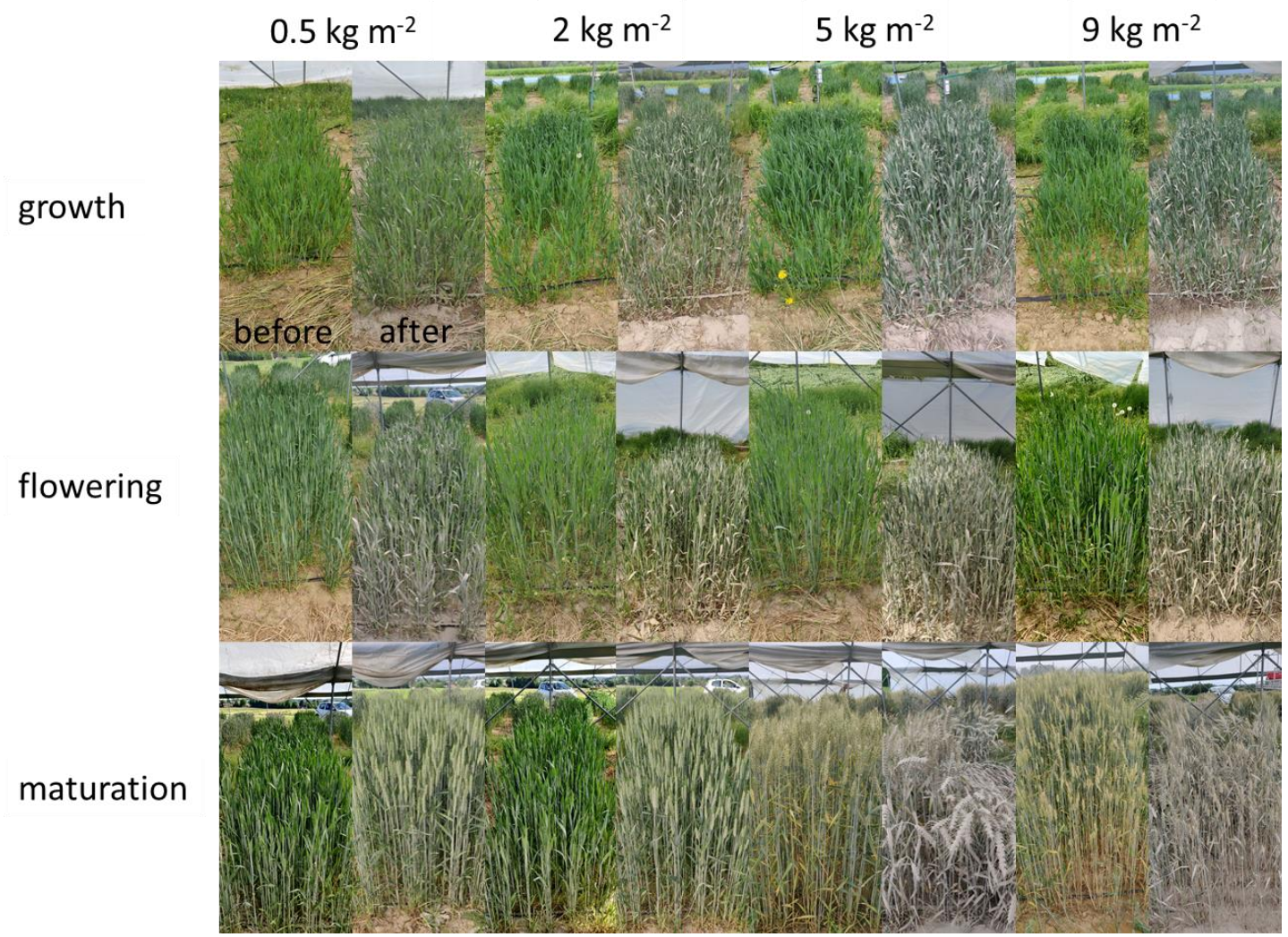

Figure S12: Wheat plants one day before (left) and one day (right) after ash treatment with the four ash mass loads applied to the plants at three growth stages. The width of the subplot is 0.9 m.

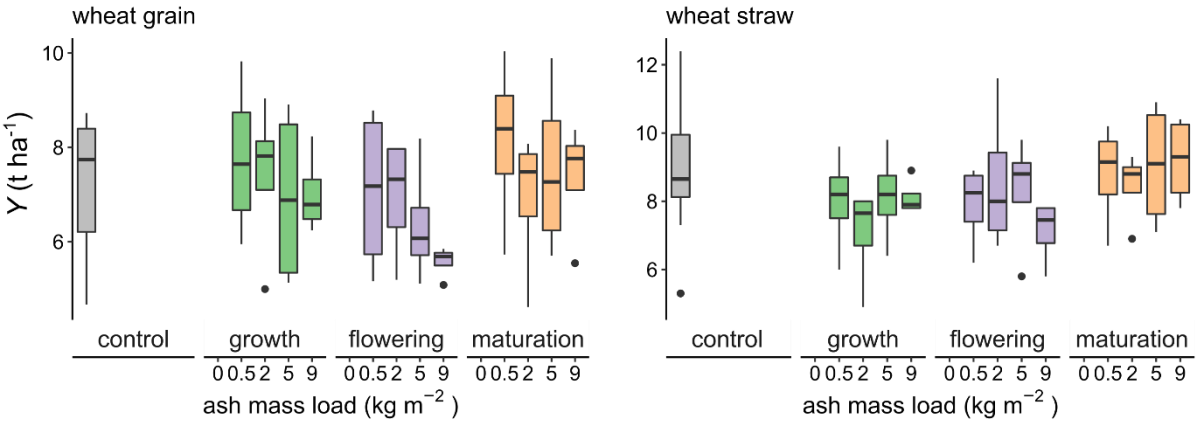

Figure S13: Wheat grain (a) and straw (b) yield (*Y*) values for the control and ash-treated plants. The *Y* values are shown for each of the ash mass loads applied at the "growth", "flowering" and "maturation" stages.

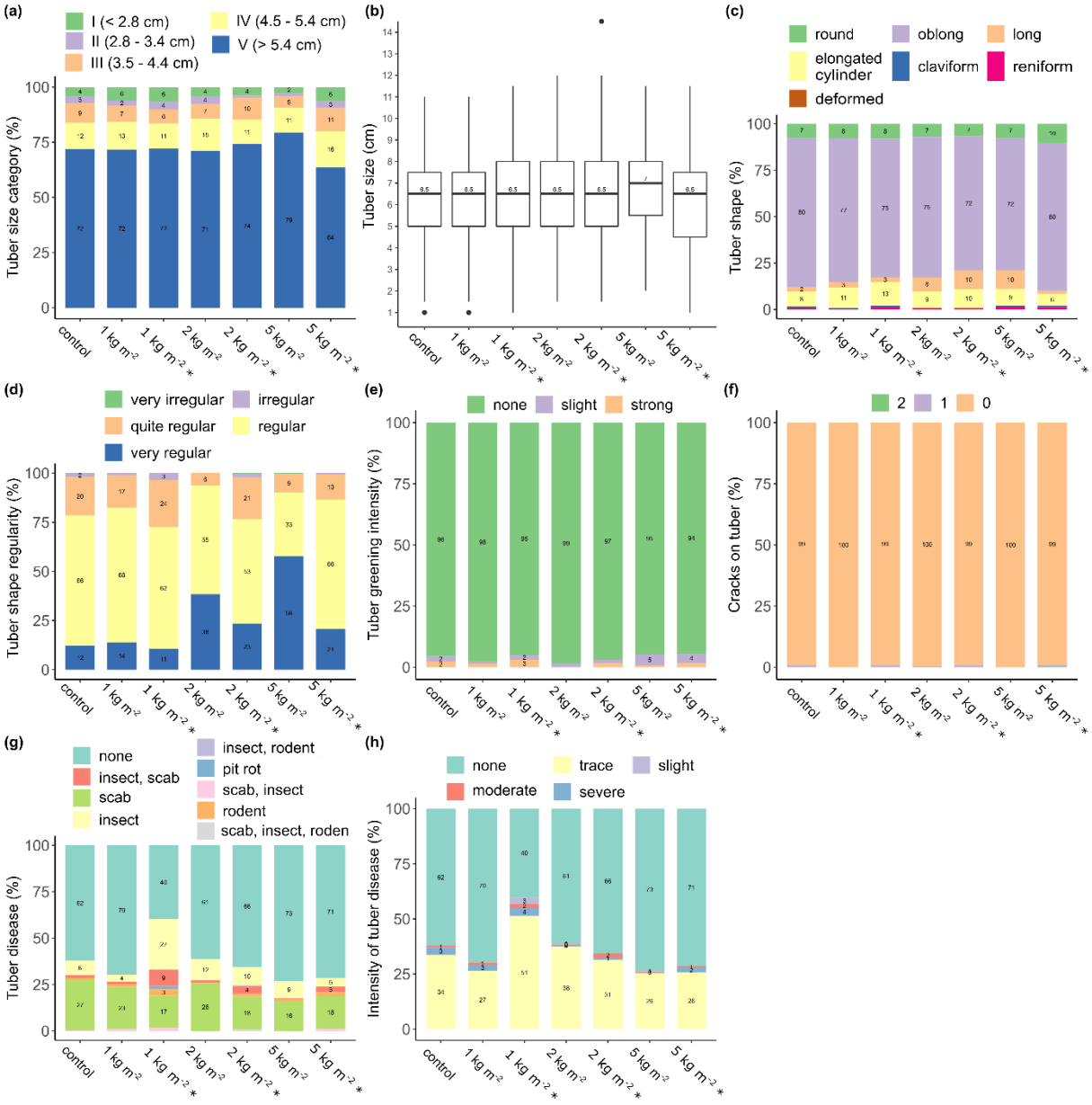

Figure S14: Potato tuber quality of the control and ash-treated plants: tuber size category (a), tuber size (b), tuber shape (c), tuber shape regularity (d), tuber greening intensity (e), number of cracks on tuber (f), tuber disease (g) and tuber disease intensity (h). *: ash treatment with mitigation.

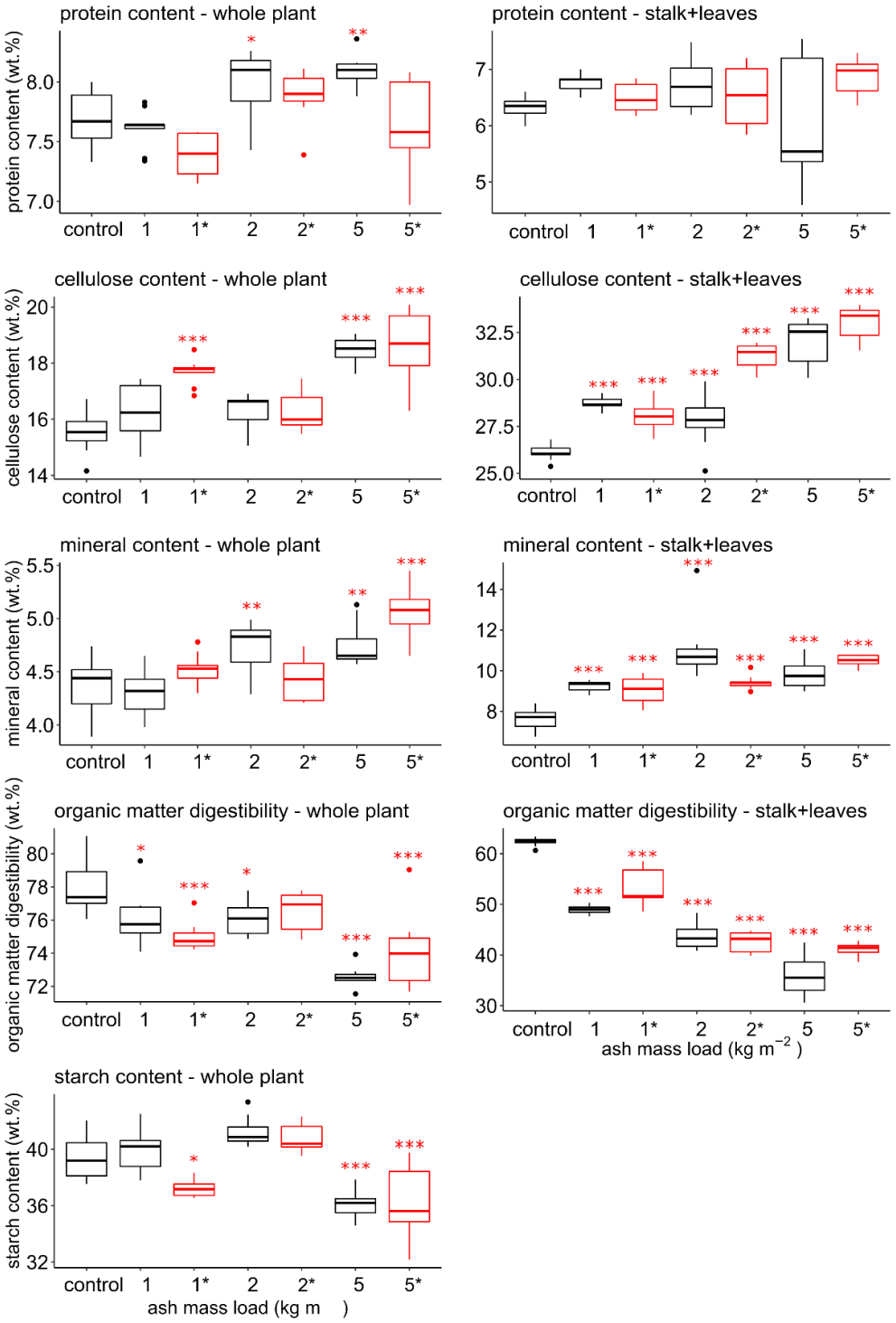

Figure S15: Corn feed analyses for the whole plant (left column) and stalk+leaves (right column) of the control and the ash-treated plants: protein content, cellulose content, mineral content, organic matter digestibility and starch content. *: ash treatment with mitigation. Each boxplot represents nine repetitions. Since we found a significant difference (p-value <0.001) in the quality parameters of the corn feed according to the ash mass load and growth stage, we performed a post-hoc Dunnett's test for comparison to the control group. The Dunnett's test p values for the 95% family-wise confidence level are: (***) 0 <p-value <0.001, (**) 0. 001 <p-value <0.01, (*) 0.01 <p-value <0.05, (.) 0.05 <p-value <0.1. The test result statistics are presented in Table S9.

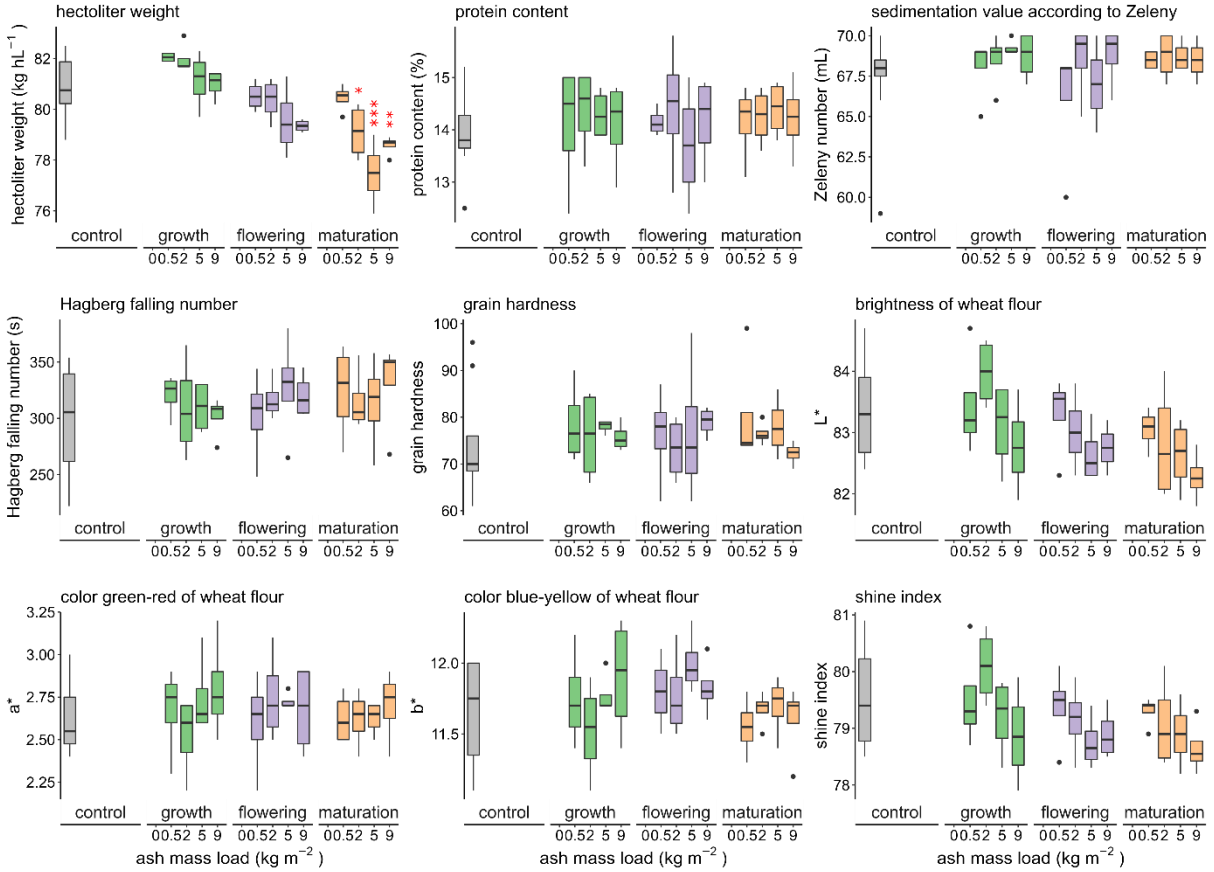

Figure S16: Results of the wheat grain quality analyses for the control and ash-treated plants. Each boxplot represents four repetitions. Since we found a significant difference in average hectolitre weight according to the ash mass load and growth stage (ash mass load: $F(2)=12.63$, p-value <0.001; growth stage: $F(2) = 19.90$, p-value <0.001), we performed a post-hoc Dunnett's test for comparison to the control group. The Dunnett's test p-values for the 95% family-wise confidence level are: (***) 0< p-value <0.001, (**) 0. 001 <p-value <0.01, (*) 0.01 <p-value <0.05, (.) 0.05 <p-value <0.1. The test result statistics are presented in Table S10.

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