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Yield and baking quality of winter wheat cultivars in different farming systems of the DOK long-term trial†

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Abstract

BACKGROUND: A challenge in wheat (*Triticum aestivum* L.) breeding for organic farming is to provide high-yielding cultivars with appropriate baking qualities under the limiting conditions of organic fertiliser input and without the use of pesticides. Cultivars are usually tested on organic and conventional farms. However, field properties may differ owing to spatial variations of soils and microclimate heterogeneity. In this study, old, organically bred and conventionally bred cultivars were tested in organic and conventional farming systems of the DOK long-term system comparison trial.

RESULTS: Effects of cultivars and systems on yield and quality parameters were statistically significant. Genotype × system interactions were generally not observed. Grain yield across all cultivars increased from 4.2 Mg ha^{-1} under organic conditions up to 6.8 Mg ha^{-1} under conventional conditions, with protein contents of 90 and 117 g kg^{-1} respectively. Conventionally bred cultivars yielded significantly more under conventional conditions than organically bred cultivars, whereas neither organically nor conventionally bred cultivars performed better under organic conditions.

CONCLUSION: Breeding for yield was successful, but only under high-input conditions, where these successes were accompanied by rising inputs of external resources. The results of this study suggest that cultivar testing in long-term system comparisons can complement standard on-farm testing.

Keywords: organic farming; plant breeding; winter wheat; yield; baking quality

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a staple food in large parts of the world and was grown on 21.7 × 10^6 ha worldwide in 2007 (www.faostat.fao.org). Many attempts have been made to improve wheat production, with yield increase and resistance to lodging and fungal diseases as the main objectives. As a result, grain yields have risen rapidly, especially during the last 60 years. In industrialised countries, this wheat yield increase has generally been accompanied by an increased input of external resources such as mineral fertilisers and pesticides.[1] In addition to the intensification of agricultural practices, breeding efforts affecting plant morphology traits and yield components have led to higher-yielding cultivars. Guarda *et al*.[2] postulated earliness, reduced plant height, increased harvest index and rising numbers of seeds m^{-2} as the most important changes.

The aim of organic farming is to produce healthy and environmentally friendly food by closing the nutrient cycle as much as possible and avoiding the use of synthetic mineral fertilisers and pesticides. The benefits of organic farming, e.g. lower external input of nutrients, maintenance of soil fertility and enhanced biological activity and biodiversity above and below ground, have been shown in many studies.[3–5]

In Switzerland the organic farming sector is constantly growing; 125 596 ha (12% of total agricultural land area) were organically farmed in 2006, thus making Switzerland one of the ten European countries with the highest percentage of organically farmed land.[6] However, only 3% (2373 ha) of winter wheat (73 910 ha) was grown organically in 2006 (www.agr.bfs.admin.ch). Although winter wheat is the most frequently grown cereal in organic farming in Switzerland, it is still a niche market of limited economic interest for breeding companies. For conventional wheat production, Swiss seed propagation cooperatives provided 17 registered

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cultivars. Despite this, out of the 13 cultivars recommended and propagated for organic wheat production in Switzerland, only six were developed in breeding programmes conducted within organic farming systems. A similar situation is described in the Netherlands, where the limited area of organically farmed land appears to deter breeding companies from establishing special programmes for organic purposes.[7] To be suitable for organic farming, cultivars must be able to tolerate certain unfavourable conditions typically linked with organic farming, such as the low soil nutrient status due to the slow release of organic fertilisers and the pressure from weeds, pests and diseases. Generally, wheat yields are lower under organic conditions than under conventional conditions.[5,8–13] Problems with weeds[14] and diseases and in particular the lower input of nutrients[11,15] are often stated as the main reasons. There is currently a lively debate on the question of how the breeding environment influences the performance of wheat cultivars under organic or low-input growing conditions. A study on wheat breeding for low-input farming compared direct selection conducted under the target conditions *versus* indirect selection conducted under conditions differing from the target environment, showing the former to be more successful.[16] Similar results were obtained in barley selection for low-input conditions.[17] For organic wheat production it was shown that direct selection under organic conditions led to higher yields under organic growing conditions.[11]

Besides yield, baking quality is the most important trait for bread wheat breeding. L-Baeckstrom *et al.*[15] found clear differences in baking quality between organically and conventionally grown wheat, with higher baking quality in the conventional system. In that ten-year study, limited nitrogen (N) in the organic systems caused most of the differences. In a Swiss study, lower values were generally observed for the rheological dough properties of organically grown cultivars compared with cultivars grown under conventional low-input conditions, though the results of the baking tests were similar.[18]

Hence a challenge in breeding for organic farming is the development of cultivars with suitable baking qualities that can also produce high yields under the limiting conditions of organic fertiliser input. Cultivar testing is normally performed on organically and conventionally managed farms. However, field properties at the compared sites may differ greatly owing to spatial variations of soils and microclimate heterogeneity. To our knowledge, comparative studies under homogeneous site conditions within one experimental field plot design are lacking. We tested the performance of old, organically bred and conventionally bred cultivars in organic and conventional farming systems of the DOK long-term system comparison trial. The DOK long-term trial is one of the most rigorously examined comparisons between organic and conventional farming systems in the world.[5,19] Our hypothesis was that cultivars bred under low-input conditions (old and organically bred cultivars) would perform better in the organic low-input systems than conventionally bred cultivars, because the former had been adapted to low-input conditions during the breeding process. This hypothesis is in line with the opinion of Wolfe *et al.*,[20] who recently defined the desired characteristics of wheat cultivars for organic agriculture. We analysed the most important parameters for wheat production during the growing period and after harvest, namely plant density, plant height, yield, yield components and parameters related to baking quality.

MATERIALS AND METHODS

Experimental design

A field experiment with ten winter wheat cultivars grown under organic and conventional management conditions was performed in the DOK trial in 2006–2007. The DOK long-term trial was set up by the Agroscope Reckenholz-Tänikon Research Station (ART) and the Research Institute of Organic Agriculture (FiBL) in 1978 at Therwil (7° 33′ E, 47° 30′ N) in the vicinity of Basel, Switzerland in order to compare two organic (bio-Dynamic and bio-Organic) and two conventional ('Konventionell' with and without manure) farming systems.[5] The soil is a haplic luvisol (sL) (typic Hapludalf) on deep deposits of alluvial loess. The climate is relatively dry and mild with a mean annual precipitation of 785 mm and a mean annual temperature of 9.5 °C. The seven-year crop rotation was the same for all systems. From 1999 to 2006 the following crops were planted: potatoes, winter wheat 1, soybean, maize, winter wheat 2, grass/clover 1 and grass/clover 2. In the conventional system, pesticides were applied only if economic thresholds for pests and diseases were exceeded, according to the integrated scheme of plant protection. In the organic farming systems, pests, weeds and diseases were managed according to biodynamic guidelines. The field experiment was replicated four times.

Ten cultivars were tested in four replicates in two organic systems (BIODYN 1 and BIODYN 2), a conventional system (CONMIN) and an unfertilised control (NOFERT), resulting in a total of 160 plots. These systems differed mainly in terms of fertilisation and plant protection strategies. The organic systems represent mixed farms with arable land and livestock, while CONMIN mimics a conventional system without livestock. The level of fertilisation increased gradually from NOFERT to BIODYN 1 (0.7 livestock units ha^{-1}), BIODYN 2 (1.4 livestock units ha^{-1}) and CONMIN. The experimental design was a split plot with systems as the main factor and wheat cultivars as the secondary factor. Soil samples at 20 cm depth were taken after wheat sowing on 5 December 2006. The main chemical soil characteristics are shown in Table 1.

Over four crop rotations (1978–2005) in the DOK trial the N_{total}, phosphorus (P) and potassium (K) nutrient inputs were much higher in the conventional system than in the organic systems. The mean annual N_{total} input in the organic systems was 81% of that in the CONMIN system. The organic systems received 59 and 66% respectively of the amount of P and K fertilisers applied in the CONMIN system.[19]

Table 1. Soil acidity, soil organic carbon content and soluble mineral elements in soil at beginning of experiment in December 2006 (0–20 cm soil depth, means, $n = 8$)

System	pH (H_2O)	C_{org} (%)	N_{min}[a] (mg kg^{-1})	P[b] (mg kg^{-1})	K[b] (mg kg^{-1})
NOFERT	5.84	1.11	11.02	8.30	27.2
BIODYN 1	6.14	1.22	12.90	8.68	48.3
BIODYN 2	6.40	1.41	16.07	12.99	68.8
CONMIN	6.34	1.23	12.78	24.45	79.7
ANOVA					
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSD (DF = 3)[c]	0.12	0.08	2.71	1.86	5.64

[a] $N_{min} = NO_3\text{-}N + NH_4\text{-}N$.
[b] Measured in double lactic acid extract.
[c] LSD, least significant difference; DF, degrees of freedom.

Table 2. Nitrogen input to winter wheat plots via fertilisers as total and available N in 2006–2007

System/fertiliser	N_{total} (kg ha^{-1})	$N_{available}$[a] (kg ha^{-1})
NOFERT	–	–
BIODYN 1	33	7
Composted manure 5 t ha^{-1}		
Slurry 30 m^3 ha^{-1}		
BIODYN2	66	14
Composted manure 10 t ha^{-1}		
Slurry 60 m^3 ha^{-1}		
CONMIN	140	140
Calcium ammonium nitrate 700 kg ha^{-1}		

[a] $N_{available}$ (NO_3-N + NH_4-N) as contained in fertilisers.

In the 2006–2007 season the BIODYN 1 and BIODYN 2 systems received split applications of 5 and 10 t ha^{-1} composted manure and 30 and 60 m^3 ha^{-1} slurry respectively. The CONMIN system received only mineral fertilisers, split into three applications. This resulted in 33, 66 and 140 kg N_{total} ha^{-1} for the BIODYN 1, BIODYN 2 and CONMIN systems respectively (Table 2).

In the CONMIN system, weeds were controlled by applying 0.2 kg ha^{-1} of the herbicide Husar (Bayer AG, DE-51368 Leverkusen) (50 g kg^{-1} iodosulfuron-methyl-natrium and 150 g kg^{-1} mefenpyr-diethyl) and 0.5 kg ha^{-1} (Rasantan, Bayer AG, DE-51368 Leverkusen) (22.5 g kg^{-1} amidosulfuron, 75 g kg^{-1} diflufenican and 375 g kg^{-1} bromoxynil active ingredients (a.i.)) on 3 March 2007. In addition, the CONMIN system received one application of the plant growth regulator (Moddus, Syngenta Agro AG, CH-8157 Dielsdorf) (263 g kg^{-1} trinexapac-ethyl) at a rate of 0.4 kg ha^{-1} on 10 April 2007. The systemic fungicide Opera (Leu & Gygax AG, CH-5413 Birmenstorf) (133 g kg^{-1} pyraclostrobin and 50 g kg^{-1} epoxiconazol) was applied on 23 May 2007 at a rate of 1.75 L ha^{-1} for disease control.

Old, organically bred and conventionally bred cultivars developed between 1840 and 2006 were sown in the trial, resulting in a total of nine cultivars and one composite cross-population (Table 3). In the composite cross-population (CCP) a large number of cultivars from the UK were intercrossed and propagated as one bulk.[21] In the following text the nine cultivars and the CCP are listed as ten cultivars. All cultivars had to be of bread wheat quality and suitable for the growing conditions prevalent in northwestern Switzerland. The old cultivars (Rouge de Bordeaux, Mont Calme 245 and Probus) were selected and released before 1950 and represent the era prior to intensification in agriculture. The so-called 'organically bred' cultivars (Scaro, Sandomir and CCP) were derived from breeding programmes in organic agriculture (as defined by Wolfe *et al*.[20]), i.e. all breeding steps were carried out on organically managed sites. Moreover, selection and propagation techniques were also compliant with organic principles. The conventionally bred cultivars (Titlis, Caphorn, Antonius and DI 9714) originated from breeding programmes for conventional agriculture. The cultivars Titlis and Antonius are also recommended for organic farming in Switzerland (www.fibl-shop.org). Four Swiss cultivars adapted to the local conditions (Mont Calme 245, Probus, Titlis and Scaro) represent the development in wheat breeding in Switzerland during the last century.

Winter wheat cultivars were sown after maize on 26 October 2006 in ten subplots (3 m × 1 m) on the margins of the 16 DOK plots (5 m × 20 m), thus comprising the four systems described above in all four replicates. BIODYN 1 plots were adjacent to BIODYN 2 plots, and NOFERT plots were adjacent to CONMIN plots. Sowing density was 420 germinating seeds m^{-2}, in accordance with organic farming recommendations. Seed density was the same in all systems and for all cultivars, as recommended for cultivar tests.[22] The seed number was adjusted according to the results of a prior germination test. Germination of the cultivars ranged from 92 to 98%. Row spacing was 16.7 cm. The ten cultivars were randomly arranged in each replicate of the DOK experiment.

Table 3. Winter wheat cultivars planted in DOK long-term experiment, their countries of origin and years of release

Cultivar (abbreviation)	Country of origin[a]	Year of release[b]	Origin/breeder[c]
Old cultivars, landraces			
Rouge de Bordeaux (RB)	FR	1840	INRA, Paris
Mont Calme 245 (MC)	CH	1926	NGB-ACW, Nyon
Probus (PR)	CH	1948	NGB-ACW, Nyon/ART, Zürich
Organically bred cultivars			
Scaro (SC)	CH	2006	Sativa Rheinau AG, Rheinau/Getreidezüchtung Peter Kunz, Hombrechtikon
Sandomir (SA)	DE	NR	Getreidezüchtung Darzau, Karl Josef Müller, Neu Darchau
Composite cross population (CCP)	UK	NR	The Organic Research Centre, Elm Farm, Newbury
Conventionally bred cultivars			
Titlis (standard) (TI)	CH	1996	DSP, Delley/ACW, Nyon
Antonius (AN)	AT	2003	DSP, Delley/Saatzucht Donau GmbH & CoKG, Probstdorf
DI 9714 (DI)	FR	NR	INRA, Paris
Caphorn (CA)	UK	2001	DSP, Delley/Monsanto UK Ltd, Cambridge

[a] FR, France; CH, Switzerland; DE, Germany; UK, United Kingdom; AT, Austria.
[b] NR, not registered.
[c] INRA, Institut National de la Recherche Agronomique; NGB-ACW, National Gene Bank, Agroscope Changins-Wädenswil; ART, Agroscope Reckenholz-Tänikon; DSP, Delley Seeds and Plants.

Initial soil analysis

Two soil samples per subplot were collected after sowing on 5 December 2006 at a depth of 20 cm, using an auger (diameter 3 cm). All ten samples of a strip of five subplots were combined in one mixed sample. We measured soil acidity in a water suspension, mineral nitrogen ($N_{min} = NH_4\text{-N} + NO_3\text{-N}$) photometrically in 0.01 mol L^{-1} $CaCl_2$, soil organic carbon by wet combustion, and phosphorus and potassium in a double lactic acid extract.

Plant height and plant density

Plant heights were measured on ten plants per cultivar per subplot after plant emergence on 13 December 2006, at early heading on 18 April 2007, after ear emergence on 25 May 2007 and at the beginning of ripening on 27 June 2007. Plant density after emergence (18 December 2006), number of tillers m^{-2} (13 April 2007) and number of ears m^{-2} (7 June 2007) were counted in two 0.5 m long rows per subplot.

Yield and harvest parameters

The subplots were harvested on 13 and 14 July 2007. Whole plants were sampled from the centre of each subplot in two 2 m long rows to determine fresh weight of straw and grain. Straw and grain samples were oven dried at 40 °C to constant weight in order to determine dry matter (DM) content and yield, thousand-kernel weight (TKW), hectolitre weight (HLW), number of seeds per ear, weight of seeds per ear and parameters related to baking quality. Harvest index (HI) was calculated as grain yield (DM)/[grain yield (DM) + straw yield (DM)]. Nitrogen harvest index (NHI) was calculated as N uptake grain/(N uptake grain + N uptake straw).

Quality parameters of wheat grain

Quality parameters of wheat grain were measured according to the standard methods of the International Association for Cereal Science and Technology (ICC), Vienna, Austria (www.icc.or.at). The Hagberg falling number (HFN), an indicator of sprouting resistance, was determined according to ICC Standard No. 107/1 in order to estimate α-amylase activity in cereal grains. The Zeleny value (ZV) was analysed according to ICC Standard No. 116/1. Wet total gluten content (G_{tot}) and gluten index (GI) were analysed according to ICC Standard No. 155 using mixed samples of four replicates. Gluten was separated from whole wheat flour by centrifugation. The GI determines the gluten characteristics, indicating whether the gluten is weak or strong.

Grain crude protein content and N concentration in straw

Oven-dried grain and straw samples were coarsely ground (Mikro Feinmühle Culatti, Type DCFH 48, Culatti AG, CH-8005 Zürich) and then finely ground with a swing mill (Retsch MM 200, Retsch GmbH, DE-42781 Haan). N concentration was measured using a CHN analyser (Leco CHN 100, Leco Instrumente GmbH, DE-41199 Mönchengladbach). Grain crude protein (GCP) content was calculated with unrounded N concentration values using the formula GCP = N × 5.7.

Statistical analyses

Analyses of variance (ANOVAs) were performed using the SPSS 13.0 software package (SPSS Inc., Chicago, IL, USA). The main effects (systems and cultivars) and their interactions were tested for significance by two-way ANOVA. Significance between means was determined by least significant difference (LSD) values where $P < 0.05$. The JMP 5.0.1.2 software package (SAS Institute Inc., Cary, NC, USA) was used for performing multiple regressions and correlations. Redundancy analysis (RDA) for yield and yield components as well as for quality parameters was performed using CANOCO 4.5 (Biometris, Plant Research International, Wageningen, The Netherlands).[23] Effects of systems or cultivars were evaluated with the Monte Carlo permutation test. RDA identified the influence of either systems or cultivars on yield or quality parameters.

RESULTS AND DISCUSSION

Plant growth development

Plant growth development, characterised by the parameters plant density after emergence, number of tillers and number of ears, is shown in Fig. 1. Plant height is shown in Table 4. Cultivars and systems showed significant effects on plant density after emergence, number of tillers, number of ears and plant height; significant genotype × system interactions were not detected by two-way ANOVA. The numbers of ears m^{-2} were 21 and 53% greater in the BIODYN 2 and CONMIN systems respectively as compared with NOFERT. According to Guarda *et al.*,[2] the number of ears m^{-2} is one of the most important factors influencing yield.

Plant height in June was strongly reduced relative to the year of release of the cultivars (Table 4). Across all systems, old cultivars grew as tall as 112 cm (cv. Probus) and 126 cm (cv. Rouge de Bordeaux). Conventionally bred cultivars grew only as tall as 70 cm (cv. Caphorn) and 94 cm (cv. Antonius), while organically bred cultivars were ranked in-between. Guarda *et al.*[2] found a similar reduction of plant height in wheat for a series of cultivars released between 1900 and 1994. Plant height in April was positively correlated with grain yield ($r = 0.476$, $P < 0.0001$, $n = 160$). Rapid early growth, also known as early vigour, is important for good plant establishment and yields. The higher N input in the CONMIN system was expected to result in taller plants; however, this did not occur, because plant growth regulators were applied in this system. The conventionally bred cv. Antonius shows that tall plants can also achieve good grain yields under both low- and high-input conditions.

Owing to overall low weed pressure in the DOK trial, the competitiveness of cultivars in terms of high plant height and tillering capacity for weed suppression[24,25] could not be analysed.

Yield and yield components

Grain and straw yields (Table 5), harvest index (HI) and nitrogen harvest index (NHI) (Table 6) were significantly affected by systems and cultivars, whereas no significant genotype × environment interactions were detected by two-way ANOVA. Higher N input rates resulted in higher yields of grain and straw. These results are in agreement with other studies comparing different levels of N fertilisation.[26,27] Accordingly, higher wheat yields were obtained under conventional conditions than under organic conditions.[5,8–11,13,15] Averaged across all cultivars, grain yield was 4.2 Mg ha^{-1} in the organic system BIODYN 2 and 6.8 Mg ha^{-1} in the conventional system CONMIN, which represents an increase of 62%. The average yield in the BIODYN 2 system was in line with the long-term average of wheat yields of the organic systems in the DOK long-term experiment.[9,19] These results were comparable

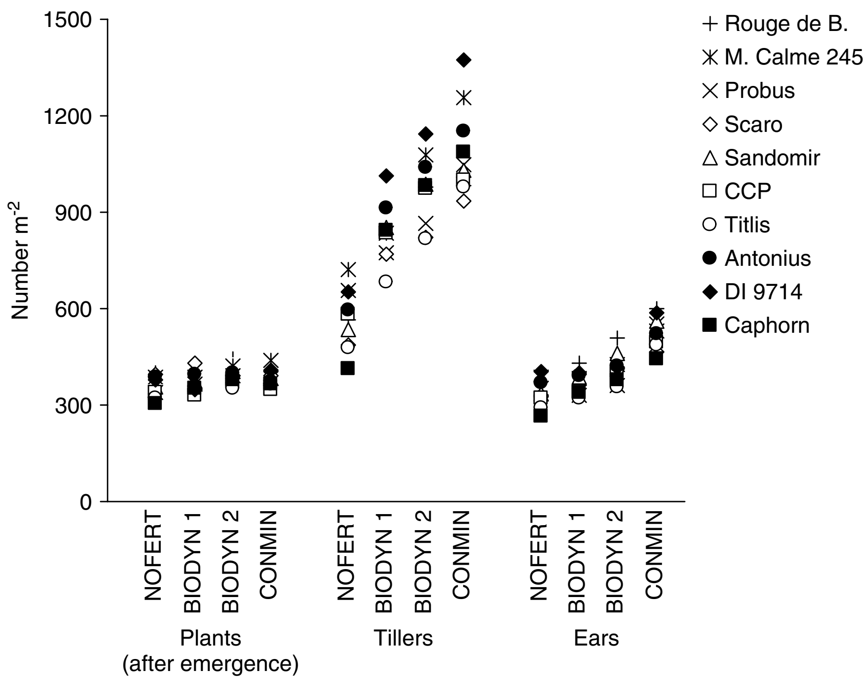

Figure 1. Plant density after emergence, number of tillers and number of ears of ten winter wheat cultivars in four farming systems (means, $n = 4$).

Table 4. Plant heights of ten winter wheat cultivars in four farming systems in June 2007

		Plant height (cm)				
		Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)
Cultivar						
Rouge de B.		126.0	111.0	132.0	130.5	130.4
M. Calme 245		111.2	99.5	113.9	115.9	115.4
Probus		114.1	102.1	116.3	117.8	120.3
Scaro		93.9	84.3	96.9	99.1	95.3
Sandomir		108.8	93.8	112.0	115.5	114.1
CCP		85.3	73.9	84.6	93.0	89.7
Titlis		87.5	74.8	91.2	92.1	91.8
Antonius		94.0	81.6	96.0	100.7	97.9
DI 9714		71.5	62.6	70.1	76.0	77.1
Caphorn		69.6	61.3	71.4	72.0	73.6
		Across all cultivars ($n = 40$)				
System						
NOFERT		84.5				
BIODYN 1		98.4				
BIODYN 2		101.2				
CONMIN		100.6				
ANOVA						
Cultivar	*P* value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	LSD (DF = 9)	4.3	12.5	4.8	9.2	7.2
System	*P* value	<0.0001				
	LSD (DF = 3)	2.7				
Cultivar × system	*P* value (DF = 27)	NS[a]				

[a] NS, not significant.

Table 5. Yield (DM) of grain and straw of ten winter wheat cultivars in four farming systems. Results of one-way and two-way ANOVA and interactions are shown. LSD is provided in case of significant ANOVA ($P < 0.05$)

		Grain yield (DM) (Mg ha^{-1})					Straw yield (DM) (Mg ha^{-1})				
		Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)	Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)
Cultivar											
Rouge de B.		3.8	2.1	3.2	4.0	6.0	7.9	4.4	7.1	9.2	10.7
M. Calme 245		4.4	2.8	3.8	4.4	6.5	7.3	5.1	6.4	7.5	10.3
Probus		3.8	2.6	3.3	3.6	5.9	7.1	4.7	6.3	7.0	10.5
Scaro		4.5	2.9	3.8	4.4	6.7	6.2	4.4	5.2	6.1	9.1
Sandomir		4.1	2.2	3.3	4.1	6.9	6.7	3.8	6.2	7.4	9.3
CCP		4.3	2.4	3.6	4.2	6.8	5.8	3.8	5.3	6.2	7.9
Titlis		4.4	2.6	4.0	4.1	7.0	6.5	3.8	5.7	6.8	9.6
Antonius		4.9	3.5	4.3	4.7	7.3	7.0	4.6	5.8	7.3	10.0
DI 9714		4.3	2.9	3.5	4.0	6.8	5.1	3.6	4.1	5.2	7.5
Caphorn		4.9	2.7	4.4	4.4	8.1	5.1	2.9	4.8	5.3	7.2
		Across all cultivars ($n = 40$)					Across all cultivars ($n = 40$)				
System											
NOFERT		2.7					4.1				
BIODYN 1		3.7					5.7				
BIODYN 2		4.2					6.8				
CONMIN		6.8					9.2				
ANOVA											
Cultivar	*P* value	<0.0001	NS	0.0039	NS	0.0044	<0.0001	NS	0.0002	<0.0001	<0.0001
	LSD (DF = 9)	0.4	–	0.6	–	1.0	0.6	–	1.1	0.1	1.2
System	*P* value	<0.0001					<0.0001				
	LSD (DF = 3)	0.2					0.4				
Cultivar × system	*P* value (DF = 27)	NS					NS				

Table 6. Harvest index and nitrogen harvest index of ten winter wheat cultivars in four farming systems. Results of one-way and two-way ANOVA and interactions are shown. LSD is provided in case of significant ANOVA ($P < 0.05$)

		Harvest index					Nitrogen harvest index				
		Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)	Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)
Cultivar											
Rouge de B.		0.32	0.31	0.31	0.30	0.36	0.78	0.60	0.80	0.84	0.88
M. Calme 245		0.37	0.36	0.37	0.37	0.39	0.84	0.72	0.87	0.87	0.89
Probus		0.35	0.36	0.34	0.34	0.36	0.81	0.70	0.81	0.85	0.87
Scaro		0.42	0.40	0.42	0.42	0.43	0.81	0.69	0.87	0.83	0.86
Sandomir		0.38	0.37	0.35	0.36	0.42	0.83	0.66	0.86	0.88	0.90
CCP		0.41	0.39	0.40	0.40	0.46	0.76	0.62	0.77	0.80	0.85
Titlis		0.41	0.40	0.41	0.38	0.42	0.83	0.67	0.88	0.84	0.91
Antonius		0.42	0.43	0.43	0.39	0.42	0.85	0.78	0.89	0.86	0.89
DI 9714		0.45	0.45	0.46	0.43	0.47	0.74	0.65	0.71	0.77	0.82
Caphorn		0.49	0.48	0.48	0.46	0.53	0.75	0.57	0.81	0.74	0.89
		Across all cultivars ($n = 40$)					Across all cultivars ($n = 40$)				
System											
NOFERT		0.39					0.67				
BIODYN 1		0.40					0.83				
BIODYN 2		0.38					0.83				
CONMIN		0.43					0.88				
ANOVA											
Cultivar	*P* value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	NS	NS
	LSD (DF = 9)	0.02	0.05	0.04	0.05	0.05	0.05	–	0.07	–	–
System	*P* value	<0.0001					<0.0001				
	LSD (DF = 3)	0.01					0.03				
Cultivar × system	*P* value (DF = 27)	NS					NS				

Table 7. Thousand-kernel weight and hectolitre weight of ten winter wheat cultivars in four farming systems. Results of one-way and two-way ANOVA and interactions are shown. LSD is provided in case of significant ANOVA ($P < 0.05$)

		Thousand-kernel weight (g)					Hectolitre weight (kg hL^{-1})				
		Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)	Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)
Cultivar											
Rouge de B.		47.9	37.8	50.1	51.7	51.8	76.5	68.8	78.4	78.8	79.9
M. Calme 245		42.5	34.4	42.7	44.3	48.5	74.6	70.1	75.3	75.3	77.6
Probus		39.5	32.8	40.4	41.4	43.2	76.8	73.1	77.4	77.8	78.6
Scaro		40.2	31.5	40.7	42.8	46.0	77.9	73.9	78.4	78.8	80.7
Sandomir		37.0	29.0	36.7	39.3	42.8	76.7	72.3	76.3	77.2	81.1
CCP		38.0	28.9	39.4	40.1	43.3	71.5	65.1	71.8	72.4	76.5
Titlis		40.6	31.2	41.6	43.3	46.2	75.5	70.5	76.0	75.8	79.5
Antonius		41.6	37.0	41.4	42.7	45.2	77.5	75.8	76.8	77.3	80.3
DI 9714		41.5	32.0	43.9	43.8	46.3	71.9	66.3	72.1	72.6	76.7
Caphorn		36.0	26.2	37.9	37.2	42.7	69.2	60.7	70.7	69.3	76.0
		Across all cultivars ($n = 40$)					Across all cultivars ($n = 40$)				
System											
NOFERT		32.1					69.7				
BIODYN 1		41.5					75.3				
BIODYN 2		42.7					75.5				
CONMIN		45.6					78.7				
ANOVA											
Cultivar	*P* value	<0.0001	NS	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	<0.0001	<0.0001
	LSD (DF = 9)	2.0	–	2.2	2.5	2.5	2.3	–	1.3	2.6	1.4
System	*P* value	<0.0001					<0.0001				
	LSD (DF = 3)	1.3					1.5				
Cultivar × system	*P* value (DF = 27)	NS					NS				

Table 8. Seeds per ear and seeds m^{-2} of ten winter wheat cultivars in four farming systems. Results of one-way and two-way ANOVA and interactions are shown. LSD is provided in case of significant ANOVA ($P < 0.05$)

		Weight of seeds per ear (g)					Number of seeds (m^{-2})				
		Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)	Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)
Cultivar											
Rouge de B.		1.0	0.9	0.9	1.0	1.2	9404	8656	6128	9347	13 485
M. Calme 245		1.3	1.1	1.3	1.3	1.5	12 840	11 917	11 113	12 308	16 023
Probus		1.3	1.1	1.3	1.2	1.5	12 555	11 511	10 293	10 844	17 572
Scaro		1.4	1.2	1.4	1.5	1.6	13 641	12 376	13 045	13 577	15 567
Sandomir		1.1	0.9	1.2	1.1	1.3	12 244	11 105	12 604	12 786	12 481
CCP		1.3	1.0	1.3	1.3	1.7	13 654	11 533	11 645	12 937	18 502
Titlis		1.5	1.2	1.5	1.6	1.7	13 510	11 121	11 863	13 153	17 903
Antonius		1.6	1.5	1.6	1.5	1.7	15 832	14 320	14 520	14 593	19 896
DI 9714		1.4	1.0	1.3	1.3	1.8	14 659	12 826	12 208	12 154	21 448
Caphorn		1.5	1.0	1.6	1.5	2.0	15 448	12 222	14 144	14 397	21 029
		Across all cultivars ($n = 40$)					Across all cultivars ($n = 40$)				
System											
NOFERT		1.1					11 759				
BIODYN 1		1.3					11 756				
BIODYN 2		1.3					12 610				
CONMIN		1.6					17 391				
ANOVA											
Cultivar	*P* value	<0.0001	0.0026	0.0005	<0.0001	<0.0001	<0.0001	NS	0.0020	NS	0.0203
	LSD (DF = 9)	0.1	0.2	0.3	0.2	0.2	2050	–	3421	–	5324
System	*P* value	<0.0001					<0.0001				
	LSD (DF = 3)	0.1					1296				
Cultivar × system	*P* value (DF = 27)	NS					NS				

Table 9. Multiple regression model explaining influence of parameters on grain yield across all farming systems and all winter wheat cultivars[a]

	Grain yield model ($n = 160$)		
Parameter	Parameter estimate	*P* value	Cumulative r^2
Intercept	−5.469	<0.0001	
Seeds per ear, harvest (g)	2.015	<0.0001	0.4963
Number of ears, June 2007 (m^{-2})	0.009	<0.0001	0.7639
Plant density, December 2006 (m^{-2})	−0.006	<0.0001	0.7962
Plant height, April 2007 (cm)	0.070	<0.0001	0.8165
Plant height, May 2007 (cm)	−0.039	<0.0001	0.8324
Hectolitre weight, harvest (kg hL^{-1})	0.060	0.0003	0.8455
Ear size, June 2007 (cm)	0.192	0.0106	0.8520

[a] The following parameters were included in the regression model: number of plants in December, number of tillers, tillers per plant, number of ears, ears per plant, plant height in December, plant height in April, plant height in May, ear size in May, plant height in June, ear size in June, seeds per ear, number of seeds per ear, number of seeds m^{-2}, thousand-kernel weight and hectolitre weight. Seeds per ear and number of ears m^{-2} accounted for 76% of the yield variation in the experiment.

to the average wheat yield of 4.0 Mg ha^{-1} under organic farming conditions in Switzerland in 2005.[28] Conventional grain yields were much higher compared with previous results in the DOK trial (6.8 *vs* 4.8 Mg ha^{-1}),[19] reflecting the increase in N applications to CONMIN from approximately 75 to 140 kg ha^{-1}. The higher yields in CONMIN are also due to chemical plant protection. We observed an increasing trend in yields as a function of the year of release of the cultivars. The conventionally bred cv. Antonius produced the highest yield across all systems (4.9 Mg ha^{-1}), which was 29% greater than the overall yield of the oldest cv. Rouge de Bordeaux (3.8 Mg ha^{-1}). A linear regression analysis of yield development by year of release of the cultivars revealed a greater increase in grain yield under conventional conditions (7.4 kg ha^{-1} $year^{-1}$ in CONMIN) than under organic conditions (1.7 kg ha^{-1} $year^{-1}$ in BIODYN 2). In contrast to other studies on wheat[11,16] and barley,[17] our results did not show that cultivars bred under low-input conditions (old and organically bred cultivars) yielded higher under low-input conditions. A different situation was found for conventional conditions, where conventionally bred cultivars yielded higher compared with old and organically bred cultivars. The deep loess soil at the DOK experiment site, which is characterised by high inherent soil fertility, good water retention and low weed pressure, could account for these contradictory results.

Yield potential progress in wheat has been associated with increased HI,[29] a trend also demonstrated in our data. Reduction in plant height, and therefore lower straw yields, accompanied by higher grain yields led to rising HIs of modern cultivars (Table 6). This is in line with many other studies.[2,30,31] The HIs of organically bred cultivars (0.38–0.42) were in the range between those of the oldest cv. Rouge de Bordeaux (0.32) and the conventionally bred cv. Caphorn (0.49). Guarda *et al.*[2] demonstrated that old wheat cultivars achieved the highest HIs under low-input conditions and that modern cultivars reached their maximum HIs at high N input levels. This trend, however, was not confirmed by our data.

NHI did not vary greatly between cultivars, indicating that the age of the cultivar had no significant influence on the NHI (Table 6). The lowest values were obtained for the conventionally bred cvs DI 9714 (0.74) and Caphorn (0.75). This can be explained by the low N concentration in the grain of these modern cultivars, which balances the higher grain yields.

Systems and cultivars had a significant effect on thousand-kernel weight (TKW), hectolitre weight (HLW) (Table 7), weight of seeds per ear and number of seeds m^{-2} (Table 8). Significant interactions were not detected by two-way ANOVA. TKW increased with nutrient input to the system. There is no general agreement in the literature regarding the influence of N input on TKW. In contrast to our findings, Schwaerzel *et al.*[13] found no differences between TKWs of organically and conventionally grown wheat. Guarda *et al.*[2] even reported lower values in systems with higher N input. Results in the literature are also contradictory for changes in TKW in comparisons of old *versus* modern wheat cultivars. In our study, TKW was generally higher for old cultivars. Across all systems the highest values for TKW were measured in the oldest cv. Rouge de Bordeaux (48 g); the lowest values were measured in the conventionally bred cv. Caphorn (36 g). This is in line with the findings of one other study.[2] Other authors reported higher TKWs for modern cultivars than for old cultivars.[31,32]

HLW increased from NOFERT to CONMIN. Averaged across all cultivars, HLW was 75.5 kg hL^{-1} in the BIODYN 2 organic system, significantly lower than in the CONMIN conventional system (78.7 kg hL^{-1}). This is consistent with the findings of Mason and Spaner.[14] In contrast, Schwaerzel *et al.*[13] did not observe differences in HLW between organically and conventionally grown wheat. Differences in HLW between cultivars were generally low. Weight of seeds per ear and number of seeds m^{-2} rose from NOFERT to CONMIN (Table 8). Within the systems, weight of seeds per ear increased from old to modern cultivars by about 20% in the organic systems but by 47% in the conventional system. Numbers of seeds m^{-2} were similar in the NOFERT and BIODYN 1 systems but increased by 7 and 47% in the BIODYN 2 and CONMIN systems respectively.

The results for yields and yield components showed a trend similar to that found in other studies comparing old and modern cultivars. The increase in grain yield was associated with increases in HI, number of grains m^{-2} and weight of seeds per ear. In a multiple regression analysis with yield as the target variable, weight of seeds per ear and number of ears m^{-2} had the strongest impact on yield. Together they accounted for 76% of the total variation in yield (Table 9). For durum wheat it has been demonstrated that yield differences are due primarily to the number of seeds m^{-2} and secondarily to the weight of the seeds.[33]

Quality parameters

Baking quality is highly dependent on protein quantity and also protein quality. Grain crude protein (GCP) content, Zeleny value (ZV), total gluten content (G_{tot}), gluten index (GI) and Hagberg falling number (HFN) are the parameters generally used to predict final behaviour during the baking process.

GCP content was 108, 94, 90 and 117 g kg^{-1} in the NOFERT, BIODYN 1, BIODYN 2 and CONMIN systems respectively (Table 10). Contents were relatively low compared with previous findings in the DOK trial (between 128 and 145 g kg^{-1} in BIODYN 2 and between 131 and 145 g kg^{-1} in CONMIN).[9] Wheat samples from the 2003 DOK trial contained between 130 (BIODYN 2) and

Table 10. Grain crude protein content of ten winter wheat cultivars in four farming systems. Results of one-way and two-way ANOVA and interactions are shown. LSD is provided in case of significant ANOVA ($P < 0.05$)

		Grain crude protein content (g kg^{-1})				
		Across all systems ($n = 16$)	NOFERT ($n = 4$)	BIODYN 1 ($n = 4$)	BIODYN 2 ($n = 4$)	CONMIN ($n = 4$)
Cultivar						
Rouge de B.		108.5	113.1	103.1	100.5	117.1
M. Calme 245		103.6	110.4	96.7	90.5	116.9
Probus		113.8	107.7	104.5	103.2	140.0
Scaro		101.1	106.0	92.8	92.7	112.9
Sandomir		101.6	109.9	96.3	80.8	119.5
CCP		98.4	104.3	88.7	90.3	110.5
Titlis		103.4	111.5	91.9	90.1	120.2
Antonius		103.4	107.8	93.1	92.3	120.6
DI 9714		95.8	99.6	85.4	88.8	109.3
Caphorn		92.9	107.8	88.4	73.3	102.1
		Across all cultivars ($n = 40$)				
System						
NOFERT		107.8				
BIODYN 1		94.1				
BIODYN 2		90.2				
CONMIN		116.9				
ANOVA						
Cultivar	*P* value	<0.0001	NS	<0.0001	0.0326	<0.0001
	LSD (DF = 9)	0.6	–	0.7	1.6	1.2
System	*P* value	<0.0001				
	LSD (DF = 3)	0.4				
Cultivar × system	*P* value (DF = 27)	NS				

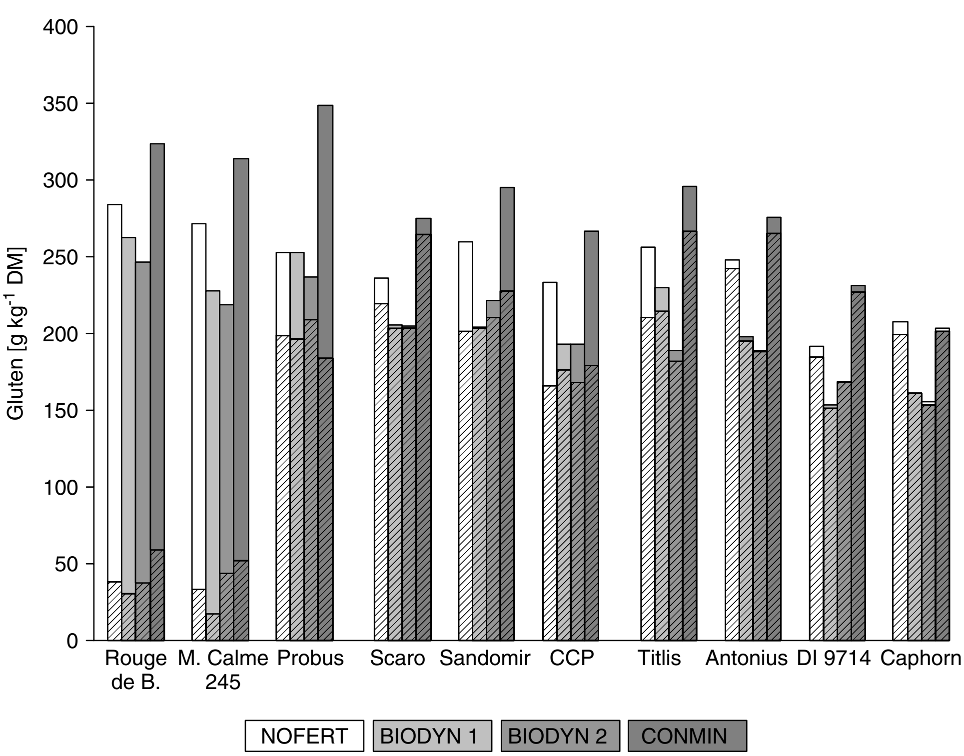

Figure 2. Total gluten content, divided into strong (hatched) and weak (not hatched) gluten, of ten winter wheat cultivars in four farming systems (means, $n = 4$).

160 (CONMIN) g kg^{-1} protein.[34] Grain protein increased with N input from BIODYN 1 to BIODYN 2 and CONMIN, which is in line with other studies.[2,27] In NOFERT, GCP content was unexpectedly high owing to low grain yields connected with small grain size. While GCP content was higher in the conventional systems than in the organic systems in our study, similar to the findings of L-Baeckstrom *et al.*,[15] other authors report no differences in protein content between farming systems.[10,12] In the study of Ryan *et al.*,[12] however, wheat was planted following N-fixing legumes, resulting in generally higher N supply, whereas wheat followed maize at the end of the crop rotation in our study. The old cultivars achieved the highest protein contents across all systems, and the differences were significant. Protein dropped from 114 (cv. Probus) to 93 (cv. Caphorn) g kg^{-1} relative to the year of release of the cultivars, which is in close agreement with previous findings.[2,30,35,36] In BIODYN 2 (73 g kg^{-1}) and CONMIN (102 g kg^{-1}) the lowest GCP content was measured for cv. Caphorn. In BIODYN 2 (103 g kg^{-1}) and CONMIN (140 g kg^{-1}) the highest GCP content was measured for cv. Probus.

ZVs were higher in modern cultivars than in old cultivars (Table 11). The lowest values across all systems were measured for the oldest cvs Rouge de Bordeaux (25.5 mL) and Mont Calme 245 (19.6 mL) and for CCP (37.6 mL). The other cultivars did not differ significantly, achieving values between 55.8 mL (cv. Antonius) and 60.5 mL (cv. Scaro). The high values in the modern cultivars indicate that lower GCP contents were compensated by a quality improvement in protein composition, as also postulated by Guarda *et al.*[2]

Parallel to the results for GCP contents, there was a decrease in G_{tot} contents with respect to the year of release of the cultivars, with the highest value (35%) obtained for cv. Probus in the CONMIN system and the lowest value (16%) obtained for cv. Caphorn in the BIODYN 2 system. The quality of gluten expressed as GI is a parameter well suited to predict baking quality of wheat. The development of total gluten (quantity) and the quality of gluten (GI) can be used to trace breeding efforts. Breeding efforts had strong effects on the composition of gluten in wheat (Fig. 2). While modern cultivars had the lowest G_{tot} contents, GIs were highest for conventionally bred cultivars. As a result, almost 100% of the total gluten was strong gluten for conventionally bred cvs Antonius, DI 9714 and Caphorn. Averaged across all systems, the organically bred cultivars still had between 8 (cv. Scaro) and 50 (CCP) g kg^{-1} DM of weak gluten, i.e. 3.4 and 22.2% of total gluten respectively. A study on Italian durum wheat revealed a similar trend among cultivars of different breeding eras.[37] Increasing GIs were measured in modern durum wheat cultivars, which is postulated as an improvement in quality compared with old cultivars.

It turned out that the systems showed similar patterns for GCP content, ZV and G_{tot} content: high values were achieved in the NOFERT control and in the CONMIN system, while low values were achieved in the BIODYN 1 and BIODYN 2 organic systems. Nitrogen accumulated in NOFERT owing to low grain numbers and weights and in CONMIN owing to the input of mineral N fertilisers. In Table 12 the correlation matrix for grain yield and quality

Table 11. Baking quality parameters (Zeleny value (ZV), total gluten (G_{tot}), gluten index (GI) and Hagberg falling number (HFN)) of ten winter wheat cultivars in four farming systems. Results of two-way ANOVA and interactions are shown. LSD is provided in case of significant ANOVA ($P < 0.05$)

		ZV (mL)	G_{tot}[a] (g kg^{-1} DM)	GI[a]	HFN (s)
Cultivar (n = 16)					
Rouge de B.		26	279	15	291
M. Calme 245		20	258	14	326
Probus		60	273	74	311
Scaro		61	230	97	362
Sandomir		57	245	87	359
CCP		38	222	79	203
Titlis		59	243	91	375
Antonius		56	228	98	308
DI 9714		57	186	98	347
Caphorn		56	182	98	264
System (n = 40)					
NOFERT		50	244	72	296
BIODYN 1		45	209	78	316
BIODYN 2		43	202	80	326
CONMIN		57	283	71	320
ANOVA					
Cultivar	*P* value	<0.0001			<0.0001
	LSD (DF = 9)	3			19
System	*P* value	<0.0001			<0.0001
	LSD (DF = 3)	2			12
Cultivar × system	*P* value (DF = 27)	0.0013			<0.0001

[a] For G_{tot} and GI ($n = 40$, mixed samples of four replicates), ANOVA could not be performed.

Table 12. Correlation matrix (*r* values) of grain yield (GY), hectolitre weight (HLW), Zeleny value (ZV), Hagberg falling number (HFN), total gluten content (G_{tot}), gluten index (GI) and grain crude protein (GCP) content ($n = 40$)[a]

	GY (DM)	HLW	ZV	HFN	G_{tot}	GI	GCP
GY (DM)	1.0	−0.12	0.29*	−0.16	−0.61***	0.50***	−0.33**
HLW	−0.02	1.0	0.10	0.47***	0.47***	−0.003	0.28*
ZV	−0.04	0.01	1.0	0.36**	−0.36**	0.86***	0.12
HFN	−0.02	0.49**	0.28	1.0	0.30*	0.13	0.32**
G_{tot}	−0.21	0.71***	−0.32	0.24	1.0	−0.70***	0.68***
GI	0.03	−0.25	0.85***	−0.02	−0.53***	1.0	−0.26*
GCP	−0.16	0.28*	−0.09	0.26	0.45***	−0.27	1.0

[a] Correlations above the diagonal represent values of the CONMIN conventional system, while correlations below the diagonal represent values of the BIODYN 2 organic system; *r* values significant at * $P < 0.05$, ** $P < 0.01$ or *** $P < 0.001$.

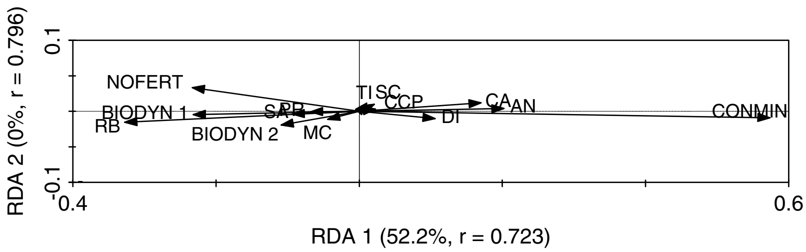

Figure 3. Constrained ordination of first two canonical axes as determined by RDA of yield and yield components (plant density after emergence m^{-2}, number of tillers m^{-2}, number of ears m^{-2}, plant height (December, May, June), ear length (May, June), weight of seeds per ear, number of seeds m^{-2}, thousand-kernel weight, yield of grain and straw, dry matter content of grain and straw) of ten winter wheat cultivars in four farming systems. Vector directions indicate maximum variation due to corresponding factor; vector lengths indicate strength of correlation. Cultivar types and abbreviations are given in Table 3.

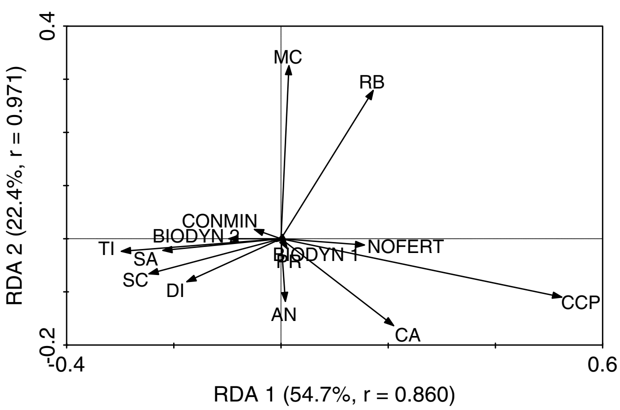

Figure 4. Constrained ordination of first two canonical axes as determined by RDA of quality parameters (grain protein content, Zeleny value, Hagberg falling number, gluten content total, gluten index) of ten winter wheat cultivars in four farming systems. Vector directions indicate maximum variation due to corresponding factor; vector lengths indicate strength of correlation. Cultivar types and abbreviations are given in Table 3.

parameters is presented for the systems BIODYN 2 and CONMIN. GCP was positively correlated with the quantitative parameter G_{tot} under conventional conditions ($r = 0.68$, $P < 0.0001$) as well as under organic conditions ($r = 0.45$, $P < 0.0001$). However, there was no positive correlation between GCP content and ZV or GI, which are parameters that evaluate the quality of protein. Because GCP content influences other baking quality parameters such as ZV, gluten quantity and gluten quality, attention is often paid to the (frequently negative) correlation between grain yield and GCP content. In our study as well as in other studies,[16,38,39] grain yield was weakly but negatively correlated with protein content. Correlation was significant in the conventional system. In contrast to our findings, where correlation was slightly stronger under conventional conditions, Brancourt-Hulmel *et al*.[16] found that correlation was stronger at low nutrient levels.

Redundancy analysis

A redundancy analysis was conducted to summarise yield and yield components (Fig. 3) as well as quality parameters (Fig. 4). The influence of systems (34%) and cultivars (19%) explained 52% of the variability of the model for yield and yield components. Yield was mainly determined by the nutrient gradient within the systems, as indicated by the horizontal distribution of the four systems and the ten cultivars. CONMIN, a system in which 140 kg N ha^{-1} $year^{-1}$ is applied to wheat, had the strongest impact (33%), whereas the low-input systems had only a minor influence (NOFERT, 6%; BIODYN 1, 5%; BIODYN 2, 1%). The ordination of the cultivars indicated an affinity of the conventionally bred cvs Caphorn, Antonius and DI 9714 and the conventional system CONMIN and of the oldest cv. Rouge de Bordeaux and the low-input systems NOFERT and BIODYN 1. The cvs Mont Calme 245 (1926) and Probus (1948) and the organically bred cv. Sandomir were grouped next to the organic system BIODYN 2. The organically bred cv. Scaro, the CCP and the conventionally bred cv. Titlis did not show a clear affinity for any one of the systems.

The influence of systems and cultivars explained 79% of the variability in the quality model. In contrast to the situation for yield, cultivar characteristics had a major influence (75%) on quality, whereas only 4% of the variability could be attributed to the systems and therefore to the nutrient input. Systems are grouped closely in the centre of the graph, underscoring their minor influence. Only the NOFERT unfertilised control had a slightly higher impact (6%). The two oldest cvs Rouge de Bordeaux and Mont Calme 245 grouped separately, but there was no further grouping of the cultivars by breeding background.

CONCLUSIONS

We tested the hypothesis that cultivars bred under low-input conditions (old and organically bred cultivars) would outperform conventionally bred cultivars in the organic low-input systems, as the former were adapted to low-input conditions during the breeding process. Generally, we observed significant effects of cultivars and systems on all tested parameters. However, the expected genotype × system interactions did not appear. While conventionally bred cultivars produced the highest yields under conventional conditions, organically bred cultivars did not produce the highest yields under organic conditions. The hypothesis can therefore not be corroborated. Under conventional farming conditions, yields strongly increased relative to the year of release of the cultivars, whereas the same set of cultivars showed only a minor increase under organic farming conditions. Under low-input and nutrient-limited organic conditions, modern cultivars could not perform to the full extent of their genetic potential, irrespective of whether the breeding took place under conventional or organic farming conditions. The results imply that breeding for yield during the last century was successful, but only under high-input conditions, wherein the development was accompanied by increasing inputs of external resources such as mineral fertilisers and fungicides. One of the goals of organic farming is the maintenance of a resilient system in the soil in order to produce healthy products without exploiting natural resources. Besides concerns for environmental protection, product safety and quality, organic agriculture must strive to increase yields and quality in order to meet the challenge of supplying food. Moreover, increasing yields would improve the economic situation for organic farmers. The sharp differentiation of the two factors (cultivars and systems) shows that the applied methodological approach, namely the testing of cultivars within a long-term, replicated system comparison in which system-immanent effects of separate cultivar trials such as soil heterogeneity and microclimate are excluded, can provide reliable results. Such trials can therefore complement on-farm testing performed on larger plots, in which the resistance of cultivars to pests and diseases may be observed more adequately.

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