

Wheat quality in organic and conventional farming: results of a 21 year field experiment

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Abstract: Consumers have become more aware of healthy and safe food produced with low environmental impact. Organic agriculture is of particular interest in this respect, as manifested by 5.768 million hectares managed pursuant to Council Regulation (EEC) 2092/91 in Europe. However, there can be a considerable risk that the avoidance of chemical inputs in organic farming will result in poor food quality. Here the results of a study on the quality of wheat (*Triticum aestivum* L.) grown in a 21 year agrosystem comparison between organic and conventional farming in central Europe are reported. Wheat was grown in a ley (grass/clover) rotation. The 71% lower addition of plant-available nitrogen and the reduced input of other means of production to the organic field plots led to 14% lower wheat yields. However, nutritional value (protein content, amino acid composition and mineral and trace element contents) and baking quality were not affected by the farming systems. Despite exclusion of fungicides from the organic production systems, the quantities of mycotoxins detected in wheat grains were low in all systems and did not differ. In food preference tests, as an integrative method, rats significantly preferred organically over conventionally produced wheat. The findings indicate that high wheat quality in organic farming is achievable by lower inputs, thereby safeguarding natural resources.

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Keywords: wheat quality; organic farming; conventional farming; wheat constituents; mycotoxins; food preference tests

INTRODUCTION

Organic agriculture is of particular interest with regard to healthy, ecologically friendly produced food, because inputs of chemicals such as synthetic fertilisers and pesticides are not allowed.¹ According to a survey in Europe (EU25), 5.768 million hectares were certified organic land corresponding to Council Regulation (EEC) 2092/91 at the end of 2004,^{2,3} of which 2.224 million hectares were arable land. For 15 countries with a total of 1.612 million hectares of arable land, wheat statistics were available. In these countries, 290 346 hectares were planted with wheat, thus representing an average share of 18% of the total organic arable land. These data show that wheat is an important crop in organic farming. The quality factors for wheat considered in this study

are, firstly, nutritional value as determined by quality-enhancing constituents found in grains, e.g. macro and micro (trace) elements, protein and amino acids, and quality-impairing substances, e.g. mycotoxins. The second set of quality factors represents utility value as reflected in milling and baking properties, which are highly dependent on protein and starch contents. The avoidance of chemical nitrogen fertilisers in organic farming could result in a lower protein content of wheat grains. Furthermore, no fungicidal sprays are used in organic agriculture. It is important to know if this results in higher mycotoxin levels.⁴

Most published findings relating to wheat quality are based on market research studies or data collected from farm comparisons.^{5–8} Here we report wheat quality findings gained through a long-term, replicated

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Contract/grant sponsor: Swiss Federal Office for Agriculture

(Received 13 January 2006; revised version received 21 June 2006; accepted 20 September 2006)

Published online 22 May 2007; DOI: 10.1002/jsfa.2866

plot, field study known as the DOK experiment.⁹ Findings concerning the effects of farming systems in the DOK experiment on soil fertility and biodiversity have been published previously.⁹ There, two organic (biodynamic, BIODYN; bio-organic, BIOORG) and two conventional (conventional with mineral fertilisers and farmyard manure, CONFYM; conventional with mineral fertilisers only, CONMIN) farming systems were compared in a ley rotation side by side in three consecutive 7 year crop rotation periods (CRPs) over 21 years. The conventional systems were adjusted to integrated farming in 1985. The farming systems differed mainly in fertilisation and plant protection, whereas crop rotation, varieties and soil cultivation were the same.

MATERIALS AND METHODS

Description of the DOK experiment

The DOK experiment has been conducted since 1978 in the vicinity of Basel. Its aim is to study the influence of two organic farming systems (BIODYN and BIOORG) and two systems managed conventionally following the Swiss integrated management standard since 1985 (CONFYM and CONMIN) on the yield and quality of selected crops and on soil processes.⁹ The integrated management comprises an integrated nutrient management as well as an integrated plant protection scheme, respecting economic thresholds. The crop rotation fulfilled the respective standards in all systems from the beginning of the DOK experiment.

The experiment is located in Therwil, 10 km south of Basel, Switzerland (7°33' E, 47°30' N). The soil type is a haplic luvisol on deep deposits of alluvial loess. It contains 150 g kg⁻¹ sand, 700 g kg⁻¹ silt and 150 g kg⁻¹ clay. Soil organic carbon ranged between 13 g kg⁻¹ in CONMIN and 16 g kg⁻¹ in BIODYN in 1998. Soil acidity was between pH (H₂O) 6.1 in CONMIN and pH (H₂O) 6.7 in BIODYN. The field experiment is designed as a randomised block with four replicates. The long-term mean precipitation averages 785 mm and the mean annual temperature is 9.5 °C. The total experimental area of 1.84 ha consists of 96 individual plots, each measuring 100 m² (5 m × 20 m).

The crop rotation was the same for all systems and comprised seven crops. Of the seven crops per rotation, three were planted every year on three subplots. In the first CRP (1978–1984) the crops grown were potato, winter wheat 1, white cabbage, winter wheat 2, barley, grass/clover 1 and grass/clover 2. In the second (1985–1991) and third (1992–1998) CRPs, white cabbage was replaced by beetroot. In the third CRP, grass/clover was planted for an additional year in place of barley. The main differences between the farming systems were the methods of soil fertilisation and plant protection used.^{9,10}

While the organic systems and CONFYM represent mixed farming types with arable land and livestock, CONMIN mimics a stockless system. Summarised

over all seven crops per rotation, the same amounts of farm-based organic amendments (means 83 t ha⁻¹ manure and 254 m³ ha⁻¹ slurry) were used in BIODYN, BIOORG and CONFYM. However, the distribution of manure and slurry in the rotation was system-specific. In CONFYM, manure and slurry were applied only to root crops, vegetables and grass/clover, while in the organic systems the cereal plots also received small amounts of slurry and, partly, also manure. Nitrogen, phosphorus, potassium and organic carbon contained in the manure and slurry were analysed consistently to adjust the total elemental amount to the target livestock unit density (1.2 LU ha⁻¹ year⁻¹ in the first and second CRPs and 1.4 LU ha⁻¹ year⁻¹ in the third CRP). CONFYM was additionally supplemented with mineral fertilisers to the plant-specific Swiss standard as recommended by official extension services. CONMIN was fertilised exclusively in mineral form. Over the three CRPs (21 years) the annual mean addition of total nitrogen to the BIODYN, BIOORG, CONFYM and CONMIN plots was 99, 93, 149 and 125 kg ha⁻¹ respectively.⁹ This meant that the input of nitrogen via the nitrogen-fixing grass/clover crop was not calculated.

Cultivation of wheat in the DOK experiment

At any given time the same variety was grown across all production systems. Only those registered on the official list of wheat varieties were used. Furthermore, varieties had to be in widespread use in agriculture and suited to both extensive and moderately intensive farming methods. During the three rotation periods from 1978 to 1998, three different varieties of 'price class I' bread wheat (the best class) as classified under the Swiss system were cultivated. The variety in the first CRP was 'Probus' as a standard, but the summer wheat variety 'Svenno' was planted in 1978 and the variety 'Calanda' in 1982. At the beginning of the second CRP it was replaced by the more robust and disease-resistant variety 'Sardona', which is more productive than 'Probus'. From the beginning of the third CRP the variety 'Tamaro' was cultivated. Two wheat crops were grown per CRP. Since every system was replicated four times on the experimental ground, sample size (*n*) was 24 per CRP and system for basic parameters such as wheat yield and mineral content. Wheat grain and straw were harvested and removed from the field plots in all farming systems.

Seed in the organic systems is not dressed, in contrast to the conventional practice. Since it was expected that this would result in a reduced emergence rate, the quantity of seed was increased by 10–25% over the amount used in the conventional systems.

Soil fertilisation varied depending on the farming system. Over the whole crop rotation, significantly more soluble (NH₄-N and NO₃-N) and total nitrogen, phosphorus and potassium were spread in the conventional than in the organic systems.⁹ Manure compost (mean 9.4 t ha⁻¹ year⁻¹) and slurry (19.1 m³ ha⁻¹ year⁻¹) were applied to wheat

grown in the BIODYN plots, while slurry alone ($19.8 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was applied to wheat grown in the BIOORG plots. Small amounts of commercial organic fertilisers were used only from 1978 to 1986 in the BIOORG wheat plots, containing $26.2 \text{ kg ha}^{-1} \text{ year}^{-1}$ total nitrogen. The conventional systems, CONMIN in particular (from the second CRP), received 2.4–5.6 times higher amounts of soluble nitrogen for wheat plots than the organic systems owing to the inputs of commercial mineral fertilisers. The mineral nitrogen fertilisation in the conventional systems was split into three doses, with the first dose being calculated by the formula 100 kg ha^{-1} nitrogen minus mineral soil nitrogen in the 0–90 cm profile.

Each year the topsoil (depth 0–20 cm) was tested to determine the content of plant-available phosphorus and potassium as extracted by CO_2 -saturated water. Soil calcium and magnesium were extracted by ammonium acetate and calcium chloride respectively. The analysis values for the elements phosphorus and potassium differed significantly in all three CRPs between systems (Table 1). The highest available phosphorus and potassium levels were found in CONFYM. Values in BIOORG were found to be 13–25% lower than in BIODYN.

Soil in BIODYN exhibited the highest content of extractable calcium in all three CRPs. The lowest levels each time were found in CONFYM (23–52% lower than in BIODYN) (Table 1). CONFYM exhibited 22–32% lower levels of extractable magnesium in the soil than BIODYN and BIOORG, where the highest levels were found.

Weed control was carried out mechanically in the organic systems and by means of herbicide spraying in the conventional systems. In the conventional systems, one or two fungicides, a growth regulator and, more rarely, insecticides were used when necessary (Table 2). Economic thresholds were thereby taken into account in the second and third CRPs.

Description of methods for analysing wheat

Wheat crops from the years 1978–1998 were subjected to chemical analysis and, in selected cases, also tested using integral techniques (food preference tests and picture-forming methods).

Yield, hectolitre weight, thousand-seed weight, macro and micro elements

Yield was measured from a centre plot of $1.7 \text{ m} \times 10 \text{ m}$. Four grain samples were taken and bulked once a year directly as the crop was harvested. These were pre-dried at 80°C until air-dry (approximately 10 h). For further chemical analysis the grain samples were ground in a vibrating disc mill and compressed into tablets on a boric acid substrate. Next the measurement of macro and micro elements was carried out by means of X-ray fluorescence (XRF) spectroscopy. Atomic absorption spectrometry was used to measure the molybdenum and cobalt contents following their extraction from the hydrochloric acid ash solution in a graphite furnace (cobalt) or over a flame (molybdenum).

Amino acid analysis

The amino acid composition of wheat samples of the 1993 harvest was determined with an Alpha Plus amino acid analyser (Pharmacia AB, Uppsala, Sweden). The amino acids were separated by cation exchange chromatography with sodium citrate buffer according to the laboratory standard procedure.¹¹ Detection of amino acids was performed after ninhydrin derivatisation, and quantification was carried out with external standards. For hydrolysis, samples were degassed under nitrogen (to avoid oxidation of the sulfur-containing amino acids) and hydrolysed in sealed glass tubes with 6 mol L^{-1} HCl for 24 h at 110°C .

Milling and baking quality

Milling and baking quality tests were conducted with wheat grown in 1993, 1995 and 1996. Tests to

Table 1. Content of soluble mineral elements in soil measured in first, second and third CRPs (annual means)

Element (mg kg^{-1} soil)	CRP	BIODYN	BIOORG	CONFYM	CONMIN ^a	ANOVA ^b	LSD ^c	<i>n</i>
P	1	2.39	1.81	3.00	1.16	***	0.67	24
	2	1.39	1.06	2.21	0.96	***	0.38	24
	3	1.16	1.01	1.74	1.23	***	0.35	24
K	1	8.72	7.51	12.8	4.73	***	2.57	24
	2	6.09	5.40	8.92	5.36	***	1.41	24
	3	7.53	5.65	12.4	7.17	***	1.74	24
Ca	1	2648	2293	2157	2490	**	386	24
	2	2684	2154	2000	2247	***	313	24
	3	2744	2061	1808	2243	**	669	24
Mg	1	102.0	99.5	84.1	86.8	***	13.3	24
	2	88.2	95.2	72.0	75.5	***	10.1	24
	3	93.5	104.5	85.2	96.1	***	11.2	24

^a CONMIN received no fertiliser in CRP 1.

^b Significance: NS, not significant; * $\alpha = 0.05$; ** $\alpha = 0.01$; *** $\alpha = 0.001$ (applies also to Tables 3–8).

^c Least significant difference based on Tukey–Kramer test ($\alpha = 0.05$) (applies also to Tables 3–8).

Table 2. Pesticides applied to conventional wheat plots

Type	Product name	Active ingredient(s)	Year(s) of application (19xx)	Amount (ha ⁻¹ year ⁻¹)
Herbicides	Erp-Actril	MCP, MCPA, ioxynil	78	4 L
	Tribunil	Methabenzthiazuron	79, 85	4 L
	Blefit	Bromofenoxim, isoproturon	81, 82, 84, 86, 88	6.5–7.5 L
	Erpanol	MCP+2,4-D	83	4 L
	Foxtar P	Isoproturon, MCP-P, bifenox	89	8 L
	Ioniz-P	Isoproturon, mecoprop-P, ioxynil, diflufenican	90, 91, 92, 93, 95, 96, 97	4 L
Fungicides	Milcap	Captafol, ethirimol	81, 84	2.5–3 L
	Tilt 1 CB	Propiconazole, carbendazim	84, 85, 88	0.5 kg
	Benlate	Benomyl	86	0.25 kg
	Daconil 500	Chlorothalonil	86	3 L
	Corbel Top	Captafol, fenpropimorph	88, 89, 90, 91	2.5 kg
	Orbit	Fenpropimorph, prochloraz	91, 92, 93, 95, 96, 97	2–4 L
	Alto-Elite	Chlorothalonil, cyproconazole	92, 96, 97	2 L
	Allegro	Epoxiconazole, kresoxime-methyl	98	1 L
Insecticides	Pirimor	Pirimicarb	81	0.5 kg
	Talstar	Bifenthrin	90	0.2 L
Plant growth regulators	Cycocel	Chlorocholine chloride	78, 83, 85, 86	0.5–2 L
	Cycocel Extra	Chlorocholine chloride, chlorocholine	79, 81, 84, 88, 89, 90, 91, 92, 93, 95	0.7–2.5 L
	Stabilan	Chlorocholine chloride	96, 97	1 L
	Moddus	Trinexapac	98	0.6 L

establish standard indirect parameters such as protein and wet gluten contents, swelling index, gluten index and maltose value, as well as parameters determining rheological properties (extensigram and farinogram) and milling properties, were carried out on grade 550 flour produced in a Bühler laboratory mill (Bühler Corp., Uzwil, Switzerland). Grade 550 flour was also used for the baking tests (rapid mix test and pan bread baking test). Additional analyses were carried out on wholemeal flour to determine protein and wet gluten contents, gluten index, sedimentation value and falling number.

Mycotoxins

Concentrations of the trichothecenes deoxynivalenol and nivalenol were analysed for the production years 1998 and 2000 using the method described by Berger *et al.*¹² Wheat samples were stored at room temperature for 2–3 months prior to analysis. Briefly, the method was performed as follows. Grain samples (100 g) were ground in an ultracentrifugal mill and sieved to 1 mm size. Samples were stored at 25 °C prior to analysis. Extraction, sample clean-up and high-performance liquid chromatography (HPLC) analysis were performed according to Ref. 12. The internal standard verrucarol (Sigma Chemie, Buchs, Switzerland) in 150 µL of methanol was added to 10 g of ground material and the mixture was shaken for 2 h with 40 mL of acetonitrile/H₂O (84:16 v/v) and filtered. Sample preparation was carried out on MycoSep 227 trichothecene cartridges and MycoSep 216 final clean-up columns (Romer Labs Inc., Union, MO, USA).

Prior to analysis the recovery standard hydrocortisone (Fluka, Buchs, Switzerland) in 150 µL of

methanol/water (1:3 v/v) was added to the sample solution. HPLC separation was carried out on a C18 modified stationary phase (Nucleosil, 120 Å pore size, 3 µm particles, normal density, 125 mm length, 2 mm i.d.; Macherey-Nagel, Oensingen, Switzerland). A linear binary gradient increasing from 25 to 98% methanol in water over 12 min was applied, followed by a 5 min rinse with 98% methanol. The flow rate was 250 µL min⁻¹. An ion trap mass spectrometer (LCQ, Finnigan MAT, San Jose, CA, USA) was used in positive ion mode, employing atmospheric pressure chemical ionisation (APCI(+)). Mass spectra were registered in full-scan mode with a mass range of 150–500 u. Quantification of the analytes was carried out by extracting mass chromatograms of the [M + H]⁺ ions. Quantitative results were corrected for recovery.¹²

Picture-forming methods

Picture-forming methods of analysis were conducted on wheat produced in the years 1992 and 1993. The methods used included Pfeiffer copper chloride crystallisation, Wala capillary dynamolysis and Pfeiffer circular chromatography.^{13–18} As in the chemical analysis tests, the flour itself forms the substrate for the analysis. However, it is not decomposed in order to measure its constituents. Instead, reactions between an aqueous extract of the flour and certain inorganic salts (e.g. silver nitrate, iron sulphate, copper chloride) result in the formation of patterns and structures as represented by chromatograms and capillary dynamolysis images as well as by copper chloride crystals, which are evaluated and interpreted by comparison with available data. For instance, copper chloride amended with aqueous extract of

wheat flour was allowed to crystallise in glass Petri dishes. The comparison of the images was done visually, based on single characteristics of the crystal image (e.g. number of crystal centres) or focusing on the whole picture (e.g. crystal needle density in the centre, the middle and the outer zone of the Petri dish). These morphological characteristics were then visually related to existing images, e.g. from unripe and ripe plant material.

Mixed samples were taken from the four sets of field experimental plots, resulting in four mixed samples from the four cultivation systems. Each mixed sample was halved, and eight coded wheat samples were analysed. Using the resulting images, it was possible to divide the samples into two main groups. Within these two main groups, pairs of samples were formed and matched to the individual organic and conventional production systems.

Feeding studies

Food preference tests were carried out using wheat from the 1995 and 2001 harvests. In such tests the test animals (here rats) are given the option to make a choice between feed from conventional and organic production. The aim of these experiments is to test the impacts of the different fertilisation and management regimes on feed quality. The test animals could choose between wheat biscuits made of BIODYN or CONFYM, BIOORG or CONFYM, and BIODYN or BIOORG grain material respectively. Such pairs of biscuits were offered as feed for four or five consecutive days, followed by the next pair. The food preference tests were carried out with 20 adult male laboratory rats (Long Evans strain) kept separately in Macrolon cages (size III) under air conditioning at 22 °C and 55% relative humidity. The basic diet for all test animals (conventional feed mixture T 779 from Tagger Co., Graz, Austria) was supplied in the cages in order to prevent any deficiency symptoms.^{19,20}

A partition, containing the water bottle, divided the feeding rack into a right and a left section, into which a defined amount of the test products was apportioned simultaneously. The remainders of the feed were weighed 24 h later in order to determine the quantity consumed. At this time, new feed was also supplied. The sides were changed with every meal in order to prevent a position preference effect.

Statistical methods

Statistical evaluation was carried out using the statistics package 'JMP® Statistics for the Apple® Macintosh®, Version 4' (SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was performed at significance levels of $\alpha = 0.05$, 0.01 and 0.001 prior to a Tukey–Kramer multiple comparison test ($\alpha = 0.05$). Correlations were calculated on the basis of linear regression analysis. Similarities between farming systems and CRPs based on repeatedly measured wheat quality parameters were calculated using principal component analysis.

RESULTS AND DISCUSSION

Soluble nitrogen input as nitrate and ammonium to the organic wheat plots was about 71% lower than that to the conventional wheat plots (Table 3). Mean dry matter yields from the organic plots were 14% inferior to those from the conventional plots (Table 4). In the first CRP the conventional systems showed lodging. In the second and third CRPs the conventional systems produced 11–24% higher grain yields owing to more intensive use of fungicides (Table 2) and higher-yielding varieties, which were also less susceptible to lodging (Table 4). Cereal crop yields under organic management in Europe are typically 60–70% of those under conventional management. Profits of organic farms in Europe are similar to those of comparable conventional farms.⁹ Protein yield was enhanced in the conventional systems in all three CRPs (Table 4).

Table 3. Supply of soluble nitrogen (NH₄-N + NO₃-N) fertiliser to wheat plots in first, second and third CRPs (annual means)

	CRP	BIODYN	BIOORG	CONFYM	CONMIN ^a	ANOVA	LSD	<i>n</i>
N _{soluble} (kg ha ⁻¹ year ⁻¹)	1	28.8	18.8	56.7	0.0	***	9.1	24
	2	18.7	17.5	59.0	71.0	***	13.7	24
	3	12.5	11.7	57.2	79.0	***	10.3	24

^a CONMIN received no fertiliser in CRP 1.

Table 4. Wheat dry matter and protein grain yield in first, second and third CRPs (annual means)

Yield	CRP	BIODYN	BIOORG	CONFYM	CONMIN ^a	ANOVA	LSD	<i>n</i>
Dry matter (t ha ⁻¹)	1	3.45	3.57	3.72	3.61	NS	0.46	24
	2	3.77	4.06	4.99	5.15	***	0.82	24
	3	4.10	4.11	4.62	4.77	***	0.43	24
Protein (kg ha ⁻¹)	1	498	512	560	495	**	57.1	24
	2	460	485	679	657	***	82.0	24
	3	535	520	649	686	***	66.9	24

^a CONMIN received no fertiliser in CRP 1.

Via grain plus straw, nitrogen export from the field plots over three rotations (1978 excluded) was 119.9, 117.7, 150.6 and 140.4 kg ha⁻¹ year⁻¹ ($n = 68$, $\alpha < 0.0001$) in BIODYN, BIOORG, CONFYM and CONMIN respectively. This is much more than the amount of mineral nitrogen fertiliser supplied to the wheat field plots (Table 3). A larger part is assumed to originate from the mineral soil nitrogen (0–90 cm soil depth), which amounted to 71.8, 74.4, 74.9 and 67.5 kg ha⁻¹ in the respective systems in early spring before plant growth started ($n = 68$, $\alpha = 0.531$). Mineralised nitrogen uptake by wheat plants from the organic soil pool between spring and ripeness was estimated to be 19.7 kg ha⁻¹ year⁻¹ in the organic systems and 27.9 kg ha⁻¹ year⁻¹ in the conventional systems ($n = 68$, $\alpha = 0.240$), whereby nitrogen gains via wet and dry deposition and losses via leaching and volatilisation were not considered. It becomes evident that the loess soil, planted for 2–3 years with grass/clover (ley) per rotation, has the potential to deliver substantial amounts of nitrogen to the crops.

When calculating the correlation between nitrogen export via grains and soluble nitrogen in the fertilisers, R^2 was 0.121 ($n = 144$, $\alpha < 0.0001$) for wheat 1 and 0.501 ($n = 144$, $\alpha < 0.0001$) for wheat 2. In a multiple regression analysis including the two parameters soluble nitrogen in fertilisers and mineral nitrogen in soil in spring, R^2 increased to 0.278 ($n = 144$, $\alpha < 0.0001$) and 0.630 ($n = 144$, $\alpha < 0.0001$) respectively. Mineral soil nitrogen was higher in wheat 1 than in wheat 2 in the second and third CRPs. This explains the less pronounced influence of fertiliser nitrogen on wheat 1.

Dry matter and protein yield as well as protein content of wheat grain data were also analysed by a two-way ANOVA for 'system \times position of wheat in rotation'. Exactly the same significant differences between the farming systems were calculated for these parameters as in a one-way ANOVA for the factor 'system'. However, as expected, yield and protein content reduction in organic systems were generally enhanced in wheat 2.

The hectolitre weight and thousand-seed weight of wheat showed no significant variations between farming systems (Table 5). High values such as those achieved in this study are characteristic of well-formed grain.

On average over the three CRPs the conventional systems exhibited a 6% higher protein content (133 g

protein kg⁻¹ dry matter in organic *versus* 141 g kg⁻¹ in conventional) (Table 6). Correlation between the soluble nitrogen added to wheat plots and the grain protein content was weak and only significant in the third CRP ($R^2 = 0.123$, $n = 96$, $\alpha = 0.0005$) when data for wheat 1 and wheat 2 were calculated together. No significant correlations were found for wheat 1; however, for wheat 2, correlations between mineral nitrogen in fertilisers and protein content in grains were $R^2 = 0.355$, 0.481 and 0.327 ($n = 48$, $\alpha < 0.0001$) in the first, second and third CRPs respectively. These findings suggest that fertiliser application is more important to the wheat 2 crop at the end of the fertility-building ley rotation with nitrogen-fixing clover. The results of relevant comparison studies agree with the trend obtained here, i.e. a higher protein content in wheat from conventional systems using mineral fertilisers.^{21–28} In a few studies,^{23,24} protein levels in organically grown wheat were found to be as low as 80–100 g kg⁻¹. In contrast, protein contents of organically grown wheat in the DOK experiment were generally high, most likely because of the use of varieties better adapted to low nitrogen input.

Macro and micro (trace) elements are important for the human body and essential to sustain various physiological functions. For the phosphorus, potassium, calcium, zinc, molybdenum and cobalt contents of wheat, no statistically significant differences between the farming systems were found (Table 6). Although a few significant system-based differences in individual CRPs occurred for magnesium, manganese and copper contents of wheat, no tendency was found towards higher or lower levels in any of the four farming systems. In contrast to these findings, highly significant differences in soil nutrient concentrations were found (Table 1). The influence of these soluble soil compounds on elemental content in the grain was almost imperceptible. Exactly the same findings have been made in two other studies.^{29,30} With regard to ash, no system-based differences were noted (Table 6).

While farming system effects on wheat constituents were small, the CRPs had a significant effect on crude protein, ash and all macro elements (phosphorus, potassium, calcium and magnesium) of wheat grains (three-way ANOVA for 'system \times position of wheat in rotation \times CRP'). Clear trends between the first and third CRPs were found for ash (–16.0%), crude protein (–9.9%), phosphorus (–14.2%) and

Table 5. Hectolitre weight and thousand-seed weight in first, second and third CRPs (annual means)

Parameter	CRP	BIODYN	BIOORG	CONFYM	CONMIN ^a	ANOVA	LSD	<i>n</i>
Hectolitre weight (kg)	1	79.1	79.7	78.7	79.9	NS	2.03	24
	2	79.2	80.4	80.9	81.0	NS	2.13	24
	3	82.9	83.2	82.6	83.1	NS	1.31	24
Thousand-seed weight (g)	1	35.8	36.3	35.2	36.2	NS	2.55	24
	2	33.4	33.8	34.7	34.2	NS	3.86	24
	3	40.0	40.2	40.5	40.6	NS	5.28	24

^a CONMIN received no fertiliser in CRP 1.

Table 6. Content of nitrogen, crude protein, ash and macro and micro elements in wheat grains of first, second and third CRPs (annual means)

Parameter	CRP	BIODYN	BIOORG	CONFYM	CONMIN ^a	ANOVA	LSD	<i>n</i>
N (g kg ⁻¹ DM) ^b	1	25.4	25.2	26.7	24.4	*	1.81	24
	2	22.5	21.8	24.4	23.1	NS	3.22	24
	3	22.9	22.2	24.6	25.4	***	1.91	24
CP ^c (g kg ⁻¹ DM)	1	144.9	143.7	152.2	138.9	*	10.31	24
	2	128.3	124.0	138.9	131.4	NS	18.33	24
	3	130.7	126.4	140.4	145.1	***	10.89	24
Ash (g kg ⁻¹ DM)	1	19.6	19.9	20.2	21.3	NS	2.10	24
	2	18.5	18.5	19.3	17.6	NS	1.85	24
	3	17.4	16.7	17.2	16.7	NS	1.27	24
P (g kg ⁻¹ DM)	1	4.47	4.30	4.50	4.28	NS	0.32	24
	2	4.15	4.08	4.17	4.03	NS	0.27	24
	3	3.86	3.73	3.79	3.65	NS	0.29	24
K (g kg ⁻¹ DM)	1	4.59	4.46	4.47	4.65	NS	0.29	24
	2	4.96	4.80	4.75	4.78	NS	0.26	24
	3	4.52	4.53	4.55	4.38	NS	0.49	24
Ca (g kg ⁻¹ DM)	1	0.51	0.50	0.50	0.52	NS	0.05	24
	2	0.47	0.45	0.43	0.44	NS	0.06	24
	3	0.44	0.44	0.46	0.48	NS	0.10	24
Mg (g kg ⁻¹ DM)	1	1.32	1.28	1.24	1.30	NS	0.16	24
	2	1.26	1.26	1.23	1.19	NS	0.14	24
	3	1.28	1.24	1.18	1.19	*	0.10	24
Mn (mg kg ⁻¹ DM)	1	34.1	35.3	39.0	35.9	*	3.84	24
	2	33.9	37.4	42.3	42.5	***	3.89	24
Zn (mg kg ⁻¹ DM)	1	34.6	36.9	38.2	35.9	NS	5.92	24
	2	30.5	33.7	33.3	32.2	NS	4.84	24
Cu (mg kg ⁻¹ DM)	1	4.38	4.71	4.40	5.49	**	0.94	24
	2	6.63	6.52	5.73	6.45	NS	0.93	24
Mo (mg kg ⁻¹ DM)	1	0.27	0.26	0.27	0.25	NS	0.05	24
Co (mg kg ⁻¹ DM)	1	0.017	0.018	0.020	0.019	NS	0.01	24

^a CONMIN received no fertiliser in CRP 1.

^b DM, dry matter.

^c Crude protein = N × 5.7, calculated with unrounded nitrogen values.

calcium (-11.8%) contents in wheat grain. These decreases may be a result of changed varieties, along with higher yields in the second and third CRPs causing dilution effects, but also due to altered soil conditions. However, only for phosphorus was a weak but significant correlation between soluble soil fraction and grain content calculated ($R^2 = 0.069$, $n = 272$, $\alpha < 0.0001$), suggesting that soluble soil nutrient contents were less important than varieties. This could have strong implications for agriculture regarding breeding programmes. Therefore wheat breeders should put a strong focus on quality aspects.

One way to characterise systems by a set of system properties is principal component analysis (PCA). Here PCA was based on the data for thousand-seed weight and contents of ash, nitrogen and the macro elements phosphorus, potassium, calcium and magnesium of the wheat grains. The first two principal components, which are synthetic variables, accounted for 77% of the total variation of the systems. It can be stated that under PCA the rotation periods form clusters of samples but the farming systems do not (Fig. 1). This suggests a varietal effect, as different varieties were sown in the three crop rotations.

The amino acid pattern of proteins largely determines protein quality. With regard to nutritional value,

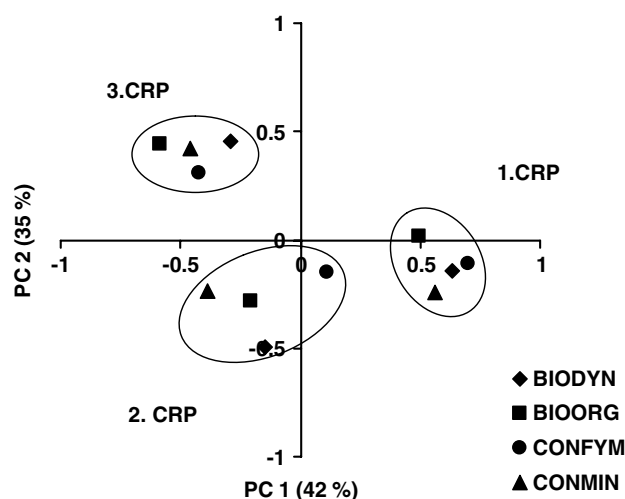


Figure 1. Plot of first two principal components (PCs) of a principal component analysis based on thousand-seed weight and ash, N, P, K, Ca and Mg contents of wheat grains. Clusters formed by three crop rotation periods (CRPs) are shown; $n = 24$ per CRP and farming system.

the essential amino acids lysine and threonine are known to limit the biological protein value of wheat. Baking quality is measured using the Osborne fractions of gliadins and glutenins. The amino acid patterns of

the 18 amino acids analysed in wheat grain¹¹ indicated no significant system-based differences (Table 7). In one comparison study²² it was found that, in conventionally produced wheat, seven out of 16 amino acids were present in greater relative amounts to a degree of more than 10%. The remaining values exhibited practically no differentiation across the amino acid spectrum. Another study reports that the protein quality in organically produced wheat was higher.⁷ Our results contradict these findings. The data basis remains limited for proper evaluation of protein quality in organic and conventional produce.

Baking quality depends largely upon wheat protein content and starch structure. Milling and baking quality tests were carried out on material harvested in two consecutive years. No major system-based influences on flour milling properties, starch quality and rheological properties of the dough were detected for the different farming systems. The single noticeable difference was a somewhat higher protein content (Table 6) and consequently higher gluten content in wheat from CONFYM. However, this had no significant influence on bread quality, as baking tests (rapid mix test and pan bread baking test) confirmed. The quality of baked products obtained from conventionally and organically grown wheat was

equally good. Comparison studies in the published literature largely support the findings (higher protein and gluten contents of conventionally grown wheat) presented here.^{21–24,26,27} In several studies in which a substantially lower protein content in organically produced wheat was found,^{21–24,27} lower bread volume and poor baking quality resulted as well.

Trichothecenes are quality-impairing toxic substances found in grain crops. They are produced by *Fusarium* fungi and can be harmful to human and animal health even in very low concentrations. Of a set of mycotoxins routinely analysed,¹² only the mycotoxins deoxynivalenol (DON) and nivalenol (NIV) were found at low levels in all farming systems (Table 8). DON is more commonly formed and about ten times less toxic than NIV. A study carried out in Norway²⁵ included analysis of the trichothecenes DON and NIV. Trichothecenes were not detected in conventionally produced wheat in any year. However, small quantities of trichothecenes were found in organically grown wheat. This can be explained by the use of *Fusaria*-resistant varieties and the relatively dry summer in both years. Likewise in a German study, no significant differences were found in DON concentrations in cereal samples from organic and integrated farming systems.³¹

Table 7. Composition of amino acids in wheat in 1993 (means)

Amino acid (g kg ⁻¹ total protein)	BIODYN	BIOORG	CONFYM	CONMIN	ANOVA	LSD	<i>n</i>
Arginine	47.2	47.3	46.6	47.2	NS	2.5	4
Histidine	23.1	22.5	22.8	22.8	NS	0.8	4
Isoleucine	34.6	35.5	35.4	35.4	NS	2.1	4
Leucine	67.1	67.3	67.0	67.1	NS	1.9	4
Lysine ^a	26.3	25.8	25.4	25.8	NS	1.0	4
Methionine	13.5	12.9	13.3	13.5	NS	1.5	4
Phenylalanine	45.9	45.6	46.4	45.4	NS	1.7	4
Threonine ^a	31.0	31.1	30.5	30.2	NS	1.2	4
Tryptophan	11.4	12.0	10.8	11.7	NS	2.4	4
Valine	42.8	43.0	42.7	43.2	NS	1.8	4
Alanine	34.8	35.2	34.3	34.9	NS	0.9	4
Aspartic acid	48.9	49.0	48.0	47.8	NS	1.9	4
Cysteine	15.5	15.8	14.2	15.3	NS	2.8	4
Glutamic acid	318.3	323.3	322.3	321.4	NS	14.2	4
Glycine	42.4	41.9	42.2	42.2	NS	0.9	4
Proline	114.5	110.6	116.1	114.2	NS	5.6	4
Serine	52.7	52.5	52.5	52.0	NS	1.9	4
Tyrosine	30.0	29.1	29.8	30.1	NS	3.1	4

^a Limiting amino acids in wheat.

Table 8. Content of trichothecenes in wheat in 1998 and 2000 (annual means)

Trichothecene (µg kg ⁻¹)	Year	BIODYN	BIOORG	CONFYM	CONMIN	ANOVA	LSD	<i>n</i>
DON	1998	47.8	74.3	80.8	140	NS	98.2	4
DON ^a	2000	27.5	41.8	81.0	10.0	NS	81.3	4
NIV ^b	2000	112	59.0	94.3	57.0	NS	164.6	4

^a DON (deoxynivalenol) values below 40 µg kg⁻¹ are estimated.

^b NIV (nivalenol) was not detectable in 1998 (<50 µg kg⁻¹); values in 2000 below 100 µg kg⁻¹ are estimated.

Table 9. Grouping of blinded wheat samples using picture-forming methods in 1992 and 1993

Year	Farming systems ^a
1992	D _I = O _I // D _{II} = O _{II} // K _I = K _{II} // M _I = M _{II}
1993	D _I = D _{II} // O _I = O _{II} // M _I = M _{II} // K _I = K _{II}

^a Indices I and II denote double-bulked wheat samples originating from four joined field replicates. Samples connected with '=' were associated as belonging to the same system. D, BIODYN; O, BIOORG; K, CONFYM; M, CONMIN.

The wheat samples were also characterised by picture-forming methods (copper chloride crystallisation, capillary dynamolysis and circular chromatography). Using these procedures, the foodstuff is tested for its ability to form patterns, shapes and structures. Based on the resulting 'pictures', a blind grouping, characterisation and identification of the samples are achieved by comparison with existing data. In both years in which this method was applied, a differentiation between organic and conventional farming was possible (Table 9). Picture-forming methods have been used successfully to distinguish between organic and conventional farming systems with beetroot³² and apples.³³ The beetroot samples were grouped correctly in the first year, similar to the experience here with wheat, and in the second year of the study they were assigned correctly to farming systems in a blind test. In the apple study³³ a significant correlation was found between a quality index based on picture-forming methods, nutritional quality, sensorial quality and technical quality. Although a differentiation of wheat samples originating from organic and conventional farming systems was possible in the DOK experiment, no direct relation could be found to the nutritional value of the grains.

As an integrative quality method, food preference tests were performed with laboratory rats. In these experiments the test animals were given the option to make a choice between wheat from conventional and organic production. In two harvest years the rats significantly preferred wheat biscuits from the BIOORG system as opposed to the CONFYM system (Fig. 2). There were contradictory findings for the two years on whether the rats preferred BIODYN or CONFYM. What reason the rats have for preferring the BIOORG-produced wheat over wheat from CONFYM has not been established. It is known, however, that feeding behaviour is influenced by smell, taste, feed texture, metabolic comfort and negative experiences such as poisons and feed shortage. In general, published studies have found a similar preference among test animals (rats, rabbits or chickens) for organically grown products.^{19,20,32,34} These results clearly indicate that animals can discriminate between organic and conventional food and usually prefer the organic feedstuff. It is remarkable that test animals distinguish between products of different origin although only very few differences in quality analysed chemically

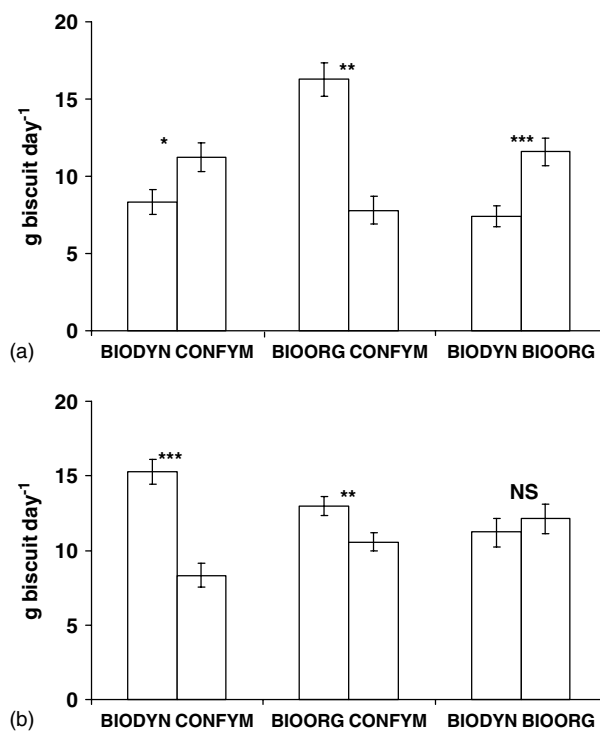


Figure 2. Food preference tests with rats fed wheat biscuits from different farming systems (BIODYN, BIOORG, CONFYM) in (a) 1995 and (b) 2001. Error bars represent standard errors of means. Significance: NS, not significant; * $\alpha = 0.05$; ** $\alpha = 0.01$; *** $\alpha = 0.001$.

were detected. It would be of interest to measure more chemical constituents, such as secondary metabolites, in order to trace the food preferences of test animals to nutritional food properties.

It is concluded that organic farming systems fulfil two important requirements of sustainable production³⁵ at the same time. This report shows that organic farming systems produce reasonable wheat yields of high quality in the long term, using far fewer external inputs in the form of fertilisers and plant protection agents. The ley (grass/clover) in the rotation is important for stable wheat yields of high quality in organic farming. Previously published results based on the DOK field experiment have shown better soil fertility (according to various indicators, e.g. microbial biomass, soil enzymes, mycorrhizal root colonisation) and higher biodiversity in organic field plots and a higher energy and nutrient efficiency in organic systems.⁹ Thus our findings suggest that organic farming can contribute substantially to solving problems related to high-external-input agriculture. These results are in line with a recent study on organic apple production – a perennial crop – in which better food quality was accompanied by higher soil fertility.³⁶

ACKNOWLEDGEMENTS

Special thanks go to the farmers and technicians for their help in realising the DOK experiment. We would like to thank the Swiss Federal Office for Agriculture, Berne, and the Richemont Bakery School, Lucerne, for carrying out baking tests. We also thank A Wiemken

for his helpful comments. We thank Helga Willer for updating the data survey on organic wheat production in Europe. We owe special thanks to the Swiss Federal Office for Agriculture for funding this project.

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