Sulfur and baking-quality of bread making wheat

Ingo Hagel[1,2]

Abstract

It is well known in biological science that all factors applied to living organisms (light, water, warmth, fertilizers etc.) show an optimum, when their input is increased. Healthy organisms and sustainable systems are, on the long run, only achieved when care is taken not to destroy this equilibrium of factors producing an optimum. With regard to the baking quality of wheat breeders and cereal scientists obviously failed to achieve this aim by breeding their cultivars on the background of ample S depositions in the ecosystems. They (involuntarily) selected plants showing definite characteristics of S deficiency (higher proportions of HMW-glutenin, stronger gluten and dough) even under conditions of ample S supply. I suppose they also selected plants with a high warmth susceptibility as this also delivers firm protein structure. When this environmental pollution was stopped and S supplies returned to natural conditions, even with a non S craving plant like wheat, problems arose with the gluten structure as doughs turned out so strong that the baking volume decreased. So one may ask, particularly with regard to S, if the plant constitutions of our modern wheat cultivars are still harmonious and in balance. And as a consequence ot that also the nutritional quality of these cultivars is rather questionable.

Key words: wheat, sulfur, baking quality, gluten, maximum resistance, temperature influence, nutritional quality

Introduction

When wheat is milled into flour and the dough is baked into bread, the developing carbon dioxide gas bubbles that develop through fermentation (yeast or sour dough) are prevented from escaping the dough by its protein or gluten matrix. By keeping the gas bubbles in place, nice bread with attractive baking volume arises, not only delighting the bakers by lowering their flour-input costs, but also appealing to the human senses. Yet baking quality was not always as outstanding as it is today. For example, in Germany until shortly before the outbreak of the Second World War, many cultivars existed with low performance (Klemt, 1934) and very soft glutens. Some of them were like glue from a tube, so one could write one's name with it on the work surface (Kosmin,1934). And even at the beginning of the 60's German grown wheat had to be blended with 25-28% Canadian or American high quality wheat (Bolling, 1989).

So it is understandable, that especially after the Second World War cereal chemists provided innumerable contributions on wheat and its quality. Breeders successfully selected wheat cultivars with ever firmer and elastic glutens, a process that is still in progress. So the question may arise if this development only shifted the protein quality of the staple food wheat from one extreme to the other. One has to keep in mind that the word "quality" with regard to wheat almost exclusively means "technological quality", and this in fact means "baking quality", not "nutritional quality". The mediation of all life processes are closely linked to proteins. As an increasing number of people nowadays suffer from wheat incompatibility, one may ask whether we have lost sight of the nutritional needs of human beings through the changing of wheat protein for merely technological reasons.

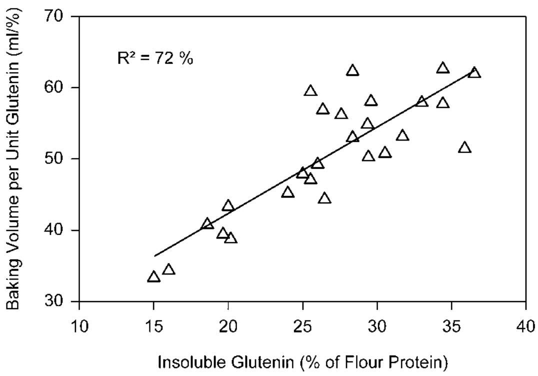

Figure 1:
Relation between the amount of acetic-acid-insoluble glutenin and the baking volume per percent-unit of protein in the flour (Orth und Bushuk, 1972, from Bushuk, 1989)

Today we will focus on the question whether the firm protein structure and excellent baking quality of modern wheat varieties comes from some sort of a S deficiency syndrome induced involuntarily by breeding (Hagel 2000a, 2002).

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Sulfur and wheat proteins

The crude protein of wheat can be separated into several fractions (according to their solubility in different solvents), which also contribute quite differently to baking quality. The salt soluble albumins and globulins are concentrated in the periphery of the grain, directly under the bran (Hagel, 2000b). Therefore their content depends very much on thousand-kernel weight and flour quality (whole grain flour or flours with a lower ash content). With regard to a flour featuring a low ash content of 0.55% they account for approximately 11 – 22% of protein, depending on the total protein content of the grain and cultivar (Wieser and Seilmeier 1998; Wieser et al., 1980a). So the vast majority of the wheat proteins in such flour are gluten proteins, comprising the gliadins and the glutenins. Type and proportion of these two protein fractions greatly influence the structure of gluten, the rheological performance of the dough and therewith the technological quality of the wheat i.e. the baking volume. While gliadins contribute to viscosity and extensibility, glutenins are regarded as the main factor for elasticity and firmness (Wieser et al., 1994). Additional gliadin leads to softer and more extensible glutens (Kim et al., 1988). On the other hand, according to the basic results of Orth and Bushuk (1972, Figure 1), the strengthening effect of glutenin to gluten and dough (Seilmeier et al., 1992; Wieser et al., 2000; Antes and Wieser, 2000; Wieser and Kieffer, 2001) (and thus leading to higher baking volume) has been consistently corroborated (Field et al., 1983; Gupta et al., 1993; Kieffer et al., 1998).

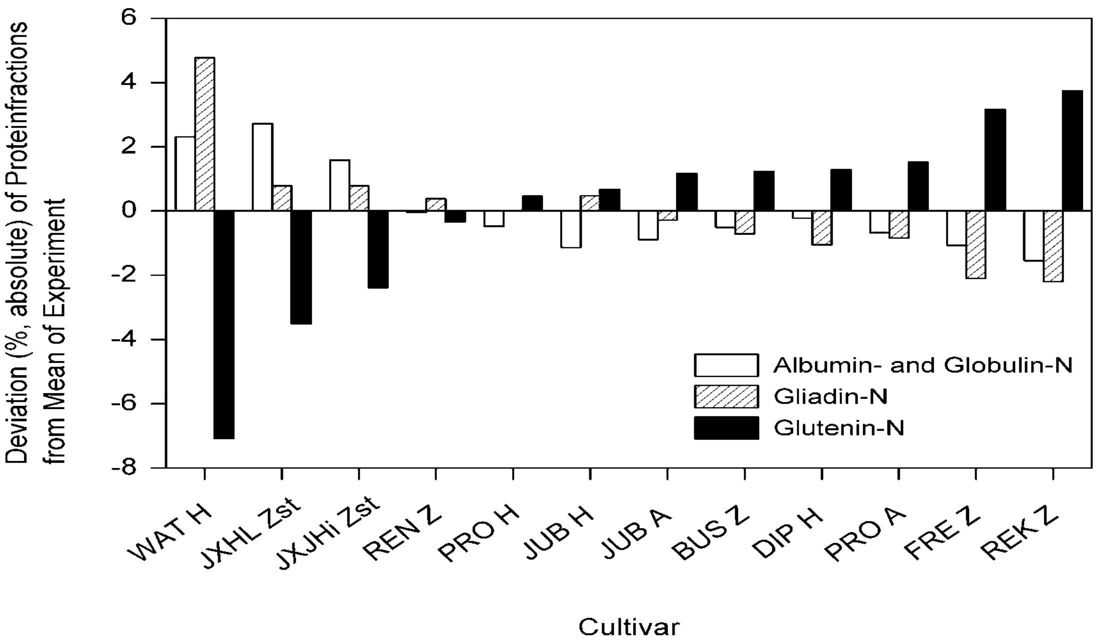

Figure 2:
Deviations (%, absolute) of protein fractions from the mean (regressions of the protein fractions versus N content) of all cultivars of wheat (whole grain, harvest 1994; Hagel et al., 1998a).

So it is understandable that in the course of the last 60 years the development from old to modern wheat cultivars has led to a drastic shift in the proportions of protein fractions (Hagel et al., 1998, Figure 2): The very old wheat type Weisser Ammertaler (WAT), a cross of the older cultivar Jubilar with an old Hessischer Landweizen (JXHL) as well as a cross of Jubilar with another Jubilar-cross (JXJHi) showed glutenin proportions far below the average of all other variants of this trial, but with higher gliadin proportions and thus leading to extremely soft glutens (gluten indices of 42-56%; Hagel et al., 1998a). On the other hand, particularly the modern cultivars Fregatt and Rektor had very high proportions of glutenin above the mean, but also the modern cultivars Bussard and the older cultivars Diplomat, Jubilar and Progress showed glutenin proportions well above the mean and lower gliadin, which led to very firm glutens (gluten indices of 84-99% (Hagel et al., 1998)). Parenthetically, from Figure 2 it can be seen that not only gliadin was replaced by glutenin, but also albumins and globulins, being the protein fractions with the highest S contents (see below and Table 1).

Table 1:
Contents (Mol-%) of cysteine, methionine and lysine of protein fractions of wheat (cultivars: KOLIBRI and REKTOR), (Wieser et al., 1980 & 1991).

	Cysteine	Methionine	Cysteine + Methionine	Lysine
Albumins	3.3	1.6	4.9	3.1
Globulina	3.2 - 3.7	2.0 - 2.1	5.8	4.1
Gliadins (total)	1.8 - 2.2	1.1 - 1.4	2.9 - 3.6	0.8
ω5-Gliadins	0	0	0	0.4 - 0.5
ω1,2-Gliadins	0	0.0 - 0.3	0.0 - 0.3	0.3 – 0.6
Glutenins (total)	1.4	1.3	2.7	2.1
HMW-Glutenins	0.6 - 1.3	0.1 - 0.3	0.7 - 1.6	0.7 – 1.1
LMW-Glutenins	1.9 - 2.6	1.2 - 1.6	3.1 - 4.2	0.2 – 0.6

Glutenins can be separated into (high-molecular-weight) HMW-glutenins (M_r = 80.000-120.000) and (low-molecular-weight) LMW-glutenins (M_r = 30.000 -52.000 (Wieser, 2000)). HMW-glutenins are highly responsible for inducing firmer protein structure i.e. higher resistances of the glutens (Wieser et al., 1994; Seilmeier et al. 1992; Schropp and Wieser, 2001) and therefore play a key-role in gluten structure (Wieser and Zimmermann, 2000). The LMW-glutenin does not (or to a much lesser extent) contribute to the firmness (resistance) of the gluten (Antes and Wieser, 2000; Wieser and Kieffer, 2001). So HMW-glutenin appeared to be such an interesting research topic for cereal chemists that Shewry et al. (1992) stated that the 1980s could well be considered as the “decade of the HMW subunit”. The ratio of HMW:LMW-glutenin of wheat cultivars of widely differing baking quality varied from 0.35-0.65 (according to data from Wieser et al., 1994, Wieser and Kieffer, 2001). These variations make it plausible that breeders consciously (by analyzing for HMW-glutenin) and involuntarily (by selecting wheat with firm and elastic glutens, high sedimentation values, high baking volumes etc.) developed their wheat cultivars not only by increasing the glutenin content (Figure 2) but also by increasing the HMW:LMW ratio, though for the latter assumption no data is available. Anyway, all these measures (including of course replacing albumins and globulins by gluten proteins (Figure 2)) led to an increase of proteins low (gliadins, glutenins) or very low (HMW-glutenins) in S compared to albumins and globulins. These salt soluble proteins are very rich not only in essential amino acids such as lysine but also in S containing cysteine and methionine (Table 1). Moreover, as mentioned above, these non-gluten-proteins are concentrated in the periphery of the grain and can make up to 37% of the total wheat protein of whole grain wheat (Hagel 2000 b, Figure 3).

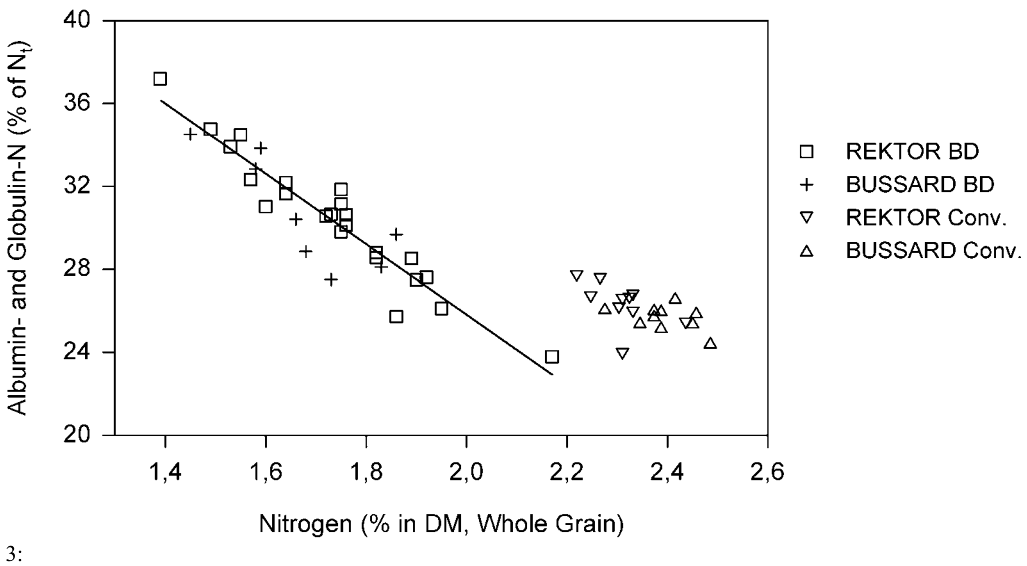

Figure 3:
Relations between nitrogen content and proportions of albumin- and globulin-nitrogen of total nitrogen content from wheat (cultivars: Rektor and Bussard, whole grain) from biodynamic (BD) and conventional (Conv.) agriculture, harvest 1996 (Hagel, 2000b).

As their content remains constant, their proportion of the total protein sharply declines with increasing protein content of the grain. So increasing the N content of the grain by N-fertilization, of which bakers are very fond of for technological reasons, increases only S low gluten proteins, not S rich albumins and globulins (Doekes and Wennekes, 1982; Wieser and Seilmeier, 1998). Consequently, for example, an increase of the protein content from approximately 1.4 to 2.2% N of the (biodynamic) wheat samples leads to a decline of the proportions of the S rich albumins and globulins from 37% to 24% of the total grain protein, respectively (Figure 3).

It becomes obvious that especially in conventional agriculture the aim of high contents of grain-N achieved by mineral fertilizers induces an imbalance between N and S, as S does not increase to the same degree as N (Hagel und Schnug, 1999; Hagel et al., 1998b). For instance, in Figure 4 the S contents fall below the diagonal of the graph. So many of the conventional wheat samples with high N content have come very near or have already crossed the line of an N:S ratio of 17:1, indicating S deficiency. Yet organically grown wheat with much lower N content is no guarantee for sufficient S supply (Hagel and Schnug, 1999). Figure 4 clearly demonstrates that the set of biodynamic samples from harvest 1996 must be differentiated into two different sub samples featuring N:S ratios < and > 14.5. Biodynamic samples from harvest 1995 also showed the same phenomenon of apparently different S supply including many samples with S deficiency (Hagel and Schnug, 1997).

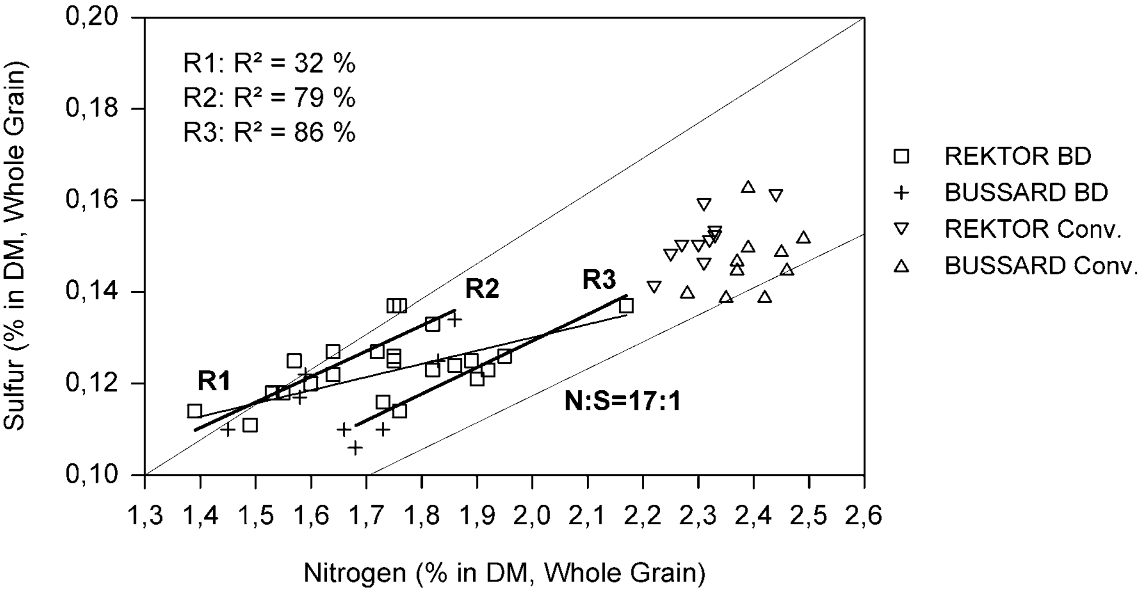

Figure 4:
Nitrogen and sulfur contents of wheat (cultivars Rektor and Bussard) from biodynamic (BD) und conventional (Conv.) agriculture (harvest 1996). Regression lines R2 and R3 differentiate the biodynamic samples into two sub-samples N:S ratio <and > 14.5:1 (Hagel et al., 1998b)

Sulfur and baking quality

With regard to gluten quality, S deficiency leads to much firmer and less extensible doughs (Moss et al., 1981; MacRitchie and Gupta 1993; Wrigley et al., 1984a). In Figure 5 the flour sufficiently supplied with S showed an extensogram with low energy (175 Brabender units at 50 mm extension). In contrast, the dough of the flour featuring S deficiency was much firmer, with a resistance of 365 Brabender units at 50 mm extension. Decreasing S contents lead to ever firmer doughs and low baking volumes, whereas S fertilization and increasing S content of the wheat grain induces less tough doughs and higher baking volumes (Figure 8; Moss et al., 1981).

Interestingly, the features of S deficient wheat described above (strong extensograms, stronger and tougher glutens and doughs) and shown in figure 5 were just what breeders and bakers were aiming at for decades on their quest for cultivars with high technological quality. Also biochemically, S deficient wheat shows characteristics of good baking quality wheat: less polypeptides with low M_rs (8,000-28,000, mainly albumins) and more polypeptides with high M_rs of 51,000-80,000 (Wrigley et al., 1984 a), higher content of HMW-glutenin (Castle and Randall, 1987), increasing amounts of

HMW-glutenin (Seilmeier et al., 2001), and increasing ratio of HMW:LMW glutenin (MacRitchie and Gupta, 1993; Seilmeier et al., 2001).

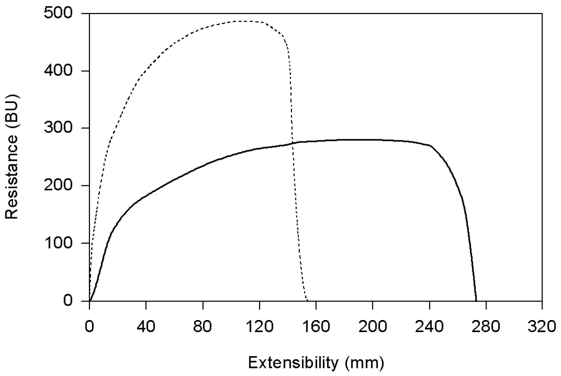

Figure 5:
Extensographs for flour (cultivar OLYMPIC) with normal and low content of sulfur. Control (—): 0.146% S, 1.82% N, N:S = 12.5:1. Flour with low sulfur content (---): 0.089% S, 1.72% N, N:S = 19.3:1 (Wrigley et al., 1984 a). BU = Brabender Units

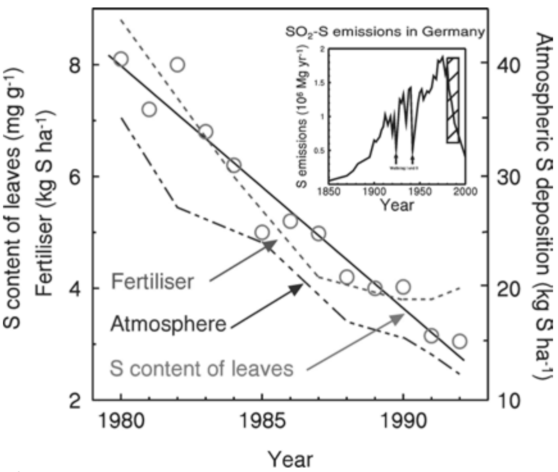

Figure 6:
Development of atmospheric SO_2- sulfur deposition, use of sulfur containing fertilizer and content of sulfur in leaves of rape (*Brassica napus*) in Northern Germany (Schnug and Haneklaus, 1994)

This development in wheat breading went "well" and led to cultivars with higher baking volumes until the moment when real S deficiency appeared. Due to the successful installation of desulfurization plants, a drastic reduction of the deposition of S in the ecosystems occurred. The application of S low mineral fertilizers also increased. By 1980 the average deposition of S in northern Germany was up to 35 kg/ha x year. This amount then decreased and in 1990 was 60% less (Schnug and Haneklaus, 1994; Figure 6). In the same period, the concentration of S in rape leaves decreased from 8 to 3 mg/g. At the beginning of the 80s no severe and relatively few cases of S deficiency (24% of all samples) could be observed in rape. At the end of the 80s the situation had changed dramatically: Only 1% of the rape samples were sufficiently supplied with S (Schnug and Haneklaus, 1994). In northern Germany an S application of 50 kg/ha is recommended (Schnug, 1991) for rape to avoid yield deficits through S deficiency.

Wheat is a crop which hungers after much less S than rape. But also with wheat S deficiency has become a problem leading to yield losses of up to 30% (Bloem et al., 1995). In contrast to rape, S deficiency in wheat cannot be compensated by foliar applications of SO_4-fertilizers (Schnug et al., 1993), because surplus S gets quickly translocated into the vacuoles, from which a re-translocation for the protoplasma of plant cells and their functions can only occur at a very moderate level (Bell et al., 1990; Cham 1990; Clarkson et al., 1993). If wheat insufficiently supplied with S shows a N:S ratio wider than 17:1, such flour leads to excessively tough and firm doughs and thus lower baking volumes (Wrigley et al., 1984b; Byers et al., 1987; Haneklaus et al., 1992; Bloem et al., 1995).

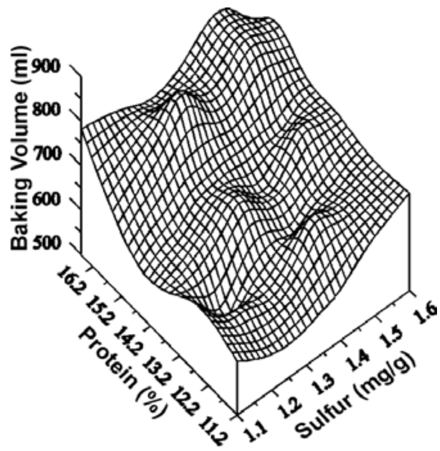

Figure 7:
Loaf volume of flour derived from German wheat varieties depending on sulfur and protein concentration in the grain (Haneklaus et al., 1992).

It is important to keep in mind that these reductions of baking volume occur not because of excessively soft glutens and doughs (as 30-50 years ago) but because of excessively firm ones: The pressure of the fermentation gases cannot sufficiently overcome the loafs' tough structure and thus produces lower baking volumes. Obviously, the breeding process selecting wheat types featuring the characteristics of S deficiency mentioned above has passed its optimum. When, in addition, a second S deficiency occurred as a changed ecologic-historical situation and decreased S depositions, unforeseen problems arose in baking technology. S fertilization now induced higher baking volumes (as known previously through N fertilization; Figure 7; Haneklaus et al., 1992), not because of any strengthening impact to the dough structure, but, on the contrary, because of the softening effect of an increasing content of grain S on the resistance of the dough, thus leading to higher baking volume (Moss et al., 1981; Figure 8).

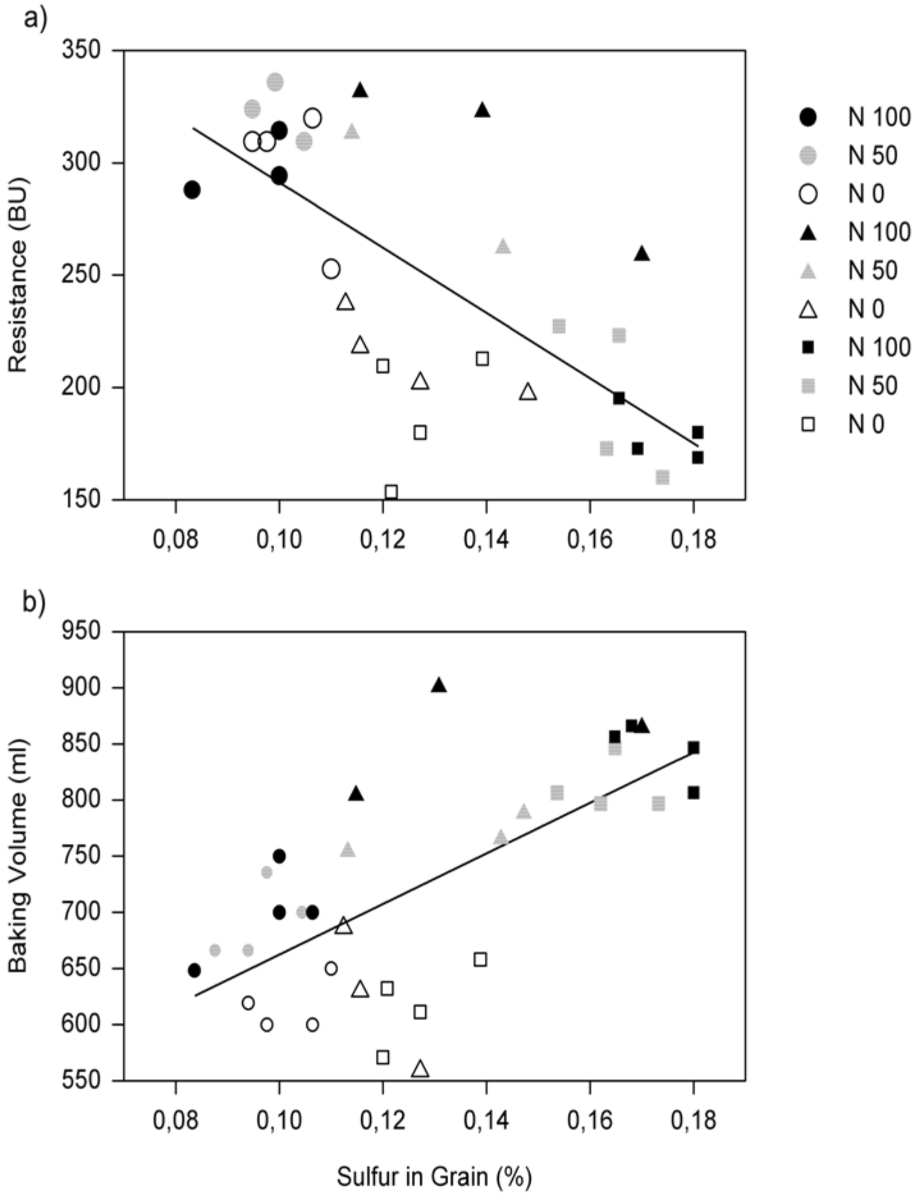

Figure 8:
Relations between content of sulfur and a) resistance of dough and b) baking volume. N0, 50 und 100 = nitrogen application in kg ha^{-1} (including different sulfur applications of 0-50 kg ha^{-1} (Moss et al., 1981). BU = Brabender Units.

Similar phenomena were observed with S fertilization trials on organic farms located in the coastal area of Northern Germany with very low rates of S deposition (Hagel, 2000c). The variability in the N content of the wheat samples shown in Figure 9 was only due to the field's variation, not to any N fertilization. One part of the samples received no S fertilizer, but in part (except the control) $MgCl_2$ in order to identify any effects in grain yield resulting from the magnesia in the S fertilizer ($MgSO_4$), but there were none. The N:S ratio of the control was 15.4 showing low S supply near to the limits. Increasing N content of these samples induced higher baking volumes only up to a certain optimum of approximately 1.95% N. Higher N contents lowered the baking volume (Figure 9), probably because of too firm doughs, though no extensograms were performed. The other part of the samples received S applications of 20, 40 and 60 kg ha^{-1} (as elemental S and $MgS0_4$). N:S ratios were 14.1 (elemental S) and 13.9 ($MgSO_4$), which were significantly lower than the control. Here with increasing N content no depression in loaf volume occurred. Instead a linear relation between the parameters was to be observed (Figure 9).

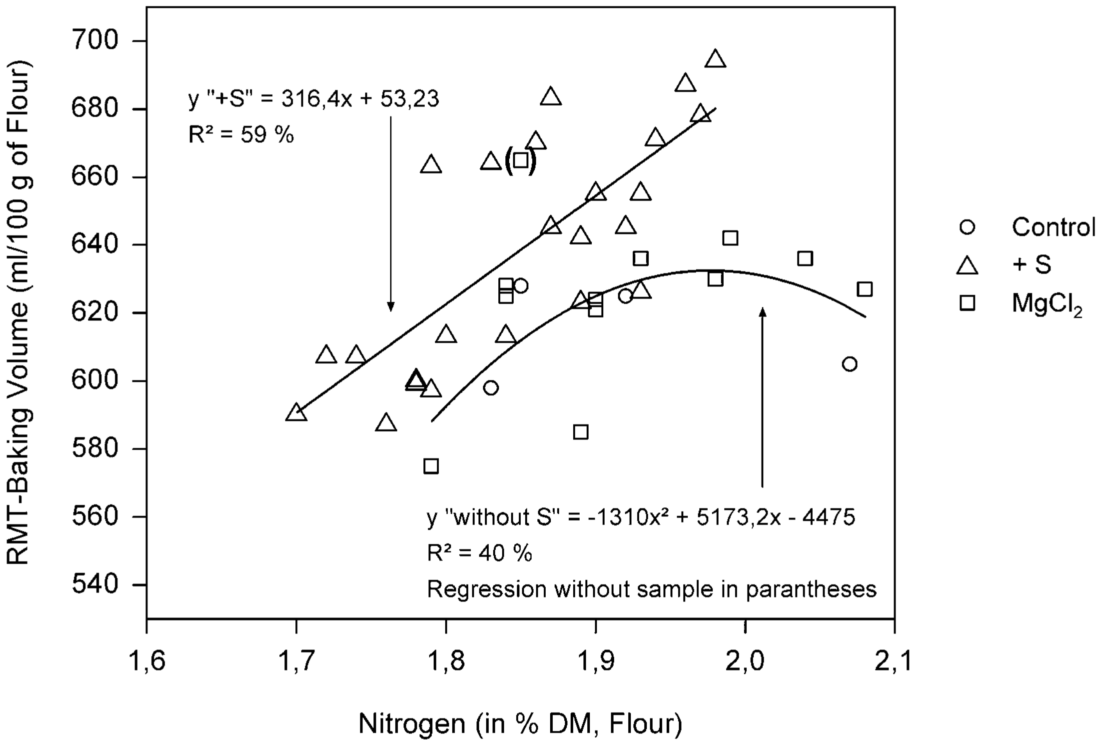

Figure 9:
Relationships between nitrogen content and baking volume (Rapid-Mix-Test = RMT) of wheat (cv. RENAN) of a sulfur fertilization trial on an organic farm (harvest 1998; location: Tröndel) (Hagel 2000 c). +S, sulfur fertilization: 20, 40 and 60 kg S ha^{-1} as elemental sulfur and $MgSO_4$-sulfur.

The effect of a S fertilization softening the protein matrix of wheat was not only demonstrated on locations where S was lacking but even on sites sufficiently supplied with this element. For this purpose up to 400 kg S/ha were applied to wheat grown on an organic farm (Hagel et al., 1999). Though the S content of the straw was increased by 50% by these quantities, the S content of the grain and the flour remained unaffected. Also the N content and the N:S ratio of the flour were not altered significantly (Table 2). But already 200 kg S ha^{-1} lowered the resistance of the gluten significantly (the impact of 100 kg S ha^{-1} only slightly differing from that) (Table 2; Figure 10). This effect was not influenced by a shift in the amount of protein fractions, especially HMW-glutenin (Table 2). Also different amounts of glutathione of the flour are probably not the reason, if the experiments as in this case are performed with flour sufficiently stored (Kieffer et al., 1998).

Warmth, baking quality and sulfur

We also have to deal with the impact of warmth with regard to the rheologie of wheat, because S and warmth are closely linked. S is exceptional for its many allotropic modifications induced simply by different temperatures as described in many textbooks (Mortimer, 1996; Cotton et al., 1999). E.g. S changes from rhombic crystals into monocline crystals upon mild heating. Further heating delivers a yellow readily flowing liquid, then a red highly viscous substance which is turned into a rubber like plastic material upon sudden cooling in water and so on. The spicy flavors of e.g. mustard, onion and garlic with their S containing glucosinolates are termed “hot” not by chance. Numerous therapeutic measures make use of these substances in nutrition and medicine (from spices to warmth stimulating baths). Looking at the phenomena, there are many relationships between S and warmth. So let us have a closer look to what happens with the baking quality of wheat grown at different temperatures.

It is well known that climate influences baking quality by altering yield and/or the protein content of the wheat (Svensson, 1974; McDonald et al., 1983). I will not focus on that now, but rather on different baking qualities induced by different temperatures, especially during the grain filling period of the wheat. Fajersson (1975) demonstrated different baking volumes of wheat (at comparable protein contents) from climatically different years (Figure 11).

Table 2:
Content of nitrogen and sulfur, N:S ratio of flour and resistance of gluten (measured in Newton) of wheat of a sulfur fertilisation-trial (0-400 kg S/ha). Multiple-Range-Test: $\alpha = 5$ %. Gliadin and Glutenin = RP-HPLC-analyses, (proportions (%) of the different subunits from total gliadin and glutenin (Hagel et al. 1999).

					Gliadin					Glutenin		
kg S/ha	% N	% S	N:S	Resistance	ω5	ω1,2	Σω	α	γ	ωb	HMW	LMW
0	1.80	0.103	17.5	0.544a	3.9	4.5	8.4	49.4	42.2	3.7	21.9	74.4
50	1.77	0.103	17.2	0.523ab	3.6	4.2	7.8	47.9	44.3	3.7	20.6	75.7
100	1.86	0.107	17.4	0.444ab	3.7	4.4	8.1	47.8	44.1	3.8	21.6	74.6
200	1.83	0.100	18.3	0.441bc	3.6	4.2	7.8	48.0	44.2	3.4	21.4	75.2
400	1.95	0.105	18.6	0.370c	3.6	4.3	7.9	49.0	43.1	3.6	22.7	73.7

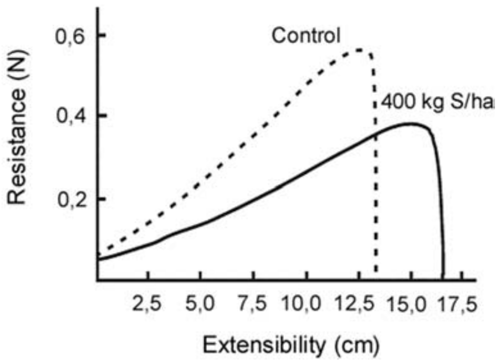

Figure 10:
Extensograms of wheat gluten of a sulfur fertilization experiment. Variants: 0 and 400 kg S ha^{-1} (Hagel et al., 1999).

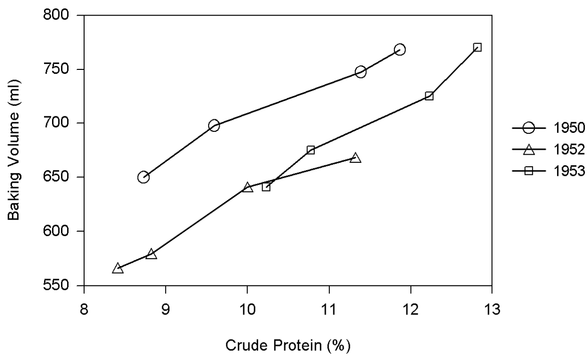

Figure 11:
Crude protein and baking volume of wheat from climatically differing harvest years (1950, 1952, 1953). Mean of five cultivars each (Fajersson, 1975).

In Sweden warm and dry climatic conditions (mean day temperatures of 20 °C) during grain filling periods of 1994 and 1995 led to high gluten strength with low bread volumes (Johansson and Svensson, 1999). Investigating the effects of weather parameters on some Swedish wheat cultivars Johansson and Svensson (1998) found that the temperature, specially during the grain filling period, was the most important weather parameter explaining only 34% of the variation in grain protein concentration, but 49% of the variation in mixogram index in spring wheat. Finney and Fryer (1958) found with hard red winter wheat samples from different states of the US and thus different climatic conditions, that increases in accumulated degrees of temperatures above 90°F (32°C) during last 15 days of the fruiting period led to loaf volumes much lower than expected with regard to the protein content (Figure 12). Although the authors did not investigate rheological parameters in detail, their descriptions of these samples with loaf volumes considerably below normal (subnormal mixing requirements and poor dough handling) characterizes excessively strong doughs exactly. Excluding these “irregular” samples increased the correlation coefficients between protein content and loaf volume from 0.76 to 0.97. The cultivar Chiefkan in particular was “highly susceptible to the damaging effects of high temperatures during fruiting”. Also Johansson and Svensson (1999) observed that the susceptibility of wheat cultivars with regard to warmth influences differed.

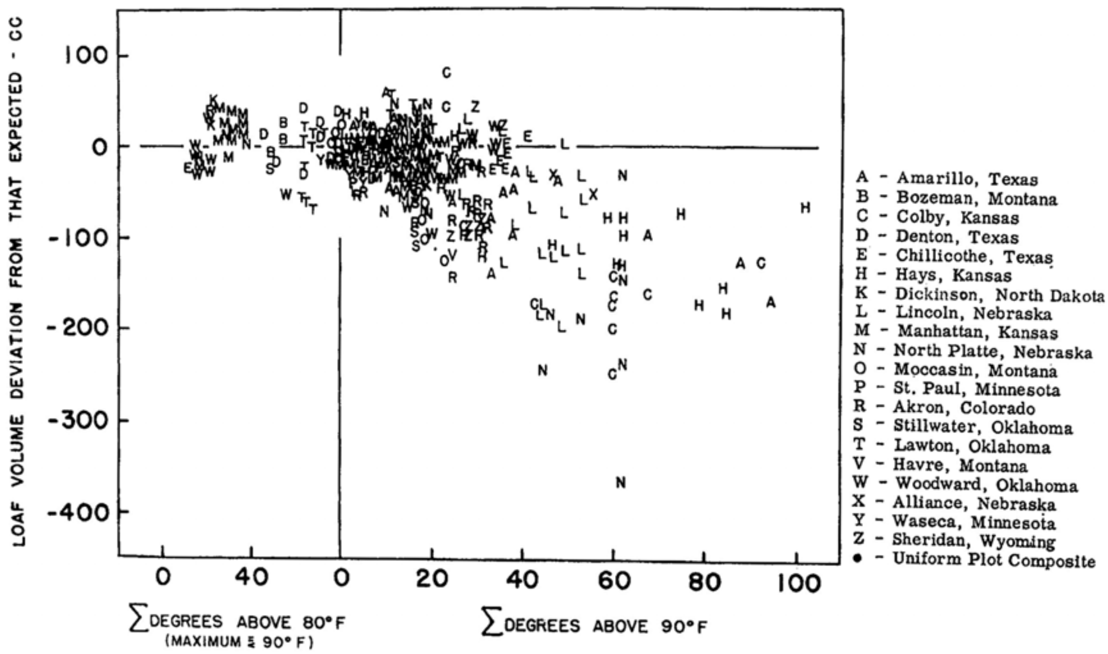

Figure 12:
Relations between loaf volume deviations from those expected and temperature during the last 15 days of the fruiting period for 391 hard red winter wheat samples. Letters indicate samples from different states of the US and 20 different experimental stations, 90° F = 32° C (Finney and Freyer 1958).

Jahn-Deesbach (1981) carried out pot experiments with wheat. With anthesis, they were transferred from outdoors into growth chambers. These variants only modestly supplied with N showed better farinograms (higher energy) under the influence of warm temperatures compared with cool conditions. In these experiments it nevertheless remained unclear, if rheological differences were only due to temperature or partly also to secondary effects on grain protein concentration. Later this handicap was tackled successfully in experiments by Schipper et al. (1986) and Schipper (1991). They grew wheat in field experiments (warmer or cooler sites during the grain filling period) and growth chambers and managed to achieve variants with comparable grain protein content. In both environments, warmer temperatures during grain filling period produced dough extensograms with lower extensibility, higher resistance and higher energy. Some examples of the many results are shown in Figure 13 and 14. Though samples grown at higher temperatures had somewhat higher glutenin:gliadin ratios, this could not explain the differences in extensograms (Schipper et al., 1986; Schipper, 1991). So possibly conformational changes in the protein structure may be the reason for these rheological differences.

Sosulski et al. (1963) conducted growth chamber experiments with wheat grown at different moisture and N levels. Different temperatures of 16.7, 21.1 and 23.9°C were applied from a very early growth stage (tillering). The results provide valuable information as they indicate different susceptibility of grain quality parameters to warmth: At comparable concentrations of grain protein sedimentation values were increased already at temperatures of 21.1°C (Figure 15a), while mixogram areas were not different from their pattern until a temperature of 23.9°C was attained (Figure 15b).

These results once more demonstrate that warmth is an important parameter influencing grain quality characteristics by strengthening protein structure and dough. Further evidence was also provided from wheat cultivars grown in glasshouses at different temperatures and under different N applications (Randall and Moss 1990). One half of the samples was moved at 30 (low N) and 34 days (high N) after anthesis to a "hot" glasshouse (23-26°C average daily temperature with a maximum temperature up to 36°C). The other half remained in the "cold" environment (18°C). Though grain N concentration of the wheat samples grown at different temperatures did not differ significantly, the maximum resistances of the doughs were significantly higher from wheat samples grown under the "hot" temperature regime, while extensibility was lowered (Table 3). Randall and Moss (1990) also point to the fact that indeed sulfur deficiency and higher temperatures have very much in common with regard to baking quality: "Sulfur deficiency increases dough resistance and decreases extensibility, and in the present work, raising the temperature caused similar changes. However, the effect of temperature on dough resistance is unlikely to be mediated through effects on grain sulfur as sulfur concentration was largely unaffected by temperature treatment".

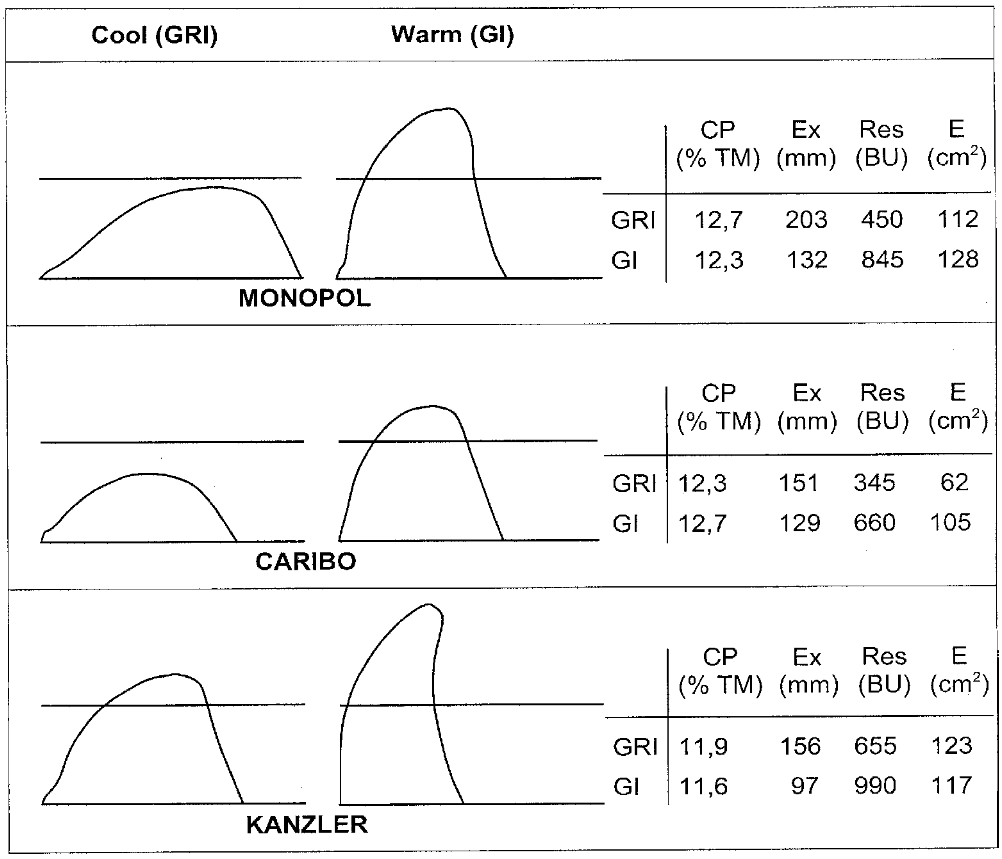

Figure 13:
Influence of different temperatures during grain filling period on wheat (cultivars: MONOPOL, CARIBO, KANZLER) of a clima-field-experiment (harvest: 1986) on the extensogram of doughs (Schipper 1991). Locations: GRI = Grimersum (cool climate); GI = Gießen (warm climate), CP = crude Protein; EX = extensibility; RES = resistance; E = energy

Table 3:
Effects of temperature on grain nitrogen and dough resistance and extensibility in three wheat cultivars, in two experiments with contrasting nitrogen levels (Randall and Moss 1990).

	OLYMPIC		HARTOG		SKUA	
Experiment	Cool	Hot	Cool	Hot	Cool	Hot
			Grain N (%)			
low N	1.51	1.72	1.78	1.88	1.63	1.72
high N	2.45	2.33	2.55	2.42	2.24	2.24
Differences: N: $P < 0.001$; temperature: n.s.; cultivar: $P < 0.01$						
			Maximum resistance (E.U.)			
low N	190	225	238	252	148	178
high N	290	383	290	345	190	215
Differences: N: $P < 0.001$; temperature: $P < 0.001$; cultivar: $P < 0.001$						
			Extensibility (cm)			
low N	16.9	16.3	20.7	18.0	16.8	15.9
high N	23.7	21.5	27.3	26.1	23.6	22.9
Differences: N: $P < 0.001$; temperature: $P < 0.001$; cultivar: $P < 0.001$						

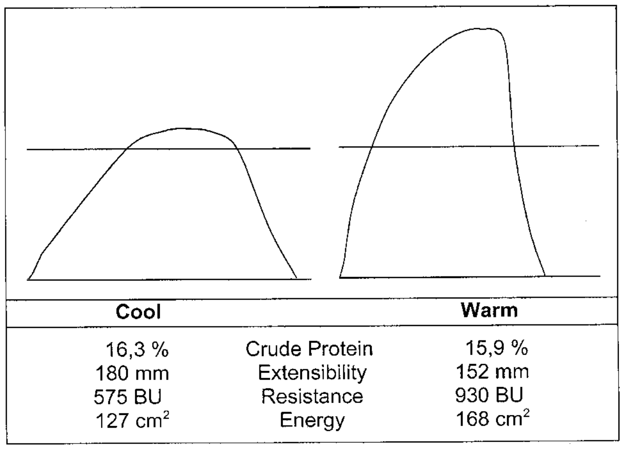

Figure 14:
Influence of different temperatures during grain filling period of wheat (cultivar: SCHIROKKO) from a pot experiment in a growth chamber in 1984 on the extensogram of dough (Schipper 1991), BU = Brabender units

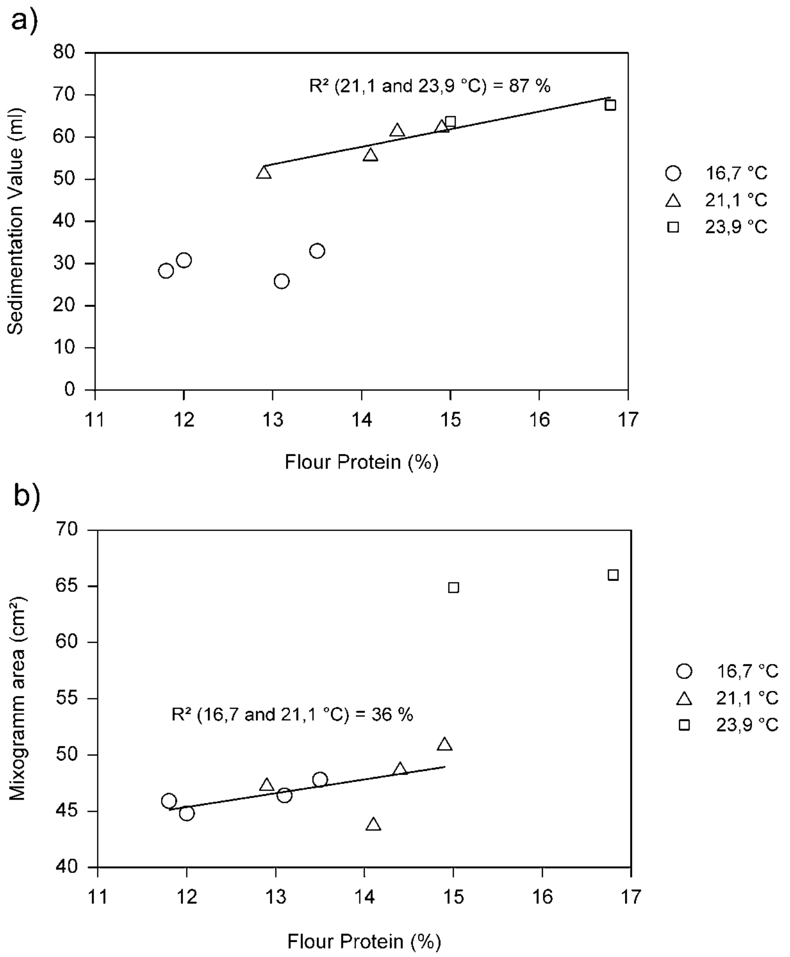

Figure 15:
a) Relationship between protein content and sedimentation value of wheat grown at different temperatures approx. 32 days after anthesis (Sosulski et al. 1963).
b) Relationship between protein content and mixogram area of wheat grown at different temperatures approx. 32 days after anthesis (Sosulski et al., 1963).

It becomes clear that gluten structure, rheological performance and the baking quality of wheat are not given, but are reactions of the plant as a living organism to certain impulses from the environment. Here S and warmth belong to the most prominent and important factors. If there is sufficient S as a substance from "below" (soil, groundwater, fertilizer) and insufficient warmth from above (cool weather, which can be regarded as little S as a process, not as a substance), the wheat plant will tend to lower proportions of HMW-glutenin and softer glutens and doughs. If on the other hand there is S deficiency from "below" and hot weather (much S from "above", which means S as a process, not as a substance) during grain filling period, the wheat plant will produce increased amounts of HMW-glutenin and tougher glutens and doughs. It is well known in biological science that all factors applied to living organisms (light, water, warmth, fertilizers etc.) show an optimum, when their input is increased. Healthy organisms and sustainable systems are, on the long run, only achieved when care is taken not to destroy this delicate equilibrium of factors producing an optimum. With regard to the baking quality of wheat breeders and cereal scientists obviously failed to achieve this aim by breeding their cultivars on the background of ample S depositions in the ecosystems. They (involuntarily) selected plants showing definite characteristics of S deficiency (higher proportions of HMW-glutenin, stronger gluten and dough) even under conditions of ample S supply. I suppose they also selected plants with a high warmth susceptibility as this also delivers firm protein structure. When this environmental pollution was stopped and S supplies returned to natural conditions, even with a non-S craving plant like wheat, problems arose with the gluten structure as doughs turned out so strong that the baking volume decreased. So one may ask, particularly with regard to the supply of S, if the plant constitutions of our modern wheat cultivars are still harmonious and in balance: On the one hand they were shifted merely for technological reasons into the realm of S deficiency characteristics, and on the other hand, in all probability, had attained an enormous warmth susceptibility. So it might well be that the nutritional quality of these cultivars is rather questionable.

The development in breeding towards ever tougher gluten and higher baking volumes is not yet complete: Both in organic and conventional agriculture the aim of lower grain protein shall be compensated through ever better technological quality. Besides milk protein wheat is often the reason for allergic reactions (Husemann and Wolff 1993). More and more people exhibit incompatibility for wheat. Several people are able to distinguish wheat (*Triticum aestivum*) from spelt (*Triticum spelta*) by observing their allergic observing their allergic symptoms (rash). They tolerate the spelt, which was not modified so intensively by breeders during the last decades. But wheat leads to skin reactions. After doubling the gluten content of baby food (< 2 years old) in Sweden there was a 300% higher incidence of celiac disease. After reducing gluten content, a reduction occurred to the normal occurrence of this illness (Ivarsson et al., 2000). Gluten-sensitivity is not confined to the small intestine (celiac disease) but also causes an inflammation of the nervous system with chronic migraine. This could be cured in 9 from 10 cases by strictly eliminating wheat from the diet (Hadjivassiliou et al., 2002).

Again several questions may arise from these phenomena: Was this alarming situation always the same or are we experiencing a sneaking development that is only the top of the iceberg? Is merely a poor human immune system the reason for the increase of allergies or does food quality play an important role? Is wheat and its protein no longer a harmless staple food? Could a shift in wheat plant constitution towards S deficiency symptoms be the reason for all the problems?

More research should be done with regard to wheat breeding with rigorous reference to the human being as a whole and his / her nutritional needs.

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References

Antes S, Wieser H (2000) Effect of HMW and LMW subunits of glutenin on the rheological dough properties and bread-making quality of wheat. Deutsche Forschungsanstalt für Lebensmittelchemie, Jahresbericht, pp 180-187

Antes S, Wieser H (2000) Effect of HMW and LMW subunits of glutenin on the rheological dough properties and bread-making quality of wheat. Deutsche Forschungsanstalt für Lebensmittelchemie, Jahresbericht, pp 180-187

Bell CI, Cram WJ, Clarkson DT (1990) Turnover of sulfate in leaf vacuoles limits retranslocation under S stress. In: Rennenberg H et al. (eds.) S nutrition and S assimilation in higher plants. SPB academic Publishing bv. The Hague, pp163-165

Bloem E, Paulsen HM, Schnug E (1995) Schwefelmangel nun auch in Getreide. DLG-Mitteilungen 8:18-19

Bolling H (1989) Qualitätsentwicklung bei Weizen und Roggen in den letzten 25 Jahren. Brot und Backweizen 9:314-327

Bushuk W (1989) Glutenin-Struktur und Einfluß des Glutenins auf die Backqualität. Getreide, Mehl und Brot 9:259-63

Byers M, Franklin J, Smith SJ (1987) The nitrogen and sulphur nutrition of wheat and its effect on the composition and baking quality of the grain. Aspects Appl Biol 15:327-344.

Castle SL, Randall PJ (1987) Effects of S deficiency on the synthesis and accumulation of proteins in the developing wheat seed. Aust. J. Plant Physiol. 14:503-516

Clarkson DT, Hawkesford MJ, Davidian J-C (1993) Membrane and long distance transport of sulfate. In: De Kok LJ et al. (eds.) S nutrition and S assimilation in higher plants. SPB Academic Publishing bv. The Hague, pp 3-19

Cotton FA, Wilkinson G, Murillo C, Bochmann M (1999) Advanced Inorganic Chemistry. 6th ed., New York, Wiley

Cram WJ (1990) Uptake and transport of sulphate. In: Rennenberg H et al. (eds.): Sulphur nutrition and sulphur assimilation in higher plants. SPB Academic Publishing, Den Haag, pp 3-13

Doekes GJ, Wennekes LMJ (1982): Effect of nitrogen fertilisation on quantity and composition of wheat flour protein. Cereal. Chem. 59:276-278.

Fajersson F (1975) Klima, Düngung, Sorte – wichtige Faktoren für die Weizenqualität. Die Mühle und Mischfuttertechnik 112:671-679

Field JM, Shewry PR, Miflin BJ (1983) Solubilisation and characterisation of wheat gluten proteins: Correlations between the amount of aggregated proteins and baking quality. J. Sci. Food Agric. 34:370-377

Finney KF, Fryer HC (1958) Effect on loaf volume of high temperatures during the fruiting period of wheat. Agron J 50:28-34

Gupta RB, Khan K, MacRitchie F (1993) Biochemical basis of flour properties in bread wheats. II Effects of variation in the quantity and size distribution of polymeric protein. J Cereal Sci 18:23-41

Ivarsson A, Persson LA, Nyström L, Ascher H, Cavell B, Danielsson L, Dannaeus A, Lindberg T, Lindquist B, Stenhammar L, Hernell O (2000) Epidemic of celiac disease in Swedish children. Acta Paediatr. 89:165-171

Jahn-Deesbach W (1981) Untersuchungen über den Einfluss von Klimafaktoren auf Ertrag und Qualität von Weizen (Klimakammerversuche). Getreide, Mehl und Brot 35:281-286

Johansson E, Svensson G (1998) Variation in breadmaking quality - effects of weather parameters on protein concentration and quality in some Swedish wheat cultivars grown during the period 1975-1996. J Sci. Food Agric 78:109-118

Johansson E, Svensson G (1999) Influences of yearly weather quality in Swedish grown wheats containing HMW glutenin subunits 2 + 12 or 5 + 10 cultivated during the period 1990 - 96. J Agric Sci 132:13-22

Hadjivassiliou M, Grünewald RA, Davies GAB (2002) Gluten sensitivity as a neurological illness. J. Neurol. Neurosurg. Psychiatry 72:560-563

Hagel I (2000 a) Biobrot aus Schwefelmangelweizen? – Ein Beitrag zur Qualitätsbeurteilung der festen Proteinstruktur moderner Weizensorten. Institut für Biologisch-Dynamische Forschung, Darmstadt, Schriftenreihe Band 14, ISBN 3-928949-14-4

Hagel I (2000 b) Differenzierung und Charakterisierung von Weizen verschiedener Anbausysteme und Sorten durch Proteinfraktionierung. Diss., Braunschweig. Landbauforschung Völkenrode, Sonderheft 208. ISBN 3-933140-30-7

Hagel I (2000 c) Auswirkungen einer Schwefeldüngung auf Ertrag und Qualität von Weizen schwefelmangelgefährdeter Standorte des Ökologischen Landbaus. Landbauforschung Völkenrode, Sonderheft 220, ISBN 3-933140-42-0

Hagel I (2002) Weizenzüchtung auf hohe technologische Qualität durch induzierten Schwefelmangel. Deutsche Gesellschaft für Qualitätsforschung e.V., XXXVII. Vortragstagung, 4. - 5. März 2002, Hannover, 307-312

Hagel I, Schnug E (1999) Proteinfraktionen und Schwefelgehalte von Winterweizen aus konventionellem und biologisch-dynamischem Anbau des Erntejahres 1997. Deutsche Gesellschaft für Qualitätsforschung (Pflanzliche Nahrungsmittel) e.V., 34. Vortragstagung, 22./23. März 1999, Freising-Weihenstephan, pp 335-340

Hagel I, Spieß H, Schnug E (1998) Proteinqualität alter und moderner Winterweizensorten und -zuchtstämme. Deutsche Gesellschaft für Qualitätsforschung (Pflanzliche Nahrungsmittel) e.V., XXXIII. Vortragstagung, 23./24. März 1998, Dresden, pp 165-170

Hagel I, Kieffer R, Schnug E (1998 b) Schwefelgehalte und Qualitätseigenschaften von Weizen aus biologisch-dynamischem und konventionellem Anbau. Deutsche Gesellschaft für Qualitätsforschung (Pflanzliche Nahrungsmittel) e.V., XXXIII. Vortragstagung, 23./24. März 1998, Dresden, pp 223-228

Hagel I, Wieser H, Schnug E (1999) Wirkungen hoher Schwefelgaben auf Proteinfraktionen und Kleberqualität von Weizen. Deutsche Gesellschaft für Qualitätsforschung (Pflanzliche Nahrungsmittel) e.V., 34. Vortragstagung, 22/23 März 1999, Freising-Weihenstephan

Haneklaus S, Evans E, Schnug E (1992) Baking quality and sulphur content of wheat. I. Influence of grain sulphur and protein concentrations on loaf volume. Sulphur in Agric 16:31-34

Husemann F, Wolff O (1993) Das Bild des Menschen als Grundlage der Heilkunst. Verlag Freies Geistesleben, Stuttgart, S. p 533

Kieffer R, Wieser H, Henderson MH, Graveland A (1998) Correlations of the breadmaking performance of wheat flour with rheological measurements on a microscale. J Cereal Sci 27:53-60

Kim J-J, Kieffer R, Belitz H-D (1988) Rheologische Eigenschaften von rekonstituierten Weizenklebern mit variierenden Anteilen an Prolaminfraktionen verschiedener Getreidearten. Z Lebensm Unters Forsch 186:16-21

Klemt G (1934) Mehllagerung und Backfähigkeit. Z. für das ges. Getreidewesen 10:217-221

Kosmin N (1934) Reifung der Weizenmehle und ihre biochemischen Grundlagen. Das Mühlenlaboratorium 4:17-32

MacRitchie F, Gupta RB (1993) Functionality-composition relationships of wheat flour as a result of variation in S availability. Aust J Agric Res 44:1767-1774

McDonald GK, Sutton BG, Ellison FW (1983) The effect of time sowing on the grain yield of irrigated wheat in the Namoi Valley, New South Wales. Aust J Agric Res 34:229-240

Mortimer C (1996) Chemie - Das Basiswissen der Chemie. Georg Thieme Verlag, Stuttgart, 412-413

Moss HJ, Wrigley CW, MacRitchie F, Randall PJ (1981) S and nitrogen fertilizer effects on wheat. II Influence on grain Quality. Aust. J Agric Res 32:213-226

Orth RA, Bushuk W (1972) A comparative study of proteins of wheats of diverse baking qualities. Cereal Chem 49:268-275

Randall PJ, Moss HJ (1990) Some effects of temperature regime during grain filling on wheat quality. Aust J Agric Res 41:603-617

Schipper A (1991) Modifizierbarkeit teigphysikalischer Eigenschaften verschiedener Weizensorten durch Umwelteinflüsse. Agribiol Res 44:114-132

Schipper A, Jahn-Deesbach W, Weipert D (1986) Untersuchungen zum Klimaeinfluss auf die Weizenqualität. Getreide, Mehl und Brot 40:99-103

Schnug E (1991) Sulphur nutritional status of European crops and consequences for agriculture. Sulphur in Agric 15:7-12

Schnug E, Haneklaus S (1994) Sulphur deficiency in brassica napus. Biochemistry - Symptomatology - Morphogenesis. Wissenschaftliche Mitteilungen der Bundesforschungsanstalt für Landwirtschaft Braunschweig - Völkenrode, Sonderheft 144

Schnug E, Haneklaus S, Murphy D (1993) Impact of sulphur supply on the baking quality of wheat. Aspects of Applied Biology 36, Cereal Quality III, pp 337-345

Schropp P, Wieser H (1994) Wirkung von HMW-Untereinheiten des Glutenins auf die rheologischen Eigenschaften von Weizenkleber. Deutsche Forschungsanstalt für Lebensmittelchemie, Jahresbericht, pp 136-147

Seilmeier W, Kieffer R, Belitz H-D (1992) Gluteninfraktionen und rheologische Eigenschaften verschiedener Weizensorten. Deutsche Forschungsanstalt für Lebensmittelchemie, Garching, Bericht 1992, pp 145-151

Seilmeier W, H. Wieser, R. Gutser und S. von Tucher (2001) Einfluss der Schwefeldüngung auf die quantitative Zusammensetzung der Kleberproteine in Weizenmehl. Deutsche Forschungsanstalt für Lebensmittelchemie, Bericht 2001, pp 183-190

Sosulski FW, Paul EA, Hutcheon WL (1963) The influence of soil moisture, nitrogen fertilization and temperature on quality and amino acid composition of Thatcher wheat. Can J Soil Sci 43:219-228

Svensson G (1974) Års variationer I brösädens kvalitet. Agri hortique Genetica, Weibullsholm 32:15-26

Wieser H, Zimmermann G (2000) Importance of amounts and proportions of high molecular weight subunits of glutenin for wheat quality. Eur Food Res Technol 210:324-330

Wieser H, Kieffer R (2001) Correlations of the amount of Gluten proteintypes to the technological properties of wheat flours determined on a microscale. J. Cereal Sci. 34:19-27

Wieser H, Seilmeier W (1998) The influence of nitrogen fertilisation on quantities and proportions of different protein types in wheat flour. J. Sci. Food Agric. 76:9-55

Wieser H, Seilmeier W, Belitz H-D (1994) Use of RP-HPLC for a better understanding of the structure and functionality of wheat gluten proteins. In: Kruger, J.E. and J.A. Bietz (eds) High-performance liquid chromatography of Cereal and Legume Proteins. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA

Wieser H, Seilmeier W, Belitz H-D (1980) Vergleichende Untersuchungen über partielle Aminosäuresequenzen von Prolaminen und Glutelinen verschiedener Getreidearten. I Proteinfraktionierung nach Osborne. Z. Lebensm. Unters Forsch 170:17-26

Wieser H, Seilmeier W, Belitz H-D (1991) Klassifizierung der Proteinkomponenten des Weizenklebers. Getreide, Mehl und Brot 45:35-38

Wrigley CW, Du Cros DL, Fullington JG, Kasarda DD (1984 a) Changes in polypeptide composition and grain quality due to S deficiency in wheat. J Cereal Sci 2:15-24