Global Warming and Wheat Quality

Predictions of human-induced global climate change are derived from increases in atmospheric levels of carbon dioxide, which cause warmer temperatures, especially the daily minima, change rainfall patterns, increase the frequency of episodes of very hot weather, decrease frost frequency, and cause rising sea levels. These trends have implications for possible fluctuations in wheat yield and quality. Already, many established wheat-growing regions experience growth temperatures well above the moderate temperature (15°C, 60°F) that is generally acknowledged to be optimal for growing wheat and related cereals (9).

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Despite this, wheat is grown successfully in temperate and hot regions of southern Europe, Asia, North and South America, southern Africa, and Australia, where expected daily maximum temperatures during the grain-filling period are well over 25°C. Average global temperatures are predicted to rise by about 2 degrees Celsius over the next 50 years, making many cereal-growing regions even less suitable, based on predicted temperature ranges. Furthermore, these regions already experience episodes of heat stress (such as a few successive days with maximum temperatures of 35–40°C) during the times of year when plants are at the grain-filling growth stage. Based on predictions, such episodes of heat stress are likely to become more frequent in the future.

Early sowing strategies are currently employed to avoid periods of heat stress, but there is an increased risk of frost at the flowering stage. This approach to escaping heat stress may be more effective in the future, given that daily minimum temperatures are increasing faster than daily maximum temperatures.

Atmospheric Carbon Dioxide—A Free Fertilizer

Atmospheric levels of carbon dioxide have risen from a historic base (a few centuries ago) of about 270 parts per million to almost 380 ppm today. A doubling of this level is predicted to occur during the current century. Estimates of historic levels come from analyses of air bubbles trapped in Antarctic ice. More recently, the record of CO_2 change is based on air sampling at the Mauna Loa crater in Hawaii, beginning in the International Geophysical Year of 1958. Small annual variations in these levels are cyclical, apparently reflecting annual changes in the rate of photosynthesis. These annual cycles illustrate the importance of plants in determining CO_2 levels. Emission of CO_2 by fossil-fuels counteracts these cycles, as is illustrated by the gradient of CO_2 from the Northern Hemisphere (where most energy is used) to the Southern Hemisphere.

Atmospheric carbon dioxide is the source of carbon for plants. Variations in its concentration have obvious implications for plant production generally and for grain yield specifically. Experimental growth of plants in atmospheres enriched with carbon dioxide clearly result in higher plant biomass yields, indicating that enrichment with carbon dioxide amounts to the addition of carbon fertilizer. This effect is more marked (given adequate water) for plant species that have the more common C3 photosynthetic pathway than for species with C4 photosynthetic pathways. C3 species include wheat, barley, and rice, whereas maize, sorghum, and sugarcane are C4 species. Under water-limiting conditions, both C3 and C4 species respond relatively strongly to elevated carbon dioxide concentrations. Many experiments have demonstrated that the fertilizing effects of carbon dioxide are more significant at higher temperatures, a combination of concomitant conditions that are predicted to accompany global warming.

Effects of Carbon Dioxide on Grain Yield and Quality

Reports on the growth of wheat in atmospheres enriched with carbon dioxide indicate that increases in grain yield can be expected as changes in the global climate progress (6). Some of these experiments have involved the use of plastic-covered tunnels placed over the growing crop to enclose an appropriate gas mixture and regulate temperature and gas flow to simulate predicted scenarios (11). Table I shows the results of a field trial in which this experimental approach was used.

The greatest increase in grain yield (35%) was achieved at a moderate daily temperature of 20°C; yield increases were much less at lower temperatures. Yield increase was due to more grains, rather than to larger grains. The grain from CO_2-enriched plants had lower protein contents, which is consistent with the concept of CO_2 acting as a carbon fertilizer. The fertilizer effect caused increases in grain starch content, seen largely as an increased proportion of large (A-type) starch granules. The latter change in quality would be welcomed by some parts of the wheat industry, such as starch-gluten manufacturers. The yield increase would be welcomed generally, but lower protein content would have serious consequences for most wheat applications. Grain from these experiments produced doughs that were relatively normal in their mixing properties, except for the weaker quality that would be expected for samples with much lower protein contents (3).

Table I. Changes in wheat yield and quality as a result of doubling the level of atmospheric carbon dioxide to 700 ppm (means of results for two varieties)[a]

	Summer Crop	Spring Crop	Winter Crop
Mean day temperature during grain filling (°C)	20	17	15
Change in grain yield (%)	+35	+9	+6
Change in grain mass (%)	–12	–8	–4
Change in protein content (%)	–19	–2	–16
Change in large starch granules (%)	+11	+17	+17

[a] Adapted from Rawson (11) and Blumenthal and coworkers (3).

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Temperature Changes and Dough Quality

The production of wheat in regions where temperatures are higher than the optimum has provided a strong stimulus for research on the effects of temperature on grain yield and quality. Temperatures higher than the optimum (15°C) accelerate the rate of maturation, causing reductions in yield and increases in protein content and the proportion of large starch granules. Grain protein composition and dough quality are changed as a result. Dough strength shows modest increases (Fig. 1) when growth temperatures increase through the 15–30°C range during grain filling (5,8,10). Uhlen and coworkers (13) demonstrated the positive effects on dough strength of increasing temperatures in the 9–21°C range during kernel development. This strengthening effect has been reported as occurring at "high temperature" by authors from regions where temperatures higher than 20°C are regarded as high.

When temperatures increase further, into the heat-stress range of a few days with daily maxima higher than 35°C, there is considerable loss of dough strength for many genotypes (as shown by the third column in each part of Fig. 1). This dough-weakening effect has been reported by many researchers during the past decade in various warmer regions of the world (1,4,5,8,10,12).

A prominent wheat breeder in a Midwestern U.S. program commented some years ago, "One of my first concerns will be the damaging effects of heat stress on dough strength." In this statement, he reflected the much earlier report (1958) from the American Midwest by Finney and Fryer (7): "Loaf volume and mixing time decreased with accumulated degrees Fahrenheit above 90°F [> 32°C] during the last 15 days of the fruiting period." They also reported that these decreases were not uniform: they were "51 to 84%, depending on variety." This theme also is seen in more recent reports, i.e., there is a naturally occurring tolerance to heat stress.

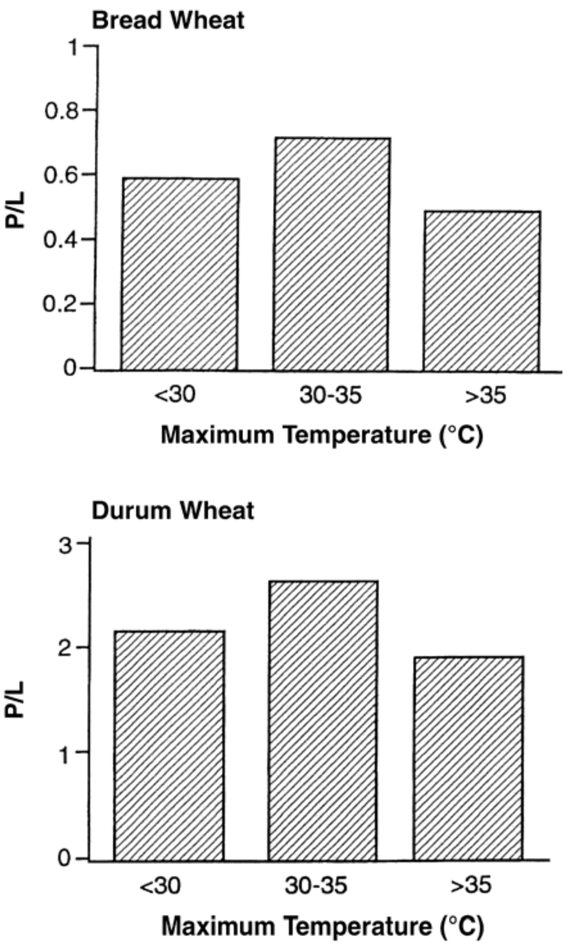

Fig. 1. Variation in dough quality (determined using an alveograph) due to changes in growth temperatures during grain filling. Results are for four bread wheat and four durum varieties grown at four sites in Italy, with sowing times and sites selected to provide the three growth-temperature ranges indicated. Adapted from Corbellini and coworkers (5).

Genotypic Tolerance to Heat Stress

Genotypic variation was demonstrated in a set of 44 wheat and one durum wheat genotypes in growth-cabinet experiments (in duplicate with controls) (2). The reactions to imposed heat stress were mostly loss of dough strength, but reactions did range from loss of dough strength to tolerance. Many of the genotypes that showed tolerance had the 5+10 pair of high molecular weight (HMW) glutenin subunits (white columns in Fig. 2); this distinction was significant at $P < 0.001$.

The same phenomenon was evident in three of four varieties that occur naturally as pairs of biotypes and differ with respect to these HMW-glutenin subunits (Table II). The pairs of biotypes were grown separately as plants in a glasshouse, with the imposition of heat stress for a few days at 40°C for the treatment set. The control plants received no heat-stress treatment. In addition to the 5+10 biotypes (control samples) showing greater strength compared with the 2+12 biotypes, they also tolerated heat stress better (significant at $P < 0.05$), except for cv. Lance. In several Australian crop reports of heat stress, mostly involving early and late sowings, the late sowings were heat-stressed. Six varieties with the 5+10 HMW subunits showed tolerance (no loss of dough strength), whereas all 10 2+12 varieties and one 5+10 variety were susceptible to heat stress.

If this phenomenon can be generalized, it should provide a valuable marker of heat-stress tolerance (with respect to dough quality) for use in breeding. It would also alert grain buyers to the possibility that heat-stress episodes prior to harvest may have damaged dough strength for some varieties.

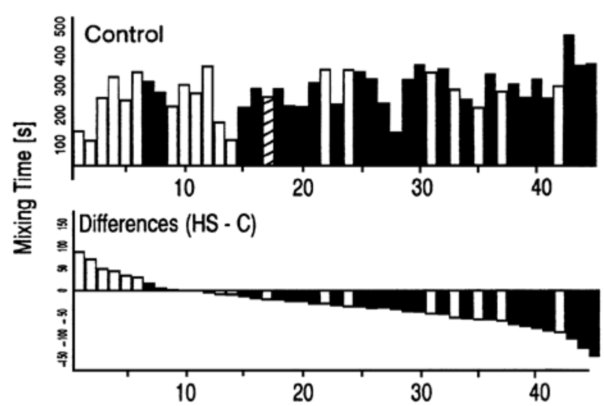

Fig. 2. Dough-strength results (as time to maximum resistance in a mixograph) for doughs from plants of 45 wheat varieties grown under controlled conditions (C; 1 day at 18°C; upper plots) and for dough from heat-stressed plants (HS; 3 days at 40°C). Changes due to heat stress (lower plots) appear as mix times for HS – C values. Black and white columns represent genotypes with 2+12 and 5+10 pairs of high molecular weight glutenin subunits, respectively. The striped column is a durum wheat. Reproduced from Blumenthal and coworkers (2).

Table II. Effects of heat stress on the dough properties of four wheat varieties with two biotype pairs[a]

Variety	2+12 Biotypes	5+10 Biotypes
Avocet	–49	+19
Lance	–65	–87
Kewell	–26	+7
Warigal	–60	–9

[a] Results appear as the difference (heat stress minus control) for mix time in a mixograph.

Conclusions

Global warming is likely to increase the frequency of heat-stress episodes and cause dough weakening. We need to be aware of this likelihood and take adaptive management and breeding steps to reduce the associated risks. These steps should involve further research to understand the mechanisms involved in dough weakening and provide breeders with selection tools to assist in the production of varieties that will tolerate heat stress. In addition, knowledge of the interaction of genotype with environmental stresses would offer buyers a means of avoiding grain that may be heat-damaged.

Based on current research, the effects of increased levels of carbon dioxide may provide the benefits of higher grain yields, with few negative effects on grain quality apart from lower protein content. Agronomic strategies must be developed to take advantage of yield potential, while maintaining protein content at acceptable levels. Breeders and cereal chemists need to continue to be aware of the many important interactions of genotype with growth conditions in managing grain quality, however.

Concerns regarding the effects of global warming on crops are not isolated to wheat. In fact, rice may be the cereal most affected by global warming, due to the loss of delta rice-growing regions resulting from rising sea levels.

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