An empirical model of wheat baking quality under elevated CO_2

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Abstract
Elevated CO_2 (eCO_2) is associated with lower grain protein concentration of wheat, and an inferior baking quality. To extend the functionality of process-based models of wheat growth and nitrogen uptake, an empirical model for bread making quality (loaf volume and dough extensibility) was developed from five years of data from the free air carbon dioxide enrichment experiment at Horsham, Victoria, for three bread-wheat cultivars – Janz, Silverstar and Yitpi.

Loaf volume was modelled by a relationship derived by linear regression, which accounted for 82% of variation, and had significant terms for eCO_2, grain protein concentration, cultivar and a cultivar-CO_2 interaction. A model of dough extensibility accounted for 79% of variation.. At a given protein concentration and CO_2 level, Janz and Silverstar both had loaf volumes over 100 cm^3 larger than Yitpi. It is suggested that acceptance criteria for grain receival into premium categories be based on cultivar-specific protein levels that produce equivalent loaf volumes. This would incentivise breeding efforts to improve the baking quality of wheat protein as an adaptation strategy for higher CO_2 levels.

Key Words
FACE, free air carbon dioxide enrichment, loaf volume, dough extensibility

Introduction

A gradual but fundamental change to world cereal markets over coming decades is the effect of higher CO_2 levels reducing the protein concentration of cereal grains. Within C3 plants there are three distinct responses to enhanced CO_2 (Leaky et al. 2009). Firstly, there is an increase in net photosynthesis because of reduced dark respiration. Secondly, there is decreased stomatal conductance, leading to increases in the water use efficiency of growth. Thirdly, there is an increase in the N use efficiency of leaves, leading to a decrease in leaf N concentrations, which in wheat (*Triticum aestivum* L.) leads to lower amounts of leaf nitrogen available for translocation to grain to during grain filling. All three effects result in a dilution of N concentration within the plant. The first two of these effects are already incorporated into some process-based crop models such as Sirius Quality and APSIM (Jamieson et al. 2000, Martre et al. 2003, Asseng et al. 2004). However, comparison with measurements under Free Air CO_2 Enhancement (FACE) (Kimball et al. 2001) indicates that these models under-estimate the effects of higher CO_2 levels on grain protein concentration because they do not take account of the third effect of leaf N concentration. Furthermore, there are cascading effects on product quality that are not accounted for in the best process-based models. Panozzo *et al.* (2014) reported that elevated CO_2 was associated with a 3-5% reduction in grain protein concentration, but a larger reduction in loaf volume of 6-10%, and a reduction in dough rheology of 7-8 %. These findings were reported from a field experiment with 3 cultivars of bread wheat grown under ambient CO_2, and elevated conditions of 550 µmol CO_2/mol. Under the highest-emission scenario developed by the Intergovernmental Panel for Climate Change, this CO_2 level can be expected about 2050 (IPCC 2014), which is within the economic life of cultivars currently under development.

The objectives of this study were to determine the impact of elevated CO_2 on acceptance of wheat grain into the premium pool based on current market standards; to develop an empirical regression-based model for 2 key parameters of baking quality that are strongly affected by elevated CO_2 – loaf volume and dough extensibility; and to extend the functionality of our process-based models (Martre et al. 2003, Nuttall et al. 2016). The study used data from the FACE study previously published by Panozzo et al. (2014), supplemented by data from 2 additional years.

Methods

Experimental

Three bread wheat cultivars (Yitpi, Silverstar and Janz) were grown in field trials in 2008, 2010, 2011, 2012 and 2013 under ambient CO_2 (aCO_2, ~365 µmol /mol) and elevated CO_2 (eCO_2, ~550 µmol /mol) at

Horsham, Victoria, Australia. These varieties are all accepted for delivery into the Australian Hard pool provided other quality parameters are met, such as a minimum protein concentration of 13.0% (GrainCorp 2015). The soil was a Vertosol according to the Australian Soil Classification (Isbell 2002), had high background levels of mineral nitrogen of ~300 kg/ha (O'Leary et al. 2015), and was not responsive to further applied nitrogen. In most years the design consisted of 2 CO_2 levels x 2 irrigation treatments (rainfed and supplementary spring watering) x 3 varieties x 4 replicates. In 2008 there were 2 times of sowing. After harvest, grain protein concentration was determined by Dumas combustion using the Leco TruMac. Results are expressed on an 11% moisture basis. Loaf volume was assessed using the long fermentation AACC 10-10B method, and dough extensibility by AACC 54-10 (AACC 2000). Further details of experimentation and laboratory methods, including yield results are provided by Panozzo et al. (2014) and Fitzgerald et al. (2016).

Statistical analysis
Grain protein concentration data were analysed by unbalanced analysis of variance for each cultivar separately. All analyses were undertaken using Genstat v17 (Payne 2013), allowing for blocking effects of year and replicate. Loaf volume and dough extensibility were first analysed using the REML procedure to determine which factors and interactions were required for a regression-based model to predict loaf volume and dough extensibility from grain protein concentration, CO_2 level, cultivar and irrigation. Secondly, the generalised linear model procedure was used to calculate coefficients, fitted values and their confidence intervals.

Results

In all three cultivars, the proportion of samples that met the current minimum protein percentage for acceptance into the hard-wheat H1 pool was lower under eCO_2 (Table 1). The greatest impact was on Silverstar, which had lower protein than the other cultivars. REML analysis for loaf volume showed significant effects of grain protein concentration, cultivar and CO_2 on loaf volume, but no significant effects of irrigation or interactions were observed. The model resolved into equations of the form

$$V = a.C + b.P + c + d.C.P + \epsilon_Y + \epsilon_B + \epsilon_{YB} + \epsilon_R$$

where V is loaf volume (cm^3), C the CO_2 level (0 for ambient, 1 for elevated), P the grain protein concentration (%),fitted coefficients a to d, of which a and c are cultivar-dependent with unexplained error consisting of year (ϵ_Y), block (ϵ_B), interaction (ϵ_{YB}) and other (ϵ_R) components (Fig. 1, Table 2). REML analysis showed that a similar model was appropriate for extensibility, apart from a significant main effect of irrigation (P <0.001) and no significant interaction between CO_2 and protein, nor between CO_2 and cultivar. However, irrigation is not practical for a predictive model because a similar effect would be expected from seasons or locations of higher rainfall, so it was excluded from the final model (Table 2). These relationships accounted for 84% of the variation in loaf volume, and 79% of the variation in extensibility.

Table 1. Summary of the number of observations, the percentage of cases satisfying the minimum protein level for the H1 grade (13%) under ambient and elevated CO_2 (aCO_2 and eCO_2 respectively), mean protein concentration, loaf volume predicted from the coefficients in Table 2 at a protein concentration of 13%, standard errors of differences (SED) and the statistical probability level of significant (*P*) determined from statistical analysis.

Cultivar	n	Percentage of samples in H1		Grain protein concentration (%)			*P*	Loaf volume (cm^3)			*P*
		aCO_2	eCO_2	aCO_2	eCO_2	SED		aCO_2	eCO_2	SED	
Janz	75	76	62	13.57	13.14	0.151	< 0.01	821	781	13.1	<0.01
Silverstar	43	64	24	12.09	11.53	0.098	<0.001	830	843	15.5	ns
Yitpi	118	81	71	13.98	13.33	0.133	<0.001	709	691	9.8	<0.1

Loaf volume was more strongly influenced by grain protein concentration under eCO_2, as evidenced by a significantly steeper slope (i.e. $b + d$) then under aCO2. For example, in Janz a 10.0% relative decrease in grain protein concentration from 13.0% to 11.7% under eCO_2 was associated with an 11.4% decrease in loaf volume, whereas under aCO_2 the 10.0% relative decrease in grain protein concentration translated to an 8.7% decrease in loaf volume. However, these steeper slopes caused a cross-over at higher protein levels where this linear model predicted larger loaf volumes under eCO_2 above grain protein levels of 11.9% for Silverstar (not represented in Fig. 1), 14.4% for Yitpi and 16.0% for Janz (Fig. 1). The cross-over between eCO2 and aCO2 relationships is due to leverage at lower grain protein concentrations, and there are relatively few points above the cross-over. At 13.0% grain protein, loaf volume predicted by this relationship was 5% lower under eCO_2 for Janz, but was not significantly affected in the other cultivars (Table 1). At a given grain protein and CO_2 level, loaf volume was over 100 cm^3 larger in Janz and Silverstar than Yitpi.

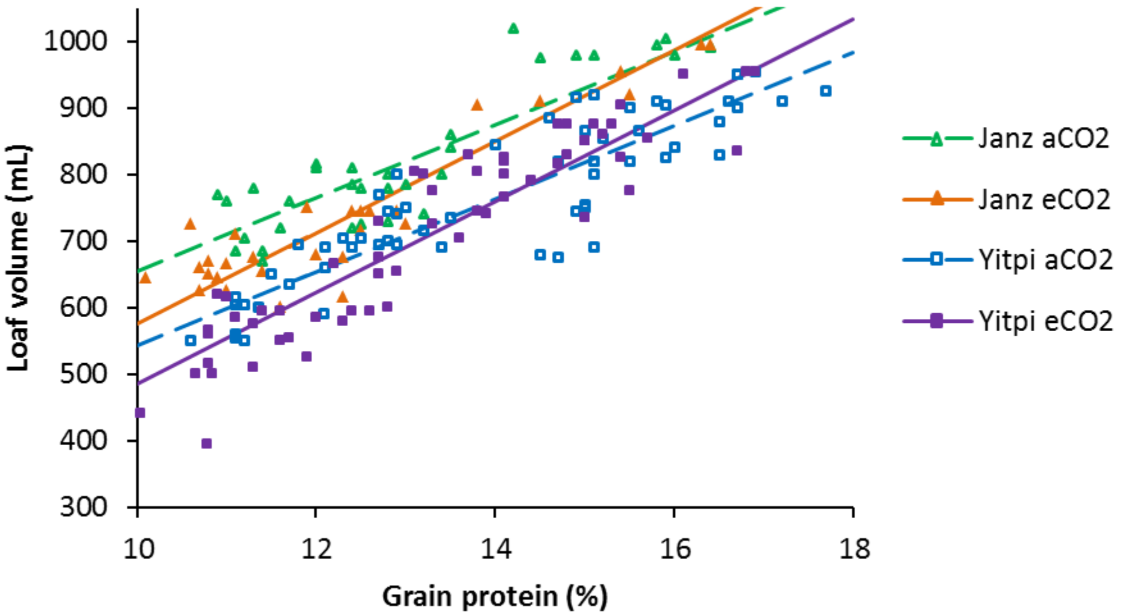

Figure 1. Relationship between grain protein concentration and loaf volume for cultivars Janz and Yitpi under ambient and elevated CO_2 (aCO_2 and eCO_2 respectively), and predictive relationships using coefficients from Table 2. (cv. Silverstar not shown for clarity).

Table 2. Coefficients of the regression relationships to estimate loaf volume and dough extensibility from grain protein percentage, cultivar and CO_2. Cultivar-specific coefficients separated by different letters are significantly different at the 5% level.

Coefficient	Loaf volume (cm^3)			Extensibility (cm)		
	Estimate	SE	P	Estimate	SE	P
a (CO_2)			<0.001	-0.172	0.172	<0.001
Janz	-215b	50.7		-	-	
Silverstar	-163a	47.9		-	-	
Yitpi	-193ab	50.7		-	-	
b (protein)	55.1	5.53	<0.001	1.22	0.127	<0.001
c (cultivar)			<0.001			<0.001
Janz	104a	38.6		6.15a	1.97	
Silverstar	113a	36.4		6.19a	1.95	
Yitpi	-8.1b	40.9		4.77b	1.96	
d (CO_2 x protein)	13.5	3.89	0.001	-	-	ns

Discussion

Our analyses show the dependence of bread-making quality (loaf volume and dough extensibility) on grain protein concentration, cultivar and atmospheric CO_2 concentration. While high CO_2 causes a reduction in protein concentration that in turn leads to a reduction in baking quality, there are additional cultivar-dependent effects of CO_2 on loaf volume. At a given protein concentration and CO_2 level, both Janz and Silverstar had loaf volumes over 100 cm^3 larger than Yitpi. Under current marketing arrangements, there is a single grain protein concentration threshold of 13% for acceptance of all "hard-wheat" cultivars into the H1 pool (GrainCorp 2015). If receival thresholds were instead cultivar dependent (based on comparable loaf volumes), this may provide an incentive for growers and breeders to select cultivars for improved baking quality at a given protein concentration that would facilitate production of a higher quality product despite higher CO_2 levels. Selected cultivars would need to translocate high amounts of nitrogen into grain and store them as proteins that achieve high baking quality. Additional research is required to move from this empirical model to more mechanistic models of grain quality so that the impact and adaptation strategies needed in other parts of Australia are better understood.

Acknowledgements
Research within the AGFACE facility was supported by the Grains Research and Development Corporation (GRDC) and the Australian Government Department of Agriculture in a joint collaboration between the Victoria State Department of Economic Development, Jobs, Transport and Resources (DEDJTR) and the University of Melbourne (UoM). We wish to acknowledge the important contributions of Russel Argall (DEDJTR), Peter Howie (UoM), Nathan Neumann (DEDJTR), Janine Fitzpatrick (DEDJTR) and Justine Ellis (DEDJTR) in running and maintaining the AGFACE facility, collecting key measurements and for sample processing.

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