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FIELD-6604; No. of Pages 10
ARTICLE IN PRESS
Field Crops Research xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Field Crops Research
journal homepage: www.elsevier.com/locate/fcr

Models of grain quality in wheat—A review

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ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
16 December 2015
Accepted 18 December 2015
Available online xxx

Keywords:
Simulation models
Protein
Glutenin
Gliadin
Heat stress
Climate change
FACE

ABSTRACT

Maintaining grain quality of wheat under climate change is critical for human nutrition, end-use functional properties, as well as commodity value. This paper reviews the current knowledge of high temperature and elevated atmospheric CO_2 on whole-grain and functional properties of wheat. It also considers the utility of contemporary crop models for investigating the impacts of climate change on wheat quality; and discusses opportunities for advancing model capability. Under elevated CO_2 wheat yield can increase by up to 36%, but universally grain protein concentration decreases and a shift in composition translates to reduced functional properties. High temperature during the post-anthesis period of crops can cause a step change reduction in grain-set, grain size and milling yield. Numerous crop models including APSIM-Nwheat, CropSyst, Sirius, GLAM-HTS account for high CO_2 effects through modification of RUE, TE or critical leaf-N concentration and high temperature by accelerated leaf senescence, grain number, potential grain weight or HI modifications. For grain quality, however, crop models are typically restricted to predicting average grain size and grain-N content (concentration), although the SiriusQuality model accounts for the major storage proteins, gliadin and glutenin. For protein composition, high temperature stress reduces the glutenin/gliadin ratio and limits the synthesis of the larger SDS-insoluble glutenin polymers which causes wheat dough to have weaker viscoelasticity properties. This link provides an opportunity to model high temperature effects on grain functional properties. Further development and testing, utilizing grain quality data from global FACE programmes will be particularly valuable for validating and enhancing the performance of such models. For whole-grain characteristics, a single-spike model approach, which accounts for intra-spike variation in assimilate deposition may provide an opportunity to predict grain size distribution and associated screenings percentage and milling yield. Taken together expanding the predictive capability of our crop models to grain quality is an important step in providing a powerful tool for developing adaptation strategies for combating the impacts of climate change to global crop production and grain quality.

1. Introduction

Maintaining grain quality under climate change is critical for human nutrition, end-use functional properties and commodity value. Wheat (*Triticum aestivum* L.) is one of the significant staple grains with worldwide production being 672 million tonnes in 2012 (FAOSTAT, 2014). Increasing environmental stress on wheat production associated with climate change will affect both the yield and quality of wheat production.

Grain quality is defined by a range of physical and compositional properties where threshold requirements are set according to end-use requirements. For staple grains such as wheat, whole-grain physical properties such as size and shape influence milling yield and screening losses, which determine the processing efficiency and value of the grain. For example, small and shrivelled grain reduce milling yield (proportion of flour extracted), with a 2% reduction in milling yield worth approximately $7 per tonne which is equivalent to $210 million/annum to the Australian grains industry, based on national production figures for 2012 (FAOSTAT, 2014). Grain protein concentration and composition is also an important quality measure which defines nutritional and end-use properties of dough mixing and rheological characteristics including dough strength, development time, extensibility, breakdown and loaf volume all of which effect the efficiency of the bread making process and product quality.

Grain quality is influenced by genetics, management and environment. There is strong genetic control over kernel attributes such as shape, germ tissue, thickness of bran and crease characteristics.

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http://dx.doi.org/10.1016/j.fcr.2015.12.011

Please cite this article in press as: Nuttall, J.G., et al., Models of grain quality in wheat—A review. Field Crops Res. (2015), http://dx.doi.org/10.1016/j.fcr.2015.12.011

However, the post-anthesis environment such as water availability and temperature strongly influence seed size, thus it is important in defining physical properties such as screenings and milling yield (Wardlaw and Wrigley, 1994; Guttieri et al., 2001). Similarly environmental conditions, particularly atmospheric CO_2 concentration and high temperature heat shock during the grain filling phase effects starch and protein deposition and functional properties including dough rheology and baking quality (Blumenthal et al., 1993; Jenner, 1994; Fernando et al., 2012).

Climate change represents a significant challenge for delivering grain of consistent quality in the future due to the complex interactions of atmospheric CO_2, changing temperature and rainfall patterns on yield and quality. In Mediterranean-type environments where maturing crops coincide with terminal drought, climate change with higher temperatures is likely to put the production (Asseng et al., 2015) and quality of grains at increasing risk (Conroy et al., 1994). For cropping regions of southern Australia it is expected that under a future climate, higher atmospheric CO_2 combined with reduced growing season rainfall and higher temperatures will exist (Howden and Crimp, 2005; IPCC, 2012). Compared with current ambient CO_2 concentration (399 ppm) by 2050 average CO_2 concentration in the atmosphere is projected to be 550 ppm in accordance with the A1B scenario, which is defined by a future world where there is rapid economic growth and there is the introduction of a range of efficient energy technologies (Carter et al., 2007). This is broadly comparable to the Representative Concentration Pathway (RCP) 8.5 which assumes a rising radiative forcing pathway leading to 805 W/m^2 in 2100 (van Vuuren et al., 2011; IPCC, 2014). It is likely that the frequency of heat waves has already increased in large parts of Europe, Asia and Australia since the mid-twentieth century and it is probable that frequency and severity of such events will continue to increase (IPCC, 2014). For example in southern Australia and New Zealand, where maximum daily temperature exceeded on average once during a 20-year period in the late-twentieth century (1981–2000), is expected to increase to once every three years by the mid-twenty first century under the A1B scenario. This compares with expected global average increases of once every two years (IPCC, 2012). Increasing climatic variability and the interaction of these competing factors make the global assessment of impacts to production and quality difficult (Porter and Gawith, 1999; Hogy and Fangmeier, 2008). This is especially true where future seasonal conditions are likely to have a variable effect on crop growth depending on agro-ecological region (O'Leary et al., 2011). Moreover, in cropping regions throughout the world, where climate is currently marginal in terms of temperature stress and water availability during the maturing phase of crops, further rises in temperature and reductions in water availability will make crops highly vulnerable (Conroy et al., 1994).

Simulation modelling provides the opportunity to understand the broad scale feedbacks between climate change and agro-production systems at a regional level. Crop models could also provide a beneficial means of determining the impact of environment on grain quality. Despite the large number of crop simulation models used throughout the world few deal with quality parameters other than grain nitrogen or protein content. Exceptions are SiriusQuality (Martre et al., 2006) and STICS (Brisson et al., 2003) as well as APSIM-Nwheat which in addition to grain nitrogen and protein includes screenings (Asseng et al., 2008). There are numerous models that do not simulate grain quality parameters such as CROPSYST (Stockle et al., 1994), EPIC-Wheat (Williams and Renard, 1985) or WOFOST (van Diepen et al., 1989). From an end-users perspective an opportunity exists to expand model capability to account for additional quality parameters which would provide a useful tool to determine better management strategies to maintain high quality grain. The value of such models is particularly important given the potential impact of climate change to grain quality in various agro-ecological zones of the world.

This review examines (i) wheat quality traits and their sensitivity to abiotic stress and expected impacts of climate change, (ii) a range of current crop models for predicting grain quality to determine how quality traits are modelled and the need to widen the capability of our contemporary suite of simulation models to include a broader range of wheat quality traits, and (iii) explore potential ways forward for expanding model capability to grain quality.

2. Wheat quality and climate change

In Mediterranean-type environments where maturing crops coincide with terminal drought, the yield and quality of grain is seasonally variable due to rainfall being low and unreliable and the significant risk of heat waves during the reproductive and grain filling phase of crops. It is anticipated that under climate change, growing-season rainfall in many arable cropping regions will be reduced and there will be a greater incidence of extreme climatic events (IPCC, 2012). The net effect of a changing climate in semi-arid cropping regions is likely to be reduced production (Asseng et al., 2015) and quality of staple grains (Panozzo et al., 2014). While the focus of this review is on the whole-grain quality, protein quantity and composition and a range of functional characteristics of wheat in relation to environment and the potential impacts of climate change, yield implications are also considered.

The effect of elevated CO_2 on C3 plants is to stimulate photosynthesis and growth, while reducing transpiration due to higher leaf CO_2 assimilation rates (Conroy et al., 1994). For grain crops this translates to an increase in production and water use efficiency (Kimball and Idso, 1983). A meta-study of 430 yield observations of 37 plant species grown with CO_2 enrichment showed that average yield increased by 36% (Kimball and Idso, 1983) with a 32% increase in yield of C3 grain crops. For other free-air carbon dioxide enrichment (FACE) studies, elevated CO_2 concentration (eCO_2) increased wheat yield by 10% (Hogy et al., 2009) and in southern Australia wheat yield by 26% (2.3 compared to 2.9 t/ha) (O'Leary et al., 2014). Although production is likely to be increased under eCO_2, the effect on grain quality is variable but usually adversely affected (Kimball et al., 2001; Hogy et al., 2009).

Optimum temperature for grain development ranges from 15 to 25 °C (Porter and Gawith, 1999) and although increasing temperature and photosynthesis boosts supply of assimilate, this does not fully compensate for shortened duration of starch deposition, where overall higher temperature produce smaller grains. Exposure to chronic temperatures up to 30 °C commencing six days after anthesis (DAA) to maturity reduced kernel weight by between 20 and 30% across two wheat cultivars (Wardlaw et al., 2002). A similar reduction in kernel weight across these cultivars also occurred after a four day heat shock treatment at 36 °C (6 DAA) indicating a heat shock response being initiated at temperatures above 30 °C. At temperature >30 °C, the rate of starch deposition decreases due to the reduced activity of enzymes catalysing starch synthesis (Jenner, 1994). Adequate water supply to crops that are heat-stressed help maintain grain-filling rate, duration and size (Altenbach et al., 2003), although high temperature where water supply is non-limiting has also been shown to cause a reduction in single grain weight (McDonald et al., 1983). Within Mediterranean-type environments, the potential benefit of adequate water to mitigate heat stress effects to crops is likely to be limited as they generally mature under terminal drought conditions. Higher frequency of extreme weather events such as heat waves is also anticipated under future climates (IPCC, 2012) where heat shock can have a non-reversible destructive impact on crop yield potential. In par-

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