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Durum wheat quality prediction in Mediterranean environments: From local to regional scale

P. Toscano[a,b,*], B. Gioli[a], L. Genesio[a], F.P. Vaccari[a], F. Miglietta[a,e], A. Zaldei[a], A. Crisci[a], E. Ferrari[c], F. Bertuzzi[c], P. La Cava[c], C. Ronchi[c], M. Silvestri[c], A. Peressotti[b], J.R. Porter[d,f]

[a] *Institute of Biometeorology (IBIMET—CNR), Via G.Caproni 8, 50145 Firenze, Italy*
[b] *Department of Agricultural and Environmental Sciences, University of Udine, Via delle Scienze, 206, 33100 Udine, Italy*
[c] *Barilla G. e R. F.lli S.p.A., Via Mantova 245, 43122 Parma, Italy*
[d] *Climate and Food Security, Plant and Environmental Sciences, University of Copenhagen, 2630 Taastrup, Denmark*
[e] *E. Mach Foundation—Iasma, Via E. Mach 1, 38010 S. Michele all'Adige (Tn), Italy*
[f] *Climate and Agriculture, University of Greenwich, Chatham Maritime ME4 4T, UK*

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ABSTRACT

Durum wheat is one of the most important agricultural crops in the Mediterranean area. In addition to yield, grain quality is very important in wheat markets because of the demand for high-quality end products such as pasta, couscous and bulgur wheat. Grain quality is directly affected by several agronomic and environmental factors. Our objective is to determine the general principles underlying how, in Mediterranean environments, grain protein content (GPC) is affected by these factors and provide a system model with high predictive ability. We initially evaluated the capability of the Delphi system to simulate GPC in the major Italian supply basins (Basilicata, Capitanata, Marche, Tuscany) for 9 years (1999–2007) a month ahead of harvesting and we then analyzed relations between Delphi system errors and selected environmental variables during flowering and grain filling stages. The results were evaluated on the basis of regression with observed GPC, while errors were calculated performing a linear correlation analysis with environmental variables. The model showed a high capability to reproduce the inter-annual variability, with important year to year differences, with better performance in the southern study areas (Basilicata and Capitanata). In this study the highest overestimation occurred in conjunction with the year (2004) characterized by the lowest quality in terms of GPC, lowest average temperature in May and highest yield production for the whole study period.

1. Introduction

Europe (EU-27) accounts for more than 26% (9.1 Mt) of the global durum wheat production and this is mainly concentrated in Mediterranean countries: Italy (4.1 Mt), France (2.4 Mt), Greece (1.3 Mt) and Spain (0.9 Mt) for a total cultivated surface of approximately 3.5 Mha (IGC, 2013).

Durum wheat is grown mainly in sub-humid dry lands under non-irrigated conditions, which makes grain yield uncertain, but offers the opportunity for high quality productions in terms of total protein content (Borghi et al., 1997).

Climate and agronomic practices exert a strong influence on technological quality parameters of durum wheat. In Mediterranean environments, sustained water deficit and thermal stress during grain filling, may cause large fluctuations in both grain yield and grain quality traits (Baenziger et al., 1985). The most important agronomic practices and variables that affect wheat protein content are: soil water content, nitrogen fertilization rate, time of nitrogen application and residual soil nitrogen (Campbell et al., 1981; Rao et al., 1993; Uhlen et al., 1998; Rharrabti et al., 2001).

About two-thirds or more (66–82%) of the proteins stored in the grain at maturity are present in the plant at pre-anthesis (Papakosta and Gagianas, 1991; Ehdaie and Waines, 2001; Masoni et al., 2007; Motzo et al., 2007; Ercoli et al., 2008), while the remaining fraction is absorbed from the soil during the period of grain development (Kramer, 1979). These proportions are considerably influenced by environmental conditions especially in the Mediterranean climate, where wheat during grain filling is subject to several biotic and abiotic stresses (Sarvestani et al., 2003).

The complexity of plant growth and development processes that interact with each other and the weather have made experimental

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* Corresponding author at: IBIMET—CNR Via Caproni 8, 50145 Firenze, Italy. Tel.: +39 0553033711; fax: +39 055308910.
E-mail address: p.toscano@ibimet.cnr.it (P. Toscano).

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studies of grain protein development and management rather difficult. Results from field experiments have been highly variable from site to site and season to season (e.g. Spiertz and Ellen, 1978; Delroy and Bowden, 1986; Rao et al., 1993).

The early and accurate prediction of durum wheat yield and quality in function of climatic conditions could be of utmost importance: for farmers to optimize their agronomic decisions and for durum wheat markets, for hedging or forward contracting (Smith and Gooding, 1999; Woolfolk et al., 2002).

Crop models have been specifically developed to predict protein content of wheat, because of the importance of gluten, about 80% of the total protein content. Gluten affects the technological characteristics of the dough. Attempts have been made to estimate grain protein concentrations under various growing conditions with specific simulation models implemented for cereals and for wheat in particular (Makowski et al., 1999; Otter-Nacke et al., 1986; Meinke, 1996; Jamieson and Semenov, 2000; O'Leary and Connor, 1996; Porter, 1993; Brisson et al., 1998; Martre et al., 2003, 2006; Asseng et al., 2002). Between wheat models, the grain protein routine of the APSIM-Nwheat model has already been quantitatively tested for *Triticum aestivum* L., showing good agreement between simulated and measured protein concentrations under various growth conditions and environments including temperate, Mediterranean and sub-tropical areas; the root mean squared deviation (RMSD) was 2% variation in grain protein concentration (Asseng et al., 2002). By the contrary the grain protein routine has not been tested for durum wheat. There are few examples of wheat models that have been calibrated and validated to simulate durum wheat quality traits such as represented by Porter et al. (1995), Jamieson et al. (2001), Rinaldi (2004), Basso et al. (2010), Ferrise et al. (2011), but are focused on an assessments of climate change impacts on durum wheat quality or on the response to different nitrogen applications. This lack of knowledge is particularly important if we consider the recent genetic improvements achieved in durum wheat quality (Subira et al., 2014) that are not considered by modelling.

The improvement of quality is one of the key priorities of durum wheat breeding programs in the EU, where dedicated premium have been established to promote the cultivation of high-quality cultivars (Royo and Briceño-Félix, 2011) and durum markets pay a reward for protein content equal to or higher than 13%. In this framework, there is still lack of forecasting systems and tools able to provide an effective help in managing the risks associated with the production process, and, as a consequence, able to reduce the volatility of returns and to support a better planning of storage and distribution strategies with the final aim of meeting the stability and high quality supply requirements of pasta production plants.

In this paper, we (i) explore the capacity of an existing state-of-the-art durum wheat modelling system (Delphi) to forecast grain protein content (GPC) a month ahead of harvest; (ii) evaluate the capability of the system to reproduce the inter-annual variability of durum wheat GPC for four district-scale study areas from 1999 to 2007 by assessing its performance against observed data; (iii) analyze relations between system errors and selected environmental variables during flowering and grain filling stages, to investigate key areas of system improvement.

The Delphi system (Toscano et al., 2012) is based on the AFRCWHEAT2 mechanistic crop model (Porter et al., 1993), and predicts GPC by modelling crop response to water and nitrogen constraints, driven by a combination of actual and scenario weather conditions. This approach has been implemented and preferred to a statistical approach, following the needs of pasta industry in terms of forecast at different scales but also of testing new agronomic hypotheses essential for supporting agricultural management strategies and policy decisions at multiple scales, from the local to broader scale.

2. Materials and methods

2.1. Delphi system—AFRCWHEAT2

Delphi system is based on AFRCWHEAT2, a model developed for bread wheat (*T. aestivum L.*) that has been calibrated and validated for different environments and pedo-climatic conditions (Porter, 1984, 1993; Porter et al., 1993; Semenov et al., 1993; Semenov and Porter, 1995; Jamieson et al., 1998; Jamieson and Ewert, 1999). In the Delphi system the model was calibrated for durum wheat to take into account the combination of cultivation areas, cultivars currently grown in the 4 study areas, crop growth constraints (water and N availability conditions, etc.) and agronomic practices. The calibration procedure (Toscano et al., 2012) was performed for three years (1995–1997) considering the dry matter partitioning of C and N that determine the grain yield and protein concentration; the latter being specifically dependent on the capacity of the plant to accumulate both carbon and nitrogen in the grains.

The crop nitrogen modelling is based on the idea that plants have an upper (Nmax) and a lower (Nmin) N concentration threshold expressed on a dry weight basis. These vary with developmental stage (Porter et al., 1995) and the rates of N-dependent crop processes are driven by how actual crop N concentration is close to Nmax or Nmin. Shoots have both a wider concentration band and usually higher N concentrations than roots. Crop demand for N is then calculated from the difference between the current N concentration of shoots and roots and their separate Nmax values for the current developmental stage. This difference, multiplied by shoot or root dry weight, gives the crop N demand for the day. An exception is made for the most newly-formed assimilate: here the target N concentration of either shoot or root is set to the Nmax value for the developmental stage. Assimilate procedure prior to the current days had that concentration, between Nmax and Nmin, resulting from the balance between previous demand and previous capacity of soil and root to supply N.

In AFRCWHEAT2, 25% of the shoot and leaf weight at anthesis is allocated to a C pool that can be drawn on during grain filling if the daily level of assimilate supply is less than the grain demand for C. A scaling factor (GFN) was introduced to reduce grain N demand when the shoot pool for C reaches 0 (i.e. is empty): (i) GFN = 1 when the shoot pool (SPOOL) is greater than zero, (ii) GFN = 0.3 when shoot pool is 0 (SPOOL = 0) for less than 4 consecutive days, (iii) GFN = 0 in all other cases. The argument for this grain nitrogen demand factor is to take into account the fact that shoot and leaves are the primary sources of N for the grain via the breakdown of Rubisco and its transport to the grain.

In this study the maximum value of N demand by grain is set at 0.001625 g N grain^{-1} °C day, lower than 0.0017 g N grain^{-1} °C day as reported in Vos, 1981 and Porter et al., 1995, to balance for the increased grain number per unit area (Gnum, grain m^{-2}) following the calibration procedure performed in Toscano et al. (2012).

The final simulated grain nitrogen value was then multiplied by a factor of 5.7, that expresses the N concentration in the grain, and by 100 to calculate the simulated GPC in %, hereafter referred to simply as GPC_{DEL}, and compare it with the observed GPC.

The Delphi system upgraded with the algorithm for the characterization and prediction of durum wheat protein content, was applied in four study areas (Fig. 1, Basilicata, Capitanata, Marche, Tuscany) for the period 1999–2007. Soil data were retrieved from soil maps of Regional Agencies and from the National Center for Soil Mapping (http://www.soilmaps.it/). Crop management inputs include sowing date, plant density, fertilizer date (type and amount), while irrigation is not required because durum wheat is sparingly irrigated in Italy (Bazzani, 2005). Agronomic data were provided by the Agricultural Consortia and by Barilla G. e R. F.lli SpA.