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Empirical modelling of regional and national durum wheat quality

P. Toscano[a,b,*], L. Genesio[a], A. Crisci[a], F.P. Vaccari[a], E. Ferrari[c], P. La Cava[c], J.R. Porter[d,e], B. Gioli[a]

[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 Agriculture, University of Greenwich, Chatham Maritime, ME4 4T, UK
[e] Climate and Food Security, Plant and Environmental Sciences, University of Copenhagen, 2630 Taastrup, Denmark

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ABSTRACT

The production of durum wheat in the Mediterranean basin is expected to experience increased variability in yield and quality as a consequence of climate change. To assess how environmental variables and agronomic practices affect grain protein content (GPC), a novel approach based on monthly gridded input data has been implemented to develop empirical model, and validated on historical time series to assess its capability to reproduce observed spatial and inter-annual GPC variability. The model was applied in four Italian regions and at the whole national scale and proved reliable and usable for operational purposes also in a forecast 'real-time' mode before harvesting. Precipitable water during autumn to winter and air temperature from anthesis to harvest were extremely important influences on GPC; these and additional variables, included in a linear model, were able to account for 95% of the variability in GPC that has occurred in the last 15 years in Italy. Our results are a unique example of the use of modelling as a predictive real-time platform and are a useful tool to understand better and forecast the impacts of future climate change projections on durum wheat production and quality.

1. Introduction

The largest global durum wheat production is concentrated in the Mediterranean basin that contributes, on average, 60% of global production (FAOSTAT, 2013). Environmental and agronomic variables, such as climate, soil, and cropping practices exert a strong influence on yield of durum wheat and on its quality, typically expressed as grain protein content (GPC, %), a key factor to define wheat grain quality and a target of pasta and bread wheat breeding programs. The effects are particularly relevant in Mediterranean environments (Nachit and Elouafi, 2004), where the climate usually leads to a sustained water deficit and thermal stress during grain filling, which may cause large fluctuations in both yield and quality (Baenziger et al., 1985). About two-thirds of the protein content in the grain at maturity are present in the plants (mainly leaves and shoots) at anthesis (Austin et al., 1977), while the remaining amount is absorbed from the soil during the grain-filling phase (Kramer, 1979; Stone and Savin, 1999).

Recently Subira et al. (2014) using an historical series of 24 durum wheat cultivars released in different periods during the 20th century in Italy and Spain, found a significant impact of environmental variables on protein content, confirming the findings of previous studies on durum wheat in Mediterranean environments (Rharrabti et al., 2003). However few studies have attempted to quantify the weight of environmental variables and then translate them into a predictive model, while several studies have reported significant decreases in grain protein content (Motzo et al., 2004; De Vita et al., 2007; Dotlačil et al., 2010; Nazco et al., 2012) associated with increases in grain yield. The negative relationship between yield and protein content (Rharrabti et al., 2001) has been explained as a dilution effect of nitrogen compounds when carbohydrate deposition increases through photosynthesis post-anthesis (Lawlor 2002; Martre et al., 2003).

The impact of environment on durum wheat quality may be substantial in the future, in view of the projected increased levels of atmospheric carbon dioxide (CO_2), rising temperatures and increased frequency and intensity of extreme events (i.e., droughts and heat waves). Conroy and Hocking (1993) reported a decline in wheat protein in Australia from 1967–1990, partially attributable to the rise in atmospheric CO_2, while Free-Air CO_2 Enrichment (FACE) experiments have shown a reduction in grain quality

* Corresponding author at: IBIMET – CNR, Via Caproni 8, 50145 Firenze, Italy. Tel.: +39 553033711; fax: +39 55308910.
E-mail address: p.toscano@ibimet.cnr.it (P. Toscano).

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Table 1
Environmental and agronomic variables used as regressors to assess the inter-relations with grain protein content (GPC). The source datasets acronyms are: NCEP (National Centers for Environmental Prediction); BARILLA (Barilla G. e R. F.lli SpA); CRA (Agricultural Research Council); ISTAT (National Institute for Statistics); NOAA (National Oceanic and Atmospheric Administration). See text for more detail.

	Source	Period	Unit	Description
$AIRT_1$	NCEP	1998–2013	°C	Mean air temperature January
$AIRT_2$	NCEP	1998–2013	°C	Mean air temperature February
$AIRT_3$	NCEP	1998–2013	°C	Mean air temperature March
$AIRT_4$	NCEP	1998–2013	°C	Mean air temperature April
$AIRT_5$	NCEP	1998–2013	°C	Mean air temperature May
$AIRT_6$	NCEP	1998–2013	°C	Mean air temperature June
$AIRT_7$	NCEP	1998–2013	°C	Mean air temperature July
$AIRT_8$	NCEP	1998–2013	°C	Mean air temperature August
$AIRT_9$	NCEP	1998–2013	°C	Mean air temperature September
$AIRT_{10}$	NCEP	1998–2013	°C	Mean Air Temperature October
$AIRT_{11}$	NCEP	1998–2013	°C	Mean air temperature November
$AIRT_{12}$	NCEP	1998–2013	°C	Mean air temperature December
PW_1	NCEP	1998–2013	kg/m^2	Precipitable water January
PW_2	NCEP	1998–2013	kg/m^2	Precipitable water February
PW_3	NCEP	1998–2013	kg/m^2	Precipitable water March
PW_4	NCEP	1998–2013	kg/m^2	Precipitable water April
PW_5	NCEP	1998–2013	kg/m^2	Precipitable water May
PW_6	NCEP	1998–2013	kg/m^2	Precipitable water June
PW_7	NCEP	1998–2013	kg/m^2	Precipitable water July
PW_8	NCEP	1998–2013	kg/m^2	Precipitable water August
PW_9	NCEP	1998–2013	kg/m^2	Precipitable water September
PW_{10}	NCEP	1998–2013	kg/m^2	Precipitable water October
PW_{11}	NCEP	1998–2013	kg/m^2	Precipitable water November
PW_{12}	NCEP	1998–2013	kg/m^2	Precipitable water December
GPC_{BAR}	BARILLA	1999–2007	%	Grain protein content
GPC_{CRA}	CRA	1998–2013	%	Grain protein content
Yield	ISTAT	1999–2007	t/ha	Regional yield production
CO_2	NOAA	1999–2007	ppm	Atmospheric carbon dioxide concentration
N	BARILLA	1999–2007	N/ha	Nitrogen applied for fertilization

under high levels of CO_2 (550 ppm) (Erda et al., 2005; Ainsworth and McGrath, 2010; Kimball et al., 2001), and a decrease in the grain protein content under doubled pre-industrial atmospheric CO_2 concentration (280 ppm) (Erbs et al., 2010). Wrigley (2006) reported reduced wheat grain quality for various locations, caused by heat stress associated with maximum temperatures exceeding 35 °C.

For these reasons understanding the impacts of the environmental variables on yields and quality of durum wheat is particularly important and crop growth modeling is a fundamental tool to assess these impacts. However, most models require extensive information related to environmental and agronomic parameters that are typically unavailable (Walker, 1989). Moreover, large differences in the structure and data input requirements among crop growth models limit their applicability from an operational perspective. Because of the complexity and data requirements of simulation models, many studies have adopted a regression approach to forecast crop yield and quality (Yang et al., 1992; Dixon et al., 1994; Kandiannan et al., 2002; Chen and Chang, 2005; Graybosch et al., 1995; Johansson and Svensson, 1998; Smith and Gooding, 1999; Guttieri et al., 2000; Johansson et al., 2008), proving that multiple regression models have high explanatory power and can infer relationships between weather conditions and crop yield and quality. Previous studies forecasting wheat quality at the spatial level have several limitations; since most quality models are not designed to produce pre-harvest predictions, and use point-based instead of spatial data (Lee et al., 2013).

Freely available gridded meteorological databases might help crop growth modelling to overcome difficulties in data requirements (Easterling et al., 1997). However such data should be used with caution as they are derived from atmospheric models and not directly measured (Tveito et al., 2006). Moreover, only a few studies using crop modelling and that also use weather gridded data are validated against observations at the same grid interval (Foley et al., 2005; Lobell et al., 2008) and this limits widespread application of these models.

In this paper, we: (i) develop a statistical inference framework to assess the effects of environmental and agronomic variables on the grain protein content (GPC) of durum wheat; (ii) define a new empirical model (TP model) based on freely available gridded global-scale atmospheric datasets; (iii) evaluate the capability of the TP model to simulate GPC in four Italian regions from 1999 to 2007 and (iv) evaluate the performance of the TP model at the Italian national scale and as a forecasting operational tool.

2. Materials and methods

2.1. Data sources

Different datasets have been considered to assess the inter-relations between selected agro-environmental variables and grain protein (Table 1). Yearly atmospheric CO_2 concentrations were obtained from the NOAA/ESRL global dataset (www.esrl.noaa.gov/gmd/) (Conway et al., 1994), averaging monthly values for the pixel corresponding to each study area.

Nitrogen fertilization datasets for each study area were provided by the Agricultural Consortia and by Barilla G. e R. F.lli SpA (Toscano et al., 2012).

Durum wheat yield data were provided by the National Institute for Statistics (ISTAT, http://agri.istat.it/) as an average of the harvested yield at the regional administrative scale for the four study areas.

Climatic variables were obtained by spatially gridded global numerical simulations from NCEP/DOE AMIP-II Reanalysis (Reanalysis-2, Kanamitsu et al., 2002), hereinafter referred to simply as NCEP; the web data hub is available online at http://www.cdc.noaa.gov/data/gridded/data.ncep.reanalysis2.html. Among the available gridded climatic variables we selected air temperature (AIRT) and precipitable water (PW) as those potentially explaining