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A simplified index for an early estimation of durum wheat yield in Tuscany (Central Italy)

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ABSTRACT

Durum wheat (*Triticum durum* L.) plays a key role for Italian agriculture and for world pasta production. Wheat production largely depends on weather. The aim of this study is to develop an operational tool to supply early forecasts of the final yield. Early forecasts will provide information for a more effective crop management that will help minimizing the uncertainty related to crop production. The climate impact on the yield, and the ability of the Leaf Area Index (LAI) to describe the environmental influences on the crop, were assessed through the model CERES-wheat in a long-term analysis. The results showed a highly significant correlation between yield and the rainfall during the leaf growth and plant tillering stages. A highly significant correlation was also found between yield and the LAI reached at the end of the vegetative season. Then, the number of March non-rainy days and the April LAI were used as independent variables in a multi-regressive model for the final yield estimation. The model was validated with ground measurements to test its ability as a simplified forecasting index. The resulting yield estimates showed highly significant correlation with those observed. The results showed that the forecasting index is suitable for operational farming applications, being able to provide, with a few input data, the first forecasts in early April well in advance to maturity.

1. Introduction

Italy is among the top twenty producers of grain wheat worldwide, despite the relatively little arable land available compared to other countries (FAOSTAT, 2010). In particular, winter durum wheat (*Triticum turgidum* L. var. *durum*) plays a major role, both for domestic annual consumption and for the export market, since it is the only species providing the raw material for the traditional pasta making. The latest data from the International Pasta Organization (2012) show a world production of pasta around 13 million tons, spread over 44 countries, of which the Italian industry accounts for almost 25%. Italian durum wheat production is concentrated mostly in the southern and central regions (ISTAT, 2011) under rainfed conditions. Compared to the soft wheat (*Triticum aestivum* L.), the durum wheat is less prone to smut and rust and more tolerant to drought conditions of semiarid areas. For these reasons, durum wheat is an important crop in all marginal areas of Mediterranean environment (Salmon and Clark, 1913), where high temperature and water scarcity are the most common production limiting factors. Important differences between soft and durum wheat responses under Mediterranean climate are reported in literature (Cossani et al., 2011). In particular, durum wheat tends to a higher grain weight and yield, has a higher variability both in

Abbreviations: ARSIA, regional agency for development and innovation in agroforestry; CAPSI, provincial agricultural consortium of Siena; CRM, coefficient of residual mass; DISPAA, Department of Agrifood Production and Environmental Sciences, University of Florence; NR, non-rainy day; NR_{march}, no-rainy day in March; EF, modeling efficiency; LAI, leaf area index; LAI_{april}, leaf area index in April; MTMAX, monthly mean maximum temperatures; MTMIN, monthly mean minimum temperatures; MY, measured yield; P, precipitation; PAR, photosynthetically active radiation; R, solar radiation; RRMSE, relative root mean squared error; SY, simulated yield; TMAX, maximum air temperature; TMIN, minimum air temperature; TP, monthly total precipitation; WD, warm days; Y, yield.

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maximum grain filling rate and duration of grain filling period, and it has less stable grain final size and weight and, consequently, a less stable yield.

Further, notwithstanding that the inverse relationship between the yield and grain nitrogen concentration (Rharrabti et al., 2001) is a common characteristic in both wheat varieties, it is more markedly in the durum one. In this respect, being grain protein content a key factor in determining the pasta quality (D' Egidio et al., 1979; Dexter et al., 1983), early forecast of durum wheat yield can provide important information for a more effective crop management, in particular for the optimization of late nitrogen supply timing. In fact, while conventional fertilizations before anthesis mainly aim to a final yield increase (Abedi et al., 2011), late season nitrogen applications are more effective in promoting the accumulation of nitrogen compounds in kernels (Bly and Woodard, 2003).

Although the nitrogen effect is well known, the set-up of an operational forecast system for durum wheat yield also requires a full understanding of climate driving variables in the specific productive area. Even though heat excesses and drought conditions are commonly considered factors that adversely impact wheat production (Dalirie et al., 2010; Lawlor and Mitchell, 2000), the extent and significance of their impact strongly depends on the affected growth phase (Lawlor and Mitchell, 2000; Li et al., 2010). Indeed, neither the high temperature nor the water deficit have a univocal effect.

A significant increase of the mean temperature at anthesis does not negatively affect the yield (Ferris et al., 1998), rather a brief exposure to maximum temperatures over a threshold (Mitchell et al., 1993; Gouache et al., 2012), as well as a mild water stress during grain-filling can promote yield (Zhao et al., 2009).

Moreover, the combined effect of meteorological variables can lead to different results compared to their single impact (Van Ittersum et al., 2003; Xiao et al., 2008), also depending on soil type and location (Ludwing and Asseng, 2006).

In such dynamic and complex system deterministic crop models can be used to identify the more susceptible crop stages, as well as the main affecting meteorological variables, in a specific location. The strength of complex models, differently from statistical approaches, mainly resides in their ability to capture the 'soil–atmosphere–plant' interactions, and for this reason they are widely adopted by researchers in the agricultural sector (Jones et al., 2003). On the other hand, the use of complex models remains confined in the research field and the yield forecasts based on model output find limitation for operational application. The major impediment is the difficulty in providing reliable and accurate model input data (Jones et al., 2003; Richter et al., 2010) with good spatial and temporal coverage, thus limiting model performances. Further, seasonal climate models provide data with different spatial and temporal scales compared to those required by crop models, so hampering their use as forecasting tools (Stone and Meinke, 2005).

Other than *Triticum aestivum* L., literature on modeling the durum wheat production and forecast in typical Mediterranean areas is quite poor. Many papers deal with models focusing on information at regional level (Rinaldi, 2004; Latiri et al., 2010; Richter et al., 2010; Dettori et al., 2011; Toscano et al., 2012), which are more suitable to drive the market and policy decisions rather than farmers plans. The use of remote sensing for durum wheat yield estimation at farm level, as well as the integration of remote sensed data with large scale climatic indices (Guasconi et al., 2011; Dalla Marta et al., 2014) were also recently studied. Nevertheless, many of these applications remains at the research level and are still difficult to translate on the field. Therefore, the development of operational tools to support crop management through harvest forecasts is still an important challenge.

In the current study, the model CERES-wheat was applied in a long-term analysis of durum wheat production in Central Italy, with the aim to identify the main system components with a predictive power for durum wheat yield, and then to formulate a forecasting index based on a simple model.

2. Materials and methods

2.1. Analysis of the crop and environment system with DSSAT-CERES

The research was carried out in Val d'Orcia, a rural area of Tuscany (Central Italy) characterized by a typical Mediterranean climate (13.6 °C and 715 mm of annual average temperature and cumulated rainfall, respectively).

The meteorological daily data of P, TMAX and TMIN over 56 growing seasons (years 1955–2011) were obtained from six ground weather stations located in the study area. R was calculated using RadEst v.3.0 software (Donatelli et al., 2003), which estimates global radiation in relation to the daily thermal range (Bristow and Campbell, 1984).

CERES-wheat (DSSAT-CSM version 4.0) is a predictive deterministic model, designed to simulate the effects of cultivar, crop management, weather and soil on crop growth, development and yield in terms of dry matter (Ritchie and Otter, 1985). The model operates on a daily time step and the minimum meteorological input includes precipitation (mm), solar radiation (MJ/m^2), and maximum and minimum air temperatures (°C). CERES-wheat simulates eight development stages, which can be related to the Zadoks et al. (1974) phenological classification (Eitzinger et al., 2003), and calculates the dry matter accumulation as a linear function based on intercepted photosynthetically active radiation (PAR). The genetic coefficients used in CERES-wheat describe the growth and development responses of each cultivar and its potential productive performance.

The model was calibrated for durum wheat cultivar 'Claudio', using data collected in 32 experimental fields over 11 productive seasons. These data were supplied by the wheat variety trials of ARSIA performed over the period 1998–2009. After calibration, CERES-wheat was validated using a data from field monitoring carried out by CAPSI. The data were available over three growing seasons (2009–2011), for a total number of 20 fields (9, 7 and 4 in 2009, 2010 and 2011 respectively) where durum wheat cv. Claudio was cultivated under rainfed system. Beside crop management (e.g. sowing, plants density, fertilization plans, etc.), data included information on crop growth, phenology, and harvest (e.g. growth stages onset and duration, grain humidity and yield in terms of dry matter). The primary soil tillage was in autumn (ploughing at 30 cm depth) and sowings were carried out between the first decade of October and the last decade of January with a density of 350–450 seeds/m^2, for a final plant density ranging from 250 to 400 plant/m^2. The amount of given nitrogen was considerably different among the experimental sites, ranging from 95 to 200 N units (kg/ha), split in two or three doses (one at sowing and two during the crop cycle). Accordingly to the soil map, experimental fields were located over the most common Val d'Orcia soil type, a 'Typic Ustorthents fine, mixed, calcareous, mesic' (USDA classification), moderately deep, weakly alkaline, with a silty-clay-loam texture and moderate to high slope (14–35%). The main characteristics of the soil profile used in CERES-wheat model calibration are shown in Table 1.

The crop productive potential and the timing of the phenological stages were calibrated by the genetic coefficients of "Winter-Europe" genotype adjusted on the basis of the best fit between the simulated (SY) and measured yields (MY) and onset dates of the main crop stages.

The model accuracy was assessed through the correlation analysis between SY and MY, as well as the computation of relative