Europ. J. Agronomy 43 (2012) 108–118

Contents lists available at SciVerse ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Durum wheat modeling: The Delphi system, 11 years of observations in Italy

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ARTICLE INFO

Article history:
Received 5 January 2012
Received in revised form 31 May 2012
Accepted 2 June 2012

Keywords:
Durum wheat
Crop modeling
Yield forecasting
Calibration
Scenarios

ABSTRACT

Crop models are frequently used in ecology, agronomy and environmental sciences for simulating crop and environmental variables at a discrete time step. The aim of this work was to test the predictive capacity of the Delphi system, calibrated and determined for each pedoclimatic factor affecting durum wheat during phenological development, at regional scale. We present an innovative system capable of predicting spatial yield variation and temporal yield fluctuation in long-term analysis, that are the main purposes of regional crop simulation study. The Delphi system was applied to simulate growth and yield of durum wheat in the major Italian supply basins (Basilicata, Capitanata, Marche, Tuscany). The model was validated and evaluated for three years (1995–1997) at 11 experimental fields and then used in operational mode for eleven years (1999–2009), showing an excellent/good accuracy in predicting grain yield even before maturity for a wide range of growing conditions in the Mediterranean climate, governed by different annual weather patterns. The results were evaluated on the basis of regression and normalized root mean squared error with known crop yield statistics at regional level.

1. Introduction

1.4 Million hectares of durum wheat are currently grown in Italy, which is the main world producer (IGC, 2010), with an average production of 4.0 million tons of grain and an average yield of 3.06 t ha^{-1} in the period 2006–2010 (ISTAT). 73% of the cultivation, which accounts for 65% of total production, is located in southern Italy, while yield in the north is higher due to the different pedology and climatic conditions (Bianchi, 1995) (Table 2). Durum wheat is the leading cereal crop in Italy, responsible for almost 40 percent of total cereal production (ISTAT, Italian Statistical Center). This generates a vast range of allied activities, both "upstream" (seed and technical supplies industries) and "downstream" (storage centers, primary and secondary processing industries), hence the strategic importance of the entire production chain. This is the result of a gastronomy in which pasta, an end product of durum wheat, is universally recognized as a symbol of Italian cuisine, one of its cornerstones and of great value for the Italian economy (1.7% GDP, Nomisma 2011, http://www.nomisma.it/index.php?id=157&no_cache=1&tx_ttproducts_pi1[backPID=157&cHash=ee38ce6558]). For these reasons, the effect of weather patterns on winter durum wheat production is of primary interest. Due to a high variability of water supply and climatic adversities that characterize the cultivation areas, the qualitative and quantitative planning of production is highly uncertain and represents an important challenge (Dalla Marta et al., 2011)

The features of durum wheat production are determined by both management and natural variables: sowing time, crop density, soil fertility, genetic characteristics interact with important weather variables, such as solar radiation, rainfall, frosts and high temperatures during grain filling, creating a "risky" environment at local scale (farmers) but also for the whole production at regional or country level (Pecetti and Hollington, 1997). Low rainfall amounts and their temporal distribution explain as much as 75% of the wheat yield variability (Blum and Pnuel, 1990), while rainfall and temperatures during grain formation and ripening are critical for durum wheat quality (Garrido-Lestache et al., 2005). A decreasing trend in the wheat production area has occurred in recent years (1999–2009, FAO global data) as outlined by Mifflin (2000), due to several factors in addition to the effects of interannual weather variability: global warming and increasing occurrence of extreme weather events, limitations in available land, increasing soil erosion, reduction of available water in irrigated

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http://dx.doi.org/10.1016/j.eja.2012.06.003

areas and increasing salinization negatively affect total production, while the new agricultural policy guidelines have steered farmers to more profitable crops (Aggelopoulos et al., 2008, Pastatrend http://www.agricoltura24.com).

In the last years, crop growth simulation models have been widely used as an important tool to investigate crop growth and development and the responses of crops and varieties to different pedoclimatic conditions in order to minimize risk. Studies have addressed a wide range of issues including the impact of climate change on crops, mixed cropping, breeding applications, water and nitrogen management, while only few studies on durum wheat modeling are available for typical Mediterranean climate conditions (Pecetti and Hollington, 1997; Rinaldi, 2004; Rezzoug et al., 2008; Richter et al., 2010; Dettori et al., 2011; Motzo et al., 1996; Pala et al., 1996; Latiri et al., 2010). A model assessing durum wheat development at regional scale, could be of great value for agronomists and help researchers to study the impact of climate change on agriculture. The potentials and limits of dynamic simulation models as predictive tools have been discussed (de Wit and Penning de Vries, 1985; McCown et al., 2002; Ahuja et al., 2002), concluding that crop modeling could provide unique advantages in several situations: for example providing a quick response when new needs arise, allowing time and space, dimensions that are often difficult to represent adequately using field experimentation, to be added to agronomic research (Bindi and Maselli, 2001). In general, the applications of dynamic crop simulation models can be defined as strategic, tactical, and forecasting, with a service aimed at farmers, consultants, policy-makers, or companies directly involved with agricultural management and production (Vogel and Bange, 2004). The main objective of such applications is to accurately predict yield before harvesting, which can be of great value in policy planning. Currently the national and international agricultural statistics services provide regular updates during the growing season of total acreage planted with a specific crop, as well as the expected yield levels. Traditionally, forecasts have been based on a combination of scouting reports as well as statistical techniques based on historical data. Based on the expected yield, the price of grain can vary significantly (Hoogenboom, 2000), with a high impact on both commodity prices and farmers incomes. Growing season forecasts of crop yields are therefore of considerable interest also to commodity market participants and price analysts. For example, future grain prices tend to be quite volatile during crop growing seasons, with the markets being quite sensitive to weather information that affects the yield potential of the growing crop. It is important for market operators to be able to predict the market price in order to maximize economics returns, but if high and volatile prices attract the most attention, low prices and volatility are problematic. Volatile prices create uncertainty and risk for producers, traders, consumers and governments and can have extensive negative impacts on the agriculture sector, food security and the wider economy in both developed and developing countries (OECD-FAO, 2011 http://www.agri-outlook.org/document/63/0,3746,en_36774715_36775671_47923007_1_1_1_1,00.html).

However, it seems that crop simulation models can play a critical role in crop yield forecasting applications: the relatively low cost and speed of assessment makes crop growth simulation models promising for areas where meteorological information is readily available.

Although there is an abundant literature on crop growth simulation model studies, typically these do not translate in tools that can run operationally on entire regions, and that can forecast future yields expected on the basis of scenario weather conditions. Actually in Europe, periodic information on expected yields is provided by the MARS (Monitoring Agriculture with Remote Sensing) Crop Yield Forecasting System operated by the Joint Research Centre (de Wit, 2007), but bulletins and outlooks refer to national scale. The Delphi system, object of this study, was implemented to overcome this lack of information and forecast durum wheat yields at regional and sub-area scale. In 1998, in collaboration with one of the largest pasta producers in the world, Delphi was implemented as an integrated forecast system based on the AFRCWHEAT2 model (Porter, 1984, 1993; Porter et al., 1993), in the major supply basins of southern and central Italy. Delphi consists of a network of weather stations in the regions of interest that acquire meteorological inputs required by the model, a tool to handle management information like sowing date, seed and fertilization amounts, a database for soil, a statistical tool for scenario data reconstruction and gap-filling, and a geographical information system for output visualization and spatialization. This study is based on the capability of a specific crop growth simulation model, driven by a combination of both measured past weather data and forecast future scenario weather data, to predict durum wheat yield, integrated into an operational seasonal forecasting tool focused on the need of crop production managers. We first assessed the ability of AFRCWHEAT2 model simulations to reproduce crop growth at 11 experimental sites by comparing model outputs and site observations and subsequently we implemented Delphi system as an operational tool at regional scale. The results were stored in a database and spatially aggregated to administrative regions, in order to be compared with official durum wheat yields provided by the National Institute for Statistics (ISTAT, http://agri.istat.it/) over a period of 11 years. Moreover we assessed the performance of Delphi as a forecast tool, in terms of accuracy and lead-time of yield forecasts that are produced operationally during the growing season.

2. Materials and methods

2.1. AFRCWHEAT2 simulation model

The Delphi system is based on AFRCWHEAT2 model (Porter, 1984, 1993; Porter et al., 1993; Semenov et al., 1993; Semenov and Porter, 1995). The model has been calibrated and "tuned" for durum wheat and Italian conditions since 1995 and is currently used by one of the major pasta manufacturers to make yield and quality predictions for durum wheat in the major Italian supply basins. AFRCWHEAT2 is a FORTRAN-based mechanistic model that incorporates crop response to water and nitrogen constraints. AFRCWHEAT2 is a complex model of wheat growth and development, describing the phenological development, dry matter production and dry matter distribution between the organs for various environmental parameters on a daily time scale. The model includes a description of plant transpiration and soil evaporation, water and nitrogen movement in the soil, and their uptake by the plant in the course of growth (Harnos, 2006).

AFRCWHEAT2 model simulates wheat development by thermal time accumulation using vernalization and photoperiod factors. Dates of emergence, double ridges, terminal spikelet, anthesis, beginning and end of grain-filling and physiological maturity are calculated by the model for a specific cultivar. Constant intervals in thermal time between developmental events are calculated separately for each pair of developmental stages. Temperature is accumulated above a base temperature and, according to developmental stage, its effects are modified by photoperiod and vernalization. To account for the range of cultivars currently grown in the study areas, model parameters calibrated using experimental data performed for 4 different cultivars grown in experimental sites (Table 1) (Simeto, Duillio, Iride and Svevo) which are among the most widely cultivated in Italy, (http://www.agraria.org/coltivazionierbacee/granoduro.htm) in order to parameterize an ideal cultivar (Harrison et al., 2000). Incoming photosynthetically active radiation (PAR) is calculated