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A sequential approach for improving AZODYN crop model under conventional and low-input conditions☆

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ABSTRACT

Advances in scientific understanding of the plant and soil behaviour in a cultivated field led to the design of numerous soil–crop models simulating crop growth. The frequent low predictive quality of these models is linked to uncertainties in inputs, parameters and equations. The AZODYN crop model predicting wheat grain yield and grain protein content was previously developed to support decision for N management of conventional and organic wheat crops. This paper outlines a sequential approach to improve the predictions of the AZODYN model by testing various formalisms. This study is based on the comparison of 38 versions of the model assessed in multi-environment trials carried out under conventional or low-input conditions. This paper describes and discusses the methodology. The results show that the predictive value of grain yield and grain protein content could be largely improved without increasing model complexity.

1. Introduction

Nitrogen (N) is a key nutrient in achieving acceptable yield and quality performances of bread-making wheat. A promising approach to support N management consists in using crop models to optimize fertilization management (Meynard et al., 2002). Hence, the use of models as decision support systems requires a good balance between simplicity and complexity, robustness and performance (Passioura, 1996). Parsimonious models, based on robust and sound principles, should require inputs easily collected by the users and a low number of parameters adapted for a wide range of environmental conditions. The predictive quality of models is often low, whatever their complexity (Barbottin et al., 2008), and has led to numerous studies aiming at improving it. Different approaches can be developed to improve the prediction value of crop models and to enlarge their domain of validity such as, for instance, the insertion of new parameters and equations (Hammer et al., 2002), or the combination with measurement data (Naud et al., 2007). Another approach consists in comparing several versions of the crop model, varying in one or several equations. The soil-crop model AZODYN (Jeuffroy and Recous, 1999) predicts the consequences of nitrogen fertilization management strategies on crop yield, grain protein content and soil mineral N at harvest, taking into account soil characteristics, weather conditions, cultivar characteristics and type of fertilizers. This model was developed to help farmers to determine the best dates and amount of N fertilizer to apply to limit detrimental N deficiency throughout the crop cycle and avoid high losses due to environmental factors. During its previous assessment to support decision making for choosing cultivars (Barbottin et al., 2006) or selecting N fertilization strategies (David et al., 2005), errors have been observed that could limit its use as a decision support tool. The purpose of this paper is to improve the performance of the AZODYN crop model through the comparison of several versions. This improvement was restricted to major errors previously observed in David et al. (2004) and Barbottin et al. (2006). Different formalisms were tested on (i) the influence of water stress on soil N mineralization, crop N uptake and plant growth, (ii) the N availability from organic and mineral fertilizers, (iii) the prediction of the senescence during the grain filling process and (iv) the reduction of the number of grains linked with N nutrition dynamics.

2. Materials and methods

2.1. The AZODYN wheat crop model

The AZODYN model had already been described and tested in previous papers (Jeuffroy and Recous, 1999; David et al., 2004) under a wide range of environments in conventional, low-input and organic conditions. This model is composed of three modules: a soil

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module simulating changes in the amount of soil mineral N over the crop cycle, a fertilizer module simulating the dynamic availability of mineral N from mineral and organic fertilizers, the gas losses from volatilization and nitrogen use efficiency of the fertilizer (from mineral and organic fertilizers), and a crop module simulating leaf area time-course change and above-ground biomass production.

2.2. Winter wheat trials

The AZODYN model was tested, in this study, under conventional and low-input conditions, with weeds and diseases controlled by pesticide applications, and with mineral or organic fertilizers application. Experiments were carried out on 22 fields from 1992 to 2002, covering a wide range of soils and climates in France (Table 1). Large variations during crop cycle were recorded on cumulative rainfall, from 303 to 1028 mm, and on average temperatures, from 8.5 to 11.7 °C. From experiments 1–18, 65 mineral N treatments were tested. The dates of application varied from the end of January (tillering period) to mid May (ear emergence). The average amount of N was equal to 150 kg N ha^{-1} with large variation from 0 to 300 kg N.ha^{-1}. From experiments 19–22, 27 organic N treatments, with guano or feather meal (amounts varying from 0 to 180 kg N ha^{-1}, average 84 kg N ha^{-1})were tested, with the same range of dates of application. Twelve experiments included a reference treatment with no N application (N0) (Table 1).

2.3. The different versions of AZODYN model

The methodological framework was based on the comparison of 38 versions of the AZODYN model, varying in one or several mathematical functions derived from literature and/or defined from previous experiments. The versions differed on (i) the prediction of the water stress on soil–crop system, (ii) the prediction of the N availability from mineral or organic fertilizer or (iii) the incidence of plant N content on the crop reproductive development.

2.3.1. Incidence of water stress on soil–crop system

2.3.1.1. Incidence of water stress on daily N mineralization from humus and crop residues. The incidence of water stress on N availability from humus and crop residues was tested using seven functions including the initial version with no effect of water stress (model Vi). The various functions tested in this paper varied on (i) the calculation of the reduction factors related to water stress, (ii) the incidence of these factors on the N mineralization from humus (versions 2, 5 and 6) and from crop residues (versions 3, 4 and 7). Two reduction factors related to water stress were compared. First, the reduction factor Fh, used in the STICS crop model (Brisson et al., 1998), is defined as:

$$\mathrm{Fh} = 0.2 + \left(0.8 \times \left(\frac{W_t}{W_{\max}}\right)\right) \quad (1)$$

The actual quantity of soil water (W_t) at day t is equal to:

$$W_t = W_{t-1} + (P_t + I_t) + \int_{zrt-1}^{zrt} \theta(z)\mathrm{d}z - T_{t-1} - E_t \quad (2)$$

where P_t is precipitation, I_t irrigation, $\theta(z)$dz is the water content in the rooting zone at date t, T_t is crop transpiration and E_t soil evaporation at date t. The equations for the calculation of the evaporation from the soil and the maximal transpiration were built using Penman's reference.

The maximum soil water content $W_{\max}$ at day t is equal to

$$W_{\max} = \mathrm{RD}_t \times \left(\frac{(\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}})}{(\mathrm{RD}_{\max} + 20)}\right) \quad (3)$$

where RD_t is the depth of the rooting zone at day t, defined as a linear function linked with the cumulative degree days from sowing, and $\mathrm{RD}_{\max}$ is the maximum depth of the rooting zone. θ_{FC} is the soil water content at field capacity. θ_{WP} is the soil water content at wilting point. Permanent hydric characteristics of the soil (soil water content at the field capacity and at the wilting point) are assumed constant within the top-soil layer.

The second reduction factor Rh, proposed by Lecoeur and Sinclair (1996), is defined as:

$$Rh = \frac{1.05}{(1 + 4.5e^{-9W_t/W_{\max} - 0.085})} \quad (4)$$

These reduction factors were applied either to the whole rooting zone (version V2 and V3 using Fh, versions V4 and V5 using Rh) or to the ploughed layer (version V6 and V7 using Fh).

Table 1
Characteristics of the experimental sites: year, location, total rainfall and mean temperature during crop cycle, soil characteristics (clay, $CaCO_3$ and total N content of the ploughed layer, genotype and number of treatments of the sites.

Experiment	Year	Location	Total rainfall	Mean temperature	Clay p.m.	$CaCO_3$ p.m.	Total N cont. p.m.	Genotype	Number of treatments
1	1991–1992	Grignon	383	8.7	289	23	1.42	Soissons	4
2	1994–1995	Grignon	531	10.1	231	6	1.39	Soissons	*5*
3	1995–1996	Grignon	221	8.5	228	5	1.32	Soissons	*6*
4	2000–2001	Jaunay Clan	689	10.4	423	15	1.7	Apache	*8*
5	2000–2001	Irais	645	11.7	258	4	1.5	Apache	*8*
6	2000–2001	Réaux	929	11.7	493	18	1.5	Apache	*7*
7	2000–2001	Les Gours	852	10.6	181	15	3.4	Apache	6
8	2000–2001	Le Magneraud	1028	11.0	350	24	2	Apache	*8*
9	2000–2001	Clermont fd	310	10.3	333	168	1.98	Soissons	*2*
10	2000–2001	Dijon	713	9.8	384	0	1.45	Soissons	2
11	2000–2001	Toulouse	521	11.9	238	2	0.97	Soissons	2
12	2000–2001	Le Moulon	768	10.0	145	0	1.38	Soissons	2
13	2000–2001	Mons	636	9.5	178	13	1.05	Soissons	2
14	2000–2001	Rennes	984	11.1	145	1	1.12	Soissons	2
15	2001–2002	Clermont fd	303	9.4	264	248	1.74	Soissons	2
16	2001–2002	Toulouse	383	10.9	238	2	0.97	Soissons	2
17	2001–2002	Le Moulon	446	9.7	145	0	1.14	Soissons	2
18	2001–2002	Rennes	476	10.7	145	1	1.12	Soissons	*2*
19	1997–1998	Grignon	517	9.6	241	3	1.28	Soissons	*9*
20	1998–1999	Etoile/Rhône	562	10.2	140	1.4	1.20	Soissons	*4*
21	1997–1998	Etoile/Rhône	704	10.9	160	3	1.42	Soissons	*5*
22	1999–2000	Etoile/Rhône	410	10.2	236	209	1.60	Soissons	*12*

In italic:including one treatment with no N application.