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Using Water and Agrochemicals in the soil, crop and Vadose Environment (WAVE) model to interpret nitrogen balance and soil water reserve under different tillage managements

**Narjes ZARE[1) BCDEF], Mohammadreza KHALEDIAN[1), 2) ABCDEF]
Jean-Claude MAILHOL[2) ABD]**

[1)] University of Guilan, Faculty of Agricultural Sciences, Irrigation and Drainage Department, Rasht, Iran;
e-mail: khaledian@guilan.ac.ir
[2)] National Research Institute of Science and Technology for Environment and Agriculture, Irstea, Montpellier, France;
e-mail: mkh572000@yahoo.com

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Abstract

Applying models to interpret soil, water and plant relationships under different conditions enable us to study different management scenarios and then to determine the optimum option. The aim of this study was using Water and Agrochemicals in the soil, crop and Vadose Environment (WAVE) model to predict water content, nitrogen balance and its components over a corn crop season under both conventional tillage (CT) and direct seeding into mulch (DSM). In this study a corn crop was cultivated at the Irstea experimental station in Montpellier, France under both CT and DSM. Model input data were weather data, nitrogen content in both the soil and mulch at the beginning of the season, the amounts and the dates of irrigation and nitrogen application. The results show an appropriate agreement between measured and model simulations (nRMSE < 10%). Using model outputs, nitrogen balance and its components were compared with measured data in both systems. The amount of N leaching in validation period were 10 and 8 $kg \cdot ha^{-1}$ in CT and DSM plots, respectively; therefore, these results showed better performance of DSM in comparison with CT. Simulated nitrogen leaching from CT and DSM can help us to assess groundwater pollution risk caused by these two systems.

Key words: *conservation tillage, corn, modeling, nitrogen balance, soil water reserve*

INTRODUCTION

Irrigation plays a dominant role in agriculture because of degrading water resources and variant distribution of the rainfalls in Mediterranean region throughout the year. Farmers need to save water and make judicious use of it, especially during the dry season. So, improving irrigation management is crucial to address water scarcity issue [ADEKALUE, FAPOHUNDA 2006]. Nowadays, understanding the processes which affect the fate of nitrogen in the root zone is essential to develop relevant management strategies to conserve surface and subsurface water resources. The application of mechanistic nitrogen models to describe the nitrogen fluxes in the soil–plant–atmosphere continuum helps us to better understand the soil nitrogen balance.

In the traditional soil management, burning of crop residues and declining of fallow periods in large-scale will reduce water infiltration and nutrient imbalances [OUEDRAOGO *et al.* 2004]. Some activities like mechanized seedbed preparation, overgrazing by cattle little would reduce abundance and biodiversity of soil organisms [BROWN *et al.* 2001]. One of the environmental conservation system is DSM (Direct Seeding into Mulch).This approach made conserve the soil, increasing crop yield and improve the environmental conditions and soil ecology [ERENSTEIN 2003]. DSM also saves the soil water by decreasing evaporation and runoff. By providing favorable food source, the activity of soil micro-organisms increases which results in degradation of organic matter, and ends up in the mineralization of nitrogen, N [SCHROTH *et al.* 2001].

To evaluate different aspects of DSM, field experiment can help us but field trials are costly and time-consuming, therefore using of crop models is recommended to save time and money. Also it made it possible to use other advantages such as examining of different management scenarios. Models are suitable tools to reestablish the real systems under physical, chemical and biological conditions; however, input supporting faced some difficulties [ADDISCOTT 2000]. Different models were developed to better understand the water and solute transportation in soil [SIMUNEK *et al.* 1999]. Crop models can predict crop growth and their development under different climate, agricultural practices, soil features and environmental conditions. Models are efficient tools for water management [PANDA *et al.* 2003]. Many models were introduced by researchers among them some models are multi-crop and others are single crop e.g., ORYZA [PANDA *et al.* 2003], WARM [CONFALONIERI *et al.* 2010], CERES-Wheat [OTTER-NACKE *et al.* 1987].

Field-tested computer models can be useful tools of assessing nutrient leaching and water movement. In particular, when data are scarce or of limited reliability, physically-based numerical models can be useful exploratory tools to understand the complexity of these processes and to quantify nitrogen leaching as a consequence of fertilizer practices. One of the numerical models in this field is WAVE (Water and Agrochemicals in the soil and Vadose Environment) model, developed and introduced by VANCLOOSTER *et al.* [1994]. This model was evaluated to predict crop water consumption and volumetric soil water content in a cropped soil during 1992 and 1993. The results showed that the model is reliable to simulate the fate of water in a sandy soil and in semi-arid conditions [FERNANDEZ *et al.* 2002]. In Bulgaria, water flow and nitrogen transport also were simulated by other models i.e. SWAP and ANIMO, to optimize agricultural practice aiming to minimize the impact on the environment. The results showed that SWAP model could satisfactorily simulated soil water dynamics, while simulations of ANIMO for nitrogen cycle present greater divergence with observations, but in assessing land use impact on groundwater quality had adequate precision [MARINOV *et al.* 2005].

The purpose of this study was to assess the performance of WAVE model in describing soil water and soil nitrogen balances on a loamy soil under both conventional tillage and direct seeding into mulch systems. This topic was identified as being important to introduce a relevant tool to better understand DSM system.

MATERIAL AND METHODS

EXPERIMENTAL SITE

An experimental study has been carried out to evaluate the N and water balances of corn (Pioneer PR35Y65 variety) in 2007 with DSM and CT. This study was conducted at Irstea experimental station which is located in Montpellier in the southeastern part of France in a Mediterranean climate with 789 mm of average annual rainfall (1991–2007). The annual evapotranspiration (ET_o) over this long term calculated by Penman–Monteith equation was 859 mm·year^{-1}. The climate data were monitored at the weather station situated in the experimental station. Figure 1 shows average monthly precipitation and ET_o (mm) at the Irstea institute (1991–2007). Figure 1 demonstrating that in corn crop season in the region (April–September), precipitation is lower than ET_o so that irrigation is necessary. According to the USDA soil classification, the soil under CT and DSM plots belongs to the loam soil category. The values of chemical properties of the soil are given in Table 1.

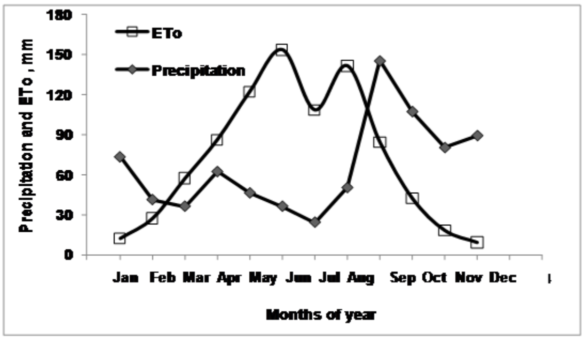

Fig. 1. Average monthly precipitation and reference evapotranspiration (ET_o, mm) at the Irstea institute (1991–2007); source: own study

Table 1. Soil chemical properties at the Lavalette Agricultural Research Station in both conventional tillage (CT) and direct seeding into mulch (DSM) plots

Plot	Organic matter	Organic carbon	N total	C:N
	%			
CT	1.39	0.78	0.08	10
DSM	1.79	1.04	0.09	11.81

Presented soil properties are for 0–30 cm depth.
Source: own study.

EXPERIMENTAL SETUP

Two main plots were considered in this study: a DSM plot of about one hectare and a CT plot of 1.7 ha. The corn planting and the harvest dates were 24 April 2007 and 28 September 2007, respectively. For a given crop season, the crop is generally subjected to different irrigation treatments, with always at least a full irrigated (430 mm of irrigation depth) and a rain-fed treatments. Other treatments were respectively 218 and 182 mm of irrigation depth. An access tube of neutron probe was installed in each treatment. Soil water reserve (SWR) was monitored once a week using a neutron probe from 0 to 2 m at 0.1 m depth interval.

A corn crop was cultivated in CT and DSM. For maintaining a thick layer of mulch on the soil surface in DSM, a mixed of oat, vetch and rape seed was sown in October 2006 in the DSM as cover crop and was destroyed by "glyphosate (Rounup)" in April 2007, before corn sowing (two weeks before sowing). The amount of residues from precedent crops at sowing and produced mulch by cover crop were 0.5 and 8 Mg·ha^{-1}, respectively. The field was fallow in the middle season of 2007 and 2008 with CT. The model was validated in this period to simulate soil water content and nitrogen balance components.

The agricultural practices and the use of plant protection agents were in accordance with local practices, official recommendations and experts' advice. The goal was to mimic as close as possible the conditions of production in commercial farms. So that, the farm scale equipment was fixed and applied. In the CT plot, at the end of July disc harrow was used to chop and bury the residues of the precedent crops. In the middle of November, tillage with plough was performed. In DSM plot, the cover crop was sown by a specific seeder. After destroying the cover crop the same seeder was used to sow the main crop. N amounts were applied in order to fully satisfy plant requirement as soon as an N soil profile was established just before sowing. Two N applications were generally performed, the first one at sowing and the second one 30–40 days after sowing (DAS). Other fertilizers (P and K) also were applied in both plots.

To determine the grain yield (GY) and dry matter yield (DM) ten 3 m^2 sub-plots were hand harvested after reaching physiological maturity. The measured GY and DM coefficient of variation (coefficient of variation, CV) ranged from 6 to 12%.

The soil mineral N content was determined before sowing and after harvest. Seven core samples per plot were taken from 0 to 0.10, 0.10 to 0.30, 0.30 to 0.60, 0.60 to 0.90, 0.90 to 1.20, and 1.20 to 1.50 m depths with an auger. Then, the samples of each layer were mixed and sieved to have a representative and a unique sample for each layer. Plant N content in leaves, stems and grains were determined at harvest with the Kjeldahl method.

THE NUMERICAL MODEL

The WAVE model [VANCLOOSTER *et al.* 1994] is a deterministic and mathematical model that simulates the transfer and the fate of agrochemicals and the movement of water in the soil-crop continuum. This model combines two models: the SWATNIT model [VEREECKEN *et al.* 1991] and SUCROS model [SPITTERS *et al.* 1988]. Because of inactivation of SUCROS model in current WAVE model version, in this study PILOTE model [KHALEDIAN *et al.* 2009] was used instead of SUCROS model. This model simulates the soil water balance and the crop yield at a daily time step under the assumption of just water as growth limiting factor [MAILHOL *et al.* 1997]. This model was calibrated and validated in the same field for corn in both CT and DSM systems by KHALEDIAN *et al.* [2009].

The WAVE model uses finite difference techniques for the solution of the physical transport equations [TIMMERMAN, FEYEN 2003].The modules currently are available in the WAVE model simulate with the following soil processes: the flow of water, transport of non-reactive solutes, the heat transport, the crop growth and the movement and transformations of nitrogen. It can deal with different soil horizons which are divided into equidistant soil compartments. A water, heat and solute mass balance equations are developed for each section, taking into account different sink/source terms.

The water transport module of WAVE is based on the Richards equation for isotropic, homogeneous, isothermal, rigid and porous media, while solute transport was modeled with a convection equation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{tx} + 1\right)\right] - Sinkwat \qquad (1)$$

where:
- $C(h)$ – the differential moisture capacity;
- $K(h)$ – the hydraulic conductivity relationship;
- h – the soil water pressure head, m;
- $Sinkwat$ – the water sink term, 1·s^{-1};
- z – the space co-ordinates, m;
- t – the time co-ordinates, s.

The water transport model is assumed that due to it the soil water flow occurs in response to a hydraulic potential gradient. The soil water retention curve is assumed to be of the form given by Van GENUCHTEN [1980]:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1+(\alpha[h])^n)^m} \qquad (2)$$

where:
- θ_s – the saturated moisture content;
- α – the inverse of entry value, 1·m^{-1};
- m, n – shape parameters.

Solute transport was described by the convection-dispersion equation with a linear reversible adsorption isotherm for reactive solute:

$$\frac{\partial(\theta C_r)}{\partial t} + \rho K_d \frac{\partial C_r}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_s \frac{\partial C_r}{\partial z}\right) - \frac{\partial(qC_r)}{\partial z}\sum_i \varphi_i \quad (3)$$

where:
- C_r – the resident concentration (kg·m^{-3}) in the solution;
- ρ – the soil bulk density, kg·m^{-3};

K_d – the solute distribution coefficient, $m^3 \cdot kg^{-1}$;
D_s – the apparent dispersion coefficient, $m^2 \cdot s^{-1}$;
q – the Darcian water flux, $m \cdot s^{-1}$;
$\Sigma_i \varphi_i$ – a solute sink term ($kg \cdot m^{-3} \cdot s^{-1}$), including crop uptake and transformation.

When solute is applied at the soil surface (during a fertilization or irrigation event), it is assumed to dissolve instantaneously in the mass of water entering the soil profile during the day of solute application (or the first day when infiltration occurs).

WAVE simulates plant uptake under tension condition by determining the fraction of the total growing season of potential uptake and the calculated convective plant water uptake. Mineralization of organic N and immobilization of inorganic N were modeled based on soil litter, soil humus and soil manure pools. In addition, potential rates for modeling such as nitrogen transformations were reduced for the temperature and the water content in the soil profile.

NITROGEN BALANCE

Modeling flow and nitrogen transport with WAVE model need multiple parameters to be estimated; however, collecting all parameters and direct estimation really are impossible. Numerical models are often used instead of inverse modeling and experimental method to solve multiple parameter problems [RITTER *et al.* 2004].

For experimental measurements, a simple method to assess the N balance in both systems was used. N mineralization was estimated in zero N application plots [SEXTON *et al.* 1996]:

$$N_{Min} = N_F - N_I + N_P + N_{MF} - N_{MI} \quad (4)$$

where N_I and N_F are the soil N contents in the beginning and in the end of the study period, respectively. N_P is the N uptake by plant. N_{MI} and N_{MF} are mulch N content at the beginning and at the end of study period. In CT, N_{MF} and N_{MI} were not considered. A loss of N in the fertilized plots (P) was calculated with equation 5 using N_{Min}, N_I, N_F, N_P, N_{MF}, and N_{MI} as defined above and N_{AP} (N fertilizer applied). A negative value of P is interpreted as a loss of N in the soil–plant system.

$$P = N_F - N_I + N_P - N_{AP} - N_{Min} + N_{MF} - N_{MI} \quad (5)$$

MODEL CALIBRATION

Sensitivity analyses are valuable tools for identifying important model parameters, testing the model conceptualization, and improving the model structure. They help to apply the model efficiently and to enable a focused planning for future research and field measurement. Sensitivity analysis of WAVE model by MUNOZ-CARPENA *et al.* [2008] showed that leaf area index, distribution coefficient of NH_4^+ and maximum N uptake had a medium sensitivity level, where crop coefficient, saturated soil water content and curve shape parameter had a high sensitivity level.

For illustrating the impact of using effective calibrated field parameters instead of laboratory scale parameters, calibrated modeling results are shown as well. Calibration was performed on a trial and error basis, using the field scale observed moisture content and nitrogen balance as objects (Tab. 2).

Table 2. Summary of simulation results ($kg \cdot ha^{-1}$) in conventional tillage (CT) and direct seeding into mulch (DSM) systems

Output	CT				DSM			
	calibration		validation		calibration		validation	
	obs.	sim.	obs.	sim.	obs.	sim.	obs.	sim.
Final NO_3^-	148.7	149.0	140.9	140.5	328.2	327.4	67	70.8
Final NH_4^+	29.5	29.8	25.5	34	24.5	25.2	27	20.2
N leaching	16	17	7	10	6	4	7	8
N mineralization	110	99	110	109	305	299	160	150

Final stock simulated in 150 cm soil.
Explanations: obs. – observation, sim. – simulation.
Source: own study.

To express the differences between the simulated and observed values in terms of statistical indices, the normalized root mean square error, nRMSE, MAE being the mean absolute error, as well as, the coefficient of residual mass, CRM were used as follows:

$$\text{nRMSE} = \frac{100}{\bar{O}} \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (6)$$

$$\text{MAE} = \frac{\sum_{i=1}^{n}|P_i - O_i|}{n} \quad (7)$$

$$\text{CRM} = 1 - \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \quad (8)$$

where:
P_i, O_i – the model calculated and observed values, respectively;
n – the number of samples;
$\bar{O}$ – the mean of the observed values.

These statistical indices were calculated on unsorted data, observed and predicted values being compared directly. nRMSE, MAE and CRM should be as close as possible to zero. The simulation is considered excellent with nRMSE less than 10%, good if nRMSE is greater than 10 and less than 20%, fair if nRMSE is greater than 20 and less than 30%, and poor if nRMSE is greater than 30% [BANNAYAN, HOOGENBOOM 2009]. The coefficient of residual mass, CRM, ranges between –infinite and + infinite, with the optimum = 0. If it is positive, it indicates that the model underestimates the prediction, if negative indicates overestimation and when it is close to zero indicates the absence of trends [BONFANTE *et al.* 2010].

RESULTS AND DISCUSSION

After running the model, N balance parameters were simulated (Tab. 2). In this table, observation and simulation values in two plots were compared. Final N content that consists of NO_3^- and NH_4^+, had suitable simulation because of closed value of simulation to observation. The most important parameter in this table is N leaching. By comparing this parameter in CT and DSM plots, derive less value in DSM plot. In some references underlined that in DSM plot, runoff and leaching have enhanced because the crop roots have disintegrated after cutting the crop [KHALEDIAN 2009], so macro pore from decomposed root make increase the deep percolation ended up in N leaching increase. But the results showed another thing. With a comparison of corresponding N leaching in two treatments, it is understood that DSM had better application of saving water and nitrogen, because of lower deep percolation and N leaching. The cause of this subject should be understood in soil chemical properties. In Table 1, values of organic carbon and organic matter in DSM and CT plots showed that DSM has higher value while organic carbon in CT and DSM were 0.78 and 1.04% and organic matter were 1.39 and 1.79%, respectively. Organic matter has involved in particle connections and reduction of soil macro pore so, the soil become more stable. According to this process, DSM has higher water saving capacity and lower N leaching. On the other hand, the root of cover crop absorbs residual nitrogen of soil and composed mulch will be released N being suitable for main crop. Therefore, DSM has an important role to save soil water and nitrogen.

In similar studies, WAVE model was used to simulate the fate of nitrogen following in France. In calibration process, modelled budget error was arisen from net mineralization of +15 and +9 kg N·ha^{-1} for controlled plot and cropping season on a plot, respectively. These values in validation were –9 and +13 kg N·ha^{-1} which was considered as very acceptable [PAYET *et al.* 2009]. DUWING *et al.* [2003] used this model to evaluate its prediction capabilities. So water and NO_3^- concentrations and fluxes were monitored in two sites (New Caledonia and France) with different surface covers (maize or bare soil) in three consecutive years. For both sites, evaluations of the model showed the best results for wet conditions.

In addition to nitrogen, SWR was simulated by WAVE. In Figures 2 and 3, observed and simulated values were compared in both plots. Figure 2 shows

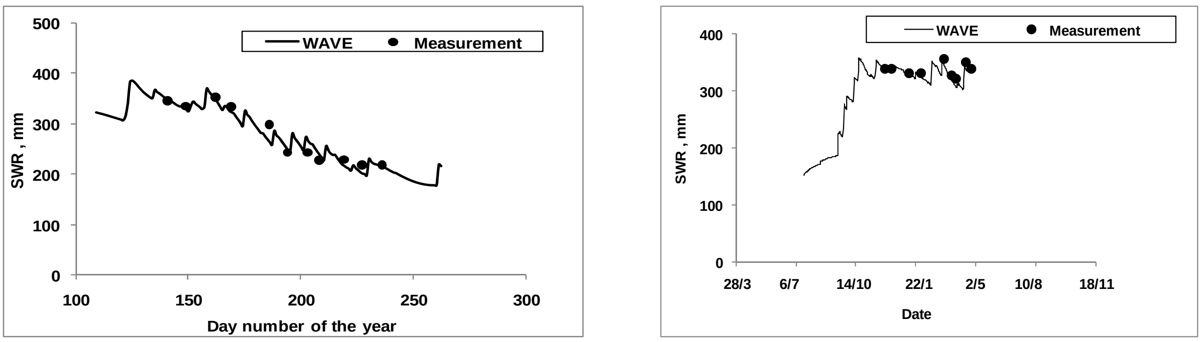

Fig. 2. Comparison between simulation and measurement values of soil water reserve (SWR) in direct seeding into mulch (DSM) plot. (Calibration (left) and Validation (right)); source: own study

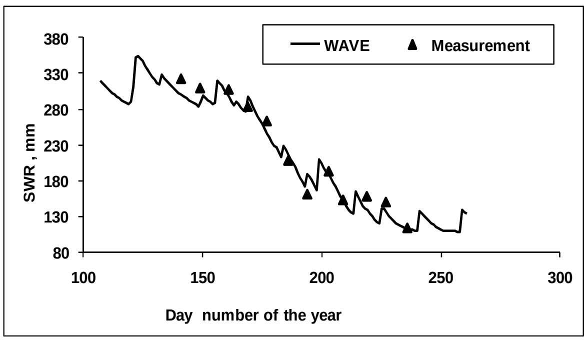

Fig. 3. Comparison between simulation and measurement of soil water reserve (SWR) in conventional tillage (CT) plot; source: own study

this comparison in calibration and validation processes in DSM plot. Left-hand side results from comparing of calibrated and observed values present a satisfied simulation of this parameter. Also validated data were so close to SWR measurements (right-hand side). Also in CT plot calibration was done. Figure 3 shows the good correlated between the two data series. Because of improper condition in bare field to measure SWR with neutron probe, measurements did not perform in CT plot. So, model evaluation in CT plot consists of calibration without validation.

Statistical indices should be used to analyze the simulated data. In Table 3 model assessment was done by CRM, nRMSE and MAE. In calibration both plots have low value of CRM. nRMSEs in all cases were less than 10%. According to acceptable values of each one, WAVE had an excellent simulation in CT and DSM plots according to nRMSE classification [BANNAYAN, HOOGENBOOM 2009]. Also assessment of the MAE values (6.3% for CT calibration and 4.6% for DSM calibration) illustrates suitable simulation of the model.

Table 3. Model soil water reserve (mm) simulation assessment in conventional tillage (CT) and direct seeding into mulch (DSM) plots

Item	Plot	RMSE mm	nRMSE %	MAE %	CRM
Calibration	CT	15	7	6.3	0.022
	DSM	15	5	4.6	0.017
Validation	DSM	9	3	7.9	0.023

Source: own study.

CONCLUSIONS

Water and nitrogen are important inputs in agricultural production systems, especially in Mediterranean climate because of erratic rainfalls. So, selecting the most appropriate cropping system, irrigation and nitrogen application managements to save those items is crucial. In this study, calibration and validation of the WAVE model in CT and DSM plots were done by analyzing of N balance and SWR. The results show that saving soil water and nitrogen in DSM plot is more effective than CT plot. In CT and DSM plot, simulated values of SWR were compared to measurements. That comparison showed a good agreement between simulated and measurement values according to statistical indices. CRM values were close to zero. Depending on low nRMSE values (less than 10%), the simulations were excellent in CT and DSM plots. According to the obtained results, Wave model can be used as a relevant tool to manage water and nitrogen in both CT and DSM systems to save water and nitrogen and mitigate negative environment effects.

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Narjes ZARE, Mohammadreza KHALEDIAN, Jean-Claude MAILHOL

Użycie modelu Water and Agrochemicals in the soil, crop and Vadose Environment (WAVE) do interpretacji bilansu azotu i glebowych zasobów wody w różnych warunkach uprawy

STRESZCZENIE

Słowa kluczowe: *bilans azotu, konserwująca uprawa gleby, modelowanie, zasoby wody w glebie, zboża*

Zastosowanie modeli do interpretacji zależności, które zachodzą w różnych systemach uprawy między glebą, wodą i roślinami umożliwia zbadanie odmiennych scenariuszy gospodarowania, a następnie wybór optymalnej opcji. Celem badań było zastosowanie modelu WAVE (Water and Agrochemicals in the soil, crop and Vadose Environment) do prognozowania zawartości wody, bilansu azotu i jego form w sezonie wegetacyjnym w warunkach konwencjonalnej uprawy (CT) i siewu bezpośrednio w mulcz (DSM). Oba systemy zastosowano do uprawy zbóż w stacji doświadczalnej Irstea w Montpellier we Francji. Danymi wejściowymi do modelu były warunki pogodowe, zawartość azotu w glebie i w mulczu na początku sezonu wegetacyjnego, dawki i terminy nawodnień oraz nawożenie azotem. Wyniki potwierdzają zgodność pomiarów i symulacji modelowych (nRMSE < 10%). Porównano bilans azotu i jego składników uzyskane za pomocą modelu i na podstawie danych z bezpośrednich pomiarów w obu wariantach upraw. Ilość wymywanego azotu w okresie badań wynosiła 10 (system CT) i 8 $kg \cdot ha^{-1}$ (system DSM). Taki wynik dowodzi korzystniejszego oddziaływania systemu DSM w porównaniu z systemem CT. Symulacja wymywania azotu z upraw w systemie CT i DSM umożliwia ocenę ryzyka zanieczyszczenia azotem wód gruntowych w wyniku stosowania obu systemów uprawy.