Evaluation of the soil-crop model STICS over 8 years against the “on farm” database of Bruyeres catchment

Nicolas Beaudoin, Marie Launay, Emmanuelle Sauboua, G. Ponsardin, Bruno Mary

► To cite this version:

Nicolas Beaudoin, Marie Launay, Emmanuelle Sauboua, G. Ponsardin, Bruno Mary. Evaluation of the soil-crop model STICS over 8 years against the “on farm” database of Bruyeres catchment. *European Journal of Agronomy*, 2008, 29 (1), pp.46-57. 10.1016/j.eja.2008.03.001 . hal-01192246

HAL Id: hal-01192246

<https://hal.science/hal-01192246>

Submitted on 31 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Evaluation of the soil crop model STICS over 8 years against the “on farm” database of Bruyères catchment

5

Beaudoin N.^{a,*}, Launay M.^b, Sauboua E.^c, Ponsardin G.^a, Mary B.^a

^a INRA Unité d'Agronomie LRM, rue Fernand Christ, 02007 Laon Cedex, France

10 ^b INRA, Unité Agroclim, Domaine St Paul, Site Agroparc, 84914 Avignon cedex 09,
France

^c INRA, UMR EGC, 78850 Thiverval-Grignon, France.

* Corresponding author:

15 nicolas.beaudoin@laon.inra.fr

tel (+33).3.23.23.99.57

fax (+33).3.23.79.36.15

Second author:

mllaunay@avignon.inra.fr

20 tel (+33).4.32.72.23.67

fax (+33).4.32.72.23.62

Correspondance address:

INRA Unité d'Agronomie LRM, rue Fernand Christ, 02007 Laon Cedex, France

25

Abstract

The European Water Framework Directive (2000) offers a new challenge for farmers and water policy makers. It requires the establishment of quantitative environmental diagnosis of water quality. This can be done using crop models properly tested in the short and long terms and taking into account current farming practices. The aim of this paper is to check the robustness of a crop model (STICS) for predicting the nitrogen uptake and nitrate leaching in various fields during 8 successive years. The model was evaluated on the soil-crop database of a small catchment in Northern France. It includes data of crop production and N uptake, water and mineral nitrogen contents in soil measured three times a year at 36 sampling sites representative of crops (wheat, sugarbeet, pea, barley, oilseed rape) and soil materials (loam, loamy clay and rocks, sand loam and limestone, sand). A few crop parameters of STICS were recalibrated on independent databases in order to improve the predictions obtained with the standard parameterization. STICS was then evaluated either by resetting simulations each year (RS) or during continuous simulations (CS) over the 8 years. A reasonable agreement was obtained between observed and simulated values, except for soil N mineral content at harvest and N content in crop residues. The model efficiencies using CS mode were 0.53, 0.94 and 0.38 for N uptake, soil water and mineral N in late autumn, respectively. The mean calculated drainage was 192 mm y⁻¹ and N leaching was estimated at 20 kg N ha⁻¹ y⁻¹. Gathering the outputs according to soil and crop type improved the quality of fit. The outputs of CS simulations were close to those obtained with RS. The mean nitrate concentration in drained water was estimated as 46 and 45 mg NO₃ l⁻¹ with RS and CS, respectively. Continuous simulations did not induce a substantial drift in mineral N in late autumn and can be trusted for predicting nitrate leaching. However, the leaching predictions were more sensitive to spatially variable parameters such as maximal rooting depth and potential

mineralisation rate for CS than for RS. This emphasizes the difficulty in upscaling the model on the long term for large spatial areas. Another important uncertainty concerns fertiliser use efficiency, which had a small effect on leaching but a marked influence on gaseous N losses. Further assessments of the model will concern the whole N balance

5 prediction on the long term.

Key words: Modelling, cropping systems, nitrate leaching, mineralisation, cumulative effect.

10

1. Introduction

The European Water Framework Directive has defined a new challenge for 2015 concerning the quality of surface and ground water (Letcher and Giupponi, 2004). One component of the quality is the nitrate concentration since diffuse pollution has significantly increased in many intensive agriculture areas in Europe. Diffuse pollution concerns both surface water and groundwater at the catchment scale but with a very different transfer time. Distributed soil crop models are useful tools to quantify the impact of agricultural practices on nitrate losses towards groundwater (Wagenet and Hutson, 1996; Loague and Corwin, 1996, Hoffmann and Johnsson, 1999). They can help to predict the mitigation effects of improved practices on soil, air and water resources (Hansen et al., 2001; Keating et al., 2003). However, there is a need to check the ability of these models to simulate crop production and N fate on the long term, at large spatial scale and in actual 'on farm' conditions.

The model performances in predicting water and nitrogen losses over the long term remain a concern because models have mostly been evaluated on annual experiments. Kovács et al. (1995) simulated a 20 year experiment in Hungary and found that the amount of N leached could be well predicted by CERES in the high N input treatments but not in those with low inputs. Blombäck et al. (2003) studied the cumulative effects of catch crops in Sweden during 7 years. They found that N leaching was overestimated both at the annual and mid-term scales despite a good prediction of soil mineral nitrogen content. Lysimeter experiments studies indicated that the cumulative leaching fluxes could be well predicted after 10 years in Germany (Kersebaum and Bebblik, 2001) or 8 years in France (Schnebelen et al., 2004) in spite of errors on annual predictions. However it is necessary to better identify the key parameters driving the whole N balance over the long term.

The second concern is upscaling soil-crop models from field to catchment scale. Any description of the spatial variation of diffuse pollution **should** be associated with an estimate of the error (Wagenet and Hutson, 1996), particularly taking into account the parameter uncertainties due to spatial variability (Gijssman et al., 2002). The challenge is to
5 get robustness, i.e. the ability to simulate various soil and climate conditions without **important** bias in the outputs (Brisson et al., 2002).

The third issue concerns the effect of actual farmer practices. Indeed they may differ from those applied on experimental sites. 'On farm' conditions may involve additional factors driving the actual production which are not covered by the model (Shaffer et al.,
10 2001; van Ittersum et al., 2003), and the agronomic inputs required by the model (sowing date, tillage depth, ...) may be unavailable or even false in these situations.

The objective of this paper is to evaluate the ability of a crop model such as STICS to predict nitrate leaching in actual cropping systems over a long period. Since we cannot routinely measure N leaching in these conditions, we check the model prediction of
15 environmental and agricultural variables of interest, mainly soil water and nitrate **contents**, N crop uptake and crop **yields**. **STICS model was first recalibrated on three independent databases and then evaluated** against the Bruyères catchment database which is representative of cropping systems of Northern France (Beaudoin et al., 2005). This database was obtained with 'on farm' conditions, where 'good agricultural practices' have
20 been implemented associating optimised fertilisation and catch crops over the whole catchment.

2. Materials and methods

2.1. Soil crop model

We have used the crop model STICS that simulates water, carbon and nitrogen dynamics in the soil crop system (Brisson et al., 1998; 2002). This model was previously
5 used at field scale to simulate the effect of N fertilisation strategy for precision agriculture (Houlès et al., 2004) or at catchment scale to compare scenarios for reducing nitrate pollution (Sauboua, 2001; Schnebelen et al., 2004). STICS is a one dimensional model with a daily time step. It distinguishes several compartments of the crop canopy and segments the soil profile into (at most) 5 layers. It has been calibrated for maize and wheat
10 (Brisson et al., 2002) and other crops.

STICS simulates the effect of water and nitrogen stress on leaf area index (LAI), root growth, C assimilation, aerial biomass and harvest index. The water and nitrogen balances (evapotranspiration and N uptake) are calculated using the concept of limiting factor between soil supply and crop demand. The effective water or N uptake is equal to the
15 smallest of these two terms. This approach enables to define water and nitrogen stress indices. The maximum and critical crop N demands are determined according to the concept of 'N dilution curves' in the aerial dry matter (Lemaire and Gastal, 1997).

Water storage considers both fine soil and stony materials. STICS is a capacity-type model with the minimal water content (permanent wilting point) and the maximal water
20 content (field capacity). Downwards water transport occurs when water content exceeds field capacity. Nitrate transport within the soil profile is simulated using the 'mixing cells' concept which accounts for convection and dispersion as shown by Mary et al. (1999).

N transformations in soil are modelled by considering three pools of soil organic matter: the fresh organic matter (FOM) that includes crop residues and organic
25 amendments, the microbial biomass, and the humified organic matter (SOM) which is

itself composed of a stable and an active pool. FOM is characterised by its C/N ratio, obtained from published references for organic amendments or by model calculation for crop residues. The N mineralisation from SOM depends on the potential mineralisation rate of the soil (V_p) and on temperature and water content in soil. V_p is a soil characteristic and depends on the organic N content, the bulk density, the clay and CaCO_3 contents, and the thickness of the mineralisation layer (*profhum*). The net mineralisation from FOM (positive or negative) depends on the decomposition rate of FOM by the microbial biomass and their C/N ratio. It is simulated using the model described by Nicolardot et al. (2001). When soil mineral nitrogen is low, it may exert a negative feedback on decomposition and N release.

The fate of fertiliser N is simulated empirically, on the basis of published ^{15}N labelled fertiliser studies, using the fertiliser use efficiency (FUE). FUE is the proportion of fertiliser-N recovered in the crop at harvest; it depends on soil pH, rate and type of fertiliser and plant N uptake rate at the time of fertiliser application (Limaux, 1999). The complement of this efficiency (1-FUE) is partitioned into gaseous losses (volatilisation and denitrification), leaching losses and microbial immobilisation in soil organic matter.

The model takes into account common farming practices: soil tillage (date, depth), residues incorporation (date, amount, depth, C/N), crop sowing (date, depth, density, cultivar), irrigation (timing, rate), N fertilisation (timing, rate, type of mineral or organic fertiliser), presence of plant mulch (amount, type). By linking several successive simulations, the decomposition of the successive organic residues added to soil (including crop residues) is simulated over the whole study period (one or several years).

STICS considers input “parameters” and “variables”: parameters remain constant throughout a single simulation while variables change with time. Parameters are classified as ‘technical’ for cropping practices, ‘soil’ for soil characteristics, and ‘plant’ for properties

relative to crop species and cultivars. Model calibration consists in getting the parameter(s) value(s) either by direct measurement or by fitting the model outputs against observed data. In the latter case, observed data originates in database(s) independent from the base used in model validation.

5 2.2. Model inputs

The data required to run the model concern the soil characteristics and its initial state, the agro-physiological characteristics (growth and development parameters) of each crop, the technical operations and the climatic conditions during the simulation period.

The main variables defining the initial state of the soil system are the amounts of
10 organic residues in the topsoil and the SWC and SMN contents of each soil layer at the beginning of simulation. These variables are either initialized at the measured values for each crop cycle in case of 'reset simulation' (RS) or set only once and then simulated in the case of a 'continuous simulation' (CS). The RS option constraints the model much more than the CS option which may lead to large divergences between simulations and
15 observations.

The permanent soil characteristics ('soil parameters') were defined on each sampling site. They were fixed using either tables proposed in STICS software or measurements carried out at Bruyères (Table 1). The water content at field capacity (W_{FC}) was estimated as the median value of gravimetric water contents measured on soil cores sampled in mid-
20 winter. The water content at permanent wilting point (W_{WP}) and the soil bulk density were estimated by implementing local pedotransfer functions based on analyses carried out on 12 representative soil profiles. Permanent wilting point was the gravimetric water content measured after a 12 hours application of a -1.5 MPa potential. Bulk density was determined using a gamma density probe and measuring the volumetric content of stones
25 in each soil layer. The physical characteristics (W_{FC} , W_{WP} and bulk density) of stony

materials (> 2 mm) were also determined by laboratory measurements. The chemical parameters (organic N, pH, ...) were measured between 1991 and 1995 in the ploughed layer. The thickness of the biologically active layer for mineralisation (parameter *profhum*) was estimated to be 10% greater than the ploughing depth, according to Mary et al. (1999).

5 The maximal rooting depth (parameter *obstarac*) was established on the basis of root observations carried out in 1993 on wheat crops, in several soils. It is strongly dependent on soil type. The evaporation parameter *q0* which defines the transition from potential to reduced evaporation was optimised using the databases C1 and C2 (see below). It was estimated by fitting the simulated drainage on database C1 and the soil water content on
10 database C3, using the simplex method (Nelder and Mead, 1964) which minimizes the root mean square error.

Most technical parameters were determined using the information provided by farmers. The amount of mulched straw (parameter *qmulch*) was either 0 (if there was no return of residues or after the first soil tillage) or equal to the amount of residues at harvest.

15 Only one parameter was calibrated using database C3: the thickness of the layer containing the buried crop residues (parameter *thickres*), which is equal or smaller than the tilled layer.

STICS version 6 included new formalisms, improving its mechanistic approach. It could simulate the LAI either a net variable or as the difference between the 'gross' LAI
20 production and the senescing LAI. We used the latter option which had been calibrated for mustard and rye-grass as catch crops (Dorsainvil, 2002), winter wheat (Houlès et al., 2004), spring pea (Corre-Hellou, 2005) and maize (Brisson et al., 2002) whereas the net LAI option was kept for cereals and peas, which appeared more robust. Hence additional plant parameters had to be estimated or re-estimated using the calibration databases. We
25 evaluated successively the parameters involved in the following modules: i) development

stages, ii) evolution of LAI and rooting depth, iii) elaboration of crop biomass and grain yield, and iv) N uptake and SMN content. Only parameters concerning the effects of drought on plant emergence and freezing on leaf losses were estimated using the Bruyères database, because greater weather variability was found in this database.

5 2.3. Databases used for model calibration

Three databases were used to calibrate some model parameters through adjustments, and to assess model performances. Two of them came from experiments carried out in bare soils and one with cropped soils.

- Database C1 comes from a lysimeter experiment with undisturbed soil monoliths
10 carried out at Fagnières (48°57'N, 4°19'E) in a chalky soil in Champagne. Drainage and leaching have been monitored over 28 years in a bare fallow soil (Ballif, 1996). Soil characteristics (organic N, ...) were measured initially and at several occasions later.

- Database C2 concerns three experiments carried out in 1994/95 and 1995/96 on bare
15 soils surrounding the sampling sites at Bruyères (see §2.3). The two years differed in management of the previous crop residues. Wheat straw was incorporated to a shallow depth in 1994/95 whereas sugarbeet crowns and leaves were deeply buried in 1995/96. Soil temperature was monitored hourly in 1993/94. Soil water content (SWC) and soil mineral nitrogen (SMN) were measured monthly in both years for 5 months.

- Database C3 gathers experimental results about growth and yield of several crop species
20 obtained in Northern France:

a) rapeseed experiments performed on chalky soils in Champagne in 1994 and 1995 (Gosse et al., 1999);

b) winter wheat studies on loamy or calcareous soils in the Paris region between 1989 and 1998 (Brisson et al., 2002);

c) sugarbeet experiments on loamy or chalky soils in Picardie and Champagne in 1993, 1994 and 2001 (Launay and Guérif, 2003);

d) spring pea experiments carried out on loamy clay soils in Picardie and Bourgogne (Voisin, 2000);

5 e) rye (as catch crop) experiments on calcareous soils in Champagne and Picardie (Beaudoin et al., 2004).

2.4. Database used for model evaluation

The main database used for model evaluation comes from Bruyères' catchment (49°52'N, 3°67'E) which covers 2 km². Full details on the site and agronomic practices can
10 be found in Beaudoin et al. (2005). Soil and crop measurements were carried out from 1991 to 1999 on 36 unreplicated permanent sampling sites, which are representative of the main crops and soil types. SWC and SMN were measured three times a year up to 90, 120 or 150 cm depth (depending on soil type). Crop yield, total biomass and N uptake were measured at harvest on main crops or catch crops. Additional crop measurements (biomass,
15 N uptake) were realized at 3 vegetative stages of each crop during the years 1996-1998.

Four main soil types were defined according to their parent material (Table 1): deep loamy soils (DL) *i.e.* neoluvisols developed on decarbonated loess; shallow loamy clay (SLC) *i.e.* calcosols developed on marl and rocks; shallow sandy loam (SSK) *i.e.* calcaric rendosols developed on coarse limestone; shallow loamy sand (SLS) *i.e.* redoxic arenosols
20 overlying sand (AFES, 1992). These soils represent 51, 25, 17 and 7% of the agricultural area, respectively (see Beaudoin *et al.*, 2005, Figure 1). All soils have good internal drainage.

Rainfall (R) and air temperature were measured continuously at two locations on the site. The potential evapotranspiration (PET; Penman, 1948) and the global radiation were
25 obtained at the nearest weather station. Over the 8 year study, the mean temperature was

10.1°C whereas the mean R and PET were 734 mm and 722 mm, respectively (Table 2).

The average annual water deficit (R-PET) was close to 0. The mean water excess (R-PET) in winter was 245 mm and was highly variable between years.

The major crops were winter wheat, sugarbeet, spring pea, winter rapeseed and winter barley; spring barley and maize were also present. Catch crops (mustard or rye) were established in most cases during long fallow periods. Soils were either bare during fallow or covered with volunteers during short fallow periods. Crop residues were either buried by disking or ploughing (70% of situations) or removed (30%). Soils were ploughed every year, except sometimes after spring pea.

We recorded the sowing practices (date, density, depth), harvest (date), irrigation (timing and amounts), mineral or organic nitrogen supply (timing, amounts, type of fertiliser or residues) and mulch residues presence. Uncertainties about dates of tillage, sowing and harvest were assessed at ± 8 , ± 5 and ± 3 days, respectively. We also estimated the uncertainties on measurements. The relative confidence interval on crop biomass, calculated using Student's law, was estimated at $\pm 5\%$ for the main crops and $\pm 15\%$ for catch crops ($p < 0.10$). The relative confidence interval for SMN was $\pm 8\%$ in deep loamy soils and $\pm 13\%$ in shallow soils. Crop yields were determined either by manual sampling and analysis or by using the global yield given by the farmer. Yields obtained by manual sampling exceeded the farmer yields by 15%, 30% and 49% for cereals, sugarbeet and pea, respectively, but were 3% lower for rapeseed, due to greater losses of seeds by manual sampling. Since the model does not consider edge effects, grain losses and other additional effects, the values measured on manual samples, except for rapeseed, were preferred in order to test the model.

2.5. Model evaluation

Model evaluation was performed in two steps according to Loague and Green (1991): comparing the model predictions with the observed values and analysing the model sensitivity to crucial parameters.

- 5 The model ability to simulate aboveground biomass, crop yield, crop N uptake, SWC and SMN for the main crops and soils was tested on Bruyères database. The comparison was made either in reset mode (RS) or in continuous simulation mode during 8 years (CS). Three statistical criteria were used to evaluate the model: the standard mean deviation (*SMD*), the root mean square error (*RMSE*) and the model efficiency (*EF*):

$$10 \quad SMD = \frac{\sum_{i=1}^n Oi - \sum_{i=1}^n Si}{\sum_{i=1}^n Oi}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Si - Oi)^2}{n}}$$

$$EF = \frac{\sum_{i=1}^n (Oi - \bar{O})^2 - \sum_{i=1}^n (Si - Oi)^2}{\sum_{i=1}^n (Oi - \bar{O})^2}$$

where Si = simulated, Oi = observed, $\bar{O}$ = mean observed value.

- 15 The 'i' subscript represents either an elementary (1 crop cycle and 1 sampling site) or an average situation. Since observed data were not replicated, we have considered pseudo replicates, as proposed by Kersebaum and Beblik (2001). The pseudo replicates were obtained by aggregating situations (in average 4 situations) having the same crop, soil type and class of organic N content.

We considered that the calibration was adequate if all the variables of interest could comply with the two following criteria: $SMD < 0.10$ and $EF > 0.50$. When these conditions were not fulfilled, we chose the set of parameters giving the best predictions of N uptake and SMN. This choice originated from the strong influence of these two variables on N leaching, as shown by Beaudoin *et al.* (2005).

The sensitivity analyses previously carried out by Sauboua (2001) and Ruget *et al.* (2002) defined the most influent STICS parameters on key output variables. Among the soil and agronomic parameters, we studied those which are spatially variable and /or difficult to estimate. The effect of six important parameters was investigated: the maximal rooting depth due to soil (*obstarac*), the potential humus mineralisation rate (Vp), the N fertiliser use efficiency (FUE), the thickness of residue incorporation (*thickres*), the amount of mulched straw (*qmulch*) and the thickness of mixing cells (*epc*) which influences solute dispersion used in the solute transfer. Other parameters such as the depth of the mineralisation layer (*profhum*) are also uncertain but highly correlated to the previous ones (Vp), so that they were not studied. The range of variation of *obstarac*, FUE and Vp was $\pm 20\%$ of the mean value. The variation in *thickres* and *qmulch* covered the maximum range, whereas *epc* varied between 1 and 10 cm (Mary *et al.*, 1999).

3. Results

3.1. Model calibration and evaluation at the crop cycle scale

The model was tested against C1 and C2 databases, in order to estimate the parameters $q0$ and *thickres*. The optimised value of $q0$ found with database C1 was 6 mm. The model could reproduce satisfactorily with a mean bias of -2%, the cumulative drainage which reached 7400 mm over 24 years in the bare fallow lysimeter (Figure 1). STICS was able to

give a good prediction of N leaching in this soil without FOM residues, which indicates that the SOM mineralisation was well simulated by the model over this long period. This was confirmed by the variation in soil organic N (-1150 kg ha^{-1}) which was in good agreement with the N mineralisation simulated by the model (1180 kg ha^{-1}) over the 24 year period. The q_0 values in other soil types were determined using database C2 which contains bare soil situations with residues. The optimized values were 6 mm for SSK and SLS and 9 mm for DL and SLC soils. An adequate prediction of SWC and soil temperature was obtained using these values (Table 3).

Concerning the parameter *thickres*, setting this parameter to the maximum tillage depth of residue incorporation lead to underestimate the SMN content by $6\text{-}10 \text{ kg ha}^{-1}$ (data not shown). This bias was attributed to an overestimation of N immobilisation in soil associated with crop residues decomposition. So we considered *thickres* as a fitting parameter in order to better mimic the N immobilisation rate. This parameter was optimized by fitting the SMN contents in the upper layer (0-30 cm). The best simulations were obtained for much lower values of *thickres* (5 cm for shallow tillage, 1 cm for ploughing) than the actual depths of tillage. We obtained satisfactory simulations of SMN in the ploughed layer by using these values, with acceptable model efficiencies ($EF = 0.35$ in 1994 and 0.65 in 1995). The quality of fit was poorer for total SMN over the rooting depth, although the RMSE ($10\text{-}15 \text{ kg ha}^{-1}$) was comparable to the variability of measurements.

Database C3 was used to test the model and calibrate some plant parameters. Using the standard parameters, the model markedly underestimated the biomass of spring pea and sugarbeet crops, and sometimes the winter wheat or rapeseed biomass (results not shown). We had to (re)-estimate some parameters involved in the drought effect on emergence, duration of development stages, leaf life duration, temperature thresholds for freezing,

sensitivity of root growth to soil compaction, root life duration, maximal symbiotic fixation rate or harvest index (depending on crop type). This calibration provided satisfactory simulations since model efficiency exceeded 0.50 for most crop variables, except for yield and N uptake of spring pea (data not shown). For spring pea, the model underestimated grain yield by 0.6 Mg ha⁻¹, i.e. 10%, and N uptake by 24 kg ha⁻¹, i.e. 9%. The calibrated model simulated winter wheat behaviour well except for LAI at the latest stages. The quality of fit for SMN was poorer and more variable than for crop production since EF varied between -0.15 and +0.79.

The independent model evaluation was carried out on Bruyères database (Table 4).

The model efficiency for crop biomass was satisfactory (greater than 0.40) for rapeseed, winter wheat, sugarbeet, winter barley and mustard, but was poor (lower than 0.10) for spring pea and rye grown as a catch crop. The model gave a poor prediction of wheat and barley yields, since EF was negative which means that the model is less efficient than the mean observed value. However, the mean deviation was often less than 10% of the mean. The prediction of soil water and mineral N contents was good in the bare fallow soils during autumn and early winter. The model did not overestimate crop yields (determined on manual samplings), suggesting that the agricultural management conditions did not add supplementary growth limiting factors at the local scale.

3.2. Comparison of continuous and reset simulations over the 8 year period

The Bruyères database was used to evaluate the model on each site during the eight year period, by comparing the reset mode every year (RS) with the continuous simulation mode (CS). Figure 2 shows an example of the evolution of three variables (SWC, SMN and crop biomass) in two contrasting soils: a coarse shallow sandy loam (SSK) and a deep loamy soil (DL). Both soils are located in the same field, so that cropping practices were similar. The soil water contents were well predicted in both soils, although the SSK soil

had a large proportion of stony material (Figure 2a). There was very little difference in the prediction of SWC by RS and CS modes. The difference was greater for the prediction of SMN (Figure 2b). The RS mode reproduced the observed SMN better than CS. The difference was greater in the DL soil, particularly in 1996-1997. In fact, the observed SMN varied less in the shallow than in the deep soil. This is due to the absence of a large surplus of N supply on the shallow soil and a higher sensitivity to leaching in this soil. Crop biomass predictions were reasonably good since the simulations were often intermediate between the two observed values (local measurements and whole field estimates) (Figure 2c). The model could reproduce the differences in crop production between the two soils, which are mainly attributable to the differences in rooting depth (Table 1).

The statistics of model evaluation on Bruyères database are given in Table 5 for all main crop and soil variables. They were made either on all data without replicates (a) or on pseudo replicated data (b). If we consider individual data, RS simulations gave acceptable and unbiased predictions of crop biomass and yield at harvest ($EF = 0.57$ and 0.56), although the RMSE values were rather high (Table 5a). The model could not predict adequately the biomass of non-harvested organs (RB) and their nitrogen content (NR). It could well reproduce the crop N uptake and the N content of harvested organs. SWC was better simulated, although it was slightly underestimated at harvest by the model ($SMD = -0.06$). SMN was less and less well simulated as time progressed: the prediction was good in late autumn ($SMD = -0.01$), but was very poor at harvest ($SMD=0.35$).

The same conclusions can be drawn with the simulations obtained in CS mode, except that the quality of fit was slightly poorer for most variables, as one might expect. However, SWC was predicted as well as with RS simulations. The drift or carry-over effects are limited because the water contents reached field capacity (W_{FC}) every winter. The ability of the model to predict SMN contents decreased when the model was not re-initialized.

However the continuous simulation did not alter the mean model deviation ($SMD = -0.02$ in late autumn and 0.37 at harvest in CS mode, corresponding to -1 and 11 kg N ha^{-1} , respectively).

The model was then evaluated on the database with pseudo replicates (Table 5b).

5 Compared to individual data, most model efficiencies were improved, except for the amount of N in crop residues (NR) and SWC and SMN at harvest. The lower efficiency for SWC or SMN at harvest is due to the fact that these variables had small amplitude of variation which was further reduced by averaging data. The mean deviations for all other variables were almost unchanged, but the RMSE were all reduced by averaging data. The errors on NR and SMN at harvest remained, meaning that they originate from model defaults. Conversely, the greatest RMSE reductions were found for the SMN in late autumn and winter: the errors decreased by 41 and 45%, respectively, in the CS simulation. Since these variables had the highest variability, this suggests that our previous hypothesis (error of prediction partly due data uncertainty) was true.

15 Figure 3 shows the comparison of observed and simulated results obtained with the CS mode with pseudo replicates. The results obtained with RS mode (not shown) were similar or slightly better. The graph confirms the good prediction of SWC at the three periods of measurement, the satisfactory estimate of SMN in late autumn and mid winter, but the poor prediction of SMN at harvest. The model could simulate reasonably well the biomass at harvest and the nitrogen content in grains, but failed to predict the nitrogen content of crop residues at harvest: it markedly overestimated nitrogen in rapeseed residues and underestimated it for winter wheat and spring pea residues. STICS adequately predicted total N uptake but did not simulate correctly the nitrogen harvest index, both for CS and RS modes.

3.3. Sensitivity analysis over a 8 year period

Table 6 presents the changes in model outputs due to variations in the six important parameters defined above. We observe that the sensitivity of annual fluxes to these parameters was greater for CS than for RS simulations, except for evaporation and crop N uptake which had a rather similar sensitivity. The changes in fertiliser-N fate were also very similar for both simulations modes. The change in parameters either positive or negative exerted a quasi symmetrical effect on model outputs, except for the first parameter, i.e. the maximum rooting depth due to soil (*obstarac*): a 20% reduction in rooting depth increased leaching by 14.3% whereas a 20% increase reduced leaching by 6% in CS mode. This parameter had little effect on crop N uptake (between 1.4 and 3.3%), probably because water stress was limited in our climatic conditions. The other soil parameter, i.e. the dispersion thickness (*epc*), mainly affected the leaching calculations: increasing the soil dispersivity by a 10 fold factor resulted in a reduction in nitrate leaching by 5.8% in CS mode and 1.5% in RS mode.

The variation in fertiliser use efficiency (*FUE*) exerted a marked effect on the fertiliser fate and a moderate effect on crop N uptake and N leaching. The variation in the N mineralisation potential (*Vp*) had a greater impact on net mineralisation and leaching. A 20% increase in *Vp* resulted in a 6.5% and 18.2% increase in nitrate leaching for RS and CS modes, respectively. This points out the importance of a good prediction of SOM turnover to predict nitrate concentration in drained water, especially with continuous simulations.

The agronomic parameters *thickres* and *qmulch* influenced the water and nitrogen balances. The absence of mulch (*qmulch* = 0) slightly increased the evaporation and reduced the drainage, in comparison with the nominal simulation which took into account the existence of a mulch of straw at soil surface after harvest. It also reduced the

mineralisation associated with residues decomposition (-6.8% in CS) and the nitrate leaching (-7.5%). The parameter *thickres* (thickness of layer containing the buried crop residues) affected the residue N mineralisation, particularly for the RS mode. However the relative variations (+13.4% and -27.5%) correspond to small amounts of N mineralised during one year (+1 to -2 kg N ha⁻¹), so that the effect of *thickres* on N balance and leaching was small.

3.4. Model predictions vs soil type and RS/CS option

STICS was then used to predict N uptake, leaching and gaseous losses for the experimental site of Bruyères. The outputs of the simulations over 8 years were compared for RS and CS modes and for each soil type (Table 7). Results first indicate that N fluxes depend on soil type, whatever the simulation mode. Cumulative drainage varied from 174 mm in deep loamy soils to 256 mm in shallow soils (CS mode), whereas leached N and nitrate concentration varied more than a two-fold factor between soils. Crop N uptake and N mineralisation were also dependent on soil type. Secondly, we found that the effect of the simulation mode (RS or CS) was rather small, except for nitrate concentration. The small differences observed on N leaching and water drainage between RS and CS simulations were amplified on their ratio, i.e. the mean nitrate concentration. However, the two simulations provided the same average concentration for all soils (45 and 46 mg NO₃ l⁻¹).

The main difference between RS and CS simulations concerns the net N mineralisation associated with residue decomposition: the mean values are -7 and -20 kg N ha⁻¹ y⁻¹, respectively (net immobilisation). The RS prediction is not the true value because it did not include the root residues of the previous crop, unlike CS. The difference between RS and CS, i.e. 13 kg N ha⁻¹ y⁻¹, is mainly attributed to the N immobilisation occurring during root decomposition after harvest. Hence the actual effect of whole crop residues on

N mineralisation is thought to be better accounted for by CS simulations. However this difference did not affect significantly the leaching calculations, since the SMN predictions at the end of autumn were similar: 45 kg N ha⁻¹ (Table 5).

A principal component analysis was conducted on the individual situations for the variables listed at Table 7, in order to examine the effects of soil type and simulation mode on the distance between these variables. It included 5280 data values. The first two components explained 49% and 30% of the variance, respectively (Figure 4). The graph shows that the simulation mode (RS or CS) does not change the correlations between variables whereas the soil type has a strong influence. The first component (horizontal) is dominated by DL and SSK soils, whereas the second component is affected by SLS and SLC soils. Surprisingly humus mineralisation is negatively correlated with soil organic N; this paradox is explained by the higher percentage of clay, calcium carbonate or stony materials in soils rich in organic matter. Crop N uptake, SMN and SWC are highest in DL soils and negatively correlated with the N fertilisation rate. This is due to the higher soil N supply in these soils which contain more mineral nitrogen in mid winter. Nitrate concentration in drained water is positively correlated with drainage and is greater in shallow soils, indicating that there is no significant dilution of water even in the most draining soils.

4. Discussion

4.1. Effect of quality of databases on model performance

Among the specific plant parameters which were calibrated, we paid particular attention to those related to leaf growth. Using APSIM wheat model, Asseng et al. (2000) found that a LAI overestimation at early stages, occurring in a period of low incident

radiation, had a small effect on the wheat biomass simulated at harvest. However, we tried to obtain a good simulation of growth at early stages in order to simulate the effect of catch crops and cereal volunteers on mineral nitrogen which could significantly influence N leaching. The net LAI option was preferred for cereals because it improved early LAI and biomass predictions.

The test of the model with Bruyères database was done independently from the calibration process in order to favour model robustness. However the model performances on this database were lower than others reported in the literature. In our study, grain yield of winter wheat was predicted with a RMSE of 2.1 Mg ha⁻¹ and SMN with an error of 25 kg ha⁻¹. The RMSE of the same variables were 1.0 Mg ha⁻¹ and 11 kg ha⁻¹ respectively for a previous STICS evaluation on winter wheat in northern France (Houlès et al., 2004) and 0.8 Mg ha⁻¹ and 9 kg ha⁻¹ by APSIM in the Netherlands (Asseng et al., 2000). The biomass of spring pea was predicted with a RMSE of 2.0 Mg ha⁻¹ at Bruyères whereas it was 0.8 on experiments reported by Corre-Hellou (2005) with the same model. The capacity to predict biomass and N uptake of catch crops (rye and mustard) was also smaller than that obtained by Dorsainvil (2002). Several causes can explain the smaller efficiencies in our study: i) the uncertainties on observed data due to the wide spatial variability, particularly for catch crops; ii) the small size of our calibration database, especially for rapeseed, rye and pea; iii) the evaluation criteria which included both environmental and agricultural and not only crop yield data. The first hypothesis is supported by the fact that RMSE often decreased when the outputs were averaged in pseudo-replicates, confirming the conclusions of Kersebaum and Beblik (2001).

The long term model performance appeared surprisingly better than that obtained annually on individual crops. We found that the model was robust enough to simulate crop production, SWC and SMN without any significant temporal drift. The absence of bias in

model predictions of above-ground crop biomass or N uptake at harvest is even surprising because STICS only simulates the effects of water and nitrogen stress whereas pests and diseases can reduce further crop production in agricultural situations (Meynard et al., 2002). This may have several explanations: i) agricultural management at Bruyères was close to experimental conditions because crops received a full plant protection; ii) the model calibration may underestimate actual crop potentials due a lack of data or the use of yields measured with combine harvester for some crops. These items reveal the difficulty of present models in simulating 'on farm' conditions, due to both formalism and available databases. Model should incorporate functional modules describing pest and disease effects (Van Ittersum et al., 2003).

4.2. Effect of the simulation duration

One challenge of crop models is to be able to simulate water, C and N cycles over both short and long terms. Although STICS was calibrated using only annual experiments, it was able to simulate adequately the soil humus mineralisation in the 24 year lysimeter experiment. It was also able to simulate N mineralisation over the short and long terms in other experiments (Gabrielle et al., 2002).

The differences which appeared between RS and CS simulations could originate from interactions occurring between N mineralisation, N absorption and water transfer. These differences were sometimes important but did not induce any significant drift later on. Gerke et al. (1999) obtained the same result in a sandy soil but observed a marked drift in a loamy soil during a 4-year study in Germany. They attributed this effect to the fact that the nitrate in the sandy soil could be 'washed out more easily' than in the deep loamy soil. Using lysimeters, Kersebaum and Beblik (2001) found that the cumulative exported nitrogen (plant uptake and leaching) was simulated satisfactorily although significant differences occurred on some single years.

The performances of CS simulations with pseudo replicates (Table 5b) were comparable to those obtained with APSIM in a long term experiment in Australia: Probert et al. (1995) predicted crop yield, SWC and SMN with RMSE of 0.9 Mg ha⁻¹, 45 mm and 28 kg ha⁻¹ respectively, i.e. with comparable relative errors to ours.

We found that RS and CS simulations gave similar predictions of N leaching over the 8-year period, in spite of difference in their predictions in residues mineralisation. In fact leaching was weakly affected by the intensity of N immobilisation during crop residues decomposition. Blombäck et al. (2003) found similar results for RS and CS with SOILN model. Initialising the model each year improved the simulation of the soil nitrate content but did not affect the leaching simulation, although leaching was overestimated by 25%. The authors suggested that the bias was due to underestimation of N uptake by omitting weed growth.

4.3. Need for improving the model

We obtained good model efficiency for SWC prediction with the calibration database (Table 3), close to the 0.90 value found by Dorsainvil (2002), but a much lower efficiency of SMN prediction than the 0.83 value given by this author. This poor prediction is unlikely to be due to error in the humus mineralisation rate, considering the good agreement observed in Figure 1. It is attributed to an overestimation in N immobilisation simulated during crop residues decomposition. Gabrielle et al. (2002) found that STICS and three other models underestimated the soil N content in bare soils soon after crop residue incorporation. This result could originate from the heterogeneous distribution of crop residues in the tilled layer which results in a lower N immobilisation than with uniform mixing, as demonstrated by Oorts et al. (2007) for C and N mineralisation. We could correct this underestimation by an empirical reduction of the thickness of residue

layer. A relevant STICS evolution would consist in taking into account the heterogeneity of residues using a similar approach to the one used by Oorts et al. (2007).

The model also failed to predict correctly SMN at harvest: there was a bias and a large dispersion. This discrepancy might result from a false prediction of fertiliser use efficiency (*FUE*) or the nitrate transfer from soil to the roots. In our study, the mean *FUE* for winter wheat was 0.58 ± 0.03 . Limaux (1999) compiled 74 experimental sites with wheat in North-East France which indicated that the N use efficiency was 0.67 ± 0.17 . This suggests that the mean and the variability of *FUE* may be underestimated by the model. The bias could arise from the fact that the model was calibrated using ^{15}N experiments which may underestimate the actual efficiency, due to substitution effects between soil and fertiliser (Hart et al., 1986). The second hypothesis concerns the simulation of nitrate movement in soil which depends on the effective diffusion coefficient of nitrate in soil. The reported values in the literature vary widely. We found that increasing this parameter could result in an unbiased simulation of SMN at harvest.

Total N gaseous losses (volatilisation and denitrification) were estimated at $26 \text{ kg ha}^{-1} \text{ y}^{-1}$, i.e. 23% of fertiliser-N inputs. Webb et al. (2000) found lower losses in a comparable context in UK, between 7 and $20 \text{ kg N ha}^{-1} \text{ y}^{-1}$. Grageda-Cabrera et al. (2004) measured $\text{N}_2 + \text{N}_2\text{O}$ losses corresponding to 12% of the fertiliser-N in a cropped vertisol in Mexico. Using LEACHN model, Acutis et al. (2000) simulated gaseous losses between 12 and 27% of the fertiliser-N, in arable cropping systems and two soils of the Po Valley.

The uncertainty concerning *FUE* cannot have influenced much the N immobilisation rate, according to the sensitivity study (Table 6). Increasing *FUE* by 20% would increase N uptake by 6% and decrease residue mineralisation by 2%, i.e. $0.4 \text{ kg ha}^{-1} \text{ y}^{-1}$ only. Leaching appeared highly sensitive to changes in mineralisation rate (*Vp*) over a long period which points out the importance of assessing this parameter for long term studies. This is in

agreement with Gerke et al. (1999) who observed a strong link between soil organic N content and N leaching.

Implementing a test at the catchment scale requires reliable soil parameters for several plots and years, especially the maximal root depth and the mineralising capacity of the soils. A source of discrepancy lies in studying a soil depth differing from the deepest rooting zone over the whole rotation (Asseng et al., 2000). Classifying soils for maximal root depth should help predicting the crop N uptake. Getting accurate values of the mineralising capacity, including the mineralisation depth (*profhum*), appears difficult for each field. We assume that uncertainties can be globally smoothed at the basin scale. These uncertainties could also be bypassed using stochastic approaches and limiting the number of random parameters (Acutis et al., 2000).

5. Conclusion

The ability of crop models to predict N leaching on hydrological catchments requires a good evaluation of the model outputs over the long term, in various soil and weather conditions and 'on farm' conditions. This was the aim of our study. STICS model was chosen for its capacity to account for agricultural practices and soil properties. The results showed a reasonable agreement between the main observed and simulated variables. However it is not possible to guarantee the reliability of the predictions for any time and any place, particularly when upscaling the model over large catchments. The mean outputs of the model continuously run during 8 years were rather close to those obtained with the model reset every year. The absence of significant drift in N leaching predictions demonstrates the potential of the model to simulate the impacts of cropping systems and climate change for several decades, at least for well managed N situations such as ours.

Indeed, the model might drift in differently managed cropping systems, such as without catch crops, with low or very high N inputs or with bad control of pests and diseases. Model improvement is needed to integrate the yield limitations due to 'on farm' conditions, both within model formalism and database content. Furthermore, the complete N balance has to be established in the future, in order to avoid pollution transfers and optimize the whole environmental impact of agricultural systems. The prediction of gaseous N losses, and especially those contributing to climate change, is less reliable than nitrate leaching and must be improved particularly as a function of agricultural practices.

Acknowledgements

The authors are grateful to the farmers involved in this study: R. Chédeville, P. and R. Mory, B. and M. Pillois. We thank E. Venet, C. Herre, P. Thiébeau and E. Gréhan for their technical assistance, G. Alavoine and O. Delfosse for the analyses, C. Van Laethem, B. Nicoulaud, M.H. Jeuffroy, M. Guérif, C. Durr, C. Salon, J. Maucorps, N. Brisson, B. Nicolardot and F. Ruget for their contribution to the database construction and P. Bernard and D. Ripoché for the model improvements. This study was supported by ADEME and Région Picardie.

References

- Acutis, M., Ducco, G., Grignani, C., 2000. Stochastic use of LEACHN model to forecast nitrate leaching in different maize cropping systems. *European Journal of Agronomy* 13, 191-206.
- 5 A.F.E.S., 1992. Référentiel pédologique des différents sols d'Europe. Editions INRA, Paris, 222 pp.
- Asseng, S., van Keulen, H., Stol, W., 2000. Performance and application of the APSIM N wheat model in the Netherlands. *European Journal of Agronomy* 12, 37-54.
- Ballif, J.L., 1996. Les lysimètres en sol de craie de Châlons-sur-Marne. In: Muller, J.C. (Ed.), Trente ans de lysimétrie en France 1960-1990, COMIFER-INRA Editions, Paris, pp. 115-149.
- 10 Beaudoin, N., Parnaudeau, V., Mary, B., Makowski, D., Meynard, J.M., 2004. Simulation de l'impact de différents scénarios agronomiques sur les pertes de nitrate à l'échelle d'un bassin hydrologique. In: Monestiez, P., Lardon S., Seguin, B. (Eds), Organisation spatiale des activités agricoles et processus environnementaux., Science Update, INRA Editions, Paris, pp. 117-141.
- 15 Beaudoin, N., Saad, J., Van Laethem, C., Maucorps, J., Machet, J.M., Mary, B., 2005. Nitrate leaching in intensive arable agriculture in Northern France: effect of farming practices, soils and crop rotations. *Agriculture, Ecosystems and Environment* 111, 292-310.
- 20 Blombäck, K., Eckersten, H., Lewan, E., Aronsson, H., 2003. Simulations of soil carbon and nitrogen dynamics during seven years in a catch crop experiment. *Agricultural Systems* 76, 95-114.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M.H., Ruget, F., Gate, P., Devienne, F., Antonioletti, R., Dürr, C., Nicoullaud, B., Richard, G., Beaudoin, N., Recous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J.M., Meynard, J.M., Delécolle, R., 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balance. I- Theory and parameterization applied to wheat and corn. *Agronomie* 18, 311-346.

Brisson, N., Ruget, F., Gate, P., Lorgeou, J., Nicoullaud, B., Tayot, X., Plenet, D., Jeuffroy, M.-H., Bouthier, A., Ripoche, D., Mary, B., Justes, E., 2002. STICS: a generic model for the simulation of crops and their water and nitrogen balance. II- Model validation for wheat and maize. *Agronomie* 22, 69-92.

Corre-Hellou, G., 2005. Acquisition de l'azote dans des associations pois-orge (*Pisum sativum* L.- *Hordeum vulgare* L.) en relation avec le fonctionnement du peuplement. Ph.D. thesis, Université d'Angers, 94 pp.

Dorsainvil, F., 2002. Evaluation par modélisation de l'impact environnemental des modes de conduite des cultures intermédiaires sur les bilans d'eau et d'azote dans les systèmes de culture. Ph.D. thesis, INA PG, Paris, 183 pp.

Gabrielle, B., Mary, B., Roche, R., Smith, P., Gosse, G., 2002. Simulation of carbon and nitrogen dynamics in arable soils: a comparison of approaches. *European Journal of Agronomy* 18, 107-120.

Gerke, H.H., Arning, M., Stöppler-Zimmer, H., 1999. Modeling long-term compost application effects on nitrate leaching. *Plant and Soil* 213, 75-92.

Gijsman, A.J., Jagtap, S.S., Jones, J.W., 2002. Wading through a swamp of complete confusion: how to choose a method for estimating soil water retention parameters for crop models. *European Journal of Agronomy* 18, 75-105.

Gosse, G., Cellier, P., Denoroy, P., Gabrielle, B., Laville, P., Leviel, B., Justes, E., Nicolardot, B., Mary, B., Recous, S., Germon, J.C., Hénault, C., Leech, P.K., 1999. Water,

carbon and nitrogen cycling in a rendzina soil cropped with winter oilseed rape: the Châlons oilseed rape database. *Agronomie* 19, 119-124.

Grageda-Cabrera, O., Medina-Cázares, T., Aguilar-Acuña, J.L., Hernández-Martínez, M., Solís-Moya, E., Aguado-Santacruz, G.A., Peña-Cabriales, J.J., 2004. Gaseous nitrogen loss by N₂ and N₂O emissions from different tillage systems and three nitrogen sources. *Agrociencia-Mexico* 38, 625-633.

Hansen, S., Thirup, C., Refsgaard, J.C., Jensen, L.S., 2001. Modeling nitrate leaching at different scales. Application of the DAISY model. In: Schaffer, M.J., Liwang, M., Hansen, S. (Eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Lewis Publishers, pp 511-548.

Hart, P. B. S., Rayner, J. H., Jenkinson, D. S., 1986. Influence of pool substitution on the interpretation of fertilizer experiments with ¹⁵N. *Journal of Soil Science* 37, 389-403.

Hoffmann, M., Johnsson, H., 1999. A method for assessing generalised nitrogen leaching estimates for agricultural land. *Environmental Modeling & Assessment* 4, 35-44.

Houlès, V., Mary, B., Guérif, M., Makowski, D., Justes, E., 2004. Evaluation of the ability of the crop model STICS to recommend nitrogen fertilisation rates to agro-environmental criteria. *Agronomie* 24, 339-349.

Kersebaum, K.C., Beblik, A.J., 2001. Performance of nitrogen dynamics model applied to evaluate agricultural management practices. In: Schaffer, M.J., Liwang, M., Hansen, S. (Eds.), *Modeling carbon and nitrogen dynamics for soil management*, Lewis Publishers, pp 550-569.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM,

a model designed for farming systems simulation. European Journal of Agronomy 18, 267-288.

Kovács, G.J., Neméth, T., Ritchie, J.T., 1995. Testing simulation models for the assessment of crop production and nitrate leaching in Hungary. Agricultural Systems 49, 385-397.

Lacroix, A., Beaudoin, N., Makowski, D., 2004. Agricultural water nonpoint pollution control under uncertainties and climate variability. Ecological Economics, 53, 115-127.

Launay, M., Guerif, M., 2003. Ability for a model to predict crop production variability at the regional scale: an evaluation for sugarbeet. Agronomie 23, 135-146.

Lemaire, G., Gastal, F. 1997. Nitrogen uptake and distribution in plant canopies. In: Lemaire G. (ed.), Diagnosis of the nitrogen status in crop. Springer-Verlag Berlin Heidelberg, pp. 3-43.

Limaux, F., 1999. Modélisation des besoins du blé en azote, de la fourniture du sol et de l'utilisation de l'engrais. Application au raisonnement de la fertilisation en Lorraine. Ph.D. thesis, INPL Nancy.

Letcher, R.A., Giupponi, C., 2005. Policies and tools for sustainable water management in the European Union. Environmental Modelling & Software 20, 93-98.

Loague, K., Corwin, D.L., 1996. Uncertainty in regional-scale assessment of non-point source pollutants. In: Corwin, D.L., Loague, K., (Eds), Application of GIS to the modelling of non-point source pollutants in the vadose zone, S.S.S.A. Inc, Madison, Special publication 48.

Loague, K., Green, R.E., 1991. Statistical and graphical method for evaluating solute transport models: overview and application. Journal of Contaminant Hydrology 7, 51-73.

Mary, B., Beaudoin, N., Justes, E., Machet, J.M., 1999. Calculation of nitrogen mineralisation and leaching in fallow soil using a simple dynamic model. *European Journal of Soil Science* 50, 549-566.

Meynard, J.M., Cerf, M., Guichard, L., Jeuffroy, M.H., Makowski, D., 2002. Which decision support tools for the environmental management of nitrogen? *Agronomie* 22, 817-829.

Nelder, J.A. and Mead R., 1964. A simplex method for function minimization. *The Computer Journal* 7: 308-313.

Nicolardot, B., Recous, S., Mary, B., 2001. Simulation of C and N mineralisation during crop residue decomposition: a simple dynamic model based on the C:N ratio of the residues. *Plant and Soil* 228, 83-103.

Oorts, K., Garnier, P., Findeling, A., Mary, B., Richard, G., Nicolardot, B., 2007. Modelling soil carbon and nitrogen dynamics in no-tillage and conventional tillage systems using PASTIS model. *Soil Science Society of America Journal* 71, 336-346.

Penman, H.L., 1948. National evaporation from open water, bare soil land grass. *Proc. Royal Society T193*, London.

Probert, M.E., Keating, B.A., Thompson, J.P., Parton, W.J, 1995. Modelling water, nitrogen, and crop yield for a long-term fallow management experiment. *Australian Journal of Experimental Agriculture* 35, 941-950.

Ruget, F., Brisson, N., Delécolle, R., Faivre, R., 2002. Sensitivity analysis of a crop simulation model, STICS, in order to choose the main parameters to be estimated. *Agronomie* 22, 133-158.

Sauboua, E., 2001. Modélisation stochastique fonctionnelle du transfert d'eau et d'azote sous culture de maïs. Application à l'évaluation de l'impact des pratiques agricoles en

Plaine de Bièvre. Ph.D. thesis, LTHE, Université de Grenoble, 199 pp.

Schnebelen, N., Nicoullaud, B., Bourennane, H., Couturier, A., Verbeque, B., Revalier, C., Bruand, A., Ledoux, E., 2004. The STICS model to predict nitrate leaching following agricultural practices. *Agronomie* 24, 423-435.

Schaffer, M.J., Liwang, M., Hansen, S., 2001. Introduction to simulation of carbon and nitrogen in soils. In: Schaffer, M.J., Liwang, M., Hansen, S. (Eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Lewis Publishers, pp 1-11.

Van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. *European Journal of Agronomy* 18, 231-234.

Voisin, A.S., 2000. Etude du fonctionnement des racines nodulées du pois (*Pisum sativum* L.) en relation avec la disponibilité en nitrates du sol, les flux de carbone au sein de la plante et la phénologie : Croissance des racines nodulées et activité fixatrice des nodosités. Ph.D. thesis, INA PG, 129 pp.

Wagenet, R.J., Hutson, J.L., 1996. Scale-dependency of solute transport modeling/GIS applications. *Journal of Environmental Quality* 25, 495-510.

Webb, J., Harrison, R., Ellis, S., 2000. Nitrogen fluxes in three arable soils in the UK. *European Journal of Agronomy* 13, 207-223.

Table 1. Characteristics of the four main soil types encountered at Bruyères: soil analysis values and estimates of STICS parameters.

* Soil types: DL = deep loamy soil; SSK = shallow sandy loam overlying limestone; SLC = shallow loamy clay overlying marl and rock; SLS = shallow loamy sand overlying sand.

5 ** Analyses: clay = clay content after decarbonation; W_{FC} = water content at field capacity, W_{WP} = water content at permanent wilting point.

*** Parameters: *profhum* = biologically active soil depth for mineralisation; *obstarac* = maximal rooting depth; q_0 = water evaporation threshold of reduced evaporation; *albedo* = albedo of the bare dry soil.

10

		DL*		SSK*		SLC*		SLS*	
Soil depth	cm	soil 0-30	subsoil 30-150	soil 0-30	subsoil 30-120	soil 0-30	subsoil 30-120	soil 0-30	subsoil 30-90
a) Soil analysis**									
Clay	g kg ⁻¹	196		122		221		101	
Organic C	g kg ⁻¹	10.7		13.0		15.8		8.8	
Organic N	g kg ⁻¹	1.21		1.40		1.67		0.92	
CaCO ₃	g kg ⁻¹	10		280		340		0	
pH (water)		7.9		8.3		8.3		8.0	
<i>W_{FC}</i>	g kg ⁻¹	240	220	230	210	290	300	180	140
<i>W_{WP}</i>	g kg ⁻¹	90	100	90	70	140	140	50	60
Bulk density	g cm ⁻³	1.38	1.56	1.39	1.42	1.40	1.35	1.33	1.42
Stones	% vol	0	0	19	25	10	16	5	0
b) STICS parameters***									
<i>profhum</i>	cm	31		30		28		35	
<i>obstarac</i>	cm	149		92		91		70	
<i>q₀</i>	mm	9		6		9		6	
<i>albedo</i>		0.23		0.29		0.28		0.25	

15

Table 2. Weather data recorded at Bruyères: rainfall (R), Penman potential evapotranspiration (PET), air temperature (T) and water balance (R-PET).

* Water balance from August 1 (year n-1) to July 31 (year n).

** Water balance from October 1 (year n-1) to March 31 (year n).

5 (sd) = standard deviation.

period	R	PET	T	R – PET*	R – PET**
	mm	mm	°C	mm	mm
1991-92	619	759	9.8	-141	148
1992-93	765	667	10.1	98	233
1993-94	853	740	10.0	114	419
1994-95	829	712	10.8	117	339
1995-96	544	716	9.4	-172	65
1996-97	746	689	9.4	58	182
1997-98	684	741	10.7	-57	185
1998-99	835	755	10.2	80	389
Mean	734	722	10.1	+12	+245
(sd)	(104)	(31)	(0.5)	(110)	(117)

Table 3. Statistics of model evaluation using database C2 for soil temperature (T), soil water content (SWC) and soil mineral nitrogen (SMN) in the upper layer (0-30 cm) or the whole profile (wp), after calibrating the parameters q_0 (water evaporation threshold) and *thickres* (depth of crop residue incorporation). 1994 experiments were done on bare soils (DL, SLC and SLS) with wheat straw. 1995 experiments were done on bare soils (SSK, SLC and SLS) with sugar beet residues. n = number of situations, $\bar{O}$ = mean of observed values. RMSE = absolute Root Mean Square Error, SMD = Standard Mean Deviation (without dimension), EF = model Efficiency (without dimension).

	T (0-30) °C	SWC (0-30) mm	SWC (wp) mm	SMN (0-30) kg ha ⁻¹	SMN (wp) kg ha ⁻¹
1994 experiments					
n	236	36	13	10	10
$\bar{O}$	11.7	78	237	6.8	50
RMSE	0.1	1	65	0.2	10
SMD	-0.02	0.10	-0.03	-0.21	0.01
EF	0.90	0.77	0.88	0.35	0.04
1995 experiments					
n		10	10	10	10
$\bar{O}$		80	243	27.1	57
RMSE		1	53	3.2	15
SMD		0.04	-0.05	-0.48	-0.48
EF		0.71	0.89	0.65	-0.88

Table 4. Statistics of STICS evaluation on Bruyères database for each crop: crop biomass, crop yield, N uptake, soil water content (SWC) and soil mineral nitrogen (SMN). RMSE = absolute Root Mean Square Error, SMD = Standard Mean Deviation, EF = model Efficiency.

5

	Biomass Mg ha ⁻¹	Crop yield Mg ha ⁻¹	N uptake kg ha ⁻¹	SWC mm	SMN kg ha ⁻¹
Rapeseed					
RMSE	2.1	1.0	53	42	24
SMD	0.01	0.05	0.24	-0.07	-0.09
EF	0.75	-0.75	0.25	0.90	-0.55
Winter wheat					
RMSE	2.1	2.1	31	37	25
SMD	0.02	0.17	-0.05	-0.02	0.00
EF	0.90	-1.08	0.76	0.92	0.50
Spring pea					
RMSE	3.4	2.0	120	35	19
SMD	0.00	-0.11	-0.24	-0.04	0.02
EF	0.08	-0.06	-0.42	0.93	0.26
Sugarbeet					
RMSE	4.8	4.9	60	52	34
SMD	-0.03	-0.23	-0.22	-0.06	0.16
EF	0.67	0.58	-0.02	0.86	0.34
Winter barley					
RMSE	1.7	1.9	28	35	26
SMD	-0.05	0.03	-0.06	-0.03	0.24
EF	0.91	-1.68	0.72	0.92	-0.42
Rye (catch crop)					
RMSE	0.9	-	16	41	22
SMD	0.27		0.11	-0.05	-0.17
EF	-2.33	-	-0.61	0.91	-0.27
Mustard (catch crop)					
RMSE	0.3	-	15	39	40
SMD	-0.18		-0.15	-0.04	0.02
EF	0.40	-	-0.57	0.89	-2.60
Bare soil					
RMSE	-	-	-	31	23
SMD	-	-	-	-0.01	-0.07
EF	-	-	-	0.89	0.43

Table 5. Statistical evaluation of STICS model on Bruyères database for crop biomass (SB), harvested dry matter (Y), residues biomass (RB), plant N uptake (U), harvested organ N content (NY), residues N content (NR), soil water content (SWC) and soil mineral N (SMN). The simulation results are given for all data individually (a) or after averaging data according to crop and soil types (b). Two types of simulations are given: reset after each crop cycle (RS) or continuous simulation (CS). The data cover 8 years (1991 to 1999). RMSE = absolute Root Mean Square Error, SMD = Standard Mean Deviation, EF = model Efficiency.

* n = number of situations; mean = mean of observed values.

** Late autumn means a date varying from November 5 to December 15; mid winter means a date varying from January 25 to February 25.

			a) all individual data									b) data averaged per crop and soil type								
			observed		RS simulated			CS simulated					observed		RS simulated			CS simulated		
			n*	mean	RMSE	SMD	EF	RMSE	SMD	EF			n*	mean	RMSE	SMD	EF	RMSE	SMD	EF
SB	harvest	Mg ha ⁻¹	213	14.7	3.2	0.00	0.57	3.8	-0.04	0.42	56	14.6	2.4	-0.01	0.69	2.7	-0.05	0.60		
Y	harvest	Mg ha ⁻¹	213	8.1	3.0	-0.02	0.56	3.1	-0.05	0.52	56	8.0	2.6	-0.02	0.62	2.7	-0.06	0.59		
RB	harvest	Mg ha ⁻¹	213	6.5	2.3	0.01	-0.41	2.5	-0.03	-0.59	55	6.6	1.9	0.01	-0.31	1.9	-0.03	-0.37		
U	harvest	kg ha ⁻¹	209	178	48	-0.01	0.49	55	-0.05	0.34	54	178	37	-0.01	0.57	39	-0.04	0.53		
NY	harvest	%	230	1.8	0.5	0.00	0.75	0.5	-0.01	0.74	59	1.9	0.4	-0.01	0.84	0.4	-0.01	0.85		
NR	harvest	%	231	0.9	0.8	-0.21	-0.30	0.8	-0.19	-0.42	59	0.9	0.7	-0.17	-0.39	0.8	-0.14	-0.55		
SWC	late autumn**	mm	211	340	39	-0.04	0.92	39	-0.04	0.92	53	339	31	-0.04	0.93	29	-0.04	0.94		
SWC	mid winter**	mm	225	368	25	-0.01	0.97	25	-0.01	0.96	54	366	25	-0.02	0.96	25	-0.02	0.96		
SWC	Harvest	mm	225	265	42	-0.06	0.90	42	-0.06	0.91	56	265	37	-0.06	0.87	37	-0.06	0.88		
SMN	late autumn**	kg ha ⁻¹	210	45	21	-0.01	0.49	28	-0.02	0.11	53	45	13	-0.01	0.61	17	-0.04	0.38		
SMN	mid winter**	kg ha ⁻¹	226	43	23	0.05	0.30	30	0.02	-0.17	54	44	15	0.03	0.39	16	0.01	0.29		
SMN	harvest	kg ha ⁻¹	225	29	26	0.35	-0.83	30	0.37	-1.33	56	29	23	0.38	-2.26	25	0.41	-2.89		

Comment citer ce document :

Beaudoin, N., Launay, M., Sauboua, E., Ponsardin, G., Mary, B. (2008). Evaluation of the soil-crop model STICS over 8 years against the "on farm" database of Bruyeres catchment. European Journal of Agronomy, 29 (1), 46-57. DOI : 10.1016/j.eja.2008.03.001

Table 6. Sensitivity analysis of STICS outputs to six parameters, calculated either for annual runs (RS) or continuous runs (CS). Values are the relative changes (%) in outputs compared to model outputs with nominal parameter values. Calculations are made on Bruyères database over the 8-year period.

Tested parameters: *obstarac* = rooting depth limitation due to soil obstacle (*only in shallow soils); *epc* = mixing cells thickness; *FUE* = fertiliser use efficiency; *Vp* = potential humus mineralisation rate; *thickres* = layer thickness of residues mixing; *qmulch* = amount of mulched straw.

	RS								CS							
	<i>Obstarac</i> *		<i>epc</i>	<i>FUE</i>	<i>Vp</i>	<i>thickres</i>		<i>qmulch</i>	<i>Obstarac</i> *		<i>epc</i>	<i>FUE</i>	<i>Vp</i>	<i>thickres</i>		<i>qmulch</i>
	-20%	+20%	x10	+20%	+20%	min	max	0	-20%	+20%	x10	+20%	+20%	min	max	0
<i>Mean annual fluxes</i>																
evaporation	0.8	-0.6	0.0	-0.6	-0.8	0.0	-0.2	4.1	0.5	-0.2	-0.1	-0.6	-0.8	-0.3	-0.3	3.1
drainage	0.1	-0.1	0.0	0.0	0.0	0.0	0.0	-1.5	3.1	-2.1	-0.1	0.0	0.1	-1.6	-1.4	-4.6
humus mineralisation	-1.2	0.8	0.0	0.0	19.1	0.1	-0.3	-1.3	-1.6	1.0	0.0	-0.1	15.9	1.8	-2.6	-2.0
residue mineralisation	0.9	-0.2	1.7	0.9	0.9	13.4	-27.5	-2.3	8.4	-5.5	1.9	-2.3	-6.2	10.0	0.9	-6.8
crop N uptake	-3.3	2.0	0.4	6.5	5.9	0.0	-0.3	0.0	-1.5	1.4	0.7	6.5	6.4	0.9	-0.6	-0.9
leaching	1.5	-1.4	-1.5	0.0	6.2	0.0	2.1	-5.7	14.3	-6.0	-5.8	4.0	18.2	6.7	-0.2	-7.5
<i>Mean Fertiliser-N fate</i>																
N immobilisation	-3.4	0.0	0.0	-16.5	0.0	0.0	0.0	0.0	-3.4	0.0	0.0	-16.5	0.0	0.0	0.0	0.0
N gaseous losses	-3.1	-0.2	-0.3	-33.6	-1.1	0.0	-0.1	0.2	-3.2	0.0	-0.5	-33.6	-1.0	0.3	-0.1	-0.4
Ndff* crop	-3.6	0.1	0.1	19.8	0.4	0.0	0.0	-0.1	-3.5	0.0	0.2	19.8	0.4	-0.1	0.0	0.2

* Ndff = Nitrogen derived from the fertiliser

Table 7. Final pools, mean annual fluxes, fertiliser-N fate and crop residues predicted by STICS model at Bruyères for each soil type, over 8 years (1991 to 1999). SWC = soil water content; SMN = soil mineral nitrogen.

		RS					CS				
		DL	SSK	SLC	SLS	all soils	DL	SSK	SLC	SLS	all soils
<i>Final pools</i>											
SWC	mm	400	180	245	99	297	398	179	243	97	294
SMN	kg ha ⁻¹	49	33	33	32	42	52	28	29	35	42
Soil organic N	Mg ha ⁻¹	5.14	4.77	5.58	4.01	5.08	5.16	4.81	5.65	3.99	5.11
<i>Mean Annual fluxes</i>											
evaporation	mm y ⁻¹	318	312	330	321	317	320	317	339	320	321
drainage	mm y ⁻¹	189	193	192	258	200	174	210	191	256	192
humus mineralisation	kg ha ⁻¹ y ⁻¹	110	100	70	135	111	112	103	74	134	112
residue mineralisation	kg ha ⁻¹ y ⁻¹	-5	-9	-5	-8	-7	-21	-22	-17	-6	-20
N fertilisation	kg ha ⁻¹ y ⁻¹	107	129	106	116	110	107	129	106	116	110
N fixation	kg ha ⁻¹ y ⁻¹	48	12	24	26	34	47	11	27	24	33
crop N uptake	kg ha ⁻¹ y ⁻¹	193	154	149	159	179	186	142	138	156	171
N leaching	kg ha ⁻¹ y ⁻¹	12	32	21	46	21	13	24	16	50	20
NO ₃ concentration	mg l ⁻¹	28	75	49	79	46	34	51	36	86	45
<i>Mean Fertiliser-N fate</i>											
immobilisation	kg ha ⁻¹ y ⁻¹	22	27	25	25	24	22	27	25	25	24
volatilisation	kg ha ⁻¹ y ⁻¹	10	15	14	12	12	10	15	14	12	12
denitrification	kg ha ⁻¹ y ⁻¹	13	16	15	15	14	13	16	15	15	14
Ndff *	kg ha ⁻¹ y ⁻¹	62	71	66	65	64	62	71	65	65	64
<i>Mean residue prediction</i>											
residue biomass	Mg ha ⁻¹ y ⁻¹	8.0	7.3	5.6	5.7	7.3	7.7	6.6	5.2	5.6	6.9
residue N	kg ha ⁻¹ y ⁻¹	64	62	44	72	62	63	54	40	72	59
residue N content	%	0.8	0.9	0.8	1.3	0.9	0.8	0.8	0.8	1.3	0.9

* Ndff = Plant nitrogen derived from the fertiliser

Comment citer ce document :

Beaudoin, N., Launay, M., Sauboua, E., Ponsardin, G., Mary, B. (2008). Evaluation of the soil-crop model STICS over 8 years against the "on farm" database of Bruyeres catchment. European Journal of Agronomy, 29 (1), 46-57. DOI : 10.1016/j.eja.2008.03.001

Figures captions

Figure 1. Cumulative drained water (W) and leached nitrate (N) observed (symbols) and simulated with STICS (continuous lines) in the bare fallow lysimeter at Fagnières, from 1978 to 2003.

Figure 2. Observed and predicted variables in two contrasted soils of the same field (1 = shallow sandy loam overlying limestone, 2 = deep loamy soil): a) soil water content, b) soil nitrate content, c) dry matter production. The model is either reinitialized after each crop cycle (RS, dashed line) or is run continuously from the beginning (CS, continuous line).

Obs 1 = Measured on microplots with manual sampling; Obs 2 = determined over the whole field (for crop biomass only).

Figure 3. Comparison of observed and simulated variables obtained with STICS-CS (continuous simulation) on the Bruyères database. Each point is the mean of 4 measured sites corresponding to a given soil type and crop type. Upper graphs: soil water content (SWC) a) in late autumn, b) in mid winter, c) at harvest. Intermediate graphs: soil nitrate amount (SMN) in a) late autumn, b) mid winter, c) harvest. Lower graphs: d) shoot dry matter at harvest, e) grain nitrogen at harvest, f) unharvested crop residue nitrogen.

WW = winter wheat, WB = winter barley; WR= winter rapeseed; S = sugarbeet, P = spring pea.

Figure 4. Plot of the values of the main final outputs of the simulations (see Table 9 and Table 10) done on 4 soil types (DL, SLS, SSK, SLS) and with two simulation modes (RS and CS) for the first two principal components.