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Evaluation of the impact of various agricultural practices on nitrate leaching under the root zone of potato and sugar beet using the STICS soil–crop model

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ABSTRACT

The quaternary aquifer of Vitoria-Gasteiz (Basque Country, Northern Spain) is characterised by a shallow water table mainly fed by drainage water, and thus constitutes a vulnerable zone in regards to nitrate pollution. Field studies were performed with a potato crop in 1993 and a sugar beet crop in 2002 to evaluate their impact on nitrate leaching. The overall predictive quality of the STICS soil–crop model was first evaluated using field data and then the model was used to analyze dynamically the impacts of different crop management practices on nitrate leaching. The model was evaluated (i) on soil nitrate concentrations at different depths and (ii) on crop yields. The simulated values proved to be in satisfactory agreement with measured values. Nitrate leaching was more pronounced with the potato crop than with the sugar beet experiment due to i) greater precipitation, ii) lower N uptake of the potato crop due to shallow root depth, and iii) a shorter period of growth. The potato experiment showed that excessive irrigation could significantly increase nitrate leaching by increasing both drainage and nitrate concentrations. The different levels of N-fertilization examined in the sugar beet study had no notable effects on nitrate leaching due to its high N uptake capacity. Complementary virtual experiments were carried out using the STICS model. Our study confirmed that in vulnerable zones agricultural practices must be adjusted, that is to say: 1) N-fertilizer should not be applied in autumn before winter crops; 2) crops with low N uptake capacity (e.g. potatoes) should be avoided or should be preceded and followed by nitrogen catch crops or cover crops; 3) the nitrate concentration of irrigation water should be taken into account in calculation of the N-fertilization rate, and 4) N-fertilization must be precisely adjusted in particular for potato crops.

1. Introduction

The European Union Nitrate Directive (91/676/EEC) is a law which aims to control nitrogen pollution and requires Member States of the European Union (EU) to identify ground water that contains more than 50 mg L^{-1} nitrate or that could contain more than 50 mg L^{-1} nitrate if preventative measures are not taken. In addition, the EEC Drinking Water Directive

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(98/83/EC) sets the maximum allowable concentration of nitrate at 50 mg NO_3^- L^{-1}. It has been shown that drinking water in excess of the nitrate limit can result in adverse health effects (Cantor, 1997) even if there is an actual medical debate regarding various reported impacts for human health. Moreover, nitrite deriving from microbial reduction of nitrate in water is a recognised problem for children less than 2 months of age (Fan and Steinberg, 1996). Ground water is a very important source of drinking water in many countries and it is often used untreated, particularly from private wells. In Europe, agriculture is probably the largest contributor of nitrogen pollution to ground water, as nitrate originates both from soil N-mineralization and nitrification and from excessive use of N-fertilizers and manure on arable crops in order to increase yields and product quality (Gustafson, 1983; Strebel et al., 1989; Bijay-Singh et al., 1995; Sapek, 2005).

The quaternary aquifer of Vitoria-Gasteiz (Basque Country, North Spain) represents a well-documented example of ground water quality degradation due to land use changes. Since the end of the 1960s to the mid-1990s, intensification of agriculture, and the increase in irrigated agriculture, in particularly for potato crops, combined with the diversion of principal rivers traversing the aquifer and the extension of the artificial drainage network of the aquifer have led to an important nitrate contamination in ground water, exceeding 150 mg NO_3^- L^{-1} (Arrate, 1994; Arrate et al., 1997; Sanchez-Perez et al., 2003). In addition, during this period, irrigation water was extracted from the aquifer. From the mid-1990s onwards, irrigated sugar beets were also cropped and replaced progressively irrigated potato crops. In order to avoid recirculation of ground water, the irrigation water came from surface water with lower nitrate concentrations (less than 50 mg NO_3^-). Moreover, in the mid-1990s N-fertilization was significantly decreased due to the decrease in N-fertilizer by farmers. In parallel to this decrease, the nitrate values of the aquifer have shown a tendency to decrease. Nevertheless, in 1998, the eastern sector of the quaternary aquifer was designated by the Basque Government as a Nitrate Vulnerable Zone according to the 91/676/EEC Nitrate Directive and a Code of Good Practice was approved. Now, nitrate concentrations of ground water are about 60–70 mg NO_3^- L^{-1} (García et al., 2005).

The environmental impact of agriculture depends on crop type, hydrometeorological conditions (climatology and hydrogeology), crop management practices and soil characteristics. For this reason, soil–crop models that simulate soil–plant system dynamics in interactions with climate and cropping techniques can be very useful in predicting nitrate leaching from the unsaturated zone of the soil to the aquifer. Models that simulate crop growth, water and nitrogen balances at the field scale have appeared in recent years, e.g CERES (Ritchie and Otter, 1984; Jones and Kiniry, 1986), ARCWHEAT (Weir et al., 1984), SWHEAT (Van Keulen and Seligman, 1987), CORNGRO (Childs et al., 1977) and STICS (Brisson et al., 1998). These models are useful for evaluating the environmental impact of irrigation and N-fertilization, both at the field scale and on a regional scale (Varcoe, 1990; Johnson and Cramb, 1991; Van Lanen et al., 1992; Singh and Thornton, 1992; Lal et al., 1993; Moen et al., 1994; Schnebelen et al., 2004).

By using the crop model STICS in the present study, we aimed to provide a better understanding of how crop management can influence nitrate leaching and, in consequence, affect the quality of ground water. Particularly, the main question was the following: was the change of crop from potato to sugar beet, and of the origin of irrigation water able to explain the decrease of nitrate concentration observed in the ground water? Because there are interactions between crop rotation, crop management and pedoclimatic conditions, it is not always easy to distinguish the individual roles of each of these components and their interactions on nitrate leaching only based on field measurements. The use of a soil–crop model could be very useful to diagnose the impacts of crop type, N-fertilization, irrigation, and climate on nitrate concentrations of drained water by making complementary simulations with combinations of agricultural practices and climatic conditions not occuring during the field experiment.

In the field studies in the Vitoria-Gasteiz region, potatoes (*Solanum tuberosum* L.) were grown in 1993 when the nitrate concentration in ground water was maximum and sugar beet (*Beta vulgaris* L.) in 2002 when the nitrate concentration had decreased to about 60 mg NO_3^- L^{-1}. The aims of our study were: (i) to evaluate the predictive quality of STICS soil–crop model outputs using field measurements for the two field crops in the case of Northern Spain; (ii) to estimate nitrate leaching under the two crops by using STICS soil–crop model; and (iii) to perform simulations (virtual experiments) to explain the processes of nitate pollution due to agricultural practices. The objective of doing such simulations was to evaluate the effects of climatic year, crop type and associated agricultural practices (N-fertilization and irrigation) on three output variables: drainage, nitrate leaching, and nitrate concentration of drainage water.

2. Materials and methods

2.1. Study area

The study site was located in the north of Spain (Basque Country) near the city of Vitoria-Gasteiz. A potato crop was grown in 1993 at Arkaute (42°50N; 2°30E) (Sanchez-Perez et al., 2003) and a sugar beet crop in 2002 at Matauko (42°51N; 2°34E). These two sites, at which the average thickness of the soil layer is ca. 5 m, are situated in the eastern sector of the quaternary aquifer of Vitoria-Gasteiz, which occupies an area of 40 km^2 located in a nitrate vulnerable zone. The water table stands at between 0 m (wetlands) and 2 m from the cropped soil surface (Arrate, 1994). The aquifer is recharged mainly by the infiltration of rainfall or irrigation water through the unsaturated zone.

Soil cores were collected at the two sites in order to determine their general characteristics (Table 1). At the Matauko site, the soil has a clayey texture (39–47% clay) in the upper horizons (0–60 cm) while the lower horizons (60–100 cm) have a muddy texture, but the clay content is 10%. At the Arkaute site, the soil has a sandy–clayey texture in the upper horizons (0–40 cm), becoming increasingly sandy with depth (40–100 cm).

Mean annual precipitation in the study area is about 700 mm. Meteorological data were collected either at Arkaute, using an automatic meteorological station, or 4 km far from

Table 1 – Main characteristics of the soils at Arkaute and Matauko

	Arkaute soil (1993)				Matauko soil (2002)		
Depth (cm)	0–20	20–40	40–60	60–100	0–30	30–60	60–100
Sand (%)	43.5	43.7	58.9	74.0	16.7	16.3	31.2
Silt (%)	21.3	19.5	17.0	16.2	44.1	36.4	45.1
Clay (%)	35.2	36.9	24.2	9.8	39.2	47.3	23.8
pH in water	8.5	8.4	8.6	8.8	7.9	8.1	8.4
$CaCO_3$ (%)	21.3	16.3	36.05	60.7	35.0	20.0	50.0
Bulk density	1.31	1.35	1.31	1.54	1.26	1.30	1.30
Field capacity (g water g^{-1} soil)	30.7	30.8	26.7	18.0	26.0	22.0	20.0
Permanent wilting point (g water g^{-1} soil)	18.0	19.2	9.0	4.7	13.0	11.0	10.0

Matauko. During the period corresponding to the potato study (6 March 1993–5 March 1994), precipitation was above average (887 mm) while it was below the average (665 mm) during the sugar beet study (6 March 2002–5 March 2003). Moreover, the mean temperature during the growing season (15 March–30 September) was higher in 1993 (14.6 °C) than in 2002 (12.9 °C), and the difference between precipitation and actual evapotranspiration was a surplus of approximately 260 mm in 1993, and only 60 mm in 2002.

2.2. Experimental data

For the two crop studies, the period of model validation extended from 6 March in one year to 5 March in the following year (approximately the end of the drainage period). For the potato study, the soil was separated into five layers of 20 cm, while for the sugar beet study the soil was divided into three layers of 30, 30, and 40 cm respectively, corresponding to pedological discontinuities (Table 1).

The potato crop was planted later at Arkaute on 9 June and harvested early on 28 September. Afterwards, an oat crop was sown on 17 November. Two applications of N-fertilizer were made, on 31 May (144 kg N ha^{-1}) and on 29 September (83 kg N ha^{-1}), just before the oat crop (local farming practice). NPK fertilizer (15/15/15) was used and the N form was ammonium nitrate. Four doses of irrigation were applied (35, 128, 206 or 287 mm), corresponding to four continuous levels of moisture monitored using tensiometers. The irrigation water was taken directly from the ground water and its nitrate concentration was that of the ground water, i.e. ca. 150 mg NO_3^- L^{-1}. There were four replications in a randomized split plot design.

The sugar beet crop was sown at Matauko on 22 March and was harvested on 23 December, which was much later than the normal harvest date (October–November) due to a very rainy autumn. Three different treatments were applied using NPK fertilizer (15/15/15): (i) unfertilized (Control); (ii) the recommended dose of 94 kg N ha^{-1} (Recommended) by advice of the Basque Government; and (iii) the local farmers' typical dose of 204 kg N ha^{-1} (Farmer). These applications were split into two (15 March and 31 May) and the N form was ammonium nitrate. Irrigation was identical for the three treatments. Five rates of approximately 40 mm were applied during July and August. However, in contrast to the potato study, irrigation water was not taken from the ground water but came from surface water, which contained approximately 50 mg NO_3^- L^{-1}. There were six plots in randomized blocks.

Soil solution from the unsaturated zone was sampled using ceramic cups (SDEC, France) every 2 weeks. The measurements of nitrate concentration were carried out only for the 35 mm irrigated treatment for the potato crop; the sampling depths were 0.15, 0.35, 0.55, 0.75, 0.95 m (Sanchez-Perez et al., 2003). There was no replication. Measurements of nitrate concentrations in the soil solution were made from 21 January of the crop year to 30 May of the following year. However until 25 May and after 1 November, the ground water level was higher than 1 m and as the STICS model was not designed to simulate the influence of ground water on nitrate concentration in the soil, only the measurements between the two dates when the ground water level was 1 m below the surface were used to evaluate STICS model performance.

For the sugar beet study twenty four ceramic cups were installed as following: 3 treatments × 2 replicates × 2 depths (0.5 and 1 m) × 2 ceramic cups per depth of sampling (Tensionic sensor, SDEC — France). With this sensor the water equilibrium is reached in a few days, depending on the hydraulic conditions of the soil (Moutonnet et al., 1993). In this way, the device takes a water sample (maximum volume 15 mL) every 2 weeks that is representative of the soil water at the depth where the sensor is located.

Ground water samples were taken monthly from a network of eight piezometers covering the aquifer. For the potato study, the water table was above 1 m depth at the beginning

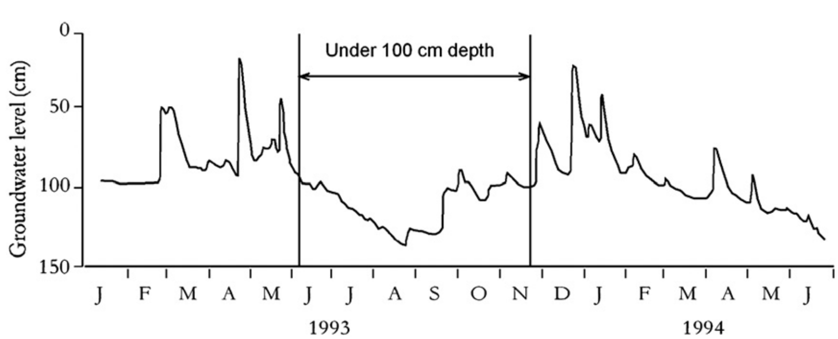

Fig. 1 – Variations in ground water level during the potato study.

and end of the study (Fig. 1). Therefore, it was necessary to adapt the depth where drainage was calculated with the model. Thus, from 6 March to 24 May and from 16 November to 31 December, the simulation depth was taken as 60 cm, whereas during the potato crop period (25 May–15 November) the simulation depth stayed at 1 m. For the sugar beet study the water table was consistently less than 1 m, allowing a constant simulation depth of 1 m.

2.3. The STICS model description: main assumptions and processes

This study was carried out using the STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) soil–crop model, which was mainly developed at the National Institute of Agronomical Research (INRA) in France. STICS is a dynamic soil–crop simulation model functioning at the day time scale (Brisson et al., 1998, 2002, 2003). The upper limit of the system is the atmosphere, characterized by standard climatic variables (solar radiation, minimum and maximum temperature, precipitation, reference evapotranspiration) and the lower limit corresponds to the soil/subsoil interface. The crop is globally characterized by its aboveground biomass (carbon and nitrogen), leaf area index, as well as the number and biomass (carbon and nitrogen) of harvested crop organs. Vegetative organs (leaves, branches, or tillers) are thereby not separated in terms of their biomass. Soil and crop interact via the roots, and these roots are defined with respect to root density distribution in the soil profile.

The water budget is used to calculate the water status of the soil and the plant as well as water stress indices that reduce leaf growth and net photosynthesis. It is based on estimating the water requirements of the soil–leaf system on the one hand and on the water supply to the soil–root system on the other hand. Soil evaporation is calculated in two steps: potential evaporation related to the energy available at the soil level and then actual evaporation related to water availability. It is then distributed over the soil profile. As part of the Beer's Law approach (described in Brisson et al., 1992), the potential evaporation of the crop is calculated assuming that none of the soil surfaces or plant surfaces are water-limited. Root absorption and leaf transpiration are assumed to be identical; total root absorption is calculated and then distributed over the soil layers according to the effective root density profile.

The nitrogen budget takes into account mineralizaton, denitrification, nitrogen absorption and symbiotic N_2 fixation for leguminous crops. Net mineralisation in the soil is the sum of humus mineralisation and the mineralisation of organic residues. The former process is permanent and is always positive, whereas the second process varies in relation to the C/N ratio of the organic residues and can either positive (net mineralisation) or negative (net immobilisation) (Nicolardot et al., 2001). The gaseous losses by denitrificaton (sum of N_2 and N_2O) are estimated by the NEMIS model (Henault and Germon, 2000). The daily absorption of nitrogen is equal to the minimum of supply available through the soil–root system and crop requirements. Crop requirements correspond to a relationship established from the upper envelope of nitrogen dilution curves (Lemaire and Gastal, 1997). Soil nitrogen supply is calculated per 1 cm layer along the rooting depth.

The description of soil includes four compartments: microporosity (or textural porosity), macroporosity (or structural porosity), fissures (in the case of swelling clay soils) and stones. The soil is divided in a maximum of 5 horizons but calculations in microporosity are done per 1 cm layer, which is the resolution required to derive nitrate concentration with relevance as shown by Mary et al. (1999). Water transport in soil micropores is calculated for each 1 cm layer using a tipping bucket approach. Water supplies cascade down filling up the layers until field capacity is reached. The permanent features of the 1 cm layers (field capacity, permanent wilting point and bulk density), as well as the initial water contents, are deduced from those of the five horizons describing the soil. An option allows the activation of macroporosity and fissures for some specific soils, e.g. such as vertisoils. The nitrogen concentration of the soil solution was calculated for each 1 cm layer. The water percolating from a layer (n) to the layer immediately below ($n+1$) carries along a certain amount of nitrate. This nitrate is assumed to mix completely with the water in the layer ($n+1$).

The data required to use the model are those relative to soil characteristics: organic nitrogen content, clay content, and carbonate content for the ploughing horizon, the soil is also characterized by thickness, bulk density, field capacity, and wilting point for all horizons. Climate is also required: such as daily minimum and maximum temperature, solar radiation, rainfall, and potential evapotranspiration. For crop management, it requires sowing (date, depth, density), mineral and organic fertlisation, irrigation, and soil tillage with ploughing of crop residues and organic products.

The STICS model was initially parametrized and validated for uncovered soil and the wheat and maize crops (Brisson et al., 1998). It has been adapted for other crops like oilseed rape, sunflower, soybean, flax, tomato, sorghum, salad, mustard, and also for sugarbeet and potato (Brisson et al., 2003).

2.4. Model evaluation

The statistical evaluation of the model mainly focused on nitrate concentration in the soil solution. Three statistical criteria were used (e.g. Smith et al., 1996):

Model efficiency (EF): optimal value = 1; if EF = 0 the simulations are not better than the mean of the observations.

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n} (Pi - Oi)^2}{\sum_{i=1}^{n} (Oi - \overline{O})^2} \quad (1)$$

Mean Error (ME) and its relative value in % (ME%): optimal value = 0

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n} (Oi - Pi);\ \mathrm{ME\%} = \left(\frac{\mathrm{ME}}{\overline{O}}\right) \times 100 \quad (2)$$

Root Mean Square Error (RMSE) and its relative value (RMSE%): optimal value = 0

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{n=1}^{n} (Oi - Pi)^2};\ \mathrm{RMSE\%} = \left(\frac{\mathrm{RMSE}}{\overline{O}}\right) \times 100 \quad (3)$$

Table 2 – Observed (mean ± standard deviation) and simulated (using STICS model) yields of potatoes and sugar beet in all treatments of the two studies (x indicates the intensity of mildew attack)

Cultivation system		Observed yield ($t\ ha^{-1}$)	Simulated yield ($t\ ha^{-1}$)
Year	Crop (treatment)		
1993	Potato (35 mm irrigation)	31.8 ± 3.8	31.3
1993	Potato (128 mm irrigation)	38.6 ± 4.6	33.6
1993	Potato (206 mm irrigation)	34.2 ± 4.1 (x)	35.8
1993	Potato (287 mm irrigation)	29.4 ± 3.5 (xxx)	37.6
2002	Sugar beet (0 kg N ha^{-1})	37.2 ± 11.4	36.7
2002	Sugar beet (94 kg N ha^{-1})	47.8 ± 4.8	40.5
2002	Sugar beet (204 kg N ha^{-1})	49.6 ± 3.7	40.9

where n is the number of observations, Oi the observed value, $\overline{O}$ is the mean of the observed values, and Pi the value predicted by the model.

3. Results and discussion

3.1. *STICS evaluation for the two experiments located in Northern Spain*

The first output variable used for STICS evaluation was the crop yield (Table 2). For the potato crop, the simulated yields were included into the range of variation of the observed yields for the 35 mm, 128 and 206 mm irrigation treatments. For the 287 mm treatment, the simulated yield was significantly overestimated. It must be mentioned that during the potato crop, a mildew attack was observed for the 206 and 287 mm irrigations. Mildew is a microscopic parasite that affects the development of the potato plant and thus the yield. The appearance and the development of this parasite are supported by warm and moist conditions (Sharma et al., 2004), which can be generated in particular by strong irrigation. The lack of accounting for biotic stresses in the model explains its overestimation of yield, as simulated yield values for high irrigation levels corresponded to production without crop damage. However, the slight underestimation of the yield with a level of irrigation of 128 mm cannot be explained either by apparent mildew attack or by experimental reasons. It may have been the result of imperfect response of the model to irrigation. For the sugar beet crop the yield simulated by STICS was included into the range of variation of the observed yield for the unfertilised control, but significantly underestimated for the other two treatments. However, the STICS model accurately simulated the lack of increase in yield when N-fertilization was further increased (from 94 to 204 kg N ha^{-1}).

Our work mainly evaluated the nitrate concentration in soil water using data from the two crop studies. The statistical criteria calculated to evaluate the accuracy of the model are reported in Table 3. Model efficiency was quite satisfactory for the sugar beet crop but less satisfactory for the potato crop. At the 15 cm depth the model efficiency was near zero, probably due to rapid and significant variations which created great differences between observed and simulated values in a few days. At 95 cm depth the efficiency was poor, a fact that could be attributed to the lack of variation in measured data, making the statistical criterion very sensitive to the weak differences between the observed values and the simulated. In fact, Root Mean Square Error (RMSE) represented only 12% of observed data (Table 3) indicating a good ability of the model to simulate plant N uptake, water and nitrate transport into the soil profile, drainage and nitrate leaching.

The RMSE was between 12% and 40% for all treatments. These values of RMSE are in agreement with others studies (Schnebelen et al., 2004; Beaudoin 2006) which were between 15% and 68% in their studies. The work of Schnebelen et al. also showed that the RMSE values for drainage and nitrate leaching were generally close to the RMSE for nitrate concentration. Unfortunately, in our study these two output variables (drainage and nitrate leaching) could not be compared to experimental data, because no measurements were available.

Fig. 2 presents the comparative changes in observed and simulated nitrate concentrations in soil water during the simulation period (from 6 March to 31 December). This figure also illustrates the simulated plant N uptake. For the potato crop (Fig. 2a), the evaluation of STICS was carried out from 25 May to 1 November only on the 35 mm irrigation since measurements were made only for this treatment. At 95 cm depth, the simulated and observed data presented no significant variation. This can be explained first because during this period precipitation was not sufficient in regard to simulated plant water uptake to make water percolation at this depth, and secondly because the maximum root depth simulated was at 70 cm. At the 15 cm depth, the nitrate concentration increased to 300 mg NO_3^- L^{-1} because the availability of N coming from mineralization of organic soil matter and N-fertilization (144 kg N ha^{-1} on 31 May) was higher than the plant N uptake capacities. The concentration then decreased due to water dilution by high rainfall events

Table 3 – Evaluation results for simulations using STICS model of the two field studies

	Nitrate concentration in soil (mg NO_3^- L^{-1})							
Crop system	Measurement depth (cm)	n	Mean observed	EF	ME	ME%	RMSE	RMSE%
Potato (35 mm irrigation)	15	9	197	−0.07	6	3	65	36
Potato (35 mm irrigation)	95	11	75	−20.34	4	5	9	12
Sugar beet (Control)	50	9	41	0.82	−3	−7	15	37
Sugar beet (Control)	100	10	72	0.87	−15	−20	21	29
Sugar beet (Recommended)	50	8	62	0.85	1	2	18	29
Sugar beet (Recommended)	100	10	77	0.98	−3	−4	10	12
Sugar beet (Farmer)	50	8	76	0.69	−1	−1	30	40
Sugar beet (Farmer)	100	10	118	0.61	31	26	41	35

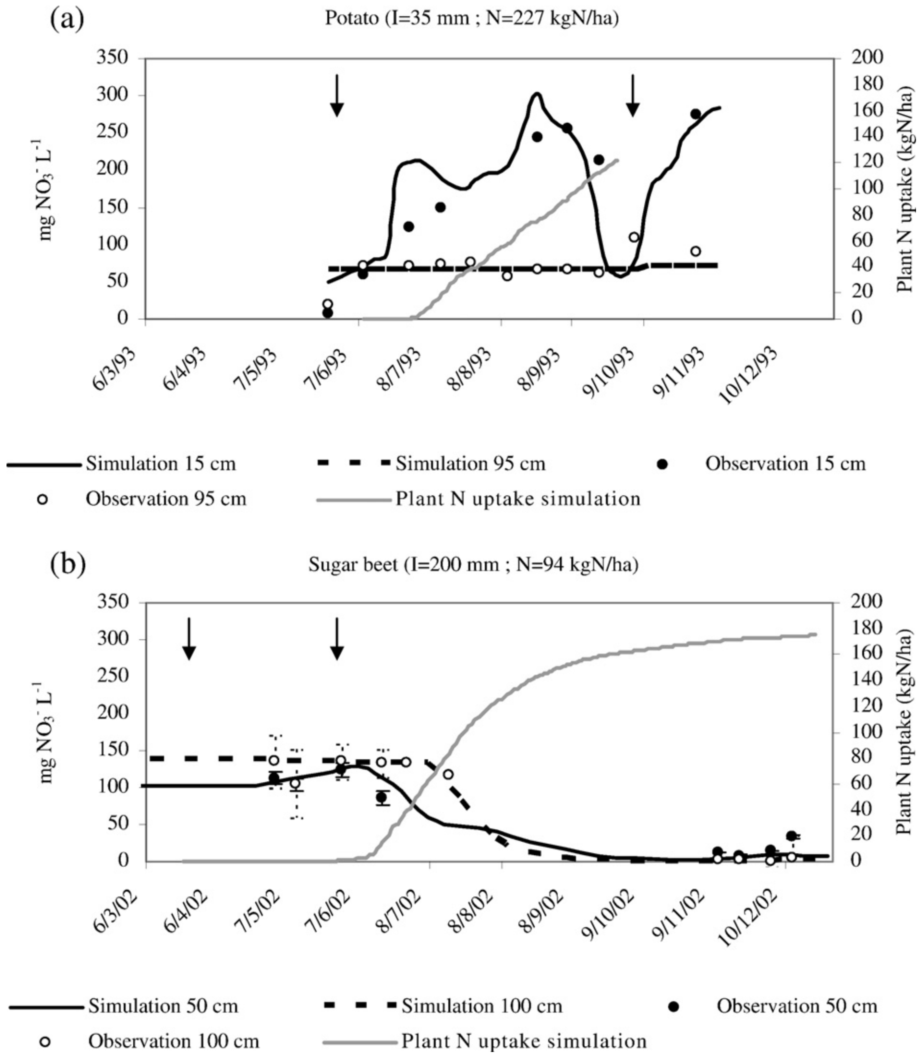

Fig. 2 – Comparison between measured and calculated nitrate concentration in soil solution using STICS model, and the simulated plant N uptake (a) for the potato crop (Irrigation I = 35 mm and N-fertilization N = 227 kg N ha^{-1}), (b) for the sugar beet crop (Irrigation I = 200 mm and N-fertilization N = 94 kg N ha^{-1}). Arrows represent N-fertilization.

in September (102 mm) and the plant N uptake occurring until the harvest stage. And finally the concentration increased again after the potato harvest as a result of residue mineralization (leaves and stems are rich in N) and the second N-fertilization for the next oat crop (83 kg N ha^{-1} on 29 September). For this experiment, even if absolute values were not always perfectly simulated (Table 3), the trends and range of variations were correctly simulated (Fig. 2) thus allowing sufficient confidence in the quality and relevance of simulations of nitrate leaching and drainage fluxes.

For the sugar beet study, the nitrate concentrations simulated by STICS were compared with data from the three N-fertilization treatments: Control, Recommended and Farmer. However, as the changes in nitrate concentrations over time for the three treatments were very close, only the data for the “Recommended” treatment are illustrated (Fig. 2b). For the three treatments, simulated and observed data were also relatively close (Table 3). The decrease in soil water nitrate concentration during summer can be explained by plant uptake and by nitrate leaching due to excess irrigation, which probably also induced nitrate dilution. For this experiment absolute values and trends were correctly simulated.

The comparison of measured soil nitrate concentration and yield values with the values simulated using STICS showed that the model could correctly simulate nitrate fluxes into the soil for various agricultural practices in the conditions tested, despite the simulations not being perfect, as expected using soil–plant models (Brisson et al., 2002). Even if these results were not always perfect as regards the absolute values, they allowed the model to be used for others calculations and the relative effects of different input variables on nitrate leaching to be assessed (Beaudoin et al., 2005).

3.2. *Simulated nitrogen and water budgets in dynamics during the two field studies*

The STICS model was able to correctly simulate the nitrate concentration in soil water and to a lesser extent the yield

Table 4 – Nitrogen budget for the two experiments based on STICS model calculations

	Year	1993	1993	1993	1993	2002	2002	2002
	Crop	Potato	Potato	Potato	Potato	Sugar beet	Sugar beet	Sugar beet
	Irrigation (mm)	35	128	206	287	200	200	200
Inputs	N-fertilization (+oat) (kg N ha^{-1})	144 (+83)	144 (+83)	144 (+83)	144 (+83)	0	94	204
	Measured initial soil N quantity (kg N ha^{-1})	41	41	41	41	78	79	88
	Contribution by irrigation (kg N ha^{-1})	14	42	68	95	22	22	22
	Calculated soil+residues mineralisation (kg N ha^{-1})	59	63	65	69	55	55	56
Outputs	Calculated plant N uptake (+oat) (kg N ha^{-1})	122 (+8)	129 (+8)	139 (+8)	156 (+8)	138	185	239
	Calculated fertilizer immobilization (kg N ha^{-1})	44	44	44	44	0	17	34
	Calculated fertilizer volatilisation (kg N ha^{-1})	29	29	29	29	0	26	52
	Calculated denitrification (kg N ha^{-1})	29	29	29	29	0	8	17
	Calculated N leaching (kg N ha^{-1})	78	113	128	143	19	18	23
	Calculated final soil N quantity (kg N ha^{-1})	31	21	24	23	7	7	6
	Calculated mean nitrate concentration in drainage water (mg NO_3^- L^{-1})	104	129	122	119	29	30	36

obtained for each level of irrigation or N-fertilization of the crops. It was then possible to use the outputs of the model to better understand and quantify the impact of crop management on nitrate leaching. The potato study enabled us to evaluate the impact of irrigation and the sugar beet study the impact of the N-fertilization. However our results were climate-dependent and were the result of multiple interactions. So we aimed to differentiate between (i) the effects due to crop, soil, and climate and (ii) the interaction between these factors.

The nitrate concentration in drainage water was at least twice as high during the potato crop than during the sugar beet crop, even with comparable levels of N-fertilization and irrigation (Table 4). Moreover as the mildew attack was not taken into account by the model, the quantities of nitrogen uptake by the potato plant were probably overestimated by simulation for the high levels of irrigation (206 and 287 mm). The nitrate concentrations in drainage water for these two levels of irrigation may have been underestimated by the model in comparison to the actual situation. However, the order of magnitude and the amount of variation were probably appropriate and thus justify the use of the model to evaluate the effects of various agricultural practices for situations where pests and diseases were well controlled.

Much of the differences in simulated nitrate concentrations can be explained by the type of crop. The higher nitrogen uptake capacity of the sugar beet crop than the potato/oat crop succession can explain the lower simulated nitrate concentration in drainage water during the sugar beet study. The results of the potato crop simulations indicated that N uptake was 122 to 156 kg N ha^{-1} according to irrigation level, whereas the sugar beet crop absorbed between 128 and 239 kg N ha^{-1} according to fertilizer rate. With equivalent irrigation and N-fertilization, the difference between the two crops was 100 kg N ha^{-1} (139 vs. 239 kg N ha^{-1} for potato and sugar beet respectively). These results of simulation were in good agreement with published data dealing with these crops. For example, Haase et al. (2007) showed that potato uptake could be 64 to 151 kg N ha^{-1} and Malnou et al. (2006) indicated that sugar beet uptake varied from 100 to 300 kg N ha^{-1} depending on the N-fertilization rate. This higher N uptake of the sugar beet crop, its longer growing season, and its ability to take up N until the date of harvest (Shepherd and Lord, 1996) can also explain why the quantity of nitrogen in the soil at the harvest was very low (under 10 kg N ha^{-1} on 1 m depth) after this crop, whereas it was higher after the potato crop (95 kg N ha^{-1} for the 35 mm treatment, 121 kg N ha^{-1} for the 128 mm treatment and 125 kg N ha^{-1} for the 206 mm and 287 mm treatments), although the initial quantity of nitrogen in the soil was higher for the sugar beet crop. In addition, the potato crop was followed by an oat crop, for which the first N-fertilization was

Table 5 – Water budget for the two experiments based on STICS model calculations

Cropping system			Inputs			Outputs			
Year	Crop	N-Fertilization (kg N ha^{-1})	Measured initial soil water content (mm)	Precipitation (mm)	Irrigation (mm)	Calculated final soil water content (mm)	Calculated soil evaporation (mm)	Calculated plant transpiration (mm)	Calculated drainage (mm)
1993	Potato	144+83	232	887	35	238	380	205	332
1993	Potato	144+83	232	887	128	256	384	219	388
1993	Potato	144+83	232	887	206	256	388	220	461
1993	Potato	144+83	232	887	287	256	392	225	533
2002	Sugar beet	0	285	665	200	285	418	166	281
2002	Sugar beet	94	285	665	200	285	401	202	262
2002	Sugar beet	204	285	665	200	285	400	204	262

applied at the beginning of the autumn. This N application in autumn could also have contributed to the higher nitrate concentration of drainage water. In fact during part of the autumn the N uptake capacity of oat was low until the next spring. Indeed, as shown for example by Di et al. (1999), N applications in autumn cause more N leaching and higher nitrate concentrations in drainage water than spring applications as also shown in our study (see Table 6).

Another factor that could have had an impact on the nitrate concentration of drainage water was the origin of the irrigation water. The irrigation water for the potato crop came from the ground water (approximately 150 mg NO_3^- L^{-1}), whereas that for the sugar beet crop came from surface water (approximately 50 mg NO_3^- L^{-1}). This corresponded to a N-fertilization of 22 kg N ha^{-1} to the sugar beet crop and 14 to 95 kg N ha^{-1} to the potato crop depending on irrigation

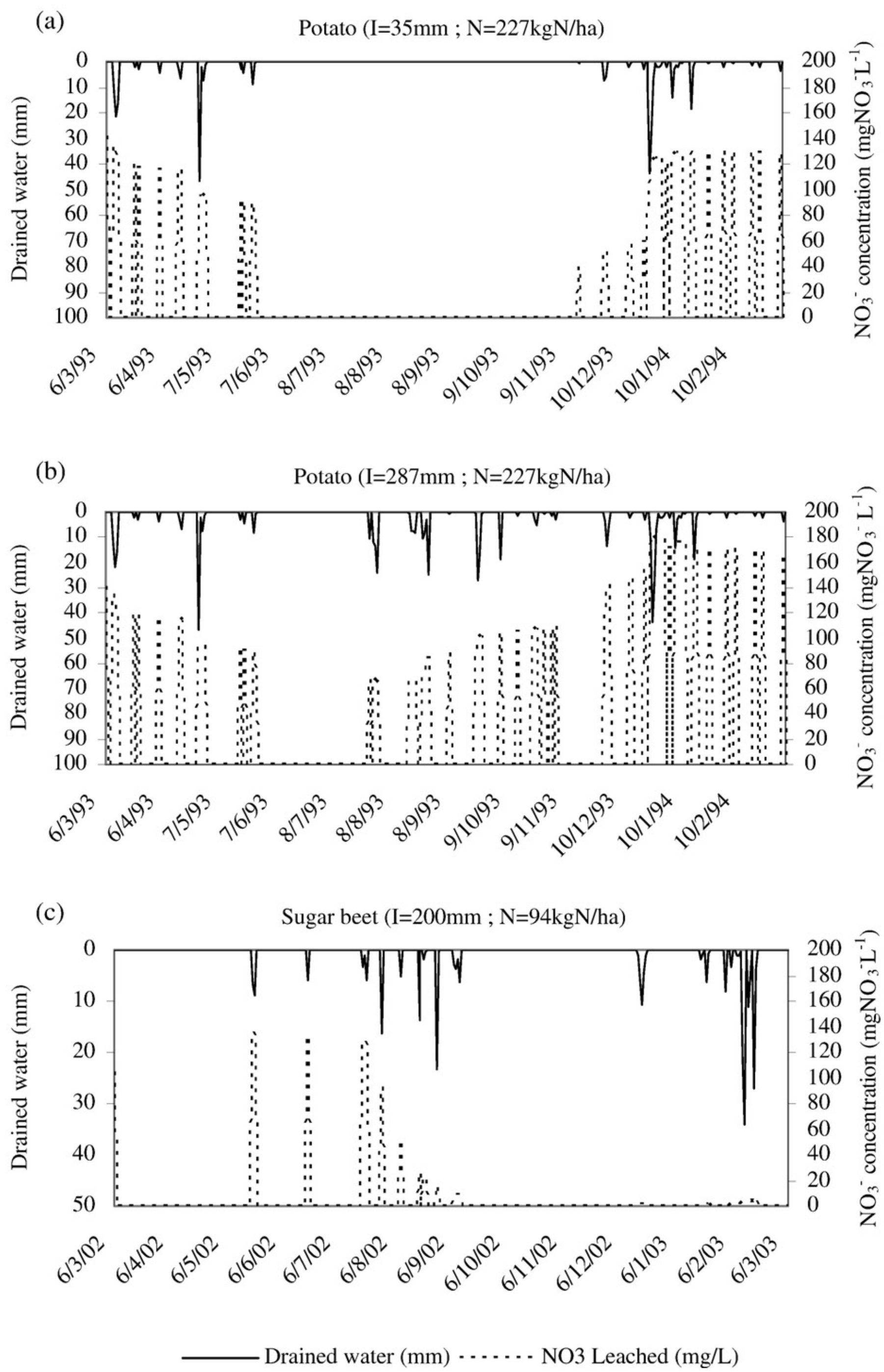

Fig. 3 – Calculated drainage and nitrate concentration in drained water using STICS model with (a) 35 mm of irrigation and (b) 287 mm of irrigation applied to the potato crop, and (c) simulated drainage and nitrate leaching for the sugar beet crop.

amount. By inverting the nitrate concentration of irrigation water between the two studies in the numerical experiments, the impact of this was analysed.

For the sugar beet crop, N-fertilization did not appear to have an impact on nitrate concentration of drainage water. Indeed, a N-fertilization of 204 kg N ha^{-1} instead of no N-fertilization caused an increase of only 7 mg NO_3 L^{-1} due to the capacity of the sugar beet to take up N as luxury consumption. Varying the N-fertilization rate of the potato crop could have been a better solution to evaluate its impact on nitrate concentration in drainage water.

The amount of drainage water was much higher during the potato study than during the sugar beet study (Table 5). Drainage amount varied between 332 and 533 mm during the potato crop (according to irrigation rate), whereas it was only 262 to 281 mm for the sugar beet crop. During the potato treatment with a small level of irrigation (35 mm), drainage was generated by excess precipitation in spring and autumn (Fig. 3a). This drainage was associated with high nitrate concentrations during spring (100 to 150 mg NO_3^- L^{-1}), and lower concentrations during autumn (50 to 130 mg NO_3^- L^{-1}). When the level of irrigation was higher (287 mm), drainage also took place during irrigation periods in summer (Fig. 3b). The nitrate concentrations associated with the water draining off during the summer were rather high (80 to 120 mg NO_3^- L^{-1}), and the water draining during the following autumn also had high nitrate concentrations (140–180 mg NO_3^- L^{-1}). This showed that poor management of irrigation can induce drainage and thus nitrate leaching to the ground water even in the middle of the summer, when the actual evapotranspiration is maximum. With the sugar beet crop, drainage occurred almost exclusively during the summer months (Fig. 3c). There were nine periods of drainage, including five during July and August related to the contributions of irrigation water. The nitrate concentrations were high during the first three episodes of drainage in spring (140 mg NO_3^- L^{-1}) and then decreased rapidly to reach almost zero due to N uptake by the sugar beet. This explains why the mean nitrate concentration of drainage water calculated for the cumulative drainage (Table 4) was much lower for the sugar beet than for the potato crop.

The different levels of irrigation (from 35 to 287 mm) applied during the potato study explained the variation in the quantity of drainage water (from 332 to 533 mm), indicating the level of excess in irrigation volumes. With an equivalent level of irrigation, the quantity of drainage water was smaller during the sugar beet study than during the potato study. This difference could be explained by precipitation being considerably more abundant (786 mm) during the potato study than in the sugar beet study (476 mm).

The calculations using the STICS model showed that the volume of drainage water and the nitrate concentrations were higher during the potato study. As a consequence, the amount of nitrate leaching was much greater during the potato crop. According to STICS model simulations, the various levels of irrigation carried out with the potato crop had a moderate effect on the mean nitrate concentration of drainage water. However, the impact on the quantity of drainage water was quite large. The amount of nitrate leaching increased according to irrigation intensity (Fig. 4a). Concerning the sugar beet study, N-fertilization had almost no effect either on the drainage or on the nitrate concentration. Consequently, the amounts of nitrate leaching were quite similar for the various levels of N-fertilization evaluated (Fig. 4b). The higher quantity of nitrate leaching in the potato study than in the sugar beet study could be explained first by a higher quantity of water drainage whatever the irrigation rate, and second by the higher nitrate concentration in drainage water during the potato study, notably at the end of the crop cycle and after harvest. This is in good agreement with results reported by Shepherd and Lord (1996) which showed that nitrate leaching was higher after a potato crop than after sugar beet. This could be both explained by the higher quantity of mineral nitrogen at harvest of potato crops and because potatoes were harvested at the end of summer. Consequently, after potato a rapid leaf decomposition due to warm soils could occur, and then induced net N-mineralization during autumn and winter, while sugar beet residues mineralized and released N mainly for the following spring. So there was a greater risk of nitrate leaching during the following winter after the potato crops. Drainage is an important factor determining the amount of N leached (Arregui and Quemada, 2006; Mantovi et al., 2006), but the results of the STICS simulation showed that controlling the nitrate concentration of drainage water was also a way to control nitrate leaching.

The use of the STICS model as a complementary tool to the two field studies enabled us to better understand and diagnose the impact of agricultural practices on nitrate leaching in more detail than when only based on some specific field measurements. Thus, even if climate and irrigation appeared to be the main parameters influencing the drainage, some questions remained regarding the nitrate concentration of drainage water. The crop type seemed to have a great impact, but we were also interested in assessing the impact of i) N-fertilization, ii) nitrate concentration of irrigation water, and iii) initial soil N quantity on a) nitrate leaching, b) drainage, and c) nitrate concentration of drainage water under the rooting zone. Numerical calculations of virtual situations were made using the STICS model to answer these questions.

3.3. *Analysis of the impact of different factors on nitrate leaching using STICS simulations*

For these simulations, corresponding to virtual experiments, only one treatment of the two crops was selected, namely that closest to actual agricultural practices in the area of Basque Country (Northern Spain). For the potato crop the treatment used was the 35 mm irrigation level, while for the sugar beet crop the 204 kg N ha^{-1} treatment was deemed to be representative in each investigated year. First, the impact of the crop type (potato vs. sugar beet) was determined, and here only an adaptation of sowing and harvesting dates was necessary. The second parameter assessed was the climate by reversing the 1993/1994 and 2002/2003 climatic years which corresponded to two very different scenarios. The N-fertilization rate was only assessed for the potato crop as it had already been evaluated for the sugar beet. In addition to the 144 (+83) kg N ha^{-1} treatment, three other levels were tested: i) avoidance of the autumn N-fertilization before oat sowing (144 kg N ha^{-1}), ii) halving of the spring application, and iii) no

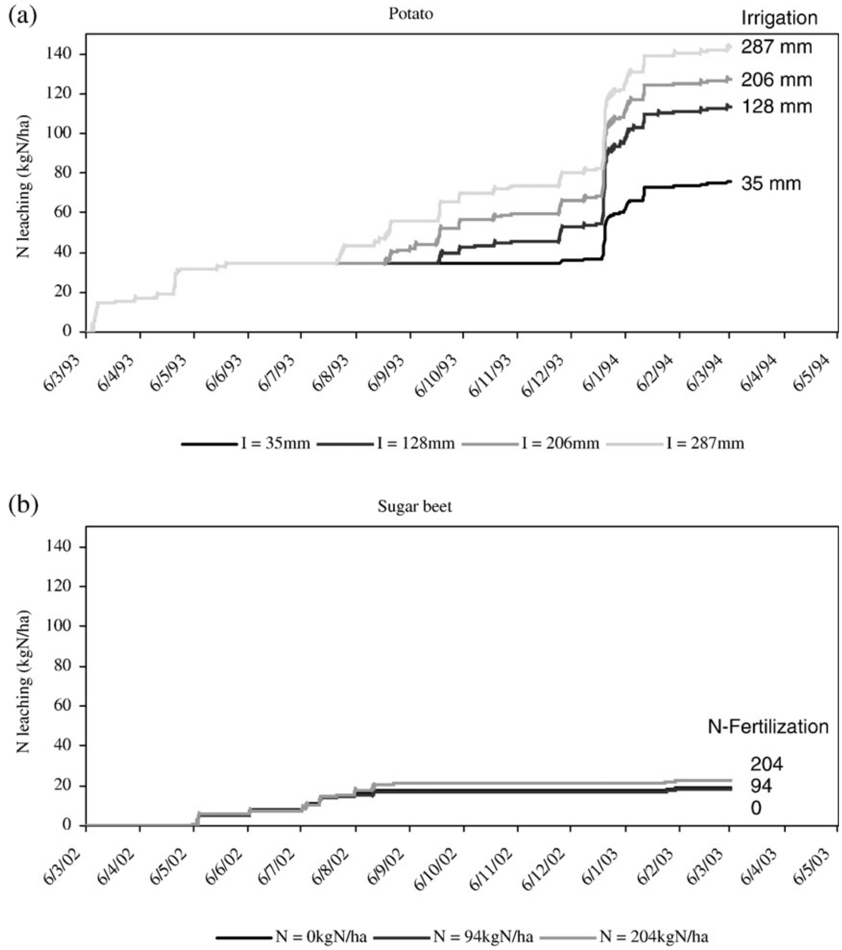

Fig. 4 – Cumulative calculated nitrate leaching using STICS model for (a) the four Irrigation treatment (I35, I128, I206, I287) treatments of the potato study and (b) the three N-fertilization (N0, N94, N204) treatments of the sugar beet study.

N-fertilization at all. The impact of irrigation level was assessed only for sugar beet such as: i) half amount (100 mm), ii) no irrigation, and iii) an increase of 80 mm (280 mm). Next, the effects of the initial soil N quantity were analyzed for each crop by using the initial quantity measured in the other crop the given year of the experiment. Finally, the nitrate concentration of irrigation water was also assessed, such as 50 or 150 mg NO_3^- L^{-1}.

Concerning drainage, the simulations confirmed that as expected, climate and irrigation were the main controlling factors (Table 6). The type of crop, the N-fertilization rate, the initial soil N quantity and the nitrate concentrations of irrigation water had no significant impact on drainage.

Concerning the nitrate concentration in drainage water, all the combinations tested had an effect (Table 6). The type of crop, the climate and the N-fertilization rate seemed to play the major roles. The high nitrate uptake capacity of the sugar beet crop can explain why the nitrate concentration of drainage water was systematically lower with this crop. Growing a sugar beet crop instead of potatoes in 1993 could have reduced the nitrate concentration of drainage water by about 35 mg NO_3^- L^{-1}, but the yield would only have been 33.5 t ha^{-1} of roots. On the other hand, growing a potato crop instead of sugar beet in 2002 would have increased the nitrate concentration by 70 mg NO_3^- L^{-1}, which is a very large increase, confirming the importance of the crop. Climate also had an impact on the nitrate concentration of drainage water, but this impact was not the same for the two crops. Thus, for the potato crop the use of the dry climate of 2002 instead of the rainy conditions of 1993 led to an increase of 60 mg NO_3 L^{-1} in drainage water, associated with a decrease in drainage quantity. This could be explained by the weak precipitation and the low N uptake capacity of the potato crop, which caused an increase in nitrate concentration of drainage water. For the sugar beet crop, the use of the rainy 1993 climatic data instead of 2002 caused an increase in nitrate concentration of drainage water that could be explained by the high initial quantity of N in combination with higher precipitation during spring of 1993 than spring of 2002 (345 mm and 177 mm respectively) which led to increased drainage with high nitrate concentrations. The sugar beet yield obtained with the 1993 climate data was higher because of higher precipitation and temperature at the end of summer and mid-autumn, which is consistent with agronomic reality. The different levels of N-fertilization tested during the sugar beet study did not significantly affect the nitrate concentration of drainage water (Table 6), but the simulations of virtual experiments carried out on the potato crop showed that a decrease in N-

Table 6 – Actual and virtual experimentation results using STICS model (previous calculations corresponding to actual field experiments highlighted)

	Parameters tested						Calculated output variables			
Effect tested	Crop type	Climatic year	Irrigation (mm)	N-fertilization (kg N ha^{-1})	Initial soil N quantity (kg N ha^{-1})	Irrigation water (mg NO_3^- L^{-1})	Drainage (mm)	N Leaching (kg N ha^{-1})	[NO_3] (mg NO_3^- L^{-1})	Yield (t ha^{-1})
Crop	Potato	1993/1994	35	144 + 83	40.9	150	332	78	104	31.3
	Sugar beet	1993/1994	35	144 + 83	40.9	150	316	49	69	33.5
	Sugar beet	2002/2003	200	204	79.3	50	262	23	36	40.9
	Potato	2002/2003	200	204	79.3	50	237	56	105	44.2
Climate	Potato	1993/1994	35	144+83	40.9	150	332	78	104	31.3
	Potato	2002/2003	35	144+83	40.9	150	173	65	166	22.8
	Sugar beet	2002/2003	200	204	79.3	50	262	23	36	40.9
	Sugar beet	1993/1994	200	204	79.3	50	365	50	61	70.1
N-fertilization	Potato	1993/1994	35	144+83	40.9	150	332	78	104	31.3
	Potato	1993/1994	35	144	40.9	150	332	61	81	31.3
	Potato	1993/1994	35	72	40.9	150	332	53	71	26.2
	Potato	1993/1994	35	0	41	150	339	52	68	18.6
Irrigation	Sugar beet	2002/2003	200	204	79.3	50	262	23	36	40.9
	Sugar beet	2002/2003	280	204	80	50	342	29	38	40.9
	Sugar beet	2002/2003	100	204	79.3	50	199	12	27	34.0
	Sugar beet	2002/2003	0	204	79.3	50	148	13	39	34.8
Initialisation	Potato	1993/1994	35	144+83	40.9	150	332	78	104	31.3
	Potato	1993/1994	35	144+83	79.3	150	330	90	121	35.1
	Sugar beet	2002/2003	200	204	79.3	50	262	23	36	40.9
	Sugar beet	2002/2003	200	204	40.9	50	262	13	22	40.8
[NO_3]irrigation	Potato	1993/1994	35	144+83	40.9	150	332	78	104	31.3
	Potato	1993/1994	35	144+83	40.9	50	332	72	96	31.3
	Potato	1993/1994	287	144+83	40.9	150	533	143	119	37.6
	Potato	1993/1994	287	144+83	40.9	50	533	91	76	37.1
	Sugar beet	2002/2003	200	204	79.3	50	262	23	36	40.9
	Sugar beet	2002/2003	200	204	79.3	150	262	29	49	40.9

fertilization rate could have an impact on nitrate concentration. Omission of the N application in autumn after the potato crop and before the winter oat crop reduced the nitrate concentration of drainage water without affecting the quantity of N uptake by the oat crop between sowing and end of simulation: only 8 kg N ha^{-1} was taken up in this period with or without N-fertilizer. Omission of the autumn N-fertilization and a reduction by half of the spring N-fertilization of the potato crop led to large reductions in nitrate leaching and in nitrate concentration of drainage water. However it caused a significant reduction in potato yield. The different levels of irrigation tested during the potato crop showed that irrigation was not an important cause of variation in nitrate concentration of drainage water (Table 6). The same conclusion was reached after testing different irrigation levels during the sugar beet study. The initial soil N quantity in spring did not appear to play a major role in nitrate concentration of drainage water. Two causes could explain this result. First, drainage mainly occurred after the spring crop during the following winter. Second, the difference between the measured values was not sufficiently large and its re-partitioning in the soil at depth too similar to induce a great difference in nitrate concentration. It had an impact on nitrate concentration of the first drainage event, but this impact was less important considering the whole simulation. The reduction in the initial amount of soil mineral N was presumably more important during 1993/1994 than during 2002/2003 since precipitation was higher in 1993/1994. This could explain why the relative effect of N-mineral initialisation was more important in 2002/2003 than in 1993/1994 (a reduction of initial soil N quantity from 79 to 41 kg N ha^{-1} induced a respective decrease of 40% and 12% in nitrate concentration). Finally, the last parameter examined was the nitrate concentration of irrigation water. When the quantity of irrigation water was large, the use of irrigation water with 50 mg NO_3 L^{-1} instead of 150 mg L^{-1} during the potato study could have significantly decreased the nitrate concentration, as in the sugar beet study. In fact, the use of irrigation water with a high nitrate concentration level could be likened to a supplementary N-fertilization that must be taken into account to reduce total N-fertilizer amount.

Fig. 5 represents the different relationships between calculated nitrate concentration in drainage water, drainage and nitrate leaching as a function of (a) irrigation and (b) N-fertilization. Nitrate leaching and drainage were positively correlated to irrigation for the potato crop. For the sugar beet crop, drainage was positively correlated but nitrate leaching showed a small increase. This indicated that in spite of the drainage increase there was only low amount of nitrate available to transport into the soil and consequently no significant increase in nitrate leaching. The high N uptake capacity of sugar beet can explain the low quantity of N available for leaching. An increase in irrigation amount led to increased drainage for the two types of crop, but involved two different responses in terms of nitrate leaching. Nitrate leaching and nitrate concentration of drainage water were positively correlated to N-fertilization for the potato crop. For the sugar beet crop, an increase in N-fertilization caused a very small and probably not significant increase in nitrate concentration of drainage water and had almost no effect on nitrate leaching. It can be concluded that for a potato crop, good management of irrigation allowed drainage during the crop cycle to be decreased, and a reduction in N-fertilization allowed the nitrate concentration of drainage water to be decreased. For the sugar beet crop only irrigation had an effect. The N-fertilization rates tested have almost no impact on nitrate concentration of drainage water and nitrate leaching. Moreover looking at the relationships between all simulations of actual and virtual situations using STICS model (results not shown), the nitrate concentrations of drainage water were positively correlated to nitrate leaching ($y=1.32x$; $r^2=0.44$; $p<0.0001$), and the nitrate leaching was positively correlated to drainage ($y=0.19x$; $r^2=0.55$; $p<0.0001$). In addition, there was no correlation between nitrate concentration of drainage water and drainage ($p=0.23$). These two points showed that drainage, which is sometimes approximated by the difference between global precipitation and evapotranspiration, is not sufficient to estimate nitrate leaching, that this reinforces the interest in the use of dynamic soil–crop models to evaluate nitrate concentration in drainage water under agricultural lands because water soil content changes need to be taken into account.

From these numerical calculations, four main recommendations can be made. First, in the vulnerable zone of this aquifer it appears necessary to promote crops such as sugar beet and winter cereal crops with a high capacity for N uptake in order to limit the risk of N leaching. In the case of potato cropping, it could be recommended to grow nitrogen catch crops or cover crops such as crucifers (mustard, rape, radish etc.) before and after the main potato crop in order to decrease the nitrate content in the soil profile and thus decrease the nitrate leaching during and after the potato crop. Indeed, even with high N applications and under the different conditions examined, the nitrate concentration of drainage water and the drainage amount remained quite low during the sugar beet study compared with the potato study. Second, even if the crop rotation includes a winter cereal such as oat, N-fertilization during autumn should be avoided, since only few kg N ha^{-1} are taken up by the crop during winter. Third, the results of simulations confirmed that the control of irrigation can be as important as decreasing N-fertilizer rate in decreasing nitrate pollution, in particular for potato crops. Finally, it is necessary to take into account the nitrate contained in the irrigation water to avoid over-N-fertilization in cases of intense irrigation.

3.4. *Relations with ground water level*

In the study area, the ground water level is relatively close to surface, and it is thus recharged by drainage water, in contrast to certain alluvial plains where the ground water level can also be controlled by the river. The nitrate concentration of drainage water influences that of the ground water directly. From 1993 to 2002, the nitrate concentration in ground water in the aquifer of this vulnerable zone here decreased progressively from ca. 150 mg NO_3^- L^{-1} to ca. 50 mg NO_3^- L^{-1}. The mean simulated nitrate concentrations of drainage water for the two crops corresponded approximately to those measured in the ground water: 150 mg NO_3^- L^{-1} in 1993 and 60 mg NO_3^- L^{-1} in 2002. However it is interesting to note that during the same period, the cropped area with potatoes decreased while the cropped area of sugar beet increased by the same amount (Sanchez-Perez et al., 2003). Thus, a change in crop type, crop management or climate could explain the decrease in nitrate concentrations observed in

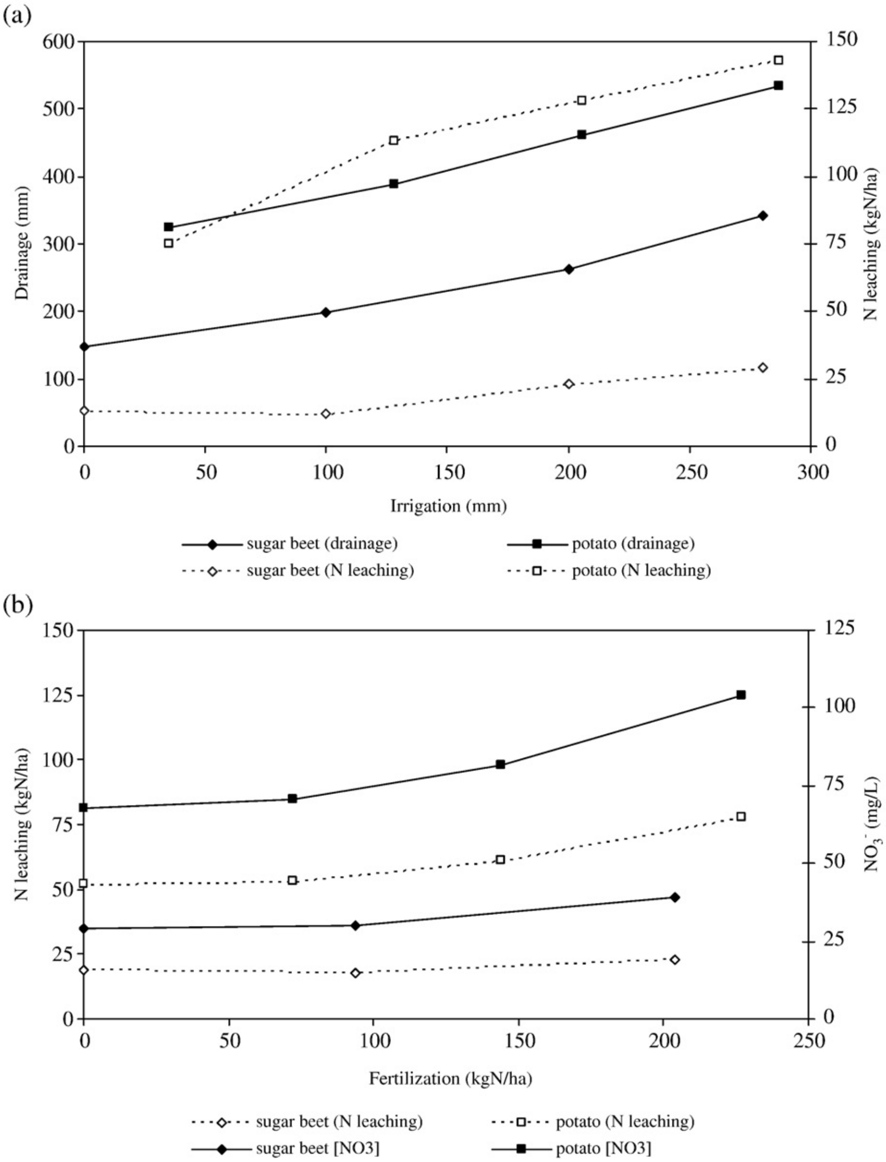

Fig. 5 – Relationships between (a) cumulative calculated nitrate leaching and cumulative calculated drainage as a function of irrigation, and (b) cumulative calculated nitrate leaching and nitrate concentration of drainage water as a function of N-fertilization.

the ground water. In order to test this hypothesis, simulations must be made for the entire aquifer during the study period (1993 to 2002). Moreover it would be necessary to evaluate the process of denitrification in soils in particular in wetlands and in the aquifers in order to understand the changes in nitrate concentration over many years.

The simulation of the potato field experiment underlined a limitation of the STICS crop model when the ground water level rose into the soil simulation zone. Even if the anoxic conditions are simulated and have an impact on root growth, the results of simulation became unsatisfactory compared with field measurements for nitrate concentration in the saturated soil zone. In order to improve the predictive capacity of the model in these conditions, a solution would be to incorporate the process representing the ground water level movements and its nitrate concentration as an input variable of the model and to simulate its effect on soil water and nitrogen content in the rooting zone, such as denitrification and dilution/concentration impacts on the nitrate concentration of soil solution.

4. Conclusions

This work has shown that even if the absolute values of nitrate concentration in solution and water and nitrate transfer were not perfectly simulated using the STICS soil–crop model, as during the potato experiment, the trends and range of variations were correctly simulated in particular for the sugar beet experiment. Moreover, the order of magnitude of the yield was correct in the case of crop without pests and diseases. Globally satisfactory results were obtained for soil water and nitrogen simulations which allowed the model to be used to analyse and better understand the impacts of climate, N-fertilization, irrigation, crop type, and nitrate concentration in irrigated water on drainage, nitrate leaching, and nitrate concentration in drainage water.

The simulations confirmed that drainage is controlled by rainfall but also by excess of irrigation, which must be avoided by strictly adjusting the water volume applied to crop requirements. In addition to excess irrigation, another important factor is the crop type. For the two crops examined here, sugar beet had a higher nitrogen uptake capacity, and a longer growing season than potato, which explained a significant part of the difference in nitrate concentration of drainage water between the two studies. N-fertilization rate also influenced the nitrate concentration in drainage water but mainly when N-fertilizer use is excessive or untimely. Thus, omission of autumn N-fertilization and a decrease in N-fertilizer rate after taking into account the nitrate concentration of irrigation water is highly recommended. Furthermore, the management of the fallow period between two main crops often plays a decisive role in the management of nitrogen pollution (Machet et al., 1996; Beaudoin et al., 2005). The use of nitrogen catch crop or cover crop during this period could be an efficient solution to reduce nitrogen leaching particularly when potato is cropped in the rotation.

STICS model simulations complemented the results obtained with the field studies. A great advantage of using a soil–crop model is that it allows the impact of various cropping sequences to be better understood, and quantified, independently of the occurring climate. A key point is that all the processes are taken into account in the water and nitrogen dynamic balance, including the estimated quantities taken up by the plant, the mineralization of soil organic matter and coming from the crop residues, and the nitrate transfer into the soil and under the rooting depth, corresponding to nitrate leaching.

In a subsequent step, the model could be used to carry out larger virtual experiments. The choice of agro-environmental criteria and the use of longer climatic series and different crop rotations could allow crop systems adapted to the risk of N leaching in this watershed to be identified. In such studies, it will be possible i) to simulate the effect of nitrogen catch crop, ii) to fertilize as rationally as possible since the model integrates all nitrogen sources, and iii) to better understand temporal changes in nitrate concentrations in ground water from the beginning of the 1990s to the present.

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