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# Simulating the long term impact of nitrate mitigation scenarios in a pilot study basin

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A B S T R A C T

The agro-hydrological model TNT2 was used to explore for a period of 14 years (1987–2001) the likely consequences of mitigation scenarios on nitrate contamination of the stream water in a small agricultural catchment. The Best Management Practices (BMPs) historically designed and implemented in 1992 and two devised agricultural scenarios (catch crop (CC) implementation and a global reduction of N fertilizer) are evaluated in term of nitrate contamination in the environment. Two of the BMPs consist in implementing natural strips of Poplar and rye-grass strips (5 meters large) along stream and ditches and the third is a delay in the burial of wheat straws (from August to October). Simulations indicated that natural strips implementation would lead to a slight decrease of Nitrate Fluxes (NF) in river by respectively 3.3% and 6.6% for rye-grass and poplar strips: a benefit associated to the non fertilization of strips area. Denitrification has not been particularly disrupted in such areas. The delay in the burial of wheat straw in autumn decreases annual mineralization rate and annual plant uptake (by respectively 9 and 13 kg N $ha^{-1}$ $y^{-1}$) but increases denitrification fluxes by 6 kg N $ha^{-1}$ $y^{-1}$. This would lead to a slight decrease by 6% of NF in stream (equivalent to 3.3 mg $NO_3^-$ $l^{-1}$) and an average decrease of the following sunflower yield by 27%. The global reduction of fertilization by 10% would decreased NF in stream by 13.8% (equivalent to 8 mg $NO_3^-$ $l^{-1}$), with a global decrease by 8 kg N $ha^{-1}$ $y^{-1}$ of plant uptake. The cumulative effect of BMPs and CC would have together lead to a decrease of nitrate concentration from 57.5 to 46.6 mg $NO_3^-$ $l^{-1}$ reaching the UE environmental quality objectives (below 50 mg $NO_3^-$ $l^{-1}$). Spring crops yield following CC would have been penalized and the decrease of NF is balanced by an increase of denitrification fluxes in the environment contributing to release of $N_2O$, a greenhouse gas, into the atmosphere.

## 1. Introduction

High nitrate concentrations in surface and ground water reservoirs are an issue for drinking water quality and the eutrophication of surface and coastal waters. High levels are mostly found in Europe and USA and are related to agricultural activities, especially to intensive farm management practices (De Wit et al., 2002). Environmental regulations have been implemented to mitigate agricultural nitrate pollution. This is the first step toward a wider control of agricultural pressure on water quality. In recognition of the importance of water quality and its associated problems, the European Water Framework Directive (WFD) was adopted in 2000, as a global objective for each European country to restore the 'good ecological status' of all water bodies by 2015. To achieve this global objective, different mitigation options have been proposed and are being evaluated (e.g. cost and benefits): the investment associated to the implementation of Best Management Practices (BMPs) has to be evaluated in terms of quantitative benefits of water quality, in order to promote future planning and adjust resource allocation to the most efficient changes. Beforehand to these cost benefit analysis, long term water quality monitoring and intensive observations are essential for assessing the effects of BMPs in a catchment (Park et al., 1994), but water quality

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models can help to select the best alternatives for a given context.

Several water quality models have been developed and these provide valuable support for the quantitative assessment of the efficiency of new agricultural practices which aim to improve water quality (Arheimer and Brandt, 1998; Arnold et al., 1998; Beaujouan et al., 2002; Bicknell et al., 1997; Christiaens and Feyen, 1997; Cooper et al., 1994; Krysanova et al., 1998; Liu et al., 2005; Lunn et al., 1996; Refsgaard et al., 1999; Reiche, 1994; Styczen and Storm, 1993; Whitehead et al., 1998). Numerous studies have proven that the process-based models are able to reproduce the major hydrological, biogeochemical and biological processes at the catchment scale (Arnold and Allen, 1996; Bouraoui and Grizzetti, 2008; Chaplot et al., 2004; Krysanova et al., 2005; Kyllmar et al., 2005). More specifically, agro-hydrological models are used to test land-use change and the impact of agricultural practices on stream water quality. In this perspective, Zammit et al. (2005) have developed the LASCAM model to test land use changes and optimal management practices effect in term of nitrate leaching and sediment export limitation. They have provided a range of land use change scenarios effects on the eutrophication of stream and rivers in large catchment areas. Hesse et al. (2008); Volk et al. (2009) also quantified the effectiveness of measures identified by decision makers to decrease both nitrate and phosphorus pollution in a large river in Germany.

The present study is based on a previous modeling work presented in Ferrant et al. (2011), focusing on the hydrological and nitrogen transfer modeling in a small agricultural catchment in south-west of France. The agro-hydrological model Topography Nitrogen Transfer and Transformation TNT2 (Beaujouan et al., 2002) and Soil Water Assessment Tool SWAT (Arnold et al., 1998) were used to simulate nitrate fluxes in the stream using the same agricultural dataset. These two models were chosen for being similar: a coupling approach between an agronomical model and a hydrological model with a focus on N processes rather than on the hydrology. Both take into account agricultural practices and land use to simulate water and nitrogen cycle at the catchment scale. The aim of this previous work was to simulate the daily stream nitrate fluxes that have been monitored accurately since 1985 in the Auradé study catchment (Ferrant et al., 2012) using climatic variable (rainfall, potential evapotranspiration and temperature), cropping pattern and fertilization practices at the plot scale (recorded by the local farmer association). The semi-distributed (SWAT) and fully distributed (TNT2) spatial approach of both models were appropriate for this small catchment where detailed agricultural informations were available. The agricultural data base was filled since 1985 to monitor agricultural practice modifications that farmer association has historically promoted to decrease the nitrate contamination. The land use changes that have occurred in 1992 consist in poplar and rye grass strips implementation along the stream and ditches network whereas practice change designed at this time was a delay in the burial of wheat straw from August to October, designed to limit the mineralization of buried straw during the hot period following the wheat harvest. Potential effects on nitrate contamination have never been evaluated yet.

We have considered the fully distributed modeling approach of TNT2 more appropriate to simulate the interaction of the water moving from the slope to the stream, crossing the natural strips implemented along the drainage network. Furthermore, Ferrant et al. (2011) consider TNT2 more appropriate to describe the nitrogen processes involved in the nitrate leaching. Mineralization process is better described on a daily base than SWAT which is essential for simulating the impact of a delay in the burial of straw. The present study intends to estimate the efficiency of each BMP in term of nitrogen fluxes in environment and nutrient use efficiency (NUE). The cumulative effect of BMPs implemented is estimated as well. Furthermore, two devised agricultural scenarios have been built based on the historical agricultural data base (for which the BMPs are implemented in 1992). Both scenarios correspond to other possible mitigation measure that could have been set up in addition to the existing BMPs: a systematic Catch Crop (CC) implementation after the winter wheat harvest (August) and before the sowing of sunflower (April) and a global fertilization reduction by 10%.

## 2. Material and methods

### 2.1. Study area

The Montoussé catchment at Auradé (Gers, France, 43°33′32″ N; 1°3′51″ E) is an experimental research site that was studied in collaboration with the fertilizer manufacturer GPN-TOTAL. Nitrate concentration measurements have been initiated in 1985 by AZF Toulouse (now GPN) to assess the impact of agricultural practices and landscape management on nitrate concentrations in streams. The Montoussé stream was selected for intensive survey because of its fast hydrological response and intensive agricultural context (Ferrant et al., 2012). It is a tributary of the Save River, which is itself a left tributary of the Garonne River, located in Gascony, an intensively cultivated region in south-west France (Fig. 1). The catchment is small, hilly and 88.5% of the surface is used for agriculture. The substratum consists in impervious Miocene molasses deposits. Only a shallow aquifer is present, since the substratum is rather impermeable (clays) except some sand lenses that supply springs. A soil mapping of the catchment area was carried out in 2006 by Sol-Conseil and EcoLab. Twelve soil types were identified in the catchment area. Two of them are located in the lower part of the catchment and are deeper (2 m) than soil in the middle slope (1 m depth). The deepest soil layer is composed by 2.1% of organic matter in the first layer (0–20 cm), and a 1.2% down to 45 cm. The other soils generally contain between 1.5 and 2% of organic matter in the first layer, which decreases with depth to 0.5% at 30 cm. Most of the soils contain 30–42% of clay in the first layers. This content generally increases with depth. The soil characteristics have been used to set most of the soil and aquifer parameters in the model.

The 'Gers' district is under the influence of both the Oceanic and the Mediterranean climate. The rainfall was monitored from 1985 to 2001 with a tipping bucket rain gauge within the catchment. The mean annual rainfall for the study period was 656 mm, with a minimum of 399 mm and a maximum of 844 mm/year. The maximal daily rainfall intensity recorded is 90 mm. Intensive rainfall are often observed during spring or autumn and generate large runoff events. Daily temperature recordings and potential evapotranspiration (PET) values were provided by Meteo France and were recorded at a station situated 50 km from the catchment area. The average temperature is 14.5 °C, with minimum around 0–1 °C in winter and maximum about 29–30 °C in summer.

The discharge was measured continuously by DIREN (Direction Régionale de l'Environnement). The annual water yield varied during the study period from 5.7 to 33% of the annual rainfall for respectively dry and humid year. Overland flow and subsurface flow are dominant because of the steep slopes (average slope is around 9% with a maximum of about 30%)and the low number of natural obstacles (even highest hill slope are cultivated).

Nitrate concentrations were monitored from 1985 to 2004 at the catchment outlet. The frequency of sampling for nitrate concentration measurement was controlled by the volume of water discharged, using an ISCO 3700 Portable Sampler. Out of the total 5814 days of the study period, 2834 days have been tested with a minimum of one sample per day for nitrate concentration. A more

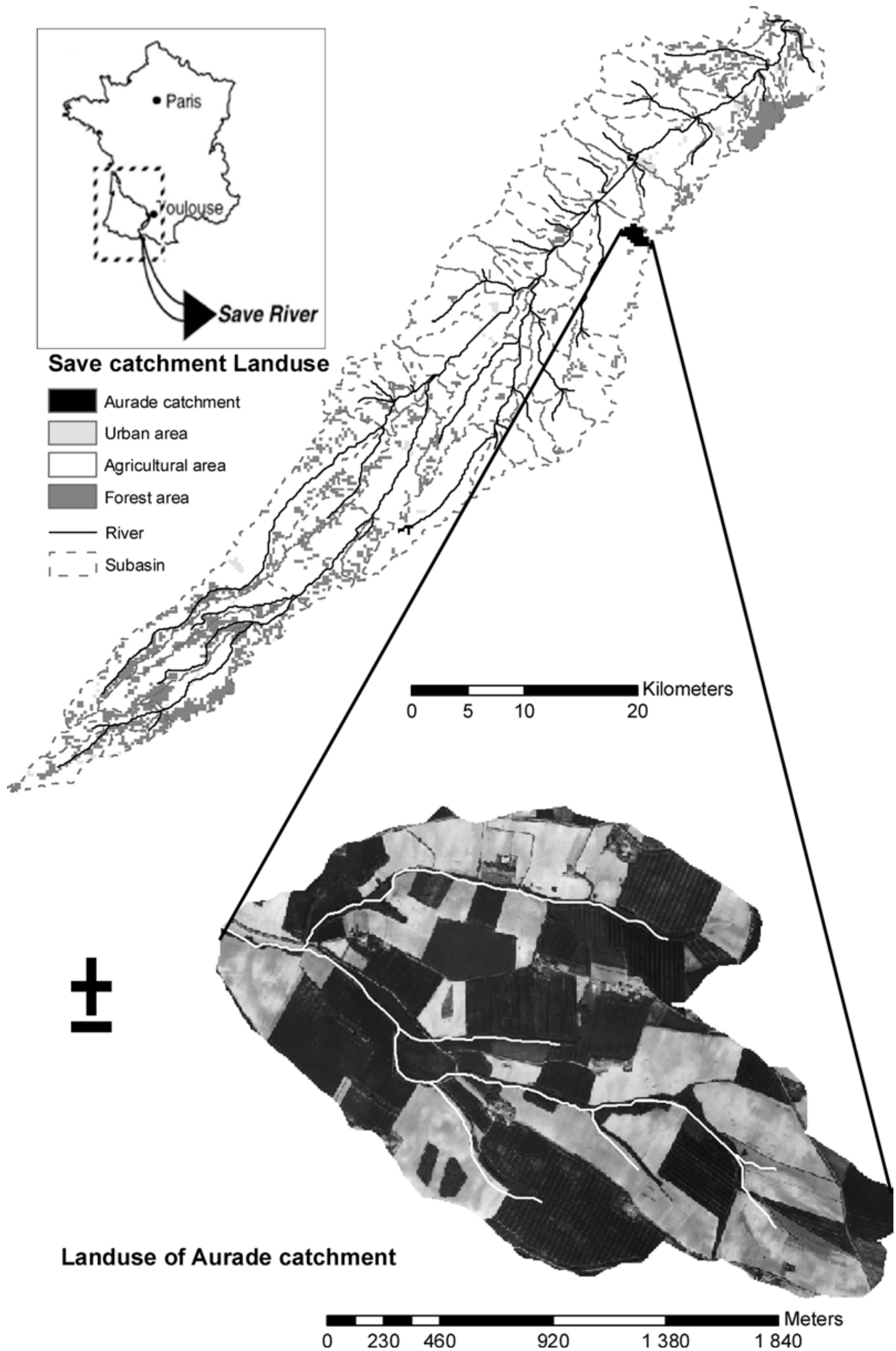


**Fig. 1.** Study site location within the Save river basin. The stream network and agricultural plot of the study site of Auradé are delineated (aerial photo, cartoexplorer; IGN).

recent monitoring program has been set up to monitor continuously nitrate concentration in the stream. Ferrant et al. (2012) have shown that 20% of stream nitrate fluxes transfer during major flood events (short period from few hours to few days). The soil lateral flow partly drains the nitrate soil content leading to high concentration peaks in the stream during short period (few hours). They have demonstrated however that errors on bi-annual nitrogen fluxes made by sub-sampling the stream water concentration are small (<10%).

A detailed agricultural data base has been filled up from 1985 to 2001 by the 'Association des Agriculteurs d'Auradé'. Dates of plant sowing, tillage operations, fertilizer application and crop harvest, amount of fertilizer applied are given for each agricultural plot type and each year. The crop rotation was dominated by sunflower and

**Table 1**
Scenarios tested in Auradé catchment using TNT2 model. Scenarios are detailed in terms of absence (-) or presence (X) of each coping measure (column).

| Scenarios | Rye-grass Strips | Delay in the burial of straws | Poplar strips | Catch crop | 10% fertilizer decrease |
|---|---|---|---|---|---|
| Scenario 0 | X | X | X | – | – |
| Historical changes | | | | | |
| Scenario 1 | X | – | X | – | – |
| Scenario 2 | X | – | – | – | – |
| Scenario 3 | – | X | X | – | – |
| Scenario 4 | – | – | X | – | – |
| Scenario 5 | – | – | – | – | – |
| Prospective scenarios | | | | | |
| Scenario 6 | X | X | X | X | – |
| Scenario 7 | X | X | X | – | X |

winter wheat succession. The winter wheat was sown in November, enriched with three mineral fertilizer applications from January to April and harvested in July. The following sunflower was sown in March, fertilized in two times in the beginning of plant growth and harvested in October. A big part of the catchment remained bare ground during 9 months in between the wheat harvest and the sunflower sowing. The average yields for durum wheat, bread wheat and sunflower were, respectively, 5.2, 6.3 and 2.4 t $ha^{-1}$. The average quantity of fertilizer applied was 182, 154 and 30 kg N $ha^{-1}$ $y^{-1}$ respectively for durum wheat, bread wheat and sunflower.

Even if the farming system was simple and homogeneous, this data base is far from complete. Some uncertainties remain, especially regarding the dates of fertilizer applications and the spatial variability of fertilization between plots.

### 2.2. Agricultural scenarios

#### 2.2.1. Best management practices (BMPs)

BMPs have been implemented in 1992. Both poplar and rye grass strips have been located along the drainage network to act as a buffer zone for the contaminant transfer. These areas represent 2.1% of the total catchment and were implemented a long time before being part of the mandatory requirements of the framework directive on water. In addition to that, the wheat straws were buried after harvest following two practices:

- before 1992, it is assumed that straws were buried after the harvest during the hottest period in summer;
- after 1992, it is assumed that straws were buried in October, before the sunflower was sown.

The aim of delaying the burial is to limit the straw mineralization during the bare ground period following the harvest of wheat in summer, in order to limit the nitrate leaching occurring during the first rainfall event in autumn.

The *scenario 0* is a picture of the agricultural conditions observed during the study period (from 1985 to 2001). It has been built using the historical agricultural data base, which includes farmer practices and landuse changes implemented in 1992.

Our aim was to investigate each BMP impact on water and nitrogen fluxes at the catchment scale. To do so, 5 scenarios have been designed from the *scenario 0*:

- *Scenario 1* is built on *scenario 0* with no delay in the burial of the wheat straws after harvest in July.
- *Scenario 2* is built on *scenario 1* without the implementation of poplar strips. The area of poplar strips remain crop after 1992.
- *Scenario 3* is built on *scenario 0* without the implementation of rye-grass strips. The area of rye-grass strips remain as crop after 1992.
- *Scenario 4* is built on *scenario 3* with no delay in the burial of the wheat straws after harvest after 1992.
- *Scenario 5* is built on *scenario 0* without any historical changes. It gave us the global efficiency of all the historical effort made on the study site to decrease nitrate losses at the outlet.

Each scenario is summarized in Table 1.

#### 2.2.2. Two prospective scenarios

The Catch Crops were identified by agronomists to be an efficient coping measure to decrease nitrogen leaching during bare ground period between two crops (Justes et al., 1999). We selected it as a relevant agricultural practice to reduce the bare ground area extent induced by the cropping pattern. This area extent varies from 20 to 48% of the catchment area each year. These annual variations are presented in Fig. 4. The *scenario 6* was built from *scenario 0*, except that a CC (mustard) was sown each time it was possible in between wheat harvest and following sunflower seed. This implementation was supposed to catch a part of soil mineral nitrogen from soil mineralization to prevent the nitrate residuals to leach into the groundwater or being transferred through the lateral flow. The catch crop was then buried and added to the soil organic matter, improving the soil structure.

Another classical coping pattern explored by agronomists was a decrease of fertilizer input to control nitrate losses in environment. This coping measure was not identified as an efficient one in literature, but was chosen in this study as a reference for the other scenario benefits. The efficiency of this measure was high only if crops were over-fertilized. The *scenario 7* consisted in a systematic decrease of crop fertilization by 10% over the simulation period.

Both projected scenarios were virtually implemented in addition to the historical BMPs. The efficiency of each measure was computed using the reference (*scenario 0*):

- *Scenario 6* was built on *scenario 0* with the implementation of a catch crop between the harvest of wheat in July and the sowing of sunflower in the following March, from 1985 to 2001.
- *Scenario 7* was built on *scenario 0* with a decrease by 10% of fertilization for all crops.

### 2.3. TNT2, a distributed agro-hydrological model

The dynamic process-based, fully distributed agro-hydrological model TNT2 was developed on the basis of the hydrological model TOPMODEL (Beven, 1997) and of the crop model STICS (Brisson et al., 2002, 1998). It was specifically designed to simulate soil-groundwater interactions (e.g. the distribution of denitrification and overland flow according to the extension dynamics of the saturated areas) to take into account spatial interactions within the catchment in a shallow aquifer context (for detailed description see Beaujouan et al., 2002; Ferrant et al., 2011; Oehler et al., 2009). The catchment is considered as a set of columns for which the processes of water and nitrogen transfer and transformation are computed. Each column corresponds to one cell of the regular Digital Elevation

Model grid (DEM). The drainage graph is created using the DEM. The soil parameters given for three vertical layers are distributed according to the soil map. The agricultural data are distributed according to the map of agricultural plots. A drainage area threshold is used to localize the stream network: for the cells over this threshold, the outflow is routed directly to the outlet. Each cell derived from the DEM cells is characterized by a soil type, a land use identifier and a hydrological gradient. The agriculture management information required are: sowing (date and crop type), fertilization (date and amount) and harvesting (date and residue management).

The in-stream routing and processes are not simulated; daily discharge at the outlet corresponds to the total water entering the stream cells. The other main modeling hypothesis is that the aquifer flows computation is based on a topographic gradient calculated for each cell. It means that local water table gradient follows the topographic gradient. Both hypotheses are verified in the study site, as it is a small catchment with a shallow aquifer.

### 2.4. Model calibration

This step was fully detailed in Ferrant et al. (2011). The calibration of the hydrology was made by optimization of the daily discharge first (for the period 1985–2001), using both hydrological parameters *To* and *m* that controls the annual water balance: *To* (the lateral transmissivity of the soil column at saturation in $m^2\,day^{-1}$) and *m* (the exponential decay factor of the hydraulic conductivity with depth, in meter). This step was followed by an agronomical calibration on the N cycle in agricultural plot and at the catchment scale. The capillarity rise was activated to sustain evapotranspiration and nitrogen removal from aquifer to soil, in order to sustain plant consumption. Mineralization and denitrification were calibrated based on agronomist's expert estimates to obtain an expected order of magnitude. Nevertheless, these two processes were identified as the main unknown processes which need *in situ* measurements. Simulations were performed at a daily time step for 16 years, from 1985 to 2001; the first 2 years (1985–1987) were used for initialization. Nash-Sutcliffe's efficiency coefficient (Nash and Sutcliffe, 1970) and RMSE were used as optimization criteria for daily discharge and N fluxes.

### 2.5. Evaluation criteria

Three efficiency estimators were computed for the whole simulation period to compare each scenario: the average stream water nitrate concentration (avConc in $mg\,N\text{–}NO_3^-\,l^{-1}$, Eq. (1)), the relative variation of the average annual nitrogen loads in the stream ($\Delta$avLoad in %, Eq. (2)) and the relative variation of average annual denitrification amount in the whole catchment ($\Delta$avDenit in %, Eq. (3)).

$$\mathrm{avConc} = \frac{\mathrm{Load}_{\mathrm{sce}i}}{\mathrm{Disch}_{\mathrm{sce}i}} \times 100 \tag{1}$$

where $\mathrm{Load}_{\mathrm{sce}i}$ and $\mathrm{Disch}_{\mathrm{sce}i}$ are respectively the average of annual nitrogen and water loads in stream, in $kgN\,ha^{-1}\,y^{-1}$ and $mm\,y^{-1}$, for the scenario *i*.

$$\Delta\mathrm{avLoad} = \frac{\mathrm{Load}_{\mathrm{sce}i} - \mathrm{Load}_{\mathrm{sce}0}}{\mathrm{Load}_{\mathrm{sce}0}} \times 100 \tag{2}$$

where $\mathrm{Load}_{\mathrm{sce}i}$ and $\mathrm{Load}_{\mathrm{sce}0}$ are the average of annual nitrogen loads in stream respectively for the scenario *i* and 0, in $kgN\,ha^{-1}\,y^{-1}$.

$$\Delta\mathrm{avDenit} = \frac{Denit_{\mathrm{sce}i} - \mathrm{Denit}_{\mathrm{sce}0}}{\mathrm{Denit}_{\mathrm{sec}\,0}} \times 100 \tag{3}$$

where $\mathrm{Denit}_{\mathrm{sce}i}$ and $\mathrm{Denit}_{\mathrm{sce}0}$ are the average of annual denitrification simulated in the catchment, respectively for the scenario *i* and 0, in $kg\,N\,ha^{-1}\,y^{-1}$.

Furthermore, we used the N use efficiency ratio (NUE) described in numerous studies to evaluate the efficiency of the fertilization operation on a cropping pattern (Shaviv and Mikkelsen, 1993). In this study, the NUE indicator is the ratio between the nitrogen exported (harvest) and nitrogen applied through fertilization, computed at the catchment scale.

## 3. Results and discussion

Table 2 presents the average annual mineral nitrogen budget simulated for the catchment area. The mineral nitrogen input (nitrogen in rainfall, mineralization, and fertilization) and output fluxes (volatilization, N uptake by the plants, denitrification and stream fluxes) are respectively 145.4 $kg\,N\,ha^{-1}\,y^{-1}$ and 145.2 $kg\,N\,ha^{-1}\,y^{-1}$. The total nitrogen output fluxes from the catchment takes only into account the exportation of yield (which is a part of N uptake by crops). This total exportation of N (organic and mineral) corresponds to 113.7 $kg\,N\,ha^{-1}\,y^{-1}$. 31.7 $kg\,N\,ha^{-1}\,y^{-1}$ of nitrogen is estimated to be stored into the soil organic matter (soil mining by the burial of straw) during the simulation period with the historical agricultural practices.

### 3.1. Delay in the burial of straw

Differences between *Scenario 0* and *Scenario 1* are explained by the impact of this BMP if it would have not been implemented in 1992. The global impact of this BMP is a slight decrease of mineralization rate (input) and a slight increase of denitrification rate (output). The plant uptake is decreasing by 13 $kg\,N\,ha^{-1}\,y^{-1}$, leading to a decrease of NUE and a loss of yield (21% for the sunflower, 2–3% for the winter wheat). The soil mining decreases by 3.2 $kg\,N\,ha^{-1}\,y^{-1}$ whereas the stream fluxes decrease by 6%, corresponding to a decrease of avConc (the average nitrate concentration) by 3.3 $mg\,NO_3^-\,l^{-1}$.

The decrease of the mineralization associated to this BMP has a small impact on stream water quality, but mainly affect the spring crop yields (sunflower).

### 3.2. Natural strips

The land use change operated in 1992 are located in some specific bottom part of the hill slopes (see Fig. 2), and concerns around 2.3% of the total catchment. The agronomical justifications of this kind of BMP were that these filter strips are supposed to slow down the water which floods from the upper slopes. Nitrate could be removed by the plant cover or by denitrification if saturated conditions are simulated. TNT2 is dedicated to the simulation of saturated zone, so is able to simulate the groundwater soil interactions that control denitrification processes in these specific areas.

The implementation of poplar strips leads to:

- a decrease of denitrification (10.9 $kg\,N\,ha^{-1}\,y^{-1}$);
- a decrease of mineralization (14.9 $kg\,N\,ha^{-1}\,y^{-1}$);
- a decrease of plant uptake (10 $kg\,N\,ha^{-1}\,y^{-1}$), expressed per ha of poplar strips.

The implementation of rye-grass area leads to:

- a decrease of denitrification (18.3 $kg\,N\,ha^{-1}\,y^{-1}$);
- an increase of mineralization (8.4 $kg\,N\,ha^{-1}\,y^{-1}$);
- a decrease of plant uptake (30 $kg\,N\,ha^{-1}\,y^{-1}$), expressed per ha of rye-grass strips.

The poplar strips (1% of the catchment surface) and the rye-grass strips (1.3% of the catchment surface) are not fertilized,

**Table 2**
Annual water and nitrogen budget for each scenario, computed from October 1993 to September 2001. *Scenario 0* is the historical agricultural scenario, with 3 BMPs implemented in 1992, *Scenario 1* without the delay of the burial of straw, *Scenario 2* without both delay of the burial of straw and poplar strips, *Scenario 3* without Rye-grass strips, *Scenario 4* without both delay of the burial of straw and Rye-grass strips, *Scenario 5* without 3 BMPs.

| scenario | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| water budget mm.y$^{-1}$ | | | | | | |
| Rainfall | 690 | 690 | 690 | 690 | 690 | 690 |
| Actual ET | 598 | 599 | 597 | 596 | 597 | 595 |
| Discharge | 114 | 113 | 115 | 116 | 115 | 117 |
| Δstock aquifer/soil | −13/−8 | −12/−9 | −13/−8 | −13/−8 | −13/−8 | −13/−8 |
| Mineral nitrogen budget kg N ha$^{-1}$ y$^{-1}$ | | | | | | |
| N in rainfall | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 |
| Mineral fertilizer | 86.9 | 86.9 | 88.0 | 88.3 | 88.3 | 89.4 |
| Fertilizer volatilization | 1.74 | 1.74 | 1.76 | 1.76 | 1.76 | 1.78 |
| Mineralization | 51.3 | 59.93 | 60.08 | 51.19 | 59.98 | 60.13 |
| Plant uptake | 106.8 | 120 | 120 | 107.5 | 121 | 121 |
| Denitrification | 23.6 | 17.6 | 17.7 | 23.84 | 17.8 | 17.9 |
| Stream losses | 13.05 | 13.85 | 14.7 | 13.52 | 14.4 | 15.26 |
| Δstock N in the basin | +0.21 | +0.84 | +1.12 | +0.07 | +0.52 | +0.79 |
| N losses | 36.65 | 31.45 | 32.4 | 37.32 | 32.2 | 33.16 |
| Quality indicator | | | | | | |
| avConc mg N l$^{-1}$ | 11.45 | 12.2 | 12.7 | 11.7 | 12.5 | 13.01 |
| ΔavLoad % | X | +6.13 | +12.6 | +3.6 | +10.3 | +16.9 |
| ΔavDenit % | X | −25.4 | −25 | +0.8 | −24.5 | −24.1 |
| Average yield t ha$^{-1}$ | | | | | | |
| Durum winter wheat | 7.5 | 7.74 | 7.74 | 7.5 | 7.74 | 7.74 |
| Bread wheat | 7.76 | 7.93 | 7.92 | 7.76 | 7.93 | 7.92 |
| Sunflower | 1.67 | 2.12 | 2.12 | 1.67 | 2.12 | 2.12 |
| Nitrogen use efficiency (N in yield)/(N in fertilizer) | | | | | | |
| NUE (mean for 1992 to 2001) | 0.88 | 0.96 | 0.96 | 0.86 | 0.96 | 0.96 |

which corresponds to an overall N input decrease of, respectively, 1.1 kg N ha$^{-1}$ y$^{-1}$ (109 kg N ha$^{-1}$ y$^{-1}$ for each hectare of poplar strips) and to 1.4 kg N ha$^{-1}$ y$^{-1}$ (106 kg N ha$^{-1}$ y$^{-1}$ for each hectare of rye-grass strips). A higher increase of mineralization is simulated for rye-grass strips than poplar strips areas, because more organic matter are restituted into the soil during the annual reaping operation of rye-grass strips. The poplar nitrogen uptake is higher than for rye-grass and a part of the organic matter is stored in the wood, less organic matter is restituted to the soil.

Fig. 3 (b) and (c) illustrates the impact of the strips' implementation on the saturated zone for respectively the rye-grass and the poplar. The reduction of the period during which saturated conditions are simulated is the consequence of the higher

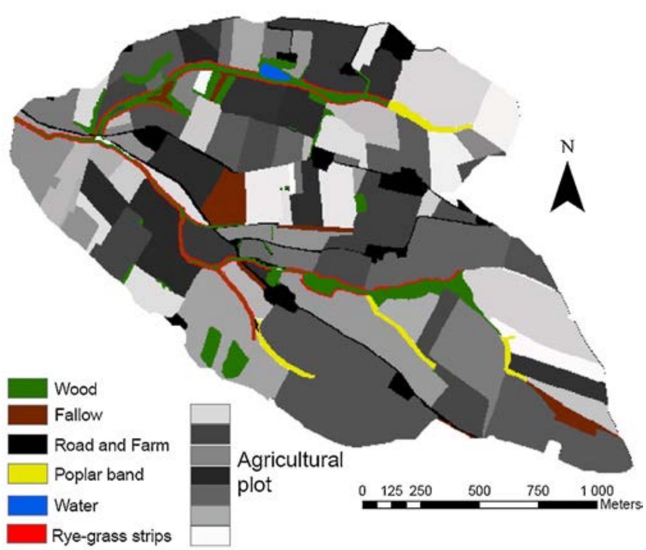


**Fig. 2.** Raster map of agricultural plot of Auradé catchment: Poplar and Rye-grass strips have been implemented on agricultural land in 1992 (source: Association des agriculteurs d'Auradé). 90% of the Utilized Agricultural Land is a winter-wheat/sunflower cropping pattern.

evapotranspiration of a polar or rye-grass cover compared to an agricultural crop. The area extent impacted by this reduction is small compared to the maximal saturated zone extent and is located in the downstream neighborhood of the rye-grass strip (see Fig. 3 (b)). The 5 meter wide rye-grass strips can impact a larger zone and lead to a decrease by between 1 and 8 days of the period of saturated conditions.

The area impacted by the poplar strips is located exclusively within the poplar zone and has no influence on downstream area (see Fig. 3(c)). The reduction of saturated condition period length is larger (from 17 days to more than 1 month) but some parts of the poplar strips are not impacted. This reduction comes with a decrease of denitrification rates, as denitrification is disabled in absence of saturated conditions. The result of this study shows a non intuitive result: the implementation of natural buffer strips along the stream network decreases denitrification. For instance, Oehler et al. (2009) have estimated that 92.6 kg N ha$^{-1}$ y$^{-1}$ of denitrification occur within riparian areas in bottom slope, along the stream and 34.5 kg N ha$^{-1}$ y$^{-1}$ in the hill slope in a much more contaminated agricultural catchment in Brittany (West of France). Denitrification rates in our study site are estimated to be much less, as the contamination is less important, the climate is drier and the saturated area extent is more limited. Other studies have tested the impact of filter strips on water quality: Hesse et al. (2008) used SWAT at the scale of Rhin catchment (Germany) to test the conversion of agricultural land use close to streams and lakes into non-fertilized grassland. The change at this large catchment scale would decrease nitrogen losses in streams by 3.1%. As SWAT is semi-distributed, the reduction simulated in this previous study is not linked to the position of the land use in the sub-catchment. This result is similar to the 3.6% decrease estimated in the present study for the implementation of rye-grass strips along the stream. Volk et al. (2009) assessed the impact of drastic land use change on a 3740 km$^2$ catchment in West-Germany. They tested the effects of an increase by 10% of the forested area; they estimated a decrease by 2.7% of the nitrate concentration in streams. We estimated that the poplar strips (1% of the catchment area) led to a decrease by 4% of the nitrate concentration in

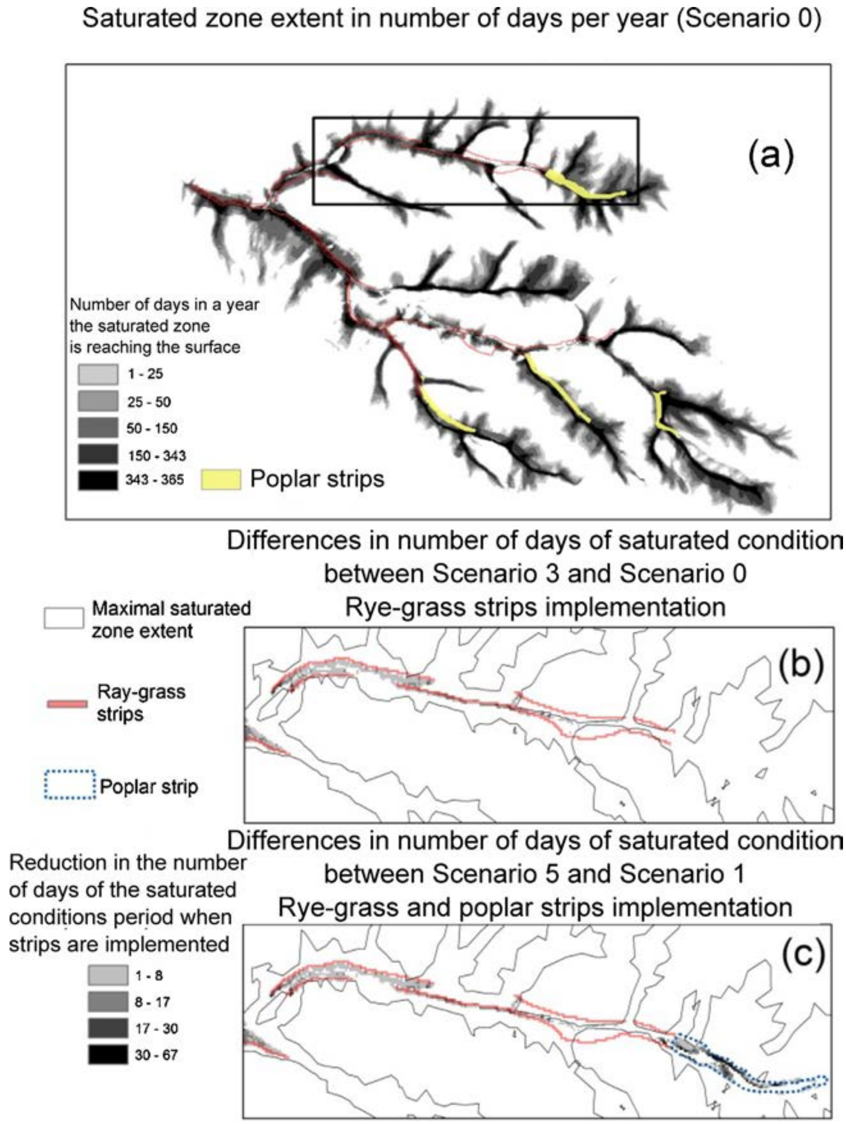


**Fig. 3.** Saturated area extent simulated with TNT2 for the *Scenario 0* (a) expressed in days per year. Reduction of the saturated period length after the ray grass strips implementation (b) and poplar strips implementation (c) in number of days. The maximal saturated zone extent is located within both black lines to illustrate the spatial impact of strips.

the Auradé stream. Strips location increases the implementation effect.

### 3.3. Cumulative benefits of BMPs

The comparison between *Scenario 5* and *Scenario 0* gives the estimate of the cumulative effect of each BMPs after 1992. This cumulative effect appears to be an addition of the benefit of each BMP in terms of stream loss decrease (Fig. 5), which corresponds to a decrease of 16.9% of nitrogen fluxes in stream. This benefit for the environment has to be balanced by the increase of denitrification fluxes by 24.1%, mainly explained by the effect of the delay in the burial of straws on this flux. This benefit could be balanced as well by the yield loss associated to this delay, abatement estimated around 0.2 and 0.4 $t\,ha^{-1}\,y^{-1}$ for respectively winter crops and spring crops.

### 3.4. Prospective Scenarios impacts

Table 3 presents annual fluxes computed for the whole simulation period (from 1987 to 2001) for *Scenario 6* (CC) and *7* (a decrease in the fertilization). Both scenarios are built on *Scenario 0*. CC implementation increases by 8 mm the average annual evapotranspiration. This increase is associated to the additional catch crop transpiration during the growth period (from 25 August to 31 November) and varies from year to year with the surface area extent of catch crop. The fertilizer reduction scenario (*Scenario 7*) does not impact the water budget.

The increase of harvested biomass and nitrogen uptake associated to the CC implementation represents 3 $kg\,N\,ha^{-1}\,y^{-1}$. The increase of the biomass buried after the CC leads to increase mineralization rates by 2 $kg\,N\,ha^{-1}\,y^{-1}$. Fig. 6 illustrates the main impact of CC on the soil processes. The simulated daily net mineralization is plotted as a function of the time for both *Scenarios 0* and *6*. Negative net mineralization phase (called immobilization) occur when the soil organic matter C/N ratio is high, just after the burial of straw. The decomposers bacteria experience a deficit of nitrogen in the soil organic matter that forces them to use the available mineral nitrogen, leading to a negative net mineralization. After few days of immobilization period, the decomposers bacteria produce more nitrates by mineralization than their own needs: the net mineralization becomes positive. Both phases experience more

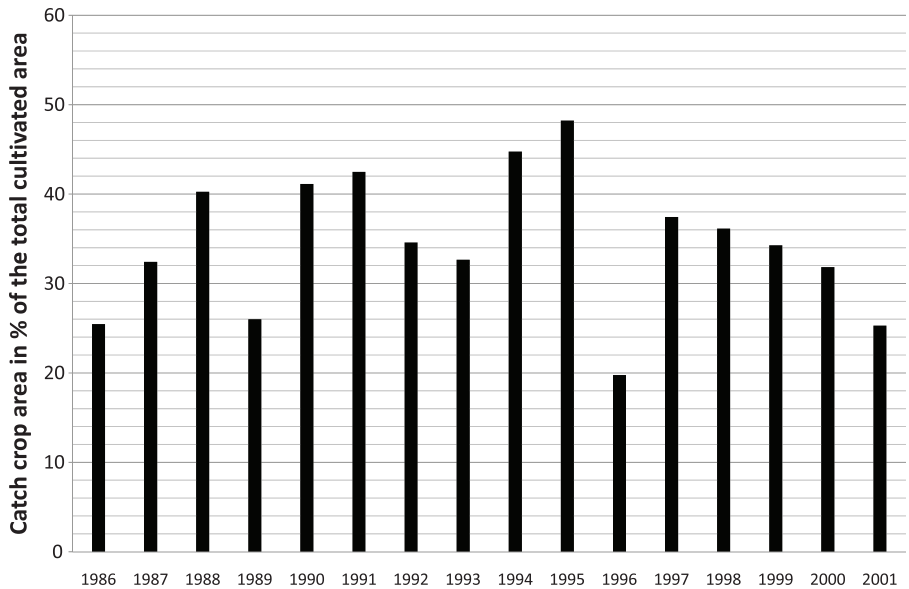


**Fig. 4.** Catch crop implementation area extent (*Scenario 6*) as a percentage of the total cultivated area. Catch crops are virtually sown in between winter wheat harvest and sunflower sown each time it is possible, to cover the bare ground areas during 9 months of intercrop.

intense fluxes when a catch crop is introduced into the crop succession. High mineralization rates during the crop growth are followed by high immobilization rates after burying a part of the crop. The balance between positive and negative net mineralization leads to a weak increase of annual mineralization. This gain benefits the wheat yield with a gain of yield of around 1.2%. The negative net mineralization which occurs after the burying of the CC residues limits the sunflower growth and the yield by 14% (from 2.01 to 1.71 t $ha^{-1}$ $y^{-1}$).

A systematic CC implementation in the cropping pattern would have decreased by 18.1% the annual nitrogen stream fluxes, corresponding to a decrease by 6.2 mg $NO_3^-$ $l^{-1}$ of the nitrate concentrations in the stream, reaching so the environmental quality objective (below 50 mg $NO_3^-$ $l^{-1}$). This effect is in accordance with previous conclusions. The effect of catch crop at the plot scale is described by Justes et al. (1999). Based on high frequency sampling of soil water, soil mineral N, dry matter and N uptake by cover crops, they quantified the impact of an autumnal radish crop cover compared to a bare soil. They demonstrated that catch crop implementation during the autumn period reduces by half the nitrate concentration in the water percolation, without a significant difference in simulated actual evapotranspiration. This result confirms

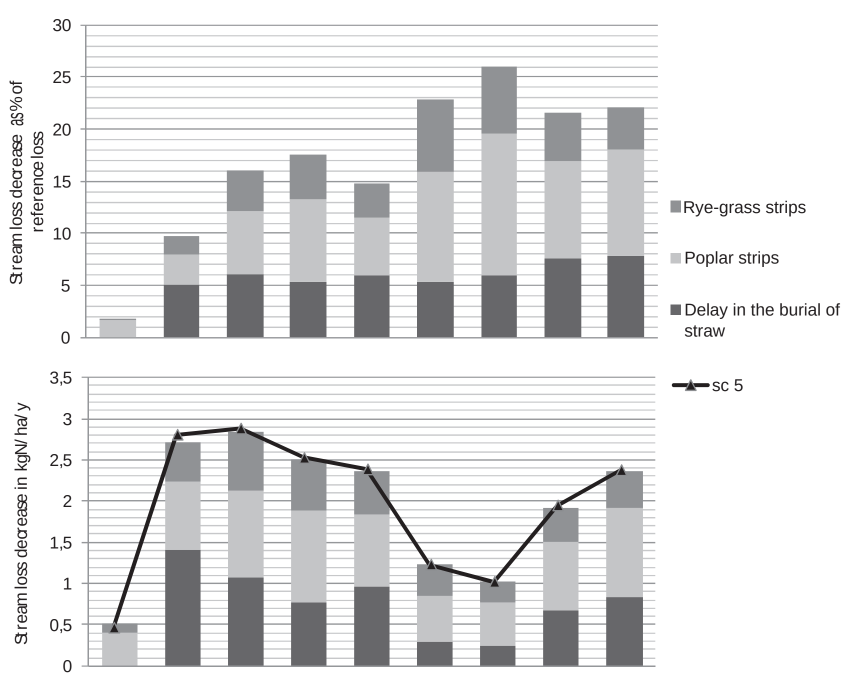


**Fig. 5.** Annual nitrogen stream flux decreases associated to each BMP implementation in % of the reference flux simulated for the *Scenario 0* (figure up) and expressed in kg N $ha^{-1}$ $y^{-1}$ (figure down). Annual nitrogen flux reductions associated with the implementation of the 3 BMPs together (*Scenario* 5 minus *Scenario 0*) are in solid black line.

**Table 3**
Annual water and nitrogen budget for each scenario, computed from October 1987 to September 2001. *Scenario 0* is the historical agricultural scenario, with 3 BMPs (delay in the burial of straw, poplar strips and ray-grass strips implementation) implemented in 1992, *Scenario 6* is built on *Scenario 0* with a systematic catch crop implementation during intercrop, *Scenario 7* is built on *scenario 0* with a decrease by 10% of fertilization.

| scenario | 0 | 6 | 7 |
|---|---|---|---|
| water budget mm y−1 | | | |
| Rainfall | 676 | 676 | 676 |
| Actual ET | 566 | 574 | 566 |
| Discharge | 110 | 102 | 110 |
| Δstock aquifer/soil | 0 | 0 | 0 |
| Mineral Nitrogen budget kg N ha$^{-1}$ y$^{-1}$ | | | |
| N in Rainfall | 7 | 7 | 7 |
| Mineral fertilizer | 96 | 96 | 86.8 |
| Fertilizer volatilization | 2 | 2 | 1.6 |
| Mineralization | 67 | 69 | 66 |
| Plant Uptake | 127 | 130 | 119 |
| Denitrification | 26 | 27 | 26 |
| Stream losses | 13.15 | 10.77 | 11.33 |
| Δstock N in the basin | +1.5 | +2.23 | +1.8 |
| N losses | 39.15 | 37.77 | 37.33 |
| Quality indicator | | | |
| avConc mg N l$^{-1}$ | 11.95 | 10.54 | 11.33 |
| ΔavLoad % | X | −18 | −13.8 |
| ΔavDenit % | X | +3.8 | 0 |
| Average yield t ha$^{-1}$ | | | |
| Durum winter wheat | 6.74 | 6.77 | 6.48 |
| Bread wheat | 7.85 | 7.94 | 7.5 |
| Sunflower | 2.01 | 1.71 | 1.93 |
| Cover crop biomass | X | 2.36 | X |
| Nitrogen use efficiency (N in yield)/(N in fertilizer) | | | |
| NUE (mean for 1992 to 2001) | 0.84 | 0.80 | 0.86 |

the low increase of evapotranspiration in the catch crop scenario. Lacroix et al. (2005) estimated nitrogen fluxes in the drained water using the agronomical model STICS at the agricultural plot scale in intensive regions in the north-east of France. They estimated an average decrease of nitrate concentration in percolation water from 32 to 22 mg $NO_3^-$ l$^{-1}$. Both studies estimated a high drop of water percolation concentration under catch crops. The present study estimated the propagation of this drop to the stream water. The decrease of 6.2 mg $NO_3^-$ l$^{-1}$ simulated in the stream water is much lower than in the drained water under crops. Indeed, the water percolated from catch crop areas is mixing with the water coming from the other parts of the catchment; the effect is diluted at the catchment scale. But the drop in the concentration remains small because the fertilization has already been limited to a quasi optimal value (NUE around 88% for the period 1993–2001 for *scenario 0*).

The reduction of fertilization by 10% (*scenario 7*) decreases basically the plant nitrogen uptake and yield (3.8 and 4.4%). The first consequence is a limitation of the buried biomass after the harvest, leading to a decrease of the mineralization from the soil organic matter. The weak change of NUE and the high loss in term of yield both indicate that fertilization has been already optimized for the crop needs in the farmer practices. Several coping measures have been indeed set up by the farmer association to decrease the fertilizer input depending on the previous biomass production and previous buried straws amount.

The small benefit of this kind of coping measures is already documented. Weaver et al. (1996) have shown that a systematic decrease of 10% of fertilizer input used in an agricultural zone in Pennsylvania has no significant impact on nitrate pollution. Another study reported by Pan and Hodge (1994) estimated that a drop by 81% of fertilizer application would be necessary to reach environmental quality objectives. These changes in agricultural practices are not realistic in terms of economic sustainability. Another study in Mississippi catchment (Ribaudo et al., 2001) estimated that a decrease of 50% of the amount of fertilizer would be more costly than the rehabilitation of wetlands, which are identified as a sink of nitrate for the river system by denitrification. This measure has never been set up due to the high cost. Results from *Scenario 7* are coherent with these large scale studies. Furthermore, the low efficiency of this scenario suggests that the historical amounts of fertilizer correspond to an optimal fertilization level. Compared to this effect, the CC effect is much more important, because it catches 3 kg N ha$^{-1}$ y$^{-1}$ in the plant cover for a decrease throughout the river about the same magnitude, against a decrease around 10 kg N ha$^{-1}$ y$^{-1}$ of fertilizer for a decrease about 2 kg N ha$^{-1}$ y$^{-1}$ only. This scenario gives a reference to evaluate the impact of the other coping measures evaluated in this study in terms of nitrate contamination.

### 3.5. *Temporal evolution of effects*

The annual nitrogen stream losses decrease associated to each BMP are plotted in Fig. 5. The abatement associated to the natural strips implementation is highly variable (from 1.5 to 8%) during the simulation period. Its amplitude is inversely proportional to the annual nitrogen stream fluxes. A more stable abatement is estimated for the delay of the burial of straw (from 5 to 8%). Both annual nitrogen stream losses decrease associated to the *Scenario 6* and *7* are plotted in Fig. 7. The relative decrease associated to the CC is positively proportional to the annual stream loss, whereas the relative efficiency of the *Scenario 7* increases from 3% to 6% between 1988 and 1998 and remains stable around 6% from 1998 to 2001 (Fig. 7 up). Both annual decreases are compared to the annual cumulated decrease associated to the BMPs (black line in Fig. 7 down). The CC implementation associated to the historical BMPs (*Scenario 0*–*Scenario 6*) have the same magnitude of stream loss decrease as the decrease associated to BMPs only (*Scenario 5*–*Scenario 0*). Both decreases are added in *scenario 6*, the decrease computed for the CC is realistic to the study site situation but underestimates certainly the potential reduction effect of the CC in a more polluted context. The cumulative effect of both BMPs and CC is a drop from 59.5 (*Scenario 5*) to 46.5 mg $NO_3^-$ l$^{-1}$ (*Scenario 6*) of the stream water concentration.

Fig. 8 shows the annual stream nitrogen fluxes simulated for the reference scenario and for the CC implementation scenario. The annual decrease associated to the CC implementation is then plotted as a function of the annual flux reference (Fig. 8, down). Abatement increases with the annual nitrogen stream losses. We have verified that the reduction is not function of the CC area extent presented in Fig. 4. The relationship between loss decrease and annual losses is not linear; CC implementation effect levels off for very high stream fluxes (around 3.5 kg N ha$^{-1}$ y$^{-1}$). In this case, the maximal CC nitrogen uptake simulated for the simulation period is around 11 kg N ha$^{-1}$ which is far from the maximal uptake of a CC estimated around 60 kg N ha$^{-1}$ (Justes et al., 1999). This limitation of CC uptake could be explained by the small excess of nitrate in soil. The limitation of the stream losses decrease for the highest stream losses (humid years) shed some light on the difficulties for CC to prevent nitrate leaching.

Denitrification is known to be highly variable over time and space at the agricultural catchment scale (Oehler et al., 2009), and no spatial measurement was carried out on the study site until now. Furthermore, no generic model has been developed to date for this process (Oehler et al., 2010). The amount of denitrification was, however, estimated using a non-generic model NEMIS (Hénault and Germon, 2000) and is found to be non-negligible (from 17 to 27 kg N ha$^{-1}$ y$^{-1}$) compared to the nitrogen stream losses (around 13 kg N ha$^{-1}$ y$^{-1}$) or the soil mining simulated (around 30 kg N ha$^{-1}$ y$^{-1}$). We identify this process as the main source of uncertainty of the virtual experiment.

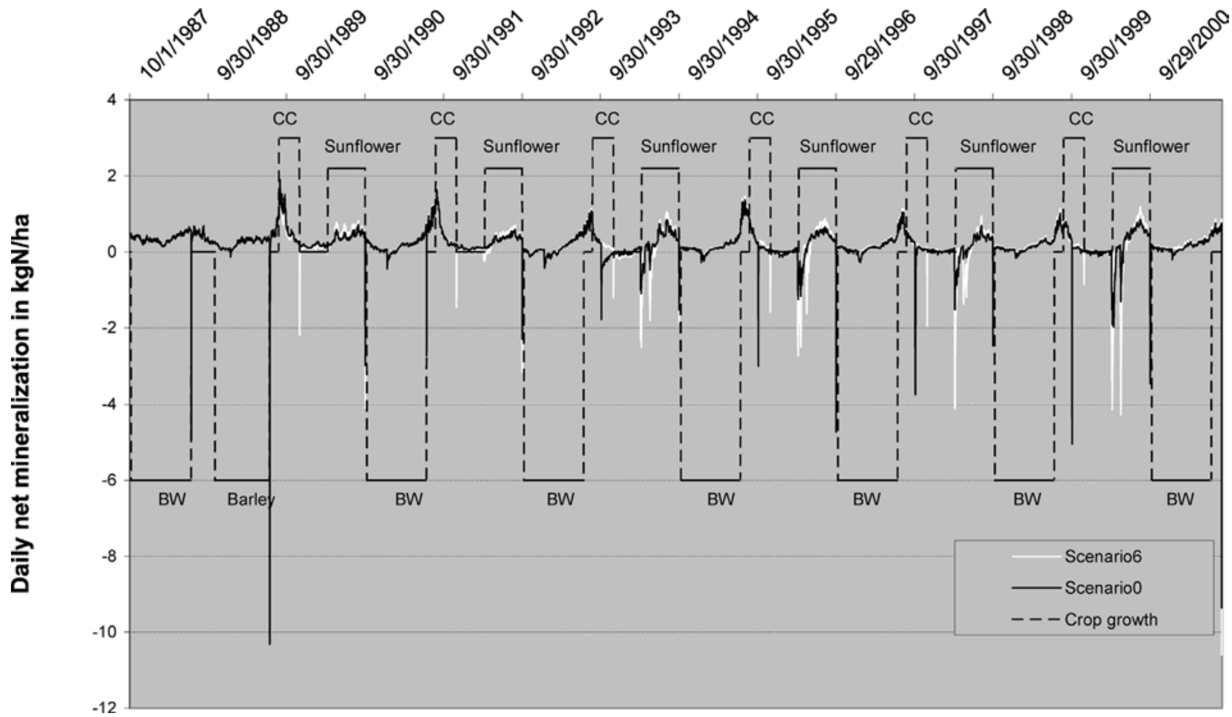


**Fig. 6.** Daily net mineralization simulated with TNT2 for one crop, for *Scenario 0* (reference) and *Scenario 6* (catch crop implementation). Negative values correspond to immobilization periods, during which decomposers use mineral nitrogen to overcome the nitrogen deficit in soil organic matter, deficit associated to each straw burial episode (high C/N ratio). CC stands for catch crop, BW stands for Bread Wheat, dotted lines delimit the plant growth period.

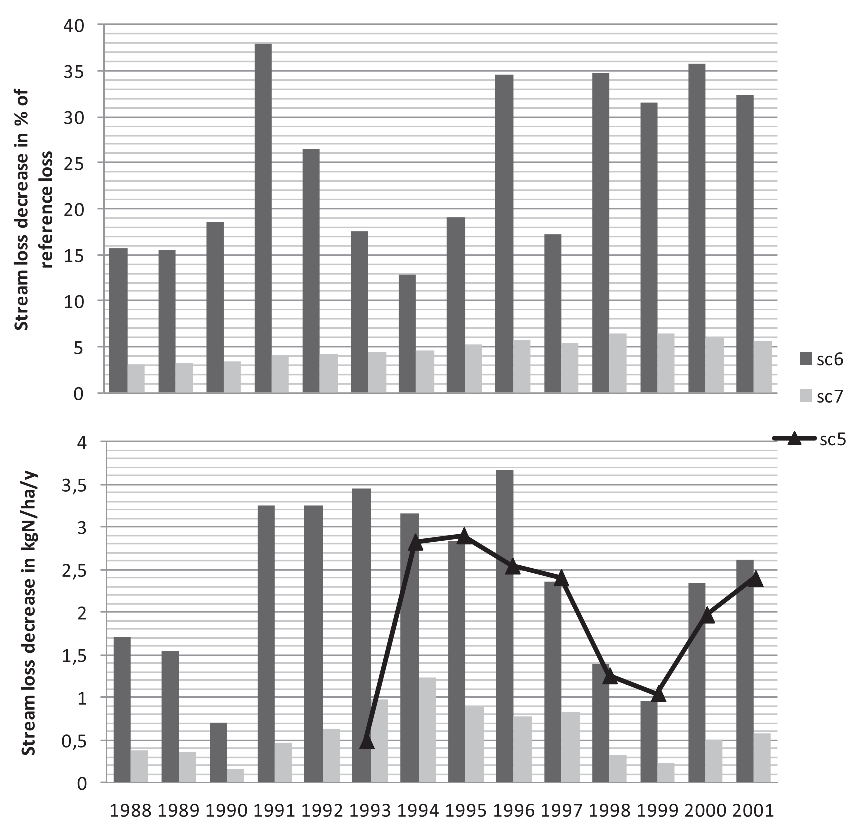


**Fig. 7.** Annual nitrogen stream loss reduction associated to the catch crop implementation *Scenario 6* and fertilizer reduction (*Scenario 7*) as a % of the reference flux (*Scenario 0*) (figure up) and in kg N ha$^{-1}$ y$^{-1}$ (figure down). The annual nitrogen loss reduction associated with the implementation of the 3 BMPs (*Scenario 5* minus *Scenario 0*) is in black line.

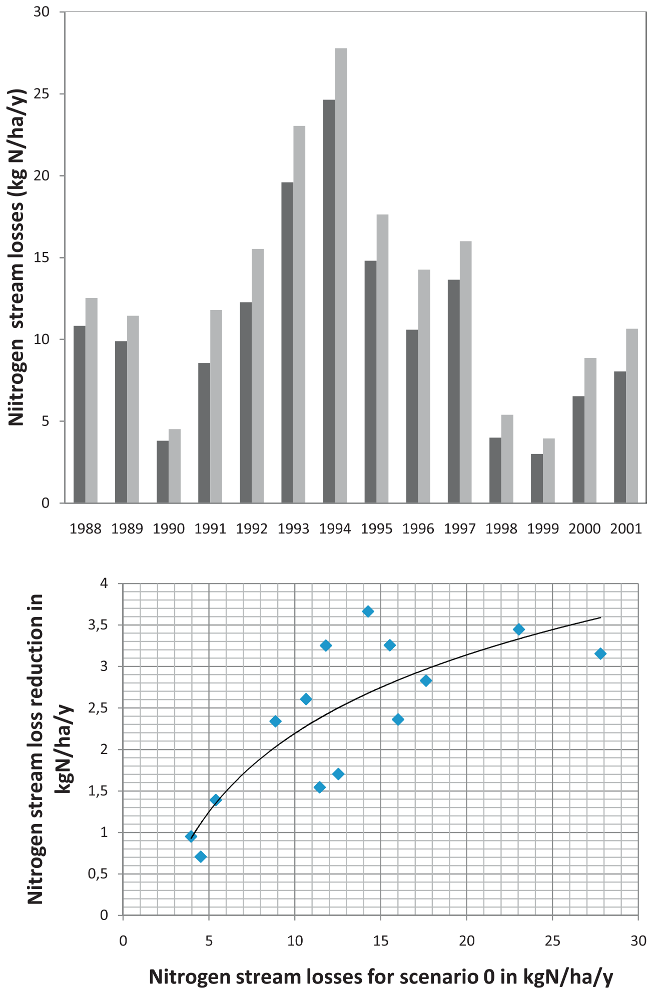


**Fig. 8.** Annual nitrogen stream loss simulated with TNT2 for *Scenario 0* (reference) and *Scenario 6* (catch crops). The log regression represents the evolution of the annual decrease of stream losses attributed to the catch crop implementation as a function of the reference loss (*Scenario 0*). $y = 1.365\ln(x) - 0.951$; $R^2 = 0.67$.

We must keep in mind that both BMPs and agricultural scenarios have been evaluated in terms of stream nitrate contamination and yield losses. A cost/benefit analysis could be done further to evaluate the performance of each BMP, taking into account the fast evolution of agricultural products gross margin and subsidies (Common Agricultural Policy) versus the environmental costs identified in the framework directive on water. But other environmental benefits of these BMPs which are not explored in this paper should be added to this kind of analysis. Indeed, these BMPs have also been designed to limit the soil erosion and pesticide transfers (rye-grass strips). Straws or CC act as protective coverage during summer storms and autumnal rainfall by limiting erosion, sediment transport and fixed pollutant transfer that occurs along with suspended matter. CC is effective to reduce soil drainage, phosphorus transfer (Laurent et al., 2007), erosion and to increase soil water retention (Munoz-Carpena et al., 2008). Additionally, the rye-grass strips have been designed to slow down water and sediment transfer along the stream network. Sediments, pesticides and phosphorus are supposed to be filtered by the permanent plant cover. Natural strips also act as a protective buffer zone for the drainage network during tillage operation, fertilizer and pesticides usage. Benefits for the rehabilitation of trees in the agricultural landscape are also multiple: biodiversity connectivity corridors, abundance of natural enemies of insect pests (Dix et al., 1995), and even esthetic quality.

## 4. Conclusion

The 5 coping measures tested in this study have been evaluated in terms of nitrate stream contamination. We have simulated the 3 BMPs effect which have been implemented in 1992 in that scope, as well as two scenarios that have been selected for their potential efficiency. This evaluation should be also linked to other water quality related issues such as suspended matter, pesticides, phosphorus or metal transfer to be implemented in a more integrated cost/benefit study. This study highlights that the efforts made in the past to cope with the nitrate contamination have had a limited but not negligible impact on stream water contamination from nitrate, a benefit balanced by a non-negligible impact on crop yields. In addition to that benefit, a systematic CC implementation in the existing cropping pattern would have decreased the stream nitrogen fluxes by 20%. Literature provides an overview of the other benefits of the catch crops in terms of erosion, phosphorus losses and suspended matter issues. These gains may be sufficient to justify the cost of implementation (i.e. an abatement of spring crop yield), even if we must consider several technical difficulties which could arise during the destruction of the catch crop at the end of autumn; tillage and destruction operations using tractors during wet periods are difficult, and the use of pesticides for the catch crop destruction could decrease the water quality.

The natural strips set up in 1992 mainly decrease denitrification and plant uptake. The mineralization increases with the higher biomass of the rye-grass cover that is restituted to the soil organic matter whereas it decreases under poplar strips because a part of organic matter is stored in the wood. In addition to that, the reduction (from few days to one month) of the saturated condition period length located within natural strips leads to a local decrease of denitrification.

The benefit of each action can be constant in time (delay in the burial of straw, decrease in fertilization rates), positively proportional (catch crop) or inversely proportional (natural strips) to the nitrogen fluxes in stream. The catch crop efficiency reaches a maximum for humid years, but the plant uptake of this crop is low because the mineral nitrogen availability is low as well in this agronomical context.

The major uncertainty of this virtual experiment is the spatial and temporal denitrification estimates, a process which has never been directly measured in the field.

The study site is representative of a wider area embedded within the Gascogne region in south-west of France where similar agronomical options are experienced (Ferrant, 2009). The results can be transposed to a whole agricultural region.

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