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ORIGINAL ARTICLE

Reduction of stream nitrate concentrations by land management in contrasted landscapes

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Abstract Optimizing management practices at the plot scale is sometimes not sufficient to reach water framework directive objectives for nitrate pollution. Land management measures involving targeted setting aside of croplands is a promising solution, but its efficiency depends on the local context. We used a distributed agro-hydrological model to compare management interventions intended to decrease vertical and lateral nitrate leaching from soil to groundwater and stream water in two contrasted agricultural catchments. The simulated scenarios combined two strategies: optimization of agricultural practices and land-use conversion from agricultural to natural land at different locations within the catchments. Long-term climate, discharge, and nitrate concentrations have been monitored for the two catchments and agricultural practices are well known over the 13-year simulation period (2002–2015). The Kervidy-Naizin site (KN) is subject to intense livestock pressure with mean nitrogen inputs of 257 kg ha^{-1} year^{-1}, while the Auradé site (AU) is primarily cereal cultivation with nitrogen inputs of 109 kg ha^{-1} year^{-1}. The results highlight a large nitrogen legacy in KN, resulting in a progressive and long lived (> 10 years) response to changes in management, while in AU, this response is perceptible after only 5–7 years. For both catchments, the most effective scenario involves wide riparian buffer strips in interception position covering about 15% of the catchment area. In KN, this land conversion scenario, simulated with the agro-hydrological model TNT2, created a decrease of nitrate concentration in stream water by 25% versus 15% in AU. Contrastingly, the implementation of best

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management practices decreased stream nitrate concentration only by 9% for KN and 4% for AU.

Keywords Distributed model · Nitrogen cycling · Mitigation scenario · Catchment · Best management practice · Riparian zone

Introduction

The deterioration of water quality due to high nitrate concentration in surface and ground waters is an issue for many developed countries (de Wit et al. 2002). This pollution can be attributed to agricultural activities based on high nitrogen inputs (Carpenter et al. 1998) combined with the generalized specialization of agriculture, which spatially concentrates production systems, and particularly livestock breeding generating large nutrient excess (Billen et al. 2010). Environmental regulations such as the European water framework directive (WFD) in 2000 have been developed to mitigate this type of pollution. They are mainly based on the implementation of best management practices (BMP). In spite of these regulations, the target of NO_3 concentration less than 50 mg L^{-1} in surface water is not always achieved, mainly in intensive livestock production areas with a high nutrient surplus (Durand 2004; Kay et al. 2012; Worrall et al. 2009). Scientists and policy makers have to find additional levers to solve the problem.

Scenario analysis can be a relevant method to evaluate the interest of innovative policies before their implementation. According to the typology suggested by Börjeson et al. (2006), the BMP implementation belongs to the preserving scenario type. BMP include fertilization adjustments, introduction of efficient cover crops, or implementation of small buffer systems (hedgerows, buffer strips). Achieving environmental goals may require the implementation of transforming scenarios. Such scenarios include deep changes in the agricultural systems, e.g., changing maize-based dairy systems into grassland-based systems (Moreau et al. 2012a), or conversion of conventional cropping to low inputs or organic agriculture. Deep changes may also concern land use via the conversion of agricultural land into environmental areas (EA), i.e., extensively managed grasslands or forests.

A recent study in Denmark (Hashemi et al. 2018) illustrated the efficiency of spatially differentiated measures combining plot scale management and setting aside areas in specific locations. The catchment response to the implementation of such measures depends strongly on the context, i.e. the current level of nitrate concentrations, the type of agrosystem (land use, agricultural practices, N excess, crop distribution), the hydrological setting, climatic conditions, soil types and distribution, and the sensitivity of water bodies (Gascuel-Odoux et al. 2010; Thomas et al. 2016). It is therefore recommended to study them in contrasting contexts to have a general assessment of their interest and identify the key factors controlling their efficiency. To achieve this, distributed biophysical models are useful multipurpose tools because of their ability to correctly simulate the processes involved in localized changes in land management (Cherry et al. 2008; Jakeman and Letcher 2003; Moreau et al. 2012b, 2013). Applying these models in well-monitored headwater catchments may help to identify the processes operating in the landscape, because at larger scales the stream chemistry is controlled by the mixing of water from subcatchments with different properties and by instream processes (Abbott et al. 2018; Dupas et al. 2016).

Under the ESCAPADE project (ANR-12-AGRO-0003) (Drouet et al. 2016), agro-environmental nitrogen management scenarios were constructed in contrasting rural headwater catchments to better understand how reactive nitrogen forms are transformed and transferred into the agro-ecosystem (Galloway et al. 2003) as a function of agricultural and landscape management. The practical aim was to assess whether different types of mitigation strategies are likely to achieve the objective of reducing nitrate concentrations in groundwater or streams (Durand et al. 2015).

This paper presents the modelling study analysing these scenarios in two small contrasting agricultural catchments of western France and southwestern France. A similar set of mitigation scenarios was simulated with the TNT2 model in both catchments. The objectives of the study are (1) to analyse the different responses to the mitigation scenarios in distinct contexts (2) to identify the key factors and mechanisms controlling the efficiency of the strategies tested (3) to discuss the broader implications of these findings for designing site specific strategies of nitrate pollution mitigation.

Materials and methods

Study sites

The two study sites are small headwater catchments located in Brittany (Western France) for Kervidy-Naizin site (KN) and in Gascogne (South-West of France) for Auradé site (Au) (Fig. 1). They were selected because they have similar size while they are contrasted in terms of agriculture type (mix farming with high livestock density and cereal cropping, respectively), soil and substratum (shale and calcareous molassic deposits, respectively), climate (oceanic influenced for the former, warmer and dryer in Gascogne region for the second one) and landscape structures (bocage for Kervidy-Naizin and hilly open field for Auradé). Both catchments are part of the French Research Infrastructure OZCAR (Network of Critical Zone Observatories http://www.ozcar-ri.org/) and, as such, are subjected to a long term and high-frequency monitoring. The data used in this paper are daily rainfall, air temperature, global radiation, Penman–Monteith PET, daily averaged discharge, nitrate concentration from grab samples. Both catchments are being monitored for discharge, climate, stream and groundwater chemistry for more than two decades. The sampling frequency for Kervidy-Naizin for nitrate concentration varied between one per day to one per 3 days during the period, with an average of 0.6 per day. For Auradé, the average sampling frequency is 0.7 per day from 2006 to 2015. All details on the monitoring methods are available online (for Kervidy-Naizin: https://www6.inra.fr/ore_agrhys_eng/ and for Auradé: http://www.ecolab.omp.eu/bvea). In both cases, the nearest weather station was used to fill the gaps in climate data.

Kervidy-Naizin site (Brittany)

The Kervidy-Naizin site is a catchment with intensive mixed-farming of 4.9 km^2 characterized by gentle slopes of less than 5% (93–135 m a.s.l). 91% of the catchment is used as Agricultural Area (AA), dominated by maize (36%), cereals (32%) and grasslands (13%) according to farm surveys realized in 2009 and 2013 and to annual landuse surveys (Fig. 2). The

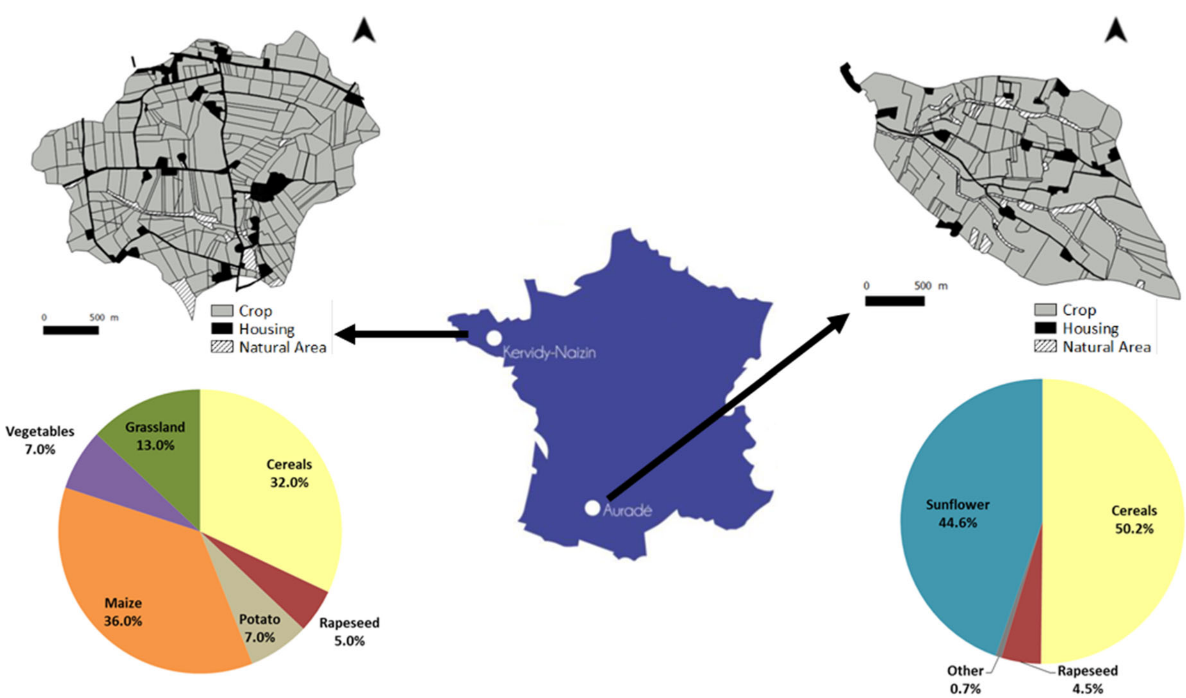

Fig. 1 Study sites location and typical land use

catchment is characterized by a high livestock density with about 5 LSU ha^{-1} with cattle, pigs and poultry. The N input on this site comprises slurry and manure fertilization (69%), mineral fertilization (mainly ammonitrate, 24%), excretion in pastures (5%) and nitrogen fixation (5%). Twenty-one farms are operating on this catchment, providing animal products, crops or both.

The mean annual rainfall over the last 13 years (from 2002 to 2015) was 827 mm $year^{-1}$, with a minimum and a maximum years average reached in 2005 (497 mm $year^{-1}$) and in 2014 (1218 mm $year^{-1}$). The minimum and maximum average monthly rainfall occur in June (43 mm $month^{-1}$) and in November (109 mm $month^{-1}$). The climate is temperate oceanic with a mean daily temperature of 11.2 °C (data from 2002 to 2015). The mean annual specific discharge is 314 mm $year^{-1}$, with a minimum discharge of 112 mm $year^{-1}$ observed in the 2004–2005 hydrological year and a maximum in 2013–2014 with 648 mm $year^{-1}$.

The soils are mainly silty-loam, 60–80 cm deep, with a slope gradient affecting the drainage (well drained upslope and poorly-drained downslope) (Dalgaard et al. 2012).

The main socio-environmental objectives of the policies forwater pollution mitigation in Brittany are the limitation of coastal eutrophication and the compliance with the European water framework directive (WFD).

Auradé site (Gascogne)

By contrast, the Auradé site is an intensive polyculture catchment of 3.2 km^2, of which 88.5% are AA. The topography is hilly with a mean slope about 9.3% (about 80% comprised between 4% and 10%) and a maximum slope of about 28.8%. Steep slopes combined with bare ground period lead to marked soil erosion (Fig. 1). The altitude ranges from 172 to 276 m a.s.l (Ferrant et al. 2011; Perrin et al. 2008). Winter wheat/sunflower is the dominant biennial crop rotation, with sometimes rapeseed as a third crop. This succession of winter crops harvested in July and summer crop sown in spring induces an intercropping period of 9 months, often left as bare soil. Thirteen farms are operating in the catchment, none of them

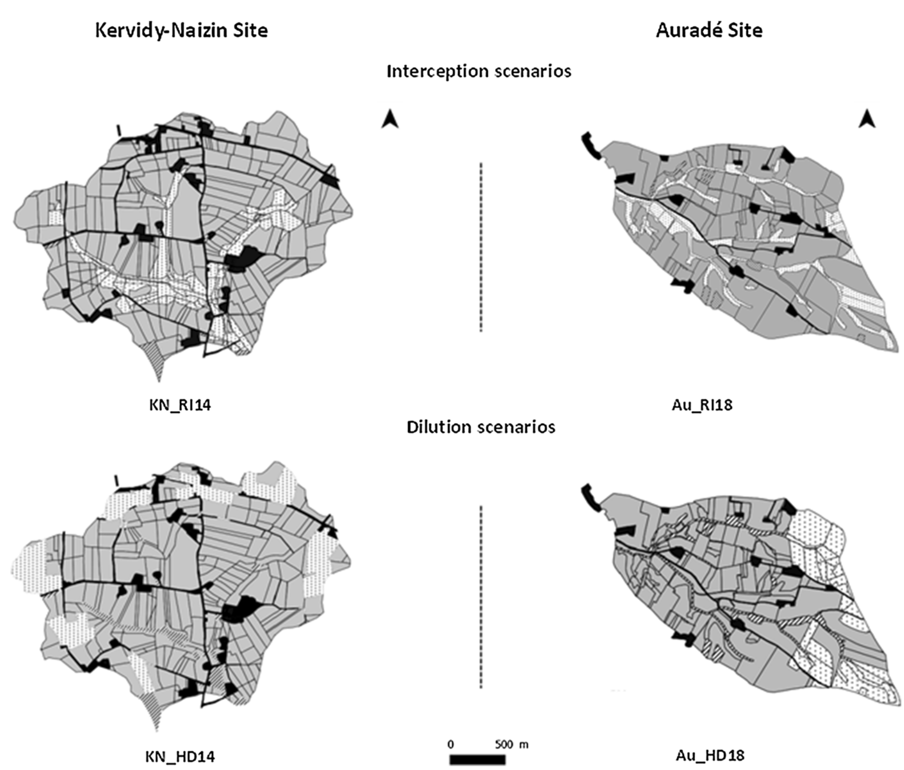

Fig. 2 Location of the converted grassland into the landscape management scenarios (in grey agricultural area (AA), in black Housing, hatched are natural areas and dotted are environmental areas (EA). The names of the scenarios are made up as follows: KN for Kervidy-Naizin site and Au for Auradé then the landscape management modality: RI (riparian interception) versus HD (Dilution) then the percentage of AA converted to EA

with livestock, except one farm with duck production for force-feeding (with intermittent production during the year). Crop fertilization on this site is exclusively mineral in ammonium nitrate form mainly.

Over the last 13 years (from 2002 to 2015), the mean annual rainfall was 646 mm. The maximum and minimum annual averages were reached in 2013 (841 mm year^{-1}) and in 2003 (479 mm year^{-1}), with minimum and maximum monthly average rainfall observed in July (42.5 mm month^{-1}) and in May (89 mm month^{-1}). The catchment is under oceanic climate influence, but with severe summer droughts, which drive it to semi-arid conditions. The mean daily temperature was of 14.1 °C (2002–2015). The mean annual specific discharge was 150 mm year^{-1} (2007–2015), with a minimum discharge of 47 mm year^{-1} observed in the 2011–2012 hydrological year and a maximum in 2013–2014 with 279 mm year^{-1}.

Calcic soils series developped on the molassic calcareous substratum. Soil type distribution depends mainly on the topographic position and the substratum. Most of the soils contain 30–50% of clay (fully described in Ferrant et al. 2016).

The main socio-environmental objective of pollution mitigation policies in the Gascogne region is to comply with WFD. Auradé is not included in the Nitrate Directive vulnerable zones.

Scenarios description

We designed the scenarios to investigate the different ways of mitigating the nitrate pollution by (1) optimizing management practices in the agriculture plots (fertilization, cover crops, manure management,…) or (2) decreasing AA and creating environmental zones with two contrasted location strategies: (1) in riparian position to maximize the possibility of intercepting upslope lateral flows and (2) in headwater position to decrease concentrations at the sources of the stream network. The main aim was to evaluate the effectiveness of field-scale and catchment-scale mitigation measures in two contrasting landscapes using the same set of scenarios. Researchers, agricultural extension institutes and some production chains partners (cooperatives) conceived together the set of scenarios.

Business as usual (BAU)

Farm surveys were performed in both catchments to describe crop rotations and crop management practices. We completed gaps using the crop rotation pattern of the well-known years and remote sensing data. Local expert knowledge helped to correct some incoherencies. Overall, these corrections and gap filling resulted in minor changes, well under the uncertainty of the data collected in the surveys. The result of this work allowed building the model input data for the scenario business as usual (KN_BAU and Au_BAU) over 13 years (from 2002 to 2015).

Best management practices (BMP)

The agricultural practices optimization at field scale was adapted to local context according to the Nitrates Directive program adopted in 2014. This approach consists in achieving a balanced fertilization for each crop in accordance with French guidelines. Although following these guidelines is mandatory since 2009 (4th action program), some surveyed practices had to be tuned, which resulted in 9% reduction at the Kervidy-Naizin site and 6% at the Auradé site.

In addition, for the Kervidy-Naizin site, the optimization scenario (KN_BMP) consisted mainly in limiting the global nitrogen balance under 50 kg ha^{-1} year^{-1} and modifying the fertilizer scheduling and manure application (longer period of spreading ban) as required in the 5th action program of the Nitrate Directive for vulnerable zone, not fully applied at the time of the farm survey.

For the Auradé site, we split the implementation of the best management practices into two scenarios. The first one (Au_BMP20) consisted in implanting cover crop over 20% of AA with a long inter-cropping period (between wheat and sunflower). The cover crop, designed to decrease nitrogen leaching during bare ground periods between two crops (Justes et al. 1999), was established in August for 3 months. In the second scenario (Au_BMP100), the cover crop was systematically implanted for each long intercropping.

For both sites, the fertilization rate was tuned based on the N balance approach for each crop in rotation according to COMIFER (2013) references. This approach takes into account the plant requirements for the average yield obtained over the last 5 years, and standardized assessment of the mineralization of the soil organic matter and of the preceding organic inputs.

Landscape management scenarios

The landscape management scenarios consisted in testing two different mechanisms spatially involved in nitrogen mitigation. The first one is the interception of nitrate-rich runoff and lateral flow coming out of the fields upslope by locating the set-aside areas in riparian position (KN_RI and Au_RI scenarios) to constitute buffer strips. This throughflow can therefore be slowed down, or decreased by storage and evapotranspiration; the nitrate transported can be uptaken by microbiota or plants or can be transformed in N_2O and N_2 by denitrification. The second one is the dilution of spring waters by locating the set-aside areas in upper slope position (KN_HD and Au_HD) to constitute a few large patches of environmental areas (EA) receiving no nitrogen input and expected to produce nitrate-poor water. Therefore, the landuse of these EA has been designed to reach rapidly a minimal N leaching rate. In this perspective, we opted for unfertilized grassland mown three times per year with exportation of the cut grass rather than for afforestation. The reason are that the net uptake rate is higher for regularly cut grassland than for recently planted trees, and regular harvest export significant amounts of N while for trees the only short term sink is the immobilisation in wood and roots (Benhamou et al. 2013). Different studies have confirmed that young forests are usually not able to limit nitrogen losses in the years following a clear cut (e.g. Palviainen et al. 2015; Vitousek and Melillo 1979) and we checked with TNT2 that it simulated higher leaching on woodlots than on extensive grasslands when implanted on previous croplands (data not presented).

In Kervidy-Naizin, 14% of the catchment area were converted to environmental area (KN_RI14 and KN_HD14), while in Auradé, the proportion was 18% (Au_RI18 and Au_HD18) (Fig. 2). The proportion and location of converted zones for the riparian interception (RI) scenarios were defined according to the soil maps, i.e., by choosing the soils classed as poorly drained near the stream. For comparison purposes, the same proportion of area was converted to EA for the headwater dilution (HD) scenarios, using the drainage area delineation tool of SAGA GIS software. For these scenarios, the remainder of agricultural land was managed according to the BMP scenario (KN_BMP and Au_BMP100).

Control scenario: zero nitrogen input

Control scenario 0_N aimed at estimating the N legacy of the catchment and the time lag necessary to go back to nearly pristine conditions, regardless the feasibility. This facilitates comparison of scenario efficiency between the two contrasted study sites. For this purpose, all the agricultural area (AA) was converted to environmental area (unfertilized cut grassland as detailed above).

Modelling

Presentation of the model

The scenarios are simulated using Topography Nitrogen Transfer and Transformation (TNT2) model, a spatially distributed agro-hydrological modelling focusing on the spatial interactions within the landscape (Beaujouan et al. 2002; Ferrant et al. 2013; Oehler et al. 2009).

TNT2 consists in the coupling of a distributed version of the hydrological model TOPMODEL (Beven 1997) and of the crop model STICS (Brisson et al. 1998, 2002). Both models were adapted to facilitate coupling and to be able to simulate a diversity of agricultural landscapes. The model is fully detailed in Beaujouan et al. (2002).

The hydrological model considers that the shallow groundwater table dynamics controls most of the discharge variations, and that the surface topography determines the direction and intensity of the water transfer in this groundwater. At the grid cell level, the subsurface flow is therefore calculated using Darcy's low applied to the saturated zone, with the hydraulic gradient assumed constant and equal to the downslope topographic gradient and the transmissivity at saturation decreasing exponentially with the saturation deficit of the regolith. The flow is then routed from cell to cell using a D8 scheme, based on the digital terrain model. When water input (sum of upslope cells flow and excess rainfall) exceeds the saturation deficit, both overland flow and exfiltration are generated. The saturation flow is assumed to occur in the drainage porosity of the regolith. The regolith (root zone and weathered bedrock) is discretized in horizontal layers (typically 5–10 cm in the root zone and 1–5 m in the weathered bedrock) with a retention porosity and a drainage porosity (with a threshold equivalent to field capacity for the soil). This double porosity scheme allows modelling a variable limit of the saturated zone based on the water table depth and the possibility of fluxes in both directions between soil and groundwater. In the unsaturated zone, drainage occurs vertically down to the saturated zone limit, using a capacity model similar to the Burns' model (Burns 1974). The retention porosity domain is where the coupling occurs between the two models, the shared variables being the soil moisture profile and nitrate concentrations.

The parameters of the hydrological module can be set separately for each soil type, but are assumed constant within a soil type.

Previous sensitivity analyses concluded that the most sensitive parameters of the hydrology module are mainly T0 (transmissivity at saturation) and M (exponential decrease coefficient), and secondarily the capacity of both saturated and unsaturated domains (porosities and thickness) (Moreau et al. 2013; Savall et al. 2019).

The STICS model is a generic crop model based on the classical coupling between intercepted radiation and growth, modulated by the phenologic developpement of the plant, described as a succession of stages (germination, vegetative growth, reproduction, etc.) driven by degree-day thresholds. Radiation interception and evaporation are described via a biomass-LAI (Leaf Area Index) relationship. This set of growth modules determines a demand of nitrogen and water that is compared to the soil supply, estimated by a set of soil modules describing water retention and transfer (capacitive approach) and nitrogen transformations. If soil N and water supply is lower than the plant requirements, water and/or nitrogen stresses are applied to limit plant growth. Organic matter decomposition (either from soil, plant residues or organic fertilisers) is simulated via the growth and decay of decomposers biomass, using the C content and C:N ratios of the different pools, and rate coefficients controlled by temperature and soil moisture. A specific module has been implemented in TNT2 to simulate nitrogen dynamics in annual crops/temporary grassland rotations, taking into account the building up of a labile organic matter pool during the presence of grassland (typically 2–10 years), which decays rapidly after the ploughing of the grassland (Vertès et al. 2007; Moreau et al. 2012b). Denitrification is simulated by modulating a potential rate using functions of temperature, nitrate concentration, water filled pore space and mean residence time of water in the drainage porosity: carbon availability is therefore supposed to be constant and included in the potential rate value (see Oehler et al. 2009a) for detailed discussion of denitrification simulation). In the first versions of the STICS (and TNT2), only organic nitrogen and nitrate were considered, through gross mineralization (aggregating mineralization and nitrification), denitrification, plant uptake and leaching. The rate of each process is modulated by temperature, water content and substrate availability. New versions, including the one used in the present paper, take into account nitrification, ammonium uptake and adsorption on soil matrix.

Most of the plant parameters are provided by the community of STICS developers and users for a large range of crop species and varieties, based on controlled experiments. The most sensitive parameters of the soil module are soil available moisture (depending on soil porosity and depth) and potential mineralization and denitrification rates.

The model runs at a daily time step. Grid size varies from 5 to 50 m, while the regolith layer thickness are typically 5–10 cm in the soil and 50–100 cm in the weathered bedrock. The influence of grid resolution and layer thickness on model parameterization has been studied in Savall et al. (2019).

TNT2 model have been thoroughly tested and is now used for research and operational studies on N cycling in landscape (Chambaut et al. 2008; Moreau et al. 2012b; Oehler et al. 2009b; Viaud et al. 2005). Detailed descriptions of the model can be found elsewhere (Beaujouan et al. 2002; Ferrant et al. 2011; Moreau et al. 2012b; Oehler et al. 2009b; Benhamou et al. 2013). The model applies more specifically to small rural catchments (typically, less than 100 km^2) in the temperate zone, with shallow groundwater systems. The model is fully distributed, with different levels of spatial discretisation: pixels (computing units), soil units (soil and hydrological parameters), fields (agricultural management data and operations), climatic zones (from meteorological data) and catchment (for discharge and N concentration calculation). In particular, agricultural practices are inputted in the model as a succession of individual management operations (sowing, fertilizer spreading, harvesting…)

for individual fields. In practice, for this model, a *scenario* will consist in a set of agricultural data, distributed spatially and temporally in the catchment, applied for a given period under given climatic conditions.

The main originality of the model is that it is able to simulate the time–space variable interactions between soils and shallow groundwater (i.e. the variable extension of saturated areas) and its consequences on nitrogen dynamics (e.g., retention by vegetation, soil immobilization or denitrification of nitrate leached upslope and transported by shallow water pathways). It is also able to simulate the nitrogen dynamics in different land uses of a temperate agricultural catchment (annual crop rotations, ley-arable rotations, permanent grassland, woodlots, riparian wetlands…) using the same basic formalism.

Simulation procedure

For the two sites, the latest version of TNT2 was used to simulate the scenarios. The scenarios run over 13 hydrological years from 2002 to 2015, with the first 2 years used to ‘spin up’ the model (i.e. reach equilibrium from the initial state), then BAU scenario was applied until 2005 and finally all the scenarios were applied for 10 years. By experience, 2 years are enough to stabilize hydrological variables, but for some biogeochemical variables (especially storage in groundwater), initial values are included in the calibration procedure. Calibration on BAU scenario comprised two steps. First, a Monte-Carlo procedure was applied to calibrate the hydrological module using the Nash–Sutcliffe coefficient (NS) (Nash and Sutcliffe 1970) for daily water discharge as the objective function. Parameter values were initialized using previous simulations Durand et al. (2015) for Kervidy-Naizin and Ferrant et al. (2011) for Auradé. The transmissivity at soil saturation, its exponential decrease coefficient and drainage porosity of the deeper layer, which are the most sensitive parameters for discharge simulation (Beaujouan et al. 2002; Moreau et al. 2013) were allowed to vary around 10% of their initial values. At each iteration, the best parameter set was retained. After 10 iterations, the NS coefficient usually stabilized. The second step consists in a trial and error approach to calibrate the nitrogen modules. For most of the crop parameters, default values provided with the STICS model were used. The only parameters that were adjusted for nitrogen processes were the initial nitrate concentration in groundwater, the soil organic matter mineralization rate and the denitrification rate. The calibration of nitrogen modules was multicriteria: the main objectives were to minimize standards errors on nitrate concentrations and fluxes, but we also check that the crop yields, denitrification and mineralization loads were within the range of the local or regional references. The calibration was carried out over the period 2002–2005 for hydrology and over the period 2002–2009 for nitrates. The initial and calibrated values of the adjusted parameters are provided in Table S1 in the Supplementary Material.

The mean values for the last 3 years of the simulation were used to compare the scenarios, to account for the variations due to climate, the crop rotations and the response time of the system.

Evaluation criteria

Several indicators were computed for the three last hydrological years to compare each scenario and each site: the mass balance (Eq. 1), the standardized fluxes (Eq. 2), two Nitrogen Use Efficiency (NUE) calculations (Eqs. 3, 4) and Nexcess (Eq. 5).

- Mass balance of the AA

$$\begin{aligned} &\text{Input} = \text{output} \\ &N_{orgF} + N_{minF} + N_{graz} + N_{fix} + N_{atm} \\ &\quad = N_{harvest} + N_{stream} + \text{Volat} + \text{Denit} + \Delta\text{N\_soil} \\ &\qquad + \Delta\text{N\_GW} \end{aligned} \tag{1}$$

Where all values are in kg N ha^{-1}

For the input:

N_{orgF}: N input by manures
N_{minF}: N input by mineral fertilizers
N_{graz}: N input from animal excretion
N_{fix}: N fixed by legumes
N_{atm}: N input from atmospheric wet deposition

For the ouput:

$N_{harvest}$: N content in the harvested parts by crops in AA (N harvest AA) and N content in the harvested parts by grass in EA (N harvest EA)
N_{stream}: fluxes of nitrates in stream water at the outlet

Volat: emission due to manure spreading
Denit: denitrification
ΔN_soil: Total variation store in soil
ΔN_GW: Total variation store in groundwater
Standardized flux decrease

$$\textit{Standardized fluxes decrease} = \frac{NO_3{-}N\ flux_{BAU} - NO_3{-}N\ flux_{sc}}{NO_3\text{-}N\ flux_{BAU} - NO_3\text{-}N\ flux_{0\_N}} \quad (2)$$

where all value is in kg N ha^{-1}

NO_3-N $flux_{BAU}$: nitrate-nitrogen flux from the BAU input scenario
NO_3-N $flux_{sc}$: nitrate-nitrogen flux from the given scenario
NO_3-N $flux_{0\_N}$: nitrate-nitrogen flux from the 0_N input control scenario

This ratio expresses the decrease of flux resulting from a given scenario relatively to the largest possible decrease considering the N legacy of the catchment, which allows a better comparison between the two sites.

- Nitrogen use efficiency (NUE):

$$NUE\ agriculture = \frac{N\ harvest\ agriculture}{N\ input\ by\ agriculture} \quad (3)$$

N harvest agriculture: N content in the harvested parts of crops in AA (N harvest AA)

$$NUE\,catchment = \frac{N\,harvest\,agriculture + N\,harvest\,EA}{N\,input\,by\,agriculture} \quad (4)$$

- N excess

$$N\ excess = N\ input - (N\ harvest\ agriculture + N\ harvest\ EA) \quad (5)$$

Results

Calibration

For the simulation of daily discharge in Kervidy-Naizin, the Nash-Sutcliff coefficient reached 0.86 and the correlation coefficient 0.8. For Auradé, the model performance was much poorer: the Nash-Sutcliff coefficient reached 0.44 and the correlation coefficient 0.5 (Fig. S1 in the Supplementary Material). In both sites, and especially in Auradé, the flood peaks were often under-estimated. In terms of variations of N fluxes, the model reproduced fairly well the seasonal variations, although in detail, it failed at simulating correctly some individual storm events and contrasted seasons (either very dry or very wet). The cumulative discharge and cumulative N fluxes simulated for the 13 years of simulation were close to the observed data, with 12% and 7% of bias for cumulative N fluxes and 5% and 3% for cumulative discharge for Kervidy-Naizin and Auradé, respectively. The seasonal and pluri-annual variations of concentrations were relatively well reproduced in both sites (relative mean absolute error of 14% for Kervidy-Naizin and 28% for Auradé), although in detail the model failed to reproduce at a daily time step the measured variations of instantaneous concentration. Further discussion on the performance of the model in both sites can be found in previous papers (Benhamou et al. 2013; Ferrant et al. 2011; Salmon-Monviola et al. 2013).

Nitrogen mass balance in the BAU scenario

There are large differences in the nitrogen mass balance of the two sites, the Kervidy-Naizin site being much more submitted to nitrogen excess (mainly under organic form) than the Auradé site (Fig. S2 in the Supplementary Material). The total input in Auradé was 2.5 times less than in Kervidy-Naizin and the N excess, 3 times less. As a result, the losses in the stream were only 18 kg N ha^{-1} $year^{-1}$ in Auradé while they reached 65 kg N ha^{-1} $year^{-1}$ in Kervidy-Naizin. The denitrification loads were also higher in Kervidy-Naizin site compared to Auradé site (25.6 and 17.9 kg N ha^{-1} $year^{-1}$, respectively).

Scenarios assessment

The big picture of the compared scenario results is the similarity of the global trends but strong differences in the amplitude and timing of the catchment responses, reflecting the contrast of the functioning of the two systems.

The results show that on both sites (1) scenarios followed the same order BAU > BMP > HD > RI > 0_N for NO_3-N concentration and (2) NUEagriculture was similar and stable between the scenarios. However, the effect of the scenarios was clearly different between sites. In the Kervidy-Naizin site, the optimization of the practices was more efficient than in Auradé with 19% of standardized decrease (Eq. 2) between BMP and BAU scenario while in Auradé, the decrease was only 5% for BMP20 and 12% for BMP100 (see Table 1). The landscape scenarios management were more efficient in Kervidy-Naizin with a standardized decrease of the average NO_3-N concentration of 28% and 53% over the last three hydrological years (2012–2015) for HD and RI scenarios, respectively, while in Auradé the decrease was only 20% and 25%, respectively, although the surface converted in environmental zone was larger in Auradé (18%) than in Kervidy-Naizin (14%). Relatively to the surface of environmental area, the headwater dilution (HD) scenarios had about the same efficiency in the two sites, while the riparian interception (RI) scenario was significantly more efficient in Kervidy-Naizin. In this site, the RI scenario differed from the other scenarios with a faster and stronger response in the years following its implementation, while for the remainder of the simulation period the trends were similar for all the scenarios. In Auradé, all the scenarios showed a quick and limited response, except the 0_N control with concentrations decreasing rapidly and stabilizing at a very low level (2.5 mg NO_3-N L^{-1}) from 2012 to 2013. Relative to the BAU scenario, the decrease in stream concentration in 0_N scenario was 74% in Auradé vs. 45% in Kervidy-Naizin.

Two different responses to scenarios implementation are highlighted in Fig. 3. The nitrate concentrations in Kervidy-Naizin followed a general downward trend for all scenarios. In Auradé the nitrate concentration remained stable in all the scenarios except the 0_N control which showed a strong decrease as soon as implemented.

Simulated cumulative fluxes

The hierarchy of scenarios in terms of nitrogen loss reduction is confirmed by the cumulative fluxes illustrated in Fig. 4 and this representation highlights, in addition, the impact of decreasing bare soil periods and areas in Auradé. First, a significant reduction of cumulative discharge was observed between BAU, BMP20 and BMP100 scenarios in Auradé (up to 4%). Second, the decrease was stronger in the HD scenario

Table 1 (a) Main features of the set of scenarios (the units are specified in brackets) and (b) corresponding results

	Kervidy-Naizin site					Auradé site					
	BAU	BMP	HD14	RI14	0_N	BAU	BMP20	BMP100	HD18	RI18	0_N
(a) *Scenarios*											
Fertilizer reduction (%)	0	9	23	19	100	0	6	6	26	14	100
Environmental area (%)			16	15	100				18	18	100
(b) *Results*											
NO_3-N concentration	14.6	13.3	12.7	11.1	8.0	9.6	9.2	8.7	8.1	7.8	2.5
NO_3-N flux	64.8	59.2	56.4	51.1	35.6	17.8	16.9	15.4	13.7	13.6	3.5
Denitrification	25.6	24.1	22.2	21.6	11.8	17.9	17.1	16.1	13.8	15.3	4.1
Groundwater nitrate Storage variation	− 25.9	− 26.1	25.5	26.5	23.3	− 1.0	− 0.9	− 0.5	− 0.7	− 1.2	− 2.1
Organic + mineral N Storage variation	15.9	13.0	− 2.9	3.5	− 102.5	1.7	0.7	0.2	− 6.2	− 2.7	− 28.6
N input by agriculture	212	192	164	172	0	107	101	101	79	92	0
N excess	100	84	59	61	− 84	38	36	37	23	31	− 22
NUE catchment	0.61	0.65	0.74	0.74	–	0.64	0.64	0.64	0.71	0.67	–
NUE agriculture	0.61	0.65	0.66	0.66	–	0.64	0.64	0.64	0.67	0.65	–

All values results are in kg N ha^{-1} $year^{-1}$ except for the concentrations in mg NO_3-N L^{-1} and dimensionless ratios (NUE); all fluxes are the mean of the 3 last hydrological years of simulation

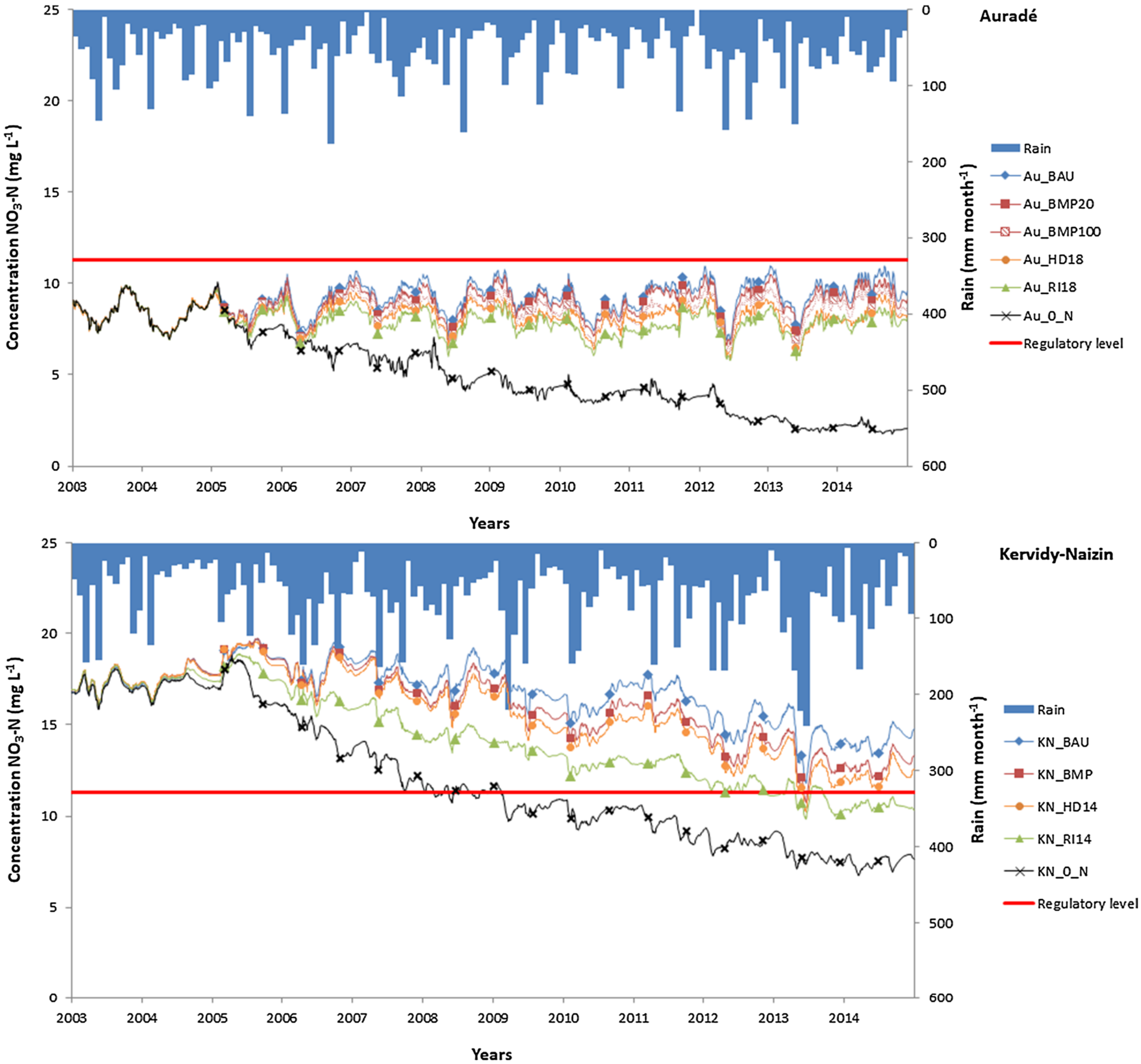

Fig. 3 Simulated temporal dynamics for each scenarios on both sites from 2003 to 2015 with BAU: Business as usual; BMP: Best management practices, then for Auradé the percentage of cover crop area; HD: Dilution; RI: Riparian interception, then the percentage of AA converted to EA; 0_N: zero nitrogen input scenarios

compared to the RI scenario (10 and 7%, respectively). Third, the decrease reaches 31% when all the soils are permanently covered in the control scenario (Au_0_N). This impact was barely detectable in Kervidy-Naizin, where the decrease of cumulative discharge is only 4% in the 0_N scenario. Therefore, the stronger decrease of the nitrate flux for the 0_N scenario in Auradé, as compared to Kervidy-Naizin (81 and 45%, respectively), is partly due to this decrease in discharge.

Standardized decrease of fluxes

The variation with time of the standardized N flux decrease (Eq. 2) magnifies the differences in the effects of the scenarios on nitrate losses between the two catchments. Figure 5 shows that the efficiency of the scenarios was rather stable over time in Auradé, whereas the efficiency of all scenarios increased with time by about 9% over the period 2006–2014 in Kervidy-Naizin.

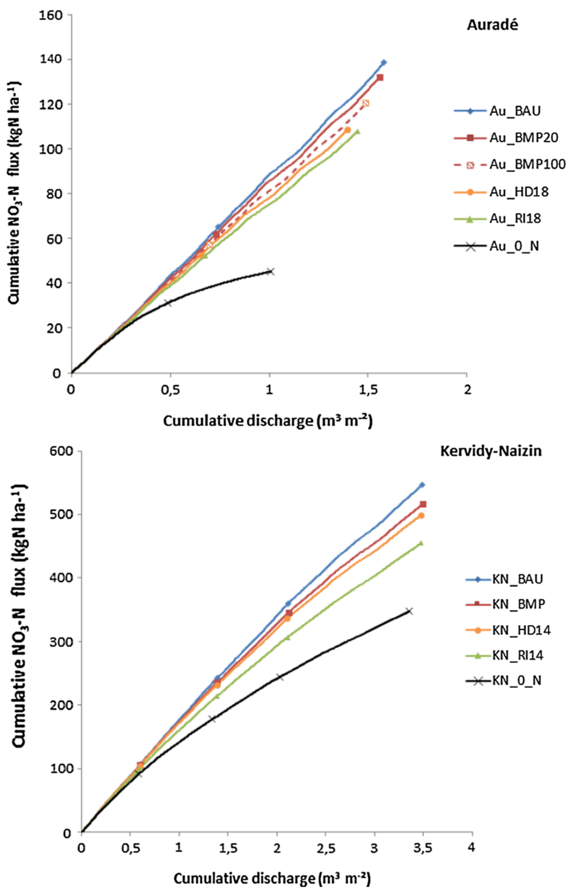

Fig. 4 Simulated cumulative discharge versus cumulative N flux for all scenarios on both sites over 10 hydrological years (from 2004 to 2015) with BAU: Business as usual; BMP: Best management practices; HD: Dilution; RI: Riparian interception, then the percentage of AA converted to EA; 0_N: zero nitrogen input scenarios

At the Auradé site, the results obtained for the Au_RI18 and Au_HD18 scenarios were very similar, while at the Kervidy-Naizin site, the efficiency of the KN_RI14 scenario was 23% (on average per year) higher than the KN_HD14 scenario. The RI14 scenario at Kervidy-Naizin was more efficient when the hydrological year was dry (i.e. 2008 and 2011). On the opposite, the KN_HD scenario was more efficient during wet years with a maximum reached in 2013, where rainfall reached a record level of 1307 mm over this period. The N fluxes at the Auradé site were not correlated to the rainfall amount but rather to the crop rotation in the catchment. Indeed, the main pattern is an alternation of sunflower/wheat with a surface ratio of one-third or two-thirds depending the year. The years showing the higher efficiency (i.e. 2007, 2009, 2011 ad 2013) were those with a maximum area occupied by wheat followed by a long intercrop period, during which a catch crop can be sown. The generalization of catch crop allowed an average improvement of 12% between BMP20 and BMP100.

Denitrification load

At both sites the denitrification load was positively correlated to the N total agricultural inputs and therefore to the overall availability of nitrogen (Fig. 6). The denitrification load was more than halved, from 25.6 kg N ha^{-1} year^{-1} to 11.8 kg N ha^{-1} year^{-1} respectively for the KN_BAU and the KN_0_N scenarios, in Kervidy-Naizin site. At Auradé site, the values were lower and the slope of the relationship was stronger, the denitrification rate being four times less (17.9 kg N ha^{-1} year^{-1} vs 4.1 kg N ha^{-1} year^{-1}) between BAU and 0_N, respectively. It is noteworthy that the RI scenarios resulted in comparatively lower denitrification loads, especially in Kervidy-Naizin.

Discussion

The differences in the catchments' response to the scenarios originate from the agricultural context and the biophysical functioning of the catchments. As a cautionary notice, it should be reminded that the modelling exercise is subjected to large uncertainties, both due to input data (especially agricultural practices), to calibration and to the simplification of the representation of the systems (especially for the hydrology of the Auradé catchment). These uncertainties are difficult to quantify, so the interpretation of the results has to focus on the comparison between the results when they suggest interesting differences in the underlying processes, rather than on the absolute values.

At the Auradé site, a specific facilitation programme for farmers is going on since 1992, resulting in the introduction of grass strips and the reduction of fertilizer inputs. The BMPs scenarios at this site are therefore very close to the BAU, the reduction in fertilization being only 6% with a surplus of 38 kg N ha^{-1} year^{-1} and 36 kg N ha^{-1} year^{-1} for BAU and BMP respectively. In Kervidy-Naizin, although it is

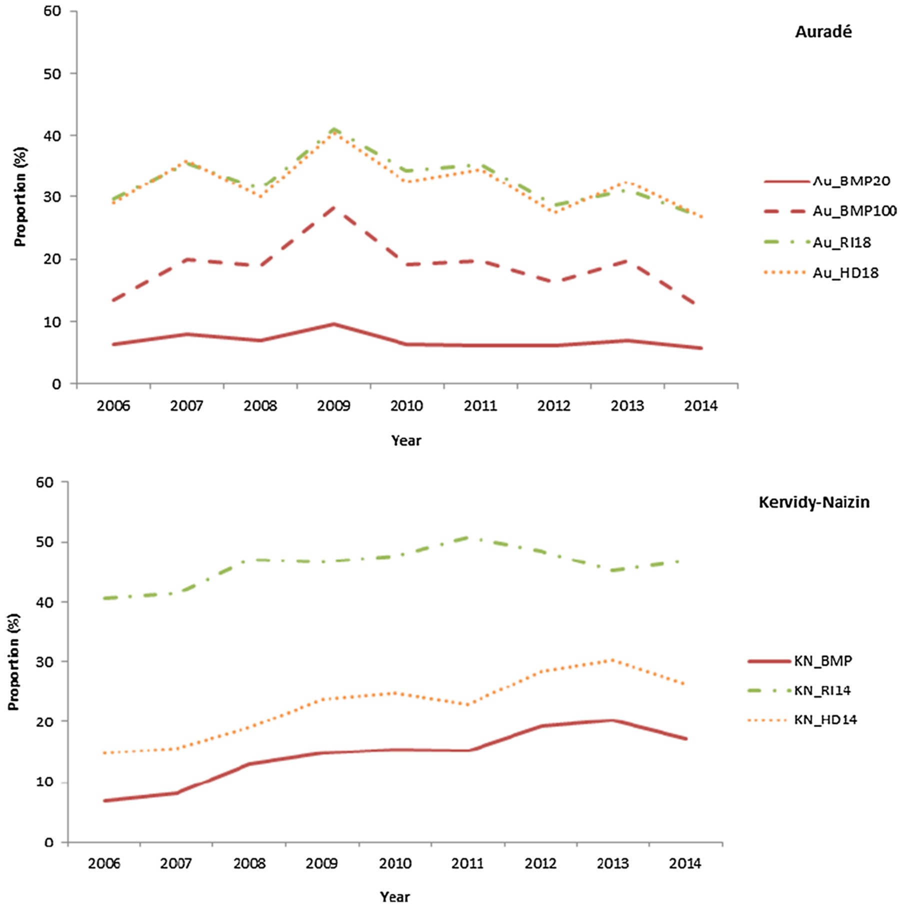

Fig. 5 Standardized N flux decrease (see Eq. 2) for each scenarios on both sites with BMP: Best management practices; HD: Dilution; RI: Riparian interception scenarios, then the percentage of AA converted to EA

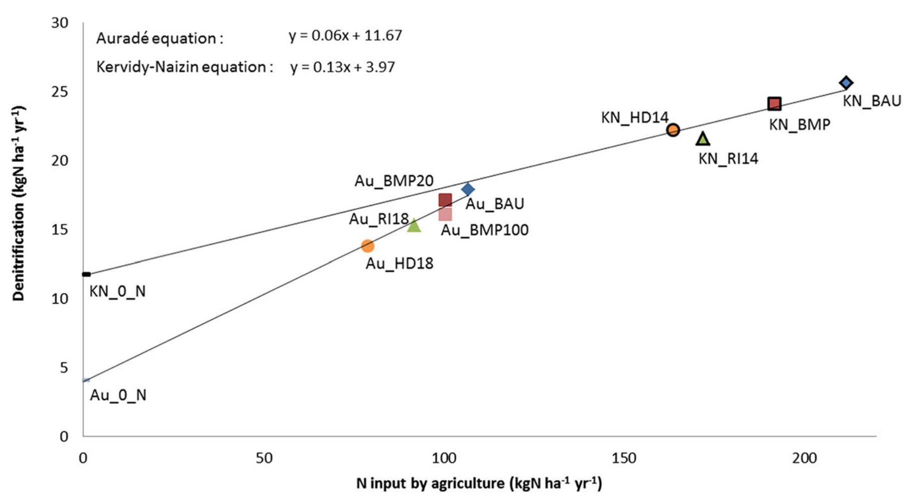

Fig. 6 Simulated denitrification load versus N total agricultural input on average over the last three hydrological years of simulation (from 2012 to 2015) with BAU: Business as usual; BMP: Best management practices; HD: Dilution; RI: Riparian interception, then the percentage of AA converted to EA; 0_N: zero nitrogen input scenarios

likely that the decreasing trend of concentrations in BAU is due to the enforcement of the regulations in the last decades at the regional level, the present practices are still not fully optimized: the reduction of fertilization allowed by BMP is 9% with a surplus of 100 kg N ha^{-1} $year^{-1}$ and 84 kg N ha^{-1} $year^{-1}$ for BAU and BMP respectively. In addition, balanced fertilization and surplus reduction are easier to achieve in a cropping system with mineral fertilizers only than in an intensive mix farming system with still high manure inputs.

Another striking difference between the catchments is the temporal dynamics of the catchments' response to changes. Figure 3 suggests that in the Kervidy-Naizin catchment, 10 years is not enough to reach a steady-state. This highlights the importance of the N legacy in this catchment, due to the large nitrate storage in the shallow groundwater (Molenat and Gascuel-Odoux 2002; Ruiz et al. 2002) and to the building up of a labile SOM (Soil Organic Matter) pool by large additions of organic manures (Wander et al. 1994). However, for the last 3 years of simulation, the decrease of fluxes is comparable between scenarios, allowing for comparison. This legacy is also responsible for the steady increase with time of the efficiency of all the scenarios but RI. The RI scenario in Kervidy-Naizin produced a faster response because the changes are localized downhill, a zone where the N groundwater concentrations are lower and the residence time shorter (Molénat et al. 2002; Molenat and Gascuel-Odoux 2002). By contrast, the response time of the Auradé catchment is much quicker, all the scenarios but the 0_N reaching rapidly a steady state. The longer response time for the 0_N is probably due to the slow decline of a more stable SOM pool (Table 1). From a broader perspective, the response time of these two catchments is however short enough to analyse the relationship between land management and nitrate losses at a decadal time scale, which is not always the case (Dupas et al. 2016; Howden et al. 2010).

As expected, the scenarios ranked in the same way in both sites in terms of decreasing concentration at the outlet: BAU > BMP > HD > RI > 0_N. In Auradé, the effect of the three mitigation scenarios (i.e. BMP, riparian interception RI scenarios and headwater dilution scenarios HD) was very limited and relatively similar, whereas in Kervidy-Naizin a marked difference was observed, the RI scenarios being by far the more efficient. The reasons for these differences are threefold. First, the N excess and the water fluxes were lower in Auradé compared with Kervidy-Naizin site, limiting the potential relative gain; second, the hydrological regime in Auradé is very contrasted, with flashy storm events separated by marked droughts, that do not favour the retention processes in riparian areas; third, the hydrological and topographic settings of Auradé (higher slopes) result in smaller potential area of interaction between shallow groundwater and soils i.e., the area where the retention and denitrification processes can occur. These areas are limited in the catchment to strips of deep soils to sand lenses patches (Paul et al. 2015). This is coherent with other modelling studies showing a large variability of the efficiency of mitigation measures and N retention processes depending on the physiographic context (Durand et al. 2015; Ferrant et al. 2013; Hashemi et al. 2018; Thomas et al. 2016).

At the Auradé site, the reduction of N losses in the scenarios is partly due to a reduction of water flows, which is not the case in Kervidy-Naizin. This is mainly because in Kervidy-Naizin the proportion of well-covered soils (by either grasslands or catch crops) is already significant in the BAU scenario, while in Auradé, the main crop rotation induce a 9-months bare soil period for about half of the surface.

At the Kervidy-Naizin site, the efficiency of the RI scenario is higher during wet years, while it is the opposite for the HD scenario. In wet year conditions, the residence time of water in the lower parts of the catchment is shorter in average (higher throughflow in the same pore volume), which hinders the retention processes that condition the efficiency of the RI scenarios. This is particularly visible because the formalism of biotransformations in waterlogged soils takes into account the residence time in the TNT2 model, which is a specificity of this model. On the opposite, high throughflows favour the dilution processes, which is the foundation of HD scenarios efficiency. In Auradé, this effect is not visible because the variations of crop/cover crop proportions between years are preponderant, and probably because the residence time is relatively short even during dry years.

The denitrification load in a catchment is often closely controlled by the nitrate availability (Clément et al. 2002), as confirmed by the results on the two study sites. Both sites show a strong correlation between total N inputs and denitrification rates. Site specific conditions, i.e., subsurface hydrology conditions (soil saturation, groundwater flow paths, residence time) and subsurface biogeochemistry conditions, in particular organic carbon supply, also are important factors governing nitrogen removal in buffers and may explain the difference in response (slope of the correlation) between sites (Mayer et al.

2007). The other major implication is that the higher efficiency of the RI scenario is not due to higher denitrification. Therefore, the explanation of this higher efficiency of this scenario is to be sought in a higher N uptake and/or N immobilization in soils, as discussed in Casal et al. (2019).

The results shows that the issue of the compared efficiency of landscape scenarios is crucial in the case of Kervidy-Naizin, where only the RI scenario allows the streamwater to reach the Nitrate Directive standard concentration. In Auradé, the average nitrate concentration is already below the standard although the concentration is highly variable in time and exceeds this threshold only temporarily (Ferrant et al. 2013). Since the model shows that most of the scenarios resulted in decreasing discharge, there may be a trade-off issue between water quality and water quantity consideration.

Conclusion

The distributed agrohydrological modelling approach developed here allowed us to compare the effects of complex mitigation scenarios, including agricultural and landscape changes, in contrasted sites. In spite of relatively large uncertainties and imperfection in the simulation of observed functioning of the catchments, the analysis of the results suggests marked differences between the scenario effects in the two contexts and gives a realistic explanation of the mechanisms responsible for these differences. Different nitrogen mitigation strategies were tested at the two sites: (1) optimization of fertilization practices (2) partial conversion of AA into environmental areas located to favour interception or dilution processes. One site showed a large legacy of nitrogen and high nitrogen retention capacity: in that case, a combination of better management practices and targeted set aside of the valley bottom would allow a quick and significant decrease of N fluxes in streamwater. In the other site, the retention capacity is much lower, due to alternation of dry spell and flashy storm events: in that case, spatial targeting may not be so important, and the implantation of cover crops is probably the more recommendable measure. Beyond these particular cases, the study highlights the risk of inefficiency of uniform mitigation measures, not taking into account the local context. This illustrates the interest of a combined analysis to design the most adequate policy, namely the analysis of the agricultural systems, to identify the practices generating the higher risk, and of the biophysical context, to assess the sensitivity and the buffering potential of the site. The next step is to use upscaling methods, such as the mesoscale analysis of the hydrochemical patterns of nested catchments, to regionalize such site-specific recommendations.

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