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Long-term nitrogen dynamics in various catch crop scenarios: test and simulations with STICS model in a temperate climate

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1. Abstract

The long term effects of repeated catch crops on N dynamics in arable farming were assessed using mid-term experiments and long-term simulations. The soil-crop model STICS (v6.9) was tested against a database provided by three experiments (13-17 years) carried out in Northern France, including treatments with or without repeated catch crops. STICS performance was checked for crop biomass, N uptake, soil water content and mineral N at harvest of main crops, drained water, N leaching and mineralization rates. The model satisfactorily reproduced these variables, except for soil mineral N and N leached at one site. N leached was predicted with a slight bias, between -3 and +7 kg N ha^{-1} yr^{-1}, and soil N mineralized was simulated with a bias lower than 7 kg N ha^{-1} yr^{-1}. The model simulated correctly the N uptake by catch crops and the kinetics of extra N mineralization due to catch crops. Seven scenarios varying in the presence of catch crops, fertilization rate and climate were simulated on long-term (60 years); their effects on N uptake, soil N storage, N mineralization and nitrate leaching were compared by difference with a control scenario. Repeated catch crops lead to reduce N leaching, sequester organic N and increase N mineralization. The model indicated that the sequestered N reached a maximum of 430-750 kg N ha^{-1} after 23-45 years depending on site. The extra-mineralization due to catch crops progressively increased up to 38-65 kg N ha^{-1} yr^{-1}. A strategy of constant N fertilizer rate resulted in raising the N uptake of main crops and slowing down the abatement of nitrate leaching. Conversely, when N fertilization rates were reduced by 20-24 kg N ha^{-1} yr^{-1}, crop production remained stable and catch crops reduced N leaching on the long term by 33-55%. Therefore catch crop is a promising technique for controlling the N cascade.

2. Introduction

The last application of the European Nitrate Directive (91/676/EC) lead governments to stipulate that catch crops must be grown in fallow periods to diminish the risk of nitrogen leaching. It is therefore important to better assess the efficiency and sustainability of this practice in various pedo-climatic contexts and cropping systems. The short-term effects of catch crops on N leaching and balance are well known, but all impacts of the practice cannot be determined at this time scale. A marked increase in N mineralization with catch crops has been reported in several studies (Schröder et al., 1996; Torstensson and Aronsson, 2000). In addition, the higher soil organic matter found after several years of repeated catch crops (Blombäck et al., 2003; Berntsen et al., 2006) indicates that the long-term effects of catch crops could be different from those observed after one or two years. The change in mineralization, which is partly due to increased soil organic matter (SOM), could result in increased N uptake by main crops after 13 to 24 years (Hansen et al., 2000; Constantin et al., 2011). However, the duration of these experiments was not long enough to determine the level and timing of steady state conditions, particularly on mineralization and organic N in soil. These authors suggested to adjust the N fertiliser rate in the long term in order to avoid the risk of increasing nitrate leaching due to extra N mineralization from catch crop residues. It has also been shown that N leaching was enhanced in fields having received repeated crops during several years after catch crops are abandoned (Thomsen and Christensen, 1999), but the duration of this effect is not well known.

Crop models can be useful tools in illustrating and predicting the long-term effects of agricultural practices on the N cycle in various conditions. Models can help determine N mitigation, leaching or turnover in soil as a result of improved agricultural practices such as catch crops (Aronsson and Tortensson, 1998; Blombäck et al., 2003). However these models must be first tested and verified against different experimental datasets in time and space in order to ensure their efficiency to correctly simulate reality. To predict changes in a given agrosystem, models must be dynamic and

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integrate the impacts of climate, soil properties, agricultural techniques and various crops, including catch crops. STICS is a soil-crop model that simulates crop development and environmental impacts, such as N leaching and sequestration (Brisson et al., 1998; Brisson et al., 2008). It has been tested in annual simulations for a number of crops (e.g. Brisson et al., 2003) and calibrated to simulate C and N dynamics during decomposition of various mature and young (catch) crops residues (Nicolardot et al., 2001; Justes et al., 2009). STICS predictions of soil net N mineralization kinetics in the short term are reasonably accurate, but the model may underestimate soil organic carbon in the long term (Gabrielle et al., 2002). STICS was evaluated over the medium-term (8 years) in a small catchment in northern France for varied soils and crops including catch crops and was able to correctly simulate N uptake by crops, N content in crop residues and soil mineral N at harvest and in late autumn (Beaudoin et al., 2008). However, longer term tests are needed to determine the ability of the model to predict long-term changes in N mineralization and storage in soil as a function of alternative agricultural practices such as catch crops and in response to climate change.

The objectives of this study were: i) to evaluate the performance of the STICS model in long-term prediction of N balance and outputs by crop and leaching; ii) to determine the ability of STICS to simulate N turnover in soil (sequestration and mineralization), particularly with continuous use of catch crops; and iii) to test longer-term scenarios with and without global warming to determine whether steady state could be reached and to analyse the effects of continuing or abandoning catch crops.

3. Materials and methods

3.1. Experimental databases

Two databases, called “reference database” and “catch crop database”, were used to calibrate and evaluate the model. The reference database is an external database used to calibrate crop parameters. It compiles several experiments with various crop species, including main crops (winter wheat, sugar beet, spring peas, spring barley, maize) and catch crops (mustard, ryegrass), as described by Beaudoin et al. (2008). It contains data on crop aerial biomass, grain yield, N in aerial biomass and harvested organs, leaf area index, rooting depth, soil water and mineral N contents in 3 to 4 layers down to 90 or 120 cm. The catch crop database gathers experimental data obtained on three long-term (13-17 years) field experiments in Northern France reported by Constantin et al. (2010). The three experiments included a treatment with (CC) or without (NoCC) catch crop; an additional N fertiliser treatment was tested on one site until 2003: reduced rate (N^-) versus conventional rate (N). Crop rotation and N inputs differed between sites, as did catch crop species and their frequency (Table 1). Biomass production and N content of main crops and catch crops were measured every year. Soil mineral N (SMN) and water content (SWC) were measured over 90-110 cm depth three times per year: at harvest, end of autumn and mid-winter. Drained water was measured in lysimeters, which were managed similarly to the field plots. Nitrate concentration was measured in porous cups installed in all treatments at 90-110 cm depth: 7 porous cups were pooled to make one replicate and were sampled 3 to 10 times per year according to drainage intensity. These methods have been shown to be relevant to assess free drainage and nitrate leaching (Webster et al., 1993). N leaching was calculated using the trapezoidal method (Lord and Shepherd, 1993), which consists in interpolating drainage between two dates of measurement in the porous cups. Fertiliser use efficiency was measured every year in two sites by the difference method (between fertilized and unfertilized plots), and also in all sites during the last two years using ^{15}N labelled fertilizers. *In situ* net N mineralization was calculated using soil N mineral balance, which takes into account N inputs (fertilization, atmospheric deposition, symbiotic fixation), N outputs (harvested N, leaching, gaseous losses) and SMN variation during the calculation period, according to the procedure described by Constantin et al. (2011). Organic N and C stocks in soil were measured at the end of the experiment at all sites. The catch crop database was managed for the three sites using the open source software Postgre-SQL (www.postgresql.org). Data on soil

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characteristics, climate variables, crops, agricultural techniques, N fertilisation and all measured data were recorded and an interface was created to allow the STICS model to be run automatically. Half of the catch crop database was used to recalibrate a few crop and soil parameters when model performance was unsatisfactory; the other half was used for model evaluation (Confalonieri et al., 2009).

3.2. Overview of STICS model

The soil crop model STICS is a dynamic model that simulates C, N and water cycles. It is a one-dimensional model with a daily time step, which takes into account soil characteristics, climate and agricultural practices (Brisson et al., 2008). The potential development stages, leaf growth and growth rate of a given crop depend on photothermal units and solar radiation. The effective crop growth rate is affected by water and nitrogen stresses and atmospheric CO_2 concentration. The soil is divided into several layers with specific characteristics such as water content at field capacity, permanent wilting point and bulk density. Residue decomposition in soil is simulated using three compartments: the fresh organic matter, the microbial biomass and humified organic matter, the last compartment being composed of an active and an inert fraction. N and C fluxes between these compartments depend on their C:N ratio, soil temperature and water content, and four parameters: the humification constant, the decomposition rate constant of the residues, the decay rate of the microbial biomass and the assimilation yield of residue-C by the microbial biomass (Nicolardot et al., 2001). The first two parameters depend on C:N ratio of residues while the last two do not. When mineral N is exhausted in the soil, the decomposition rate of organic residues is reduced, the C:N ratio of microbial biomass increases and the proportion of humified N is reduced (Giacomini et al., 2007). Model parameterization of mature and catch crops residues was made using a large dataset of laboratory incubations (Justes et al., 2009). The N mineralized from humified organic matter depends on the potential mineralization rate of the soil, which depends on clay, $CaCO_3$ and organic

N contents in the biologically active layer, and the temperature and moisture conditions occurring in this layer. STICS also simulates the gaseous losses (volatilisation and denitrification) derived from fertilizer. They were simulated at the same level in the treatments with and without catch crops; this result is consistent with the findings of Constantin et al. (2010).

3.3. Inputs and calibration of the STICS model

The models inputs concerning crop management and climate are available in the catch crop database since they were routinely recorded. The soil characteristics of each site used in STICS are shown at Table 2. The bulk density, the initial soil organic C content and C:N ratio of the soil were set at the values measured in 2007. The water contents at field capacity (W_{FC}) and wilting point (W_{WP}) were estimated using frequency analysis of measured water contents over the whole experimental period (13-17 years). W_{FC} is defined as "the water content held in soil after excess water has drained away, which usually takes place within 2–3 days after a rain" (Hénin et al., 1969). In our experiments, water contents were never measured during rainy days, so that W_{FC} was calculated as the mean of the highest values (first decile) of water contents measured in mid-winter. W_{WP} was calculated as the mean of the lowest values (third centile) of the water contents measured at summer harvests. The results compare favourably with those obtained with pedotransfer functions (PDF): the mean value of W_{WP} differed by 7 g kg^{-1} soil from the PDF function of Wösten et al. (2001); W_{FC} was greater than PDF (obtained at -10 kPa) by 27 g kg^{-1}, but W_{FC} is known to be highly dependent on soil structure and does not correspond to a constant water potential value (e.g. Wösten et al., 2001). The depth of the biologically active layer ('mineralization depth') was assumed to be 10% greater than the ploughing depth (Brisson et al., 2008). Using this rule, Beaudoin et al. (2008) were able to simulate the N mineralization kinetics and organic matter evolution of a permanent bare soil in a lysimeter.

The first step of calibration consisted in model calibration and evaluation against the independent reference database. The model used in this paper (STICS version 6.9) had been previously

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calibrated and validated on the reference database for all crops grown at the three study sites, except for radish. An additional parameterisation of spring barley was made on an additional independent database. The model was then evaluated against the catch crop database. If necessary, a second calibration was realized by adjusting a few crop and soil parameters against half of the catch crop database (dataset without catch crops), using annual or continuous (over 13-17 years) simulations. Annual simulations involved resetting SMN and SWC every year at harvest of main crops using the observed values, while the model was initialised only once in continuous simulations and simulations were run over 13-17 years. The calibration was applied when either the crop (biomass or N uptake) or soil variables (SMN or SWC) were not satisfactorily simulated by the model. Three parameters were calibrated using annual simulations: the maximal rooting depth, the lifespan of leaves, and the potential of fertilizer loss which influences the N use efficiency of fertilizer. For these annual simulations, the calibration method consisted in minimizing the sum of squared errors between observed and simulated values by the simplex method using the software package OptimiSTICS (Wallach et al., 2011). Continuous simulations were used to calibrate two other soil parameters: the initial organic N content (which was not measured) and the active fraction of humified organic matter, in order to correctly simulate the soil organic N and N mineralization kinetics observed in the field. A trial-error method was used for this calibration step. The objective was to mimic as well as possible N uptake, mineralization and leaching in control treatments (without catch crops).

3.4. Evaluation of STICS model performance

Three statistical criteria were used to evaluate the performance of the model: the root mean square error (RMSE), the mean deviation (MD) and the model efficiency (EF), calculated as follows:

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

$$MD = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$$

where n is the number of observations, S_i and O_i are the simulated and observed values respectively and $\bar{O}$ is the mean value of observed data. The *RMSE* provides the model prediction error, while the *MD* gives the bias of the model. The *EF* estimates the model performance relative to the experimental mean (Nash and Sutcliffe, 1970). An *EF* value close to zero indicates that the simulation does not perform better than a constant model equal to the mean of observed data. The combination of these indices gives a good overview of the model accuracy.

The mean effect of the improved practices (i.e. CC and N^-) was obtained by difference with the conventional practices (i.e. NoCC and N). The cumulative "extra mineralization" and leaching due to catch crops was obtained by difference with the control treatment (CC - NoCC). At Thibie, it was averaged between the fertilisation rate treatments (N and N-) because there was no significant interaction between the two factors (Constantin et al., 2010).

3.5. Catch crop management scenarios

The model was used to simulate various scenarios in the long term. Simulations were performed over 60 years (1990-2050), which include the first years of observations and the following 45 years. The crop rotation and agricultural management were assumed to remain constant and similar to those observed during the first 15 years. At Thibie, the initial rotation (sugarbeet – spring pea – winter wheat) was simulated throughout and the introduction of spring barley after 13 years was not considered. Seven scenarios (S0-S6) were simulated, varying in the presence and frequency of catch crops, N fertilisation rate and climate (Table 3). The reference scenarios, S0 and S1, considered no catch crop and standard fertilisation combined with constant or changing climate, respectively. Scenarios S2 and S3 included repeated catch crops during 60 years and standard fertilisation without and with climate change, respectively. Scenario S4 considered a lower frequency of catch crop establishment (once every three years at Boigneville and Thibie and once every four years at Kerlavic) under changing climate and standard fertilisation. Scenario S5 simulated repeated catch crops, climate change and a reduction in fertiliser rate after 15 years. The fertiliser dose was decreased so that the simulated crop biomass in the treatment with catch crops remained equal to that simulated for the control treatment (without catch crops), with a 3% tolerance. Scenario S6 considered constant fertilisation and climate change, but with abandonment of catch crops after 15 years.

Two climate series were built for each site by considering constant climate or climate change. The first series was built using random sampling of the 13-17 climatic years of experiment to constitute a 60-year scenario. The second series, taking into account climate change, was made using the A1B scenario (IPCC Special Report on Emissions Scenarios). It is based on extrapolating the actual climate data of our experimental period using the A1B climate scenario, which considers that the mean world temperature will increase between 2.5 and 3.5°C by 2100. This scenario was applied to each site using the statistical error correction proposed by Déqué (2007). It predicts that mean temperature will increase by ~0.8-1.0 °C by 2050. Annual rainfall would decrease at Kerlavic by 125 mm (with a marked decrease in spring and summer), but would not change much at Boigneville and Thibie (-23 and +24 mm). The change in CO_2 concentration in the atmosphere was not simulated continuously, but a constant concentration of 450 ppm was assumed over the 60 year period. This corresponds to the average of the present CO_2 concentration and the expected value in 2050.

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4. Results

4.1. Model calibration

The statistics of the model evaluation against the reference database for the crops involved in our study are given at Table 4. All results are available on the STICS website. The model efficiency was greater than 0.50 for 80% of crops and variables. The prediction of soil water contents (throughout the year) was satisfactory in all situations. Mineral N contents were also well simulated except for spring pea and maize. Crop biomass was satisfactorily predicted as well as aerial N uptake. The poorest agreement between observed and simulated values was for harvested biomass. The model evaluation of the catch crop database was not as good, so that a calibration was made against the calibration dataset (Table 5). The maximal rooting depths were slightly reduced, particularly at Kerlavic, in order to account for local soil conditions. The potential of fertilizer N loss which determines the denitrification losses derived from fertilizer was increased at Kerlavic in order to properly mimic the fertiliser use efficiency (which decreased from 66 to 62%), while it was well simulated on average at the two other sites. This specific calibration relies on the assumption that the higher rainfall at Kerlavic favoured the denitrification process. The lifespan of leaves for winter wheat, mustard, radish and ryegrass was decreased by 100, 60, 50 and 60 days respectively, to better simulate aerial biomass of these crops which was systematically overestimated by the model. The fitted values of initial organic N were close to those measured in 2007 at Boigneville and Thibie, suggesting that the stocks were more or less at steady state. This result was not surprising because the previous land use at these two sites was arable cropping with constant management. At Kerlavic, where the previous land use was grassland, organic N decreased over time and was higher at the beginning (calibrated at 3.20 g kg^{-1}) than in 2007 (measured at 2.78 g kg^{-1}). Finally, the active fraction had to be increased from 35 to 44% of total SOM at Boigneville and to 60% at Kerlavic in order to allow good simulation of net N mineralization and final N stock.

4.2. Model evaluation

4.2.1. Evaluation on crop and soil variables

STICS performance was evaluated in continuous simulations against the catch crop database. The model could simulate well the soil water contents both in the reference database and the catch crop database (Figure 1). However the predictions were better in the reference database which showed a larger variance and a better efficiency. Table 6 summarizes STICS performance for the catch crop database. It shows that the quality of fit was about the same for the calibration and validation datasets. SWC at harvest was well predicted, except at Kerlavic where it was overestimated (*MD* = 23-35 mm) particularly at harvest of winter wheat. SMN content at harvest was slightly overestimated on average (in spite of a good prediction of net mineralization, see further) and the model could not reproduce its variability. The model correctly simulated the aerial biomass of main crops and catch crops at Boigneville and Thibie (*EF* = 0.72-0.92), as well as the harvested biomass. At Kerlavic, the lower efficiency was associated with a large overestimation of wheat biomass, which could be due to limiting factors not taken into account by the model. The total N uptake was well simulated on all sites (*EF* = 0.41-0.90) without any bias; harvested N was correctly predicted except at Boigneville where it was underestimated (mean *MD* = -20 kg ha^{-1}). STICS could also correctly simulate drainage and leaching, although the amount of drained water was slightly overestimated on all sites (by 10-20%) and leached N overestimated (by about 25%) at Boigneville. The variability of both variables was well mimicked by the model (positive efficiency), except for N leached at Boigneville.

4.2.2.Ability to reproduce the effect of agricultural practices

The effect of agricultural practices on N uptake and N leaching was calculated by difference between paired treatments: with *vs* without catch crops or reduced *vs* standard fertilisation (Table 7). The two practices had contrasted impacts: catch crops exerted a small effect on N uptake and a strong effect on leached N whereas the opposite occurred for the reduction of fertilization. The model was able to satisfactorily predict these effects: model efficiency was 0.67 and 0.55

respectively. The other variables of interest were soil N mineralized and organic N content. The kinetics of net mineralization was well reproduced at all sites, with a slight underestimation at Thibie (Figure 2). The mean difference between observed and simulated values of annual mineralization was -1, -2 and +7 kg N ha^{-1} yr^{-1} at Boigneville, Thibie and Kerlavic, respectively. The dynamics of extra N mineralization due to catch crops (i.e. the difference between CC and NoCC treatments) differed between sites for both observed and simulated data (Figure 4). At Boigneville, the model underestimated the net release of N due to catch crops (white mustard) during the first years and gave satisfactory predictions thereafter. This underestimation was probably due to the fact that the predicted C:N ratio of mustard residues was greater than that observed, inducing a smaller release of mineral N in the months following catch crop destruction. The extra mineralization due to radish was slightly overestimated after 12-15 years at Thibie, whereas the mineralization due to ryegrass was well simulated over time at Kerlavic, with N immobilisation in the first years followed by net N release. The simulated organic N stocks in soil at the end of experiments (13-17 years) were rather close to those observed in the field (Figure 3). The N sequestered due to catch crops varied from 162 to 351 kg N ha^{-1}. It was slightly overestimated by the model, but predictions remained within the confidence interval of measurements. The effect of reduced fertilisation, mainly due to a reduction in C and N returns to the soil, was well predicted by the model. Finally, the model appeared to give satisfactory prediction of the effects of catch crops and reduced fertilisation on N uptake, leaching, mineralization and sequestration; despite a small underestimation of the positive effect of catch crops on N uptake, it could be used for simulating scenarios in the long term.

4.3. Simulation with catch crops over 60 years

4.3.1. N sequestered in soil

Figure 3 shows the evolution of N sequestered in soil due to catch crops since the beginning of the experiments, simulated during 60 years in scenarios S3 to S6. It confirms the positive effect of catch crops on the long term: scenarios including catch crops allowed soil organic N to increase between 430 and 750 kg N ha^{-1} in comparison with bare fallow soil (S1) depending on site and climate series. The highest sequestration due to catch crops occurred at Kerlavic with ryegrass, while the lowest was at Boigneville with mustard, N sequestration from radish at Thibie being intermediate. Climate change resulted in slightly lower N sequestration at all sites (results not shown). When catch crop frequency in the rotation was lowered from once every one or two years (S3) to once every three or four years (S4), the N sequestered due to catch crops diminished by 292 to 388 kg N ha^{-1} yr^{-1} (compared to scenario S3). In scenario S5, N fertilisation was adjusted (reduced by 20-24 kg ha^{-1} yr^{-1} after the first 13-16 years) to account for the greater mineralization due to continuous catch crops and maintain the crop yields at the same level than in the control scenario. This resulted in a slight decrease of N stocks (-73 to -132 kg ha^{-1}) compared with scenario S3, because crop production and crop residues diminished. Abandoning catch crops (scenario S6) led to a progressive decline in the extra N stored in the soil. The benefit of 13-16 years of repeated catch crops disappeared progressively to reach zero after 60 years.

4.3.2. Extra N mineralization due to catch crops

In parallel to change in N sequestration, continuous catch crops enhanced soil mineralization compared with simulations without catch crops. After 60 years of continuous catch crops (S3), the cumulative extra N mineralized reached 2950-3000 kg ha^{-1} at Boigneville and Thibie and 1780 kg ha^{-1} at Kerlavic (Figure 4). Thus the mean amount of N mineralized annually due to catch crops would represent 50 and 30 kg ha^{-1} yr^{-1} respectively. Adjusting fertilisation (S5) slightly decreased extra mineralization by 9-16% compared to S3. Reducing the frequency of catch crops decreased it much further, from 53% to 68% according to site. Abandoning catch crops would induce a slow return to the level of net mineralization simulated in the control treatment. N mineralization remained higher during several years after catch cropping ceased, as long as organic N in soil remained higher than in the control treatment. The extra mineralization (ΔM) of year n can be compared to the input of N from catch crop residues (N_{CC}) during year *n*-1; the ratio of these two variables gives the relative mineralization rate: $M_{CC} = \Delta M / N_{CC}$ (Constantin et al., 2011). Figure 5 shows the evolution of M_{CC} simulated during 60 years, without or with climate change (scenarios S2 and S3 respectively). The model simulates annual fluctuations due to variability in climate and catch crop production with regard to quantity and quality of residues. However, the general trend is an asymptotic increase in extra N mineralization over time for both climate scenarios. The results could be fitted to an exponential function, the asymptote of which was reached (within 10%) in 23, 26 and 45 years at Boigneville, Thibie and Kerlavic respectively, without climate change. The asymptote was M_{CC} = 1.18, 1.29 and 1.14 corresponding to an extra mineralization of 58, 65 and 38 kg ha^{-1} yr^{-1} respectively. These values were little affected by the climate change (scenario S3) which resulted in a small decrease in the annual N input from catch crops only at Thibie (-7 kg ha^{-1} yr^{-1} on average). The mean relative mineralization rate (M_{CC}) over the 60-year period was 1.01, 1.02 and 0.74 at Boigneville, Thibie and Kerlavic, respectively. The lower annual extra mineralization simulated at Kerlavic is mainly attributed to the type of catch crop residue with a higher C:N and secondarily to the soil type.

4.3.3. Nitrate leaching

Figure 6 shows the cumulative reduction in nitrate leached due to catch crops over time, expressed versus the cumulative amount of drained water. Over 60 years, the N saved from leaching with continuous catch crops (scenario S3) represented 1209, 665 and 670 kg N ha^{-1} at Boigneville, Thibie and Kerlavic respectively. Repeated catch crops resulted in a mean abatement of nitrate concentration in drained water of 46, 35 and 8 mg NO_3^- L^{-1} respectively. The kinetics were almost linear during the first twenty years, indicating that catch crop efficiency in reducing nitrate leaching was constant during these years. Later on, the kinetics became curvilinear, particularly at Kerlavic, showing that catch crops became less and less efficient at preventing nitrate leaching. This change was mainly due to the progressive increase in N mineralization rate which is harmful particularly during the long intercrop period (wheat-maize). An alternative to limit this effect (without changing rotation) was to reduce N fertilisation rate, as proposed in scenario S5. Comparing scenarios S3 and S5 shows that fertiliser adjustment was efficient in reducing N leaching on the long term. It was able to save an extra 120, 102 and 299 kg N ha^{-1} over 60 years at Boigneville, Thibie and Kerlavic respectively. However, catch crop efficiency still decreased over time. A lower frequency of catch crop establishment in the rotation (scenario S4) also weakened its efficiency in reducing nitrate leaching, since the reduction in N leached was only 476, 325 and 114 kg ha^{-1} over the 60-year period, and the corresponding nitrate abatement in drained water was 18, 17 and 1 mg L^{-1} respectively. After abandonment of catch crops, N leaching increased greatly and became greater than without previous catch crop history during about the next 25 years. Over this period, the mean amount of N leached was 4, 9 and 3 kg ha^{-1} yr^{-1} greater than in the control treatment (NoCC), with a strong difference in the first years. This adverse effect on N leaching was due to higher mineralization which resulted in higher N losses during winter. However, the establishment of catch crops during 15 years had a global beneficial effect because they could save 251, 146 and 50 kg N ha^{-1} over the 60 years period at Boigneville, Thibie and Kerlavic respectively.

5. Discussion

5.1. Performance of STICS model in continuous simulations

The first step of this study consisted of evaluating the performance of the model in simulating crop growth and uptake and environmental variables in three different pedo-climatic situations. After this calibration stage which appeared necessary, the continuous simulations at the three sites over 15 years were satisfactory and as good as found in annual studies (e.g. Brisson et al., 2002; Jego et al., 2008). The simulated fertiliser N use efficiencies, which depend on fertiliser type, crop growth rate and soil properties, were close to the mean measured values. The model simulated slightly negative effects of catch crops on the N uptake of succeeding crops whereas the observed effects were nil or

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slightly positive (Table 7). Positive effect on biomass and N uptake have been reported by Hansen and Djurhuus (1997). The absence of positive effects in the first years could be due to either a lack of sensitivity of N uptake to N mineralization, or a lack of synchrony between extra mineralization due to catch crops and crop N demand in the model. Since the residue decomposition model in STICS has been successfully validated on decomposition of various catch crop residues in soil (Justes et al., 2009), the first hypothesis seems the most appropriate. We also found that soil mineral N was poorly simulated, although unbiased and better than reported by Houlès et al. (2004). In contrast to another evaluation of STICS model (Sierra et al., 2003), soil water content at harvest was not as well simulated, although it remained correct. In our study, drainage was overestimated by 10 to 20%, as also reported by Schnebelen et al. (2004); however, we did not obtain a systematic overestimation of N leaching which was correctly simulated. The simulated effects of catch crops on leaching were well predicted in two sites out of three.

5.2. N mineralization and storage in soil over 13-17 years

The kinetics of net mineralization *in situ* was well simulated by the STICS model after calibration. This result was obtained with standard parameterisation of soil mineralization at Thibie, while modifications were needed on the two other sites to simulate well both mineralization and organic N sequestration in soil. The dynamics of mineralization at Boigneville and Kerlavic were correctly simulated by increasing the fraction of active organic matter in soil from 35% to 44% and 60% respectively, indicating that this fraction could be dependent on soil characteristics, particularly on previous land use history. According to models and authors, the active fraction can vary from 20-40% (Ludwig et al., 2003; Ludwig et al., 2007) to 90% (ROTHC, Coleman and Jenkinson, 1996). The large active fraction found at Kerlavic is attributed to the specific history of this site, with a previous grassland. Extra N mineralization due to catch crops was well simulated by the model over 13-17 years after calibration. The hypotheses made about the importance of root biomass had a significant impact on the simulated dynamics and its consistence with measured data. Indeed, we

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had to consider a large root biomass of ryegrass (larger than measured at harvest) in order to correctly simulate N dynamics at Kerlavic (Constantin et al., 2011). Roots could represent an important contribution to C and N storage in soil (e.g. Balesdent and Balabane, 1996). The importance of this phenomenon has not received much attention in STICS model for two reasons: the lack of experimental data and the fact that the model has mainly been used in annual simulations. In summary, STICS model thus parameterized was able to simulate correctly and the effects of catch crop on N mineralization and sequestration in the mid-term and could be used to extrapolate to the longer term.

5.3. Long-term effects of catch crops and steady state

The model predicted that under constant rotation and repeated catch crops, the annual mineralization increased progressively and then stabilised (within 10%) after 23 to 45 years. The former prediction was confirmed in two out three sites since significant cumulative effects were observed at Thibie and Kerlavic during the first 15 years (Constantin et al., 2011). The annual extra mineralization due to catch crops on year *n* originate both from fresh catch crop residues (grown in year *n*-1) and from stabilized organic matter formed earlier during decomposition of the previous catch crop residues (grown in years 1 to *n*). The fresh residues contribute positively or negatively to this annual rate depending on their C:N ratio (e.g. Whitmore and Groot, 1997; Trinsoutrot et al., 2000; Justes et al., 2009). The immobilisation of N due to the higher C:N ratio of ryegrass residues explains the lower annual mineralization rate simulated over 60 years at Kerlavic (74%) than at the two other sites (>100%). N immobilization occurs in soil during the first stages of decomposition, at the expense of soil mineral N. Therefore the total amount of N which becomes stabilized exceeds the amount of N contained in the crop residues. This is why the relative rate of mineralization (*Mcc*) can be greater than 1 as mentioned previously. These high annual rates highlight the necessity of considering the previous catch crop history when evaluating the annual effect of catch crops.

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5.4. N stock changes with continuous catch crops and effects of climate change

The model also predicted that the N sequestered due to catch crops allowed maintaining the soil organic matter level at steady state at two sites. At the third site (Kerlavic), repeated catch crops limited but could not hamper the decline in SOM after grassland destruction. The range of decrease at Kerlavic corresponded to the 30-50% decrease found after conversion of natural to agricultural ecosystems over 50-100 years in temperate regions (Lal, 2008). The positive effect of catch crops on N sequestration simulated by the model is in accordance with previous reports of positive effects on N and C sequestration (Singh et al., 1998; Blombäck et al., 2003). In our simulations, climate change led to a moderate increase in net N mineralization and reduction in soil organic N, which agrees with previous results for soil organic carbon (Hungate et al., 2009). In fact, the climate change involves two opposing effects: an increase in mineralization rate and an increase in SOM humification due to higher crop biomass and C return (Lal, 2008). The steady state obtained after 23-45 years with continuous catch crops was reached when the inputs in soil humified matter were equal to the outputs, meaning that the annual input of humified N due to catch crops (N of residues + N immobilised from the soil) was equal to the extra annual mineralization. The steady state occurred at a lower level when catch crop frequency declined due to smaller N inputs. When catch crops were abandoned, the extra soil organic N progressively decreased to become negligible after 60 years. This decline was also simulated by the FASSET model in Danish conditions when catch crops were stopped after 30 years (Bernsten et al., 2006). It occurred at a slower rate: nearly 20% of extra N sequestered remained in the soil 75 years after ceasing catch crops, while only 6-8% remained after 60 years in our simulations.

5.5. Catch crop efficiency in decreasing leaching and fertilisation

The reduction in nitrate leaching simulated by the model over the long-term confirmed that fertilisation rate needs to be adjusted after a few years to maintain the efficiency of the catch crops to reduce N leaching. The decrease in N fertilisation rate by 20-24 kg ha^{-1} yr^{-1} to maintain crop

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biomass production at the level of the control was similar to the reduction of 15-27 and 23 kg ha^{-1} yr^{-1} estimated in previous studies after 19 to 25 years of repeated catch crops (Hansen et al., 2000; Berntsen et al., 2006). It allows compensating for the increase in net N mineralization with repeated catch crops; when the annual mineralization rate reaches a steady state, the fertilisation rate does not have to be reduced further. The decrease in catch crop efficiency for reducing nitrate concentration in drained water can be expected at constant N fertilisation because of the enhanced mineralization (Berntsen, 2006). The enhanced mineralization due to the extra organic N remaining in soil after stopping catch crops resulted in greater amounts of N leached than in the control, confirming previous findings (Thomsen and Christensen, 1999; Hansen et al., 2000). However, in our case this phenomenon lasted much more than four years and nitrate leaching remained higher than in the control during the whole simulation period, although with a progressive decrease. Overall catch crops had a positive effect on N leaching over 60 years and their negative effects could be minimised by adjusting the fertilisation rate to the higher mineralization, particularly during the first years after stopping catch crops. In all cases, catch crops lead to slow down the nitrogen cascade (Galloway et al., 2003). The 17-18% N leaching reduction when catch crop frequency was 33-50% was slightly lower than the 23-28% found in other studies (Olesen et al., 2004; Beaudoin et al., 2005). Our results indicate that, even with a low catch crop frequency, the fertilisation rate should be decreased in the long term to maintain a good reduction in nitrate leaching. This is contradictory with the hypothesis of MacDonald et al. (2005) that adjustments of fertiliser N recommendations are not necessary in the case of small cover crops grown once every 3-4 years.

6. Conclusions

The crop-soil model STICS satisfactorily predicted crop and soil parameters in continuous simulations over 15 years, confirming the robustness of the model which correctly reproduced the N fate in three different pedo-climatic situations. A few parameters had to be calibrated because they were not or could not be measured. Long-term simulations allowed us to determine the steady state of net N mineralization and storage in soil due to repeated catch crops and confirmed the need to adjust fertilisation rates when catch crops are grown repeatedly. The model simulated negative effects of abandoning catch crops on N leaching, linked to changes in extra N in soil and extra mineralization, years after catch cropping has ceased. The model outputs are logical with our understanding of SOM turnover, although we cannot be sure of the intensity of the reduction in catch crop efficiency with respect to nitrate leaching. The results presented here should be compared with data from very long-term experiments to confirm these results. To obtain more reliable simulations over the longer term, better data are needed on catch crop biomass, particularly the root system, and the effects on nitrate leaching. Similarly, the active organic fraction should be determined according to soil characteristics and previous land history. Long-term experiments and simulation studies are complementary tools for defining sustainable agricultural practices.

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	Boigneville	Thibie	Kerlavic
Rotation [a]	SP /[b]/WW /[b]/ SB /[b]/	SP /[b]/ WW /[b]/ S /[b]/ (until 2003) SB /[b]/ S / WW /[b]/ (after 2003)	M / WW /[b]/
Fallow period [c]	CC or NoCC	CC or NoCC	CC or NoCC
Catch crop: species, frequency	White mustard (*Sinapis alba*), every year	Radish (*Raphanus satinus*), every year [d]	Italian ryegrass (*Lolium multiflorum*), 1 year/2
Nitrogen treatment [e]	N	N or N-	N
Form of N fertiliser	Solid ammonium nitrate	Liquid urea ammonium-nitrate	Solid ammonium nitrate
Mean N rate (kg $ha^{-1}yr^{-1}$)	103	85 (N-) and 124 (N)	125
Duration (years)	16	13 (N-) or 17 (N)	13

[a] WW = winter wheat, SB = spring barley, SP = spring pea, M = silage maize, S = sugarbeet.
[b] Fallow period with catch crops in the CC treatment.
[c] CC = with catch crop, No CC = without catch crop.
[d] 2 years out of 3 after 2003.
[e] N = recommended rate, N- = reduced rate (69% of recommended rate).

Table 1: Main characteristics of the three mid term experiments.

		Boigneville		Thibie		Kerlavic	
		0-30 cm	30-90 cm	0-30 cm	30-110 cm	0-30 cm	30-90 cm
Clay	g kg^{-1}	230		90 [a]		159	
Organic N [b]	g kg^{-1}	1.14		1.51		2.78	
Organic C [b]	g kg^{-1}	10.5		14.2		29.8	
C:N ratio [b]		9.2		9.4		10.7	
$CaCO_3$	g kg^{-1}	20		808		0	
pH		7.0		8.3		5.8	
Bulk density [b]	g cm^{-3}	1.42	1.50	1.40	1.50	1.26	1.43
W_{FC} [c]	g kg^{-1}	251	243	269	240	332	271
W_{WP} [c]	g kg^{-1}	114	115	109	119	131	112
Albedo of bare soil [d]		0.16		0.31		0.15	
Mineralisation depth [e]	cm	25.3		26.4		18.7	

[a] Measured after decarbonation.
[b] Measured at harvest in 2007.
[c] Water content at field capacity and permanent wilting point, respectively.
[d] Estimated with soil texture as proposed by Brisson et al. (2008).
[e] Equal to 110% of ploughing depth.

Table 2: Mean soil characteristics used in STICS model at each site.

Scenario	Catch crop frequency (%)		Reduced N fertilisation		Climate change
	0-X years [a]	X-60 years	0-X years	X-60 years	
S0[b]	0	0	No	No	No
S1	0	0	No	No	Yes
S2[b]	100 [c]	100 [c]	No	No	No
S3	100 [c]	100 [c]	No	No	Yes
S4	33 [d]	33 [d]	No	No	Yes
S5	100 [c]	100 [c]	No	Yes	Yes
S6	100 [c]	0	No	No	Yes

[a] X = 16 at Boigneville and 13 at Thibie and Kerlavic (duration of experimental period).
[b] Scenario observed over 13-16 years.
[c] 50% at Kerlavic (once every two years).
[d] 25% at Kerlavic (once every four years).

Table 3: Scenarios tested over 60 years.

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Crop		Wheat	Sugarbeet	Pea	Maize	Barley	Mustard	Ryegrass
	n	132	34	9	29	48	39	34
SWC	MD	18	3	-19	2	-3	2	-2
(mm)	RMSE	51	35.4	29.0	29	47	19	22
	EF	*0.58*	*0.93*	*0.87*	*0.91*	*0.82*	*0.85*	*0.84*
SMN	MD	5	-11	9	-27	-14	-14	-12
(kg N ha^{-1})	RMSE	41	74	35	55	44	27	33
	EF	*0.37*	*0.63*	*0.20*	*0.18*	*0.36*	*0.59*	*0.66*
Aerial biomass	MD	0.4	-1.6	-0.4	-1.6	-0.9	-0.3	0.2
(t DM ha^{-1})	RMSE	2.1	3.6	1.1	2.9	2.7	0.8	1.2
	EF	*0.90*	*0.85*	*0.94*	*0.83*	*0.70*	*0.88*	*0.34*
Harvested biomass	MD	-0.4	0.9	-1.2		-1.6		
(t DM ha^{-1})	RMSE	1.6	2.6	1.5	ND	2.2	ND	ND
	EF	*0.57*	*0.85*	*-3.5*		*-0.49*		
Aerial N uptake	MD	-2	-15	-17	1	10	-17	-8
(kg N ha^{-1})	RMSE	34	42	38	31	34	30	31
	EF	*0.84*	*0.75*	*0.85*	*0.80*	*0.64*	*0.81*	*0.60*

Table 4: Performances of STICS model for various crops against the "reference" database

		Annual simulations				Continuous simulations	
		Maximal rooting depth (cm)	Lifespan of winter wheat leaves (days)	Lifespan of catch crop leaves (days)	Potential of fertilizer N loss [a] (%)	Active SOM fraction (%)	Initial organic N content (g kg^{-1})
Boigneville	Initial	90	200	150	15%	0.35	1.14 [b]
	Fitted	70	100	90	15%	0.44	1.21
Thibie	Initial	90	200	150	15%	0.35	1.51 [b]
	Fitted	85	100	100	15%	0.35	1.52
Kerlavic	Initial	90	200	140	15%	0.35	2.78 [b]
	Fitted	60	100	80	35%	0.60	3.20

[a] Due to denitrification (% of fertilizer-N added)
[b] Measured in 2007

Table 5: Model parameter values before ('initial') and after model calibration ('fitted'). The calibration was applied to half the "catch crop" database and the validation was made on the other half, for each site.

		Calibration dataset			Validation dataset		
		Boigneville	Thibie	Kerlavic	Boigneville	Thibie	Kerlavic
Number of observations		15	84	24	15	84	24
SWC at harvest (mm)	M[a]	217	220	233	221	217	221
	MD[b]	3	2	23	-1	10	35
	RMSE[c]	27	39	42	23	39	51
	EF[d]	0.11	0.26	0.38	0.43	0.23	0.01
SMN at harvest (kg N ha^{-1})	M	44	44	36	42	39	43
	MD	15	2	6	6	10	6
	RMSE	25	29	14	26	29	17
	EF	-1.95	-0.93	-0.48	-2.00	-1.06	-0.28
Aerial biomass (t DM ha^{-1})	M	8.1	10.4	10.2	9.0	9.4	10.1
	MD	0.7	0.4	2.2	0.2	0.6	2.2
	RMSE	1.8	4.3	3.9	1.7	4.3	3.8
	EF	0.90	0.72	0.18	0.92	0.72	0.24
Harvested biomass (t DM ha^{-1})	M	6.3	9.4	-	6.5	9.8	-
	MD	-0.5	0.2	-	-0.9	-0.3	-
	RMSE	1.2	2.9	-	1.6	2.8	-
	EF	0.53	0.73	-	0.20	0.76	-
Aerial N uptake (kg N ha^{-1})	M	142	161	156	155	152	153
	MD	4	-8	12	-2	-7	11
	RMSE	26	51	36	24	48	37
	EF	0.90	0.68	0.41	0.89	0.75	0.53
Harvested N (kg N ha^{-1})	M	147	125	-	149	128	-
	MD	-16	4	-	-26	-4	-
	RMSE	28	31	-	36	29	-
	EF	0.41	0.06	-	0.13	0.22	-
Drained water (mm)	M	152	130	593	148	107	563
	MD	33	13	67	30	23	88
	RMSE	57	53	160	67	54	181
	EF	0.49	0.66	0.58	0.38	0.57	0.44
Leached N (kg N ha^{-1})	M	25	22	55	23	19	55
	MD	4	-3	7	9	-2	6
	RMSE	18	18	26	21	14	29
	EF	-0.34	0.41	0.44	-0.36	0.54	0.18

[a] M = mean observed value.
[b] MD = mean deviation
[c] RMSE = root mean square error
[d] EF = model efficiency

Table 6: Model evaluation against the "catch crop" database using continuous simulations: mean observed value and statistical criteria for soil water content (SWC), mineral N content (SMN), crop production at harvest, drained water and leached N.

	Effect*	Site	Observed	Simulated	*Correlation coefficient*	*Model efficiency*
			kg ha^{-1} yr^{-1}			
ΔN uptake	S2-S0	Boigneville	0	-8	*0.91(ns)*	*0.67*
	S2-S0	Thibie	4	-7		
	S2-S0	Kerlavic	4	3		
	N^{-}- N	Thibie	-24	-21		
ΔN leached	S2-S0	Boigneville	-11	-25	*0.80 (ns)*	*0.55*
	S2-S0	Thibie	-18	-18		
	S2-S0	Kerlavic	-32	-28		
	N^{-}- N	Thibie	-3	-1		

* S2-S0 = catch crop effect
N^{-} - N = reduced fertilisation effect.

Table 7: Observed and simulated extra N uptake and extra N leached due to catch crops (S2) and reduced fertilisation (N^{-}), compared with conventional practices (S0 and N) in continuous simulations.

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Figure 1 Observed and simulated water contents in the soil profile (SWC) a) at several dates per year in the "reference" database and b) at harvest of the main crops in the "catch crop" database.

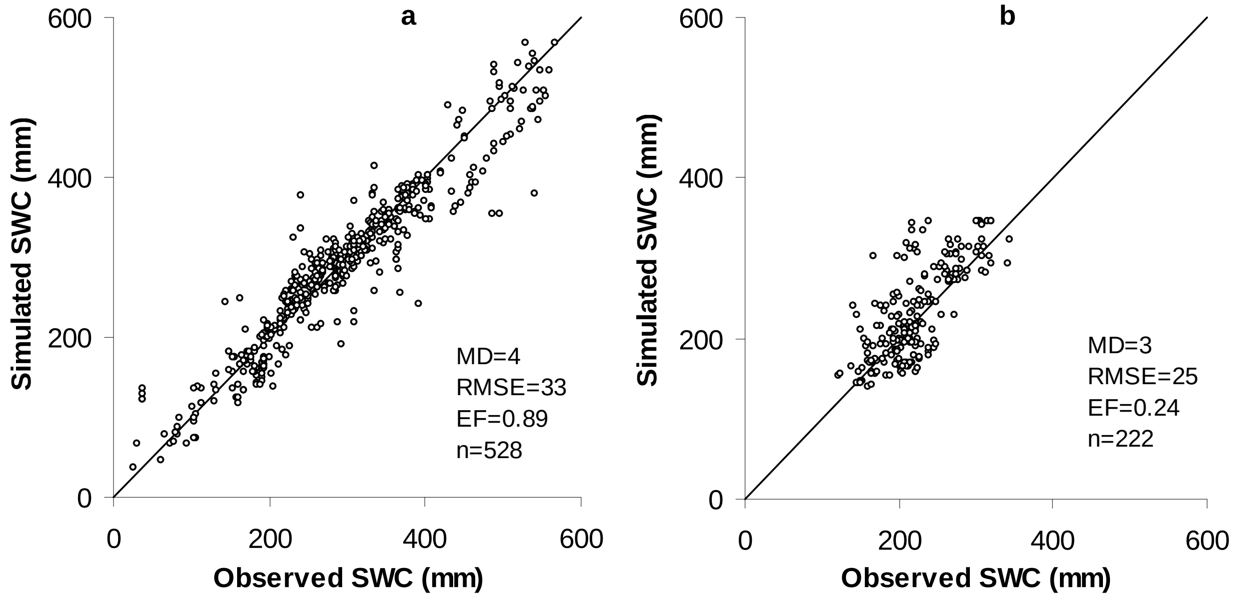

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Figure 2 Observed and simulated kinetics of cumulative net N mineralization at Boigneville (a), Thibie (b) and Kerlavic (c), for scenarios S0 and S2 over 13-17 years in continuous simulations.

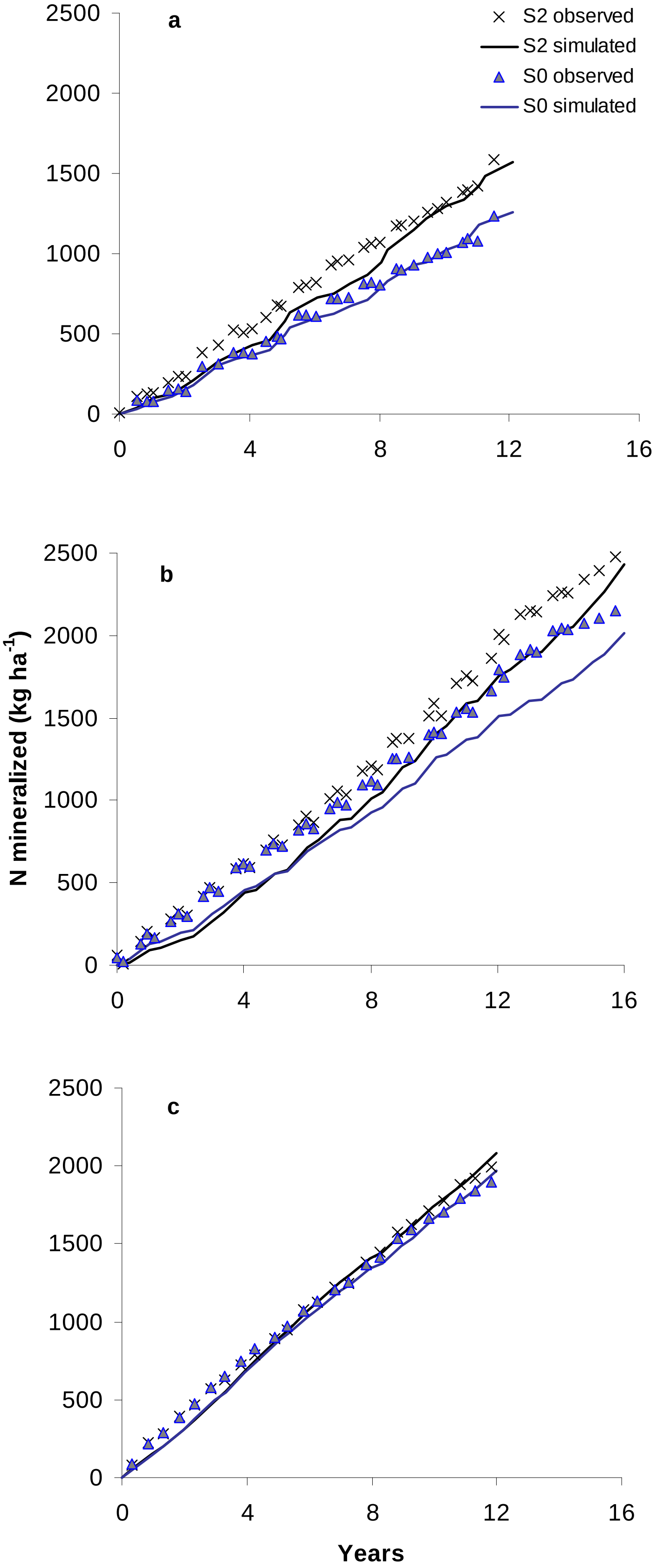

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Figure 3 Kinetics of organic N sequestered in soil (ΔN stock) due to catch crops, simulated with four scenarios (continuous lines) at Boigneville (a), Thibie (b) and Kerlavic (c). The symbols represent the mean and confidence interval of the measured ΔN stock after 13-17 years (corresponding to scenario S3).

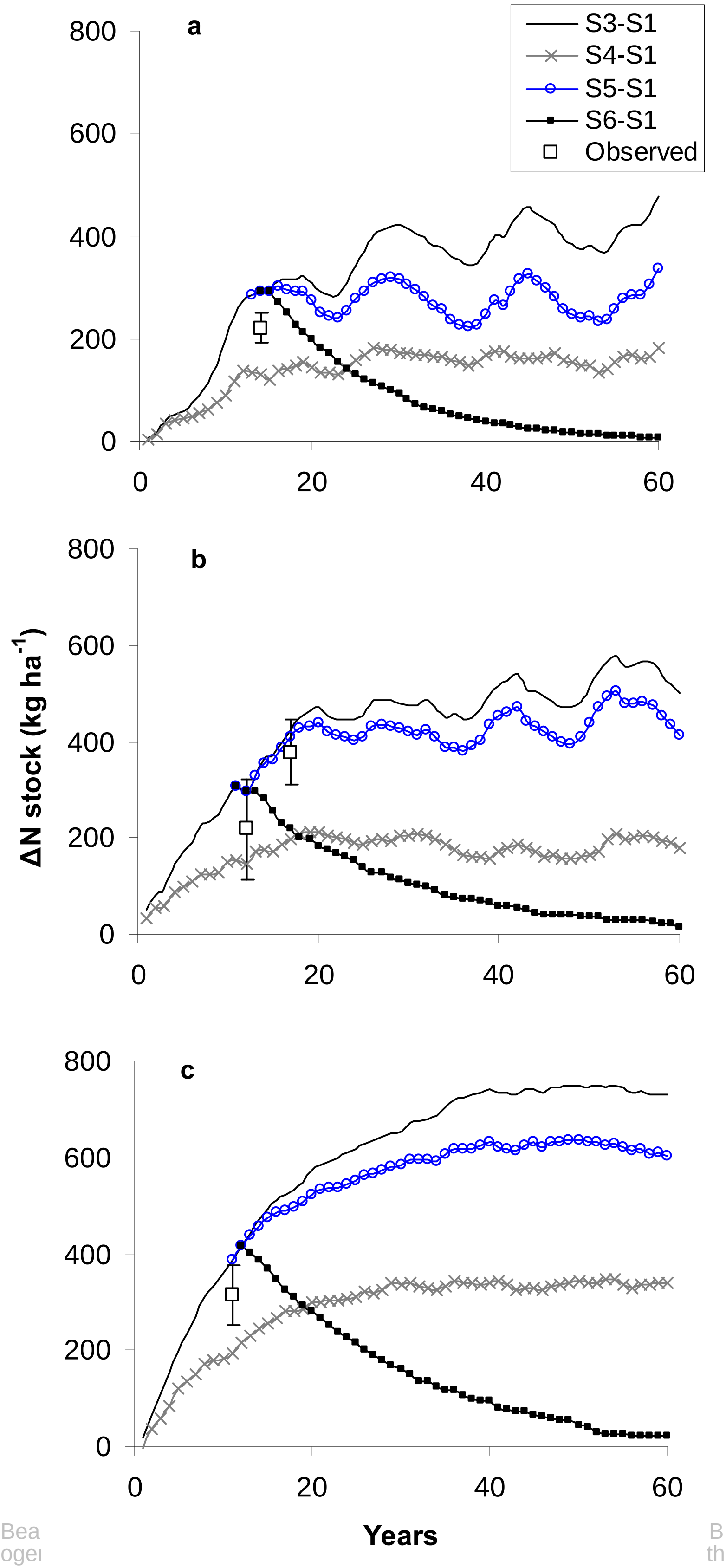

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Figure 4 Kinetics of extra N mineralization (cumulative) due to catch crops, simulated with the four scenarios (continuous lines) at Boigneville (a), Thibie (b) and Kerlavic (c). The symbols represent the "observed" values which were calculated using a N mass balance (see text) and correspond to scenario S3.

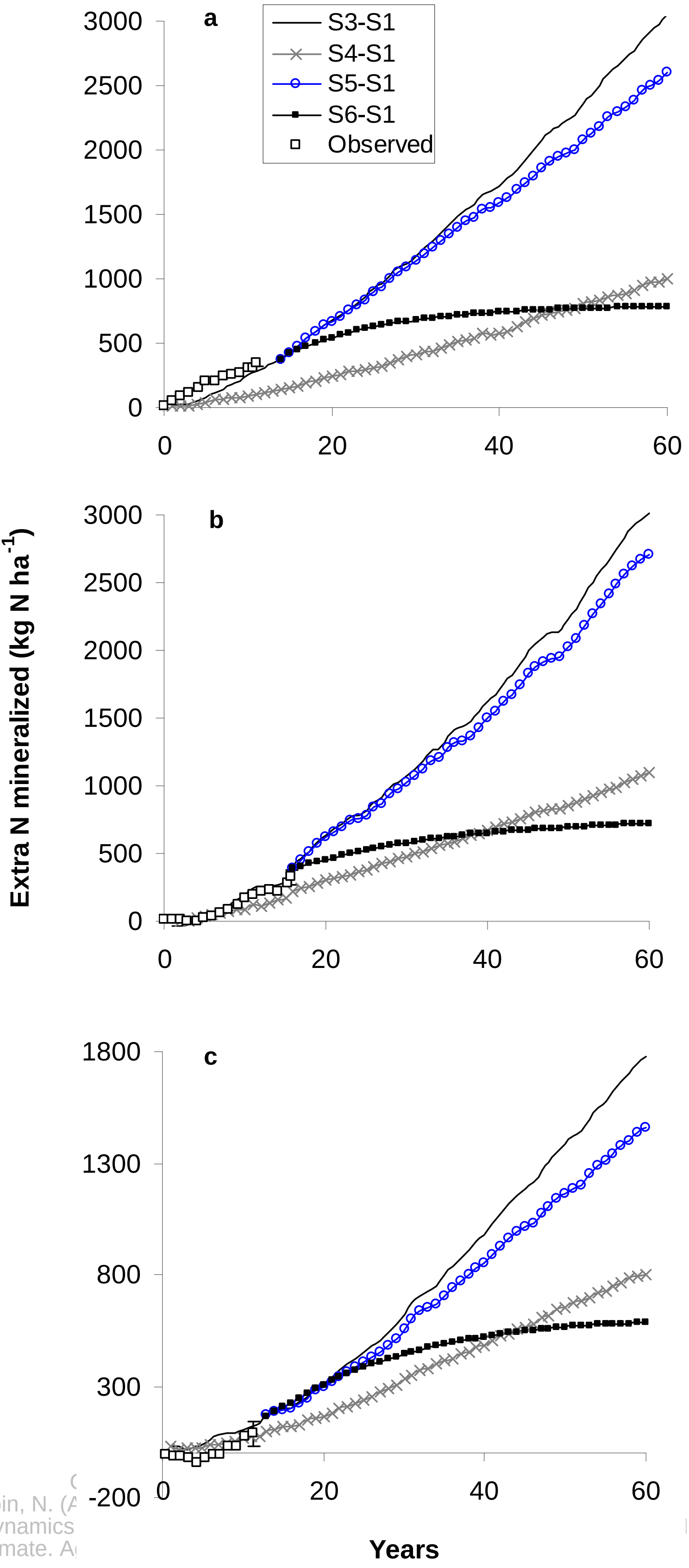

Figure 5 Evolution of the annual relative mineralization rate (M_{CC}) due to catch crops simulated over 60 years in scenarios S2 and S3 at Boigneville (a), Thibie (b) and Kerlavic (c). M_{CC} is the ratio between the extra N mineralized due to catch crops during year *n* and the N added to soil by catch crops during year *n*-1. Symbols are the values simulated by STICS; continuous lines are the fitted curves (exponential).

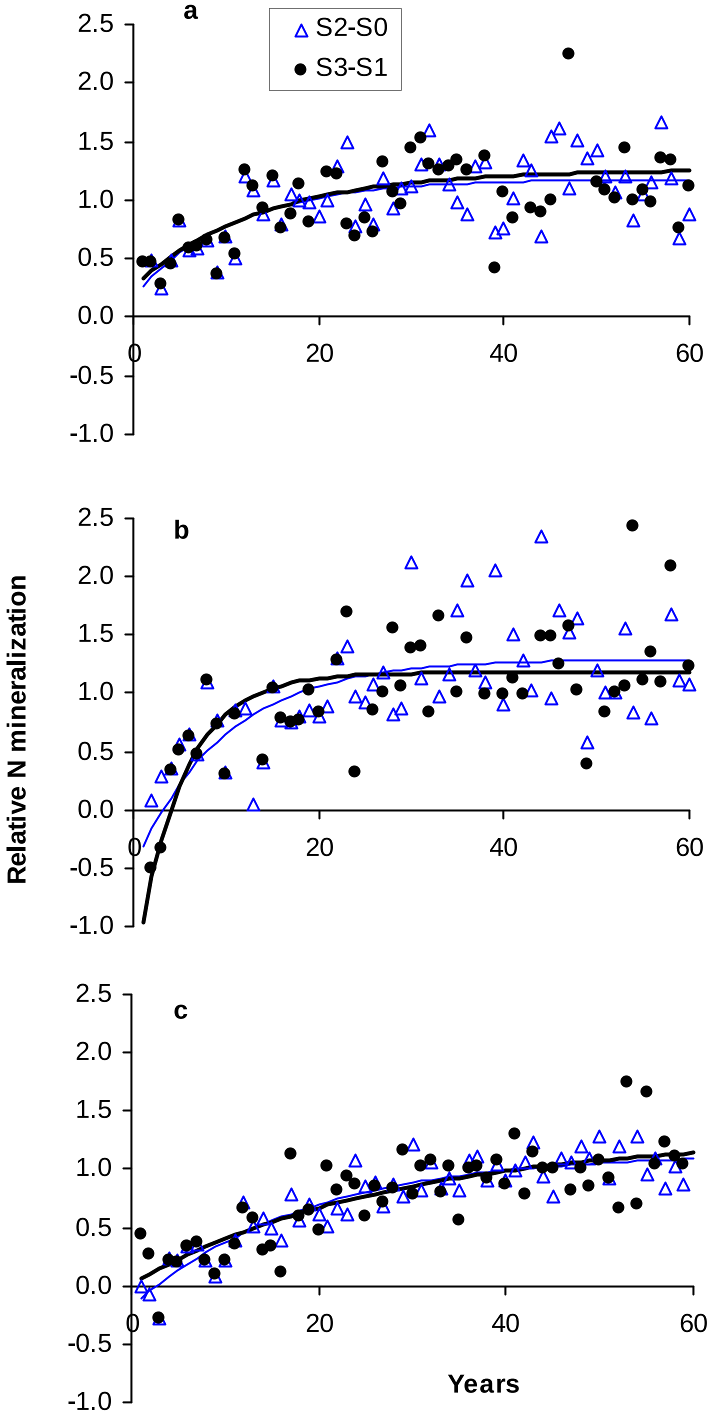

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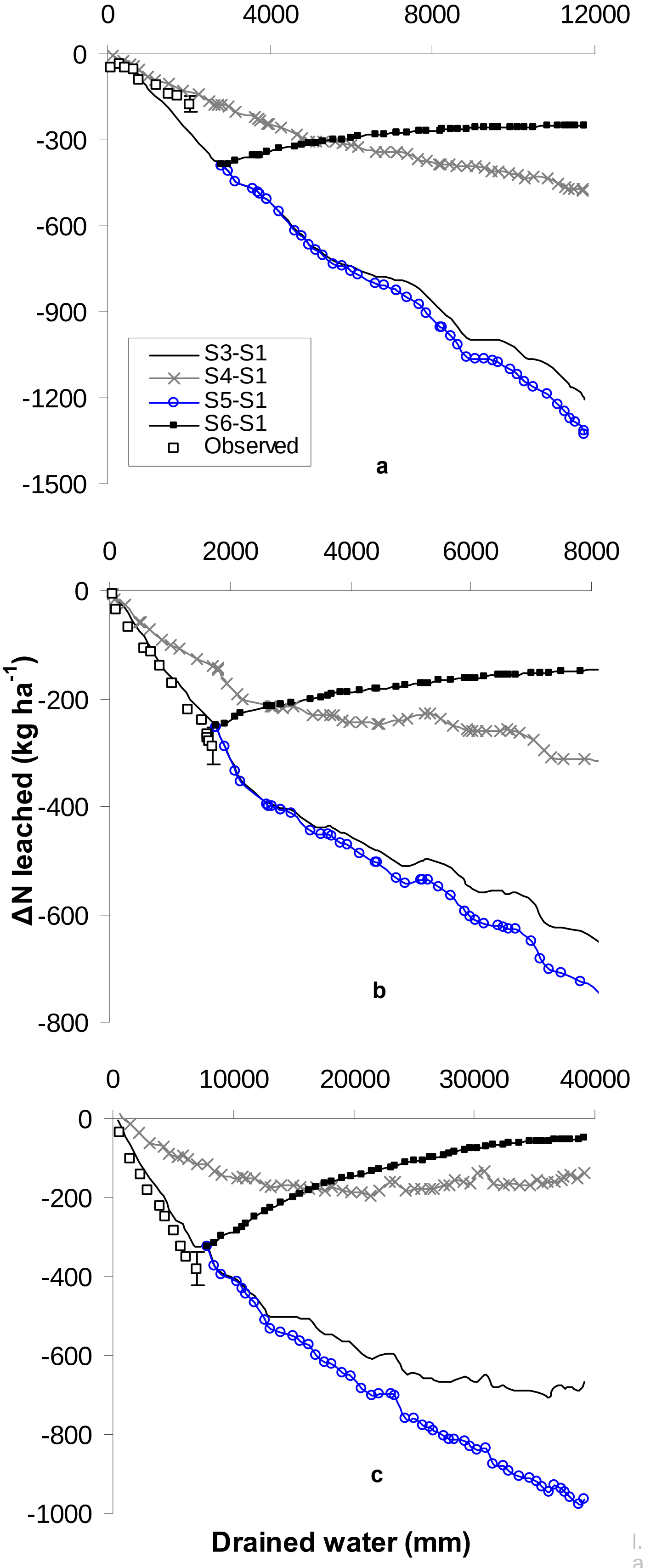
Figure 6 Cumulative extra N leached due to catch crops versus cumulative drained water, simulated over 60 years in scenarios S3-S6 at Boigneville (a), Thibie (b) and Kerlavic (c). The symbols represent the mean and confidence interval of the measured extra N leached (corresponding to scenario S3).



Co l., Duval, J., Mary, B. (2012). L and simulations with STICS model in a temperate climate. Agriculture, Ecosystems and Environment, 147, 36-46. , DOI : 10.1016/j.agee.2011.06.006