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

Julie Constantin, Nicolas Beaudoin, Marie Launay, Jérôme Duval, Bruno B. Mary

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3 Constantin J.[1], Beaudoin N.[1], Launay M.[2], Duval J.[1], Mary B.[1]

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5 [1] INRA Agro-Impact, Site de Laon, Pôle du Griffon, 02000 Barenton-Bugny, France

6 [2] INRA Agroclim, Domaine Saint Paul, Site Agroparc 84914 Avignon Cedex 9, France

7

8 <u>Corresponding author</u>: Nicolas Beaudoin

9   Tel: (+33) 323-240 766 240 766

10   E-mail: nicolas.beaudoin@laon.inra.fr

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1. Abstract

16

17   The long term effects of repeated catch crops on N dynamics in arable farming were assessed using

18   mid-term experiments and long-term simulations. The soil-crop model STICS (v6.9) was tested

19   against a database provided by three experiments (13-17 years) carried out in Northern France,

20   including treatments with or without repeated catch crops. STICS performance was checked for

21   crop biomass, N uptake, soil water content and mineral N at harvest of main crops, drained water, N

22   leaching and mineralization rates. The model satisfactorily reproduced these variables, except for

23   soil mineral N and N leached at one site. N leached was predicted with a slight bias, between -3 and

24   +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

25   model simulated correctly the N uptake by catch crops and the kinetics of extra N mineralization

26   due to catch crops. Seven scenarios varying in the presence of catch crops, fertilization rate and

27   climate were simulated on long-term (60 years); their effects on N uptake, soil N storage, N

28   mineralization and nitrate leaching were compared by difference with a control scenario. Repeated

29   catch crops lead to reduce N leaching, sequester organic N and increase N mineralization. The

30   model indicated that the sequestered N reached a maximum of 430-750 kg N ha^{-1} after 23-45 years

31   depending on site. The extra-mineralization due to catch crops progressively increased up to 38-65

32   kg N ha^{-1} yr^{-1}. A strategy of constant N fertilizer rate resulted in raising the N uptake of main crops

33   and slowing down the abatement of nitrate leaching. Conversely, when N fertilization rates were

34   reduced by 20-24 kg N ha^{-1} yr^{-1}, crop production remained stable and catch crops reduced N

35   leaching on the long term by 33-55%. Therefore catch crop is a promising technique for controlling

36   the N cascade.

37   **2. Introduction**

38   The last application of the European Nitrate Directive (91/676/EC) lead governments to stipulate

39   that catch crops must be grown in fallow periods to diminish the risk of nitrogen leaching. It is

40   therefore important to better assess the efficiency and sustainability of this practice in various pedo-

41   climatic contexts and cropping systems. The short-term effects of catch crops on N leaching and

42   balance are well known, but all impacts of the practice cannot be determined at this time scale. A

43   marked increase in N mineralization with catch crops has been reported in several studies (Schröder

44   et al., 1996; Torstensson and Aronsson, 2000). In addition, the higher soil organic matter found after

45   several years of repeated catch crops (Blombäck et al., 2003; Berntsen et al., 2006) indicates that

46   the long-term effects of catch crops could be different from those observed after one or two years.

47   The change in mineralization, which is partly due to increased soil organic matter (SOM), could

48   result in increased N uptake by main crops after 13 to 24 years (Hansen et al., 2000; Constantin et

49   al., 2011). However, the duration of these experiments was not long enough to determine the level

50   and timing of steady state conditions, particularly on mineralization and organic N in soil. These

51   authors suggested to adjust the N fertiliser rate in the long term in order to avoid the risk of

52   increasing nitrate leaching due to extra N mineralization from catch crop residues. It has also been

53   shown that N leaching was enhanced in fields having received repeated crops during several years

54   after catch crops are abandoned (Thomsen and Christensen, 1999), but the duration of this effect is

55   not well known.

56   Crop models can be useful tools in illustrating and predicting the long-term effects of agricultural

57   practices on the N cycle in various conditions. Models can help determine N mitigation, leaching or

58   turnover in soil as a result of improved agricultural practices such as catch crops (Aronsson and

59   Tortensson, 1998; Blombäck et al., 2003). However these models must be first tested and verified

60   against different experimental datasets in time and space in order to ensure their efficiency to

61   correctly simulate reality. To predict changes in a given agrosystem, models must be dynamic and

62   integrate the impacts of climate, soil properties, agricultural techniques and various crops, including

63   catch crops. STICS is a soil-crop model that simulates crop development and environmental

64   impacts, such as N leaching and sequestration (Brisson et al., 1998; Brisson et al., 2008). It has been

65   tested in annual simulations for a number of crops (e.g. Brisson et al., 2003) and calibrated to

66   simulate C and N dynamics during decomposition of various mature and young (catch) crops

67   residues (Nicolardot et al., 2001; Justes et al., 2009). STICS predictions of soil net N mineralization

68   kinetics in the short term are reasonably accurate, but the model may underestimate soil organic

69   carbon in the long term (Gabrielle et al., 2002). STICS was evaluated over the medium-term (8

70   years) in a small catchment in northern France for varied soils and crops including catch crops and

71   was able to correctly simulate N uptake by crops, N content in crop residues and soil mineral N at

72   harvest and in late autumn (Beaudoin et al., 2008). However, longer term tests are needed to

73   determine the ability of the model to predict long-term changes in N mineralization and storage in

74   soil as a function of alternative agricultural practices such as catch crops and in response to climate

75   change.

76   The objectives of this study were: i) to evaluate the performance of the STICS model in long-term

77   prediction of N balance and outputs by crop and leaching; ii) to determine the ability of STICS to

78   simulate N turnover in soil (sequestration and mineralization), particularly with continuous use of

79   catch crops; and iii) to test longer-term scenarios with and without global warming to determine

80   whether steady state could be reached and to analyse the effects of continuing or abandoning catch

81   crops.

82   **3. Materials and methods**

83   **3.1. Experimental databases**

84   Two databases, called "reference database" and "catch crop database", were used to calibrate and

85   evaluate the model. The reference database is an external database used to calibrate crop

86   parameters. It compiles several experiments with various crop species, including main crops (winter

87   wheat, sugar beet, spring peas, spring barley, maize) and catch crops (mustard, ryegrass), as

88   described by Beaudoin et al. (2008). It contains data on crop aerial biomass, grain yield, N in aerial

89   biomass and harvested organs, leaf area index, rooting depth, soil water and mineral N contents in 3

90   to 4 layers down to 90 or 120 cm. The catch crop database gathers experimental data obtained on

91   three long-term (13-17 years) field experiments in Northern France reported by Constantin et al.

92   (2010). The three experiments included a treatment with (CC) or without (NoCC) catch crop; an

93   additional N fertiliser treatment was tested on one site until 2003: reduced rate (N$^-$) versus

94   conventional rate (N). Crop rotation and N inputs differed between sites, as did catch crop species

95   and their frequency (Table 1). Biomass production and N content of main crops and catch crops

96   were measured every year. Soil mineral N (SMN) and water content (SWC) were measured over

97   90-110 cm depth three times per year: at harvest, end of autumn and mid-winter. Drained water was

98   measured in lysimeters, which were managed similarly to the field plots. Nitrate concentration was

99   measured in porous cups installed in all treatments at 90-110 cm depth: 7 porous cups were pooled

100 to make one replicate and were sampled 3 to 10 times per year according to drainage intensity.

101 These methods have been shown to be relevant to assess free drainage and nitrate leaching (Webster

102 et al., 1993). N leaching was calculated using the trapezoidal method (Lord and Shepherd, 1993),

103 which consists in interpolating drainage between two dates of measurement in the porous cups.

104 Fertiliser use efficiency was measured every year in two sites by the difference method (between

105 fertilized and unfertilized plots), and also in all sites during the last two years using ^{15}N labelled

106 fertilizers. *In situ* net N mineralization was calculated using soil N mineral balance, which takes

107 into account N inputs (fertilization, atmospheric deposition, symbiotic fixation), N outputs

108 (harvested N, leaching, gaseous losses) and SMN variation during the calculation period, according

109 to the procedure described by Constantin et al. (2011). Organic N and C stocks in soil were

110 measured at the end of the experiment at all sites. The catch crop database was managed for the

111 three sites using the open source software Postgre-SQL (www.postgresql.org). Data on soil

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112   characteristics, climate variables, crops, agricultural techniques, N fertilisation and all measured

113   data were recorded and an interface was created to allow the STICS model to be run automatically.

114   Half of the catch crop database was used to recalibrate a few crop and soil parameters when model

115   performance was unsatisfactory; the other half was used for model evaluation (Confalonieri et al.,

116   2009).

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118   **3.2. Overview of STICS model**

119   The soil crop model STICS is a dynamic model that simulates C, N and water cycles. It is a one-

120   dimensional model with a daily time step, which takes into account soil characteristics, climate and

121   agricultural practices (Brisson et al., 2008). The potential development stages, leaf growth and

122   growth rate of a given crop depend on photothermal units and solar radiation. The effective crop

123   growth rate is affected by water and nitrogen stresses and atmospheric CO_2 concentration. The soil

124   is divided into several layers with specific characteristics such as water content at field capacity,

125   permanent wilting point and bulk density. Residue decomposition in soil is simulated using three

126   compartments: the fresh organic matter, the microbial biomass and humified organic matter, the last

127   compartment being composed of an active and an inert fraction. N and C fluxes between these

128   compartments depend on their C:N ratio, soil temperature and water content, and four parameters:

129   the humification constant, the decomposition rate constant of the residues, the decay rate of the

130   microbial biomass and the assimilation yield of residue-C by the microbial biomass (Nicolardot et

131   al., 2001). The first two parameters depend on C:N ratio of residues while the last two do not. When

132   mineral N is exhausted in the soil, the decomposition rate of organic residues is reduced, the C:N

133   ratio of microbial biomass increases and the proportion of humified N is reduced (Giacomini et al.,

134   2007). Model parameterization of mature and catch crops residues was made using a large dataset

135   of laboratory incubations (Justes et al., 2009). The N mineralized from humified organic matter

136   depends on the potential mineralization rate of the soil, which depends on clay, $CaCO_3$ and organic

137   N contents in the biologically active layer, and the temperature and moisture conditions occurring in

138   this layer. STICS also simulates the gaseous losses (volatilisation and denitrification) derived from

139   fertilizer. They were simulated at the same level in the treatments with and without catch crops; this

140   result is consistent with the findings of Constantin et al. (2010).

141   **3.3. Inputs and calibration of the STICS model**

142   The models inputs concerning crop management and climate are available in the catch crop

143   database since they were routinely recorded. The soil characteristics of each site used in STICS are

144   shown at Table 2. The bulk density, the initial soil organic C content and C:N ratio of the soil were

145   set at the values measured in 2007. The water contents at field capacity (W_{FC}) and wilting point

146   (W_{WP}) were estimated using frequency analysis of measured water contents over the whole

147   experimental period (13-17 years). W_{FC} is defined as "the water content held in soil after excess

148   water has drained away, which usually takes place within 2–3 days after a rain" (Hénin et al., 1969).

149   In our experiments, water contents were never measured during rainy days, so that W_{FC} was

150   calculated as the mean of the highest values (first decile) of water contents measured in mid-winter.

151   W_{WP} was calculated as the mean of the lowest values (third centile) of the water contents measured

152   at summer harvests. The results compare favourably with those obtained with pedotransfer

153   functions (PDF): the mean value of W_{WP} differed by 7 g kg^{-1} soil from the PDF function of Wösten

154   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

155   highly dependent on soil structure and does not correspond to a constant water potential value (e.g.

156   Wösten et al., 2001). The depth of the biologically active layer ('mineralization depth') was

157   assumed to be 10% greater than the ploughing depth (Brisson et al., 2008). Using this rule,

158   Beaudoin et al. (2008) were able to simulate the N mineralization kinetics and organic matter

159   evolution of a permanent bare soil in a lysimeter.

160   The first step of calibration consisted in model calibration and evaluation against the independent

161   reference database. The model used in this paper (STICS version 6.9) had been previously

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162 calibrated and validated on the reference database for all crops grown at the three study sites, except

163 for radish. An additional parameterisation of spring barley was made on an additional independent

164 database. The model was then evaluated against the catch crop database. If necessary, a second

165 calibration was realized by adjusting a few crop and soil parameters against half of the catch crop

166 database (dataset without catch crops), using annual or continuous (over 13-17 years) simulations.

167 Annual simulations involved resetting SMN and SWC every year at harvest of main crops using the

168 observed values, while the model was initialised only once in continuous simulations and

169 simulations were run over 13-17 years. The calibration was applied when either the crop (biomass

170 or N uptake) or soil variables (SMN or SWC) were not satisfactorily simulated by the model. Three

171 parameters were calibrated using annual simulations: the maximal rooting depth, the lifespan of

172 leaves, and the potential of fertilizer loss which influences the N use efficiency of fertilizer. For

173 these annual simulations, the calibration method consisted in minimizing the sum of squared errors

174 between observed and simulated values by the simplex method using the software package

175 OptimiSTICS (Wallach et al., 2011). Continuous simulations were used to calibrate two other soil

176 parameters: the initial organic N content (which was not measured) and the active fraction of

177 humified organic matter, in order to correctly simulate the soil organic N and N mineralization

178 kinetics observed in the field. A trial-error method was used for this calibration step. The objective

179 was to mimic as well as possible N uptake, mineralization and leaching in control treatments

180 (without catch crops).

181 **3.4. Evaluation of STICS model performance**

182 Three statistical criteria were used to evaluate the performance of the model: the root mean square

183 error (RMSE), the mean deviation (MD) and the model efficiency (EF), calculated as follows:

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

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

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

185   where n is the number of observations, S_i and O_i are the simulated and observed values respectively

186   and $\overline{O}$ is the mean value of observed data. The *RMSE* provides the model prediction error, while the

187   *MD* gives the bias of the model. The *EF* estimates the model performance relative to the

188   experimental mean (Nash and Sutcliffe, 1970). An *EF* value close to zero indicates that the

189   simulation does not perform better than a constant model equal to the mean of observed data. The

190   combination of these indices gives a good overview of the model accuracy.

191   The mean effect of the improved practices (i.e. CC and N⁻) was obtained by difference with the

192   conventional practices (i.e. NoCC and N). The cumulative "extra mineralization" and leaching due

193   to catch crops was obtained by difference with the control treatment (CC - NoCC). At Thibie, it was

194   averaged between the fertilisation rate treatments (N and N-) because there was no significant

195   interaction between the two factors (Constantin et al., 2010).

196   **3.5. Catch crop management scenarios**

197   The model was used to simulate various scenarios in the long term. Simulations were performed

198   over 60 years (1990-2050), which include the first years of observations and the following 45 years.

199   The crop rotation and agricultural management were assumed to remain constant and similar to

200   those observed during the first 15 years. At Thibie, the initial rotation (sugarbeet – spring pea –

201   winter wheat) was simulated throughout and the introduction of spring barley after 13 years was not

202   considered. Seven scenarios (S0-S6) were simulated, varying in the presence and frequency of catch

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203   crops, N fertilisation rate and climate (Table 3). The reference scenarios, S0 and S1, considered no

204   catch crop and standard fertilisation combined with constant or changing climate, respectively.

205   Scenarios S2 and S3 included repeated catch crops during 60 years and standard fertilisation

206   without and with climate change, respectively. Scenario S4 considered a lower frequency of catch

207   crop establishment (once every three years at Boigneville and Thibie and once every four years at

208   Kerlavic) under changing climate and standard fertilisation. Scenario S5 simulated repeated catch

209   crops, climate change and a reduction in fertiliser rate after 15 years. The fertiliser dose was

210   decreased so that the simulated crop biomass in the treatment with catch crops remained equal to

211   that simulated for the control treatment (without catch crops), with a 3% tolerance. Scenario S6

212   considered constant fertilisation and climate change, but with abandonment of catch crops after 15

213   years.

214   Two climate series were built for each site by considering constant climate or climate change. The

215   first series was built using random sampling of the 13-17 climatic years of experiment to constitute

216   a 60-year scenario. The second series, taking into account climate change, was made using the A1B

217   scenario (IPCC Special Report on Emissions Scenarios). It is based on extrapolating the actual

218   climate data of our experimental period using the A1B climate scenario, which considers that the

219   mean world temperature will increase between 2.5 and 3.5°C by 2100. This scenario was applied to

220   each site using the statistical error correction proposed by Déqué (2007). It predicts that mean

221   temperature will increase by ~0.8-1.0 °C by 2050. Annual rainfall would decrease at Kerlavic by

222   125 mm (with a marked decrease in spring and summer), but would not change much at Boigneville

223   and Thibie (-23 and +24 mm). The change in CO_2 concentration in the atmosphere was not

224   simulated continuously, but a constant concentration of 450 ppm was assumed over the 60 year

225   period. This corresponds to the average of the present CO_2 concentration and the expected value in

226   2050.

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

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4.2.1. Evaluation on crop and soil variables

253   STICS performance was evaluated in continuous simulations against the catch crop database. The

254   model could simulate well the soil water contents both in the reference database and the catch crop

255   database (Figure 1). However the predictions were better in the reference database which showed a

256   larger variance and a better efficiency. Table 6 summarizes STICS performance for the catch crop

257   database. It shows that the quality of fit was about the same for the calibration and validation

258   datasets. SWC at harvest was well predicted, except at Kerlavic where it was overestimated ($MD =$

259   23-35 mm) particularly at harvest of winter wheat. SMN content at harvest was slightly

260   overestimated on average (in spite of a good prediction of net mineralization, see further) and the

261   model could not reproduce its variability. The model correctly simulated the aerial biomass of main

262   crops and catch crops at Boigneville and Thibie ($EF = 0.72$-0.92), as well as the harvested biomass.

263   At Kerlavic, the lower efficiency was associated with a large overestimation of wheat biomass,

264   which could be due to limiting factors not taken into account by the model. The total N uptake was

265   well simulated on all sites ($EF = 0.41$-0.90) without any bias; harvested N was correctly predicted

266   except at Boigneville where it was underestimated (mean $MD = $ -20 kg ha^{-1}). STICS could also

267   correctly simulate drainage and leaching, although the amount of drained water was slightly

268   overestimated on all sites (by 10-20%) and leached N overestimated (by about 25%) at Boigneville.

269   The variability of both variables was well mimicked by the model (positive efficiency), except for

270   N leached at Boigneville.

4.2.2. Ability to reproduce the effect of agricultural practices

272   The effect of agricultural practices on N uptake and N leaching was calculated by difference

273   between paired treatments: with *vs* without catch crops or reduced *vs* standard fertilisation (Table

274   7). The two practices had contrasted impacts: catch crops exerted a small effect on N uptake and a

275   strong effect on leached N whereas the opposite occurred for the reduction of fertilization. The

276   model was able to satisfactorily predict these effects: model efficiency was 0.67 and 0.55

277 respectively. The other variables of interest were soil N mineralized and organic N content. The

278 kinetics of net mineralization was well reproduced at all sites, with a slight underestimation at

279 Thibie (Figure 2). The mean difference between observed and simulated values of annual

280 mineralization was -1, -2 and +7 kg N ha^{-1} yr^{-1} at Boigneville, Thibie and Kerlavic, respectively.

281 The dynamics of extra N mineralization due to catch crops (i.e. the difference between CC and

282 NoCC treatments) differed between sites for both observed and simulated data (Figure 4). At

283 Boigneville, the model underestimated the net release of N due to catch crops (white mustard)

284 during the first years and gave satisfactory predictions thereafter. This underestimation was

285 probably due to the fact that the predicted C:N ratio of mustard residues was greater than that

286 observed, inducing a smaller release of mineral N in the months following catch crop destruction.

287 The extra mineralization due to radish was slightly overestimated after 12-15 years at Thibie,

288 whereas the mineralization due to ryegrass was well simulated over time at Kerlavic, with N

289 immobilisation in the first years followed by net N release. The simulated organic N stocks in soil at

290 the end of experiments (13-17 years) were rather close to those observed in the field (Figure 3). The

291 N sequestered due to catch crops varied from 162 to 351 kg N ha^{-1}. It was slightly overestimated by

292 the model, but predictions remained within the confidence interval of measurements. The effect of

293 reduced fertilisation, mainly due to a reduction in C and N returns to the soil, was well predicted by

294 the model. Finally, the model appeared to give satisfactory prediction of the effects of catch crops

295 and reduced fertilisation on N uptake, leaching, mineralization and sequestration; despite a small

296 underestimation of the positive effect of catch crops on N uptake, it could be used for simulating

297 scenarios in the long term.

298 **4.3. Simulation with catch crops over 60 years**

299 *4.3.1. N sequestered in soil*

300 Figure 3 shows the evolution of N sequestered in soil due to catch crops since the beginning of the

301 experiments, simulated during 60 years in scenarios S3 to S6. It confirms the positive effect of catch

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302 crops on the long term: scenarios including catch crops allowed soil organic N to increase between

303 430 and 750 kg N ha^{-1} in comparison with bare fallow soil (S1) depending on site and climate

304 series. The highest sequestration due to catch crops occurred at Kerlavic with ryegrass, while the

305 lowest was at Boigneville with mustard, N sequestration from radish at Thibie being intermediate.

306 Climate change resulted in slightly lower N sequestration at all sites (results not shown). When

307 catch crop frequency in the rotation was lowered from once every one or two years (S3) to once

308 every three or four years (S4), the N sequestered due to catch crops diminished by 292 to 388 kg N

309 ha^{-1} yr^{-1} (compared to scenario S3). In scenario S5, N fertilisation was adjusted (reduced by 20-24

310 kg ha^{-1} yr^{-1} after the first 13-16 years) to account for the greater mineralization due to continuous

311 catch crops and maintain the crop yields at the same level than in the control scenario. This resulted

312 in a slight decrease of N stocks (-73 to -132 kg ha^{-1}) compared with scenario S3, because crop

313 production and crop residues diminished. Abandoning catch crops (scenario S6) led to a progressive

314 decline in the extra N stored in the soil. The benefit of 13-16 years of repeated catch crops

315 disappeared progressively to reach zero after 60 years.

316 ### *4.3.2. Extra N mineralization due to catch crops*

317 In parallel to change in N sequestration, continuous catch crops enhanced soil mineralization

318 compared with simulations without catch crops. After 60 years of continuous catch crops (S3), the

319 cumulative extra N mineralized reached 2950-3000 kg ha^{-1} at Boigneville and Thibie and 1780 kg

320 ha^{-1} at Kerlavic (Figure 4). Thus the mean amount of N mineralized annually due to catch crops

321 would represent 50 and 30 kg ha^{-1} yr^{-1} respectively. Adjusting fertilisation (S5) slightly decreased

322 extra mineralization by 9-16% compared to S3. Reducing the frequency of catch crops decreased it

323 much further, from 53% to 68% according to site. Abandoning catch crops would induce a slow

324 return to the level of net mineralization simulated in the control treatment. N mineralization

325 remained higher during several years after catch cropping ceased, as long as organic N in soil

326 remained higher than in the control treatment. The extra mineralization (*ΔM*) of year *n* can be

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327   compared to the input of N from catch crop residues (N_{CC}) during year *n*-1; the ratio of these two

328   variables gives the relative mineralization rate: $M_{CC} = \Delta M / N_{CC}$ (Constantin et al., 2011). Figure 5

329   shows the evolution of M_{CC} simulated during 60 years, without or with climate change (scenarios

330   S2 and S3 respectively). The model simulates annual fluctuations due to variability in climate and

331   catch crop production with regard to quantity and quality of residues. However, the general trend is

332   an asymptotic increase in extra N mineralization over time for both climate scenarios. The results

333   could be fitted to an exponential function, the asymptote of which was reached (within 10%) in 23,

334   26 and 45 years at Boigneville, Thibie and Kerlavic respectively, without climate change. The

335   asymptote was M_{CC} = 1.18, 1.29 and 1.14 corresponding to an extra mineralization of 58, 65 and 38

336   kg ha^{-1} yr^{-1} respectively. These values were little affected by the climate change (scenario S3) which

337   resulted in a small decrease in the annual N input from catch crops only at Thibie (-7 kg ha^{-1} yr^{-1} on

338   average). The mean relative mineralization rate (M_{CC}) over the 60-year period was 1.01, 1.02 and

339   0.74 at Boigneville, Thibie and Kerlavic, respectively. The lower annual extra mineralization

340   simulated at Kerlavic is mainly attributed to the type of catch crop residue with a higher C:N and

341   secondarily to the soil type.

4.3.3. Nitrate leaching

343   Figure 6 shows the cumulative reduction in nitrate leached due to catch crops over time, expressed

344   versus the cumulative amount of drained water. Over 60 years, the N saved from leaching with

345   continuous catch crops (scenario S3) represented 1209, 665 and 670 kg N ha^{-1} at Boigneville,

346   Thibie and Kerlavic respectively. Repeated catch crops resulted in a mean abatement of nitrate

347   concentration in drained water of 46, 35 and 8 mg NO_3^- L^{-1} respectively. The kinetics were almost

348   linear during the first twenty years, indicating that catch crop efficiency in reducing nitrate leaching

349   was constant during these years. Later on, the kinetics became curvilinear, particularly at Kerlavic,

350   showing that catch crops became less and less efficient at preventing nitrate leaching. This change

351   was mainly due to the progressive increase in N mineralization rate which is harmful particularly

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352   during the long intercrop period (wheat-maize). An alternative to limit this effect (without changing

353   rotation) was to reduce N fertilisation rate, as proposed in scenario S5. Comparing scenarios S3 and

354   S5 shows that fertiliser adjustment was efficient in reducing N leaching on the long term. It was

355   able to save an extra 120, 102 and 299 kg N ha^{-1} over 60 years at Boigneville, Thibie and Kerlavic

356   respectively. However, catch crop efficiency still decreased over time. A lower frequency of catch

357   crop establishment in the rotation (scenario S4) also weakened its efficiency in reducing nitrate

358   leaching, since the reduction in N leached was only 476, 325 and 114 kg ha^{-1} over the 60-year

359   period, and the corresponding nitrate abatement in drained water was 18, 17 and 1 mg L^{-1}

360   respectively. After abandonment of catch crops, N leaching increased greatly and became greater

361   than without previous catch crop history during about the next 25 years. Over this period, the mean

362   amount of N leached was 4, 9 and 3 kg ha^{-1} yr^{-1} greater than in the control treatment (NoCC), with a

363   strong difference in the first years. This adverse effect on N leaching was due to higher

364   mineralization which resulted in higher N losses during winter. However, the establishment of catch

365   crops during 15 years had a global beneficial effect because they could save 251, 146 and 50 kg N

366   ha^{-1} over the 60 years period at Boigneville, Thibie and Kerlavic respectively.

367

5. Discussion

5.1. Performance of STICS model in continuous simulations

370   The first step of this study consisted of evaluating the performance of the model in simulating crop

371   growth and uptake and environmental variables in three different pedo-climatic situations. After this

372   calibration stage which appeared necessary, the continuous simulations at the three sites over 15

373   years were satisfactory and as good as found in annual studies (e.g. Brisson et al., 2002; Jego et al.,

374   2008). The simulated fertiliser N use efficiencies, which depend on fertiliser type, crop growth rate

375   and soil properties, were close to the mean measured values. The model simulated slightly negative

376   effects of catch crops on the N uptake of succeeding crops whereas the observed effects were nil or

16

377 slightly positive (Table 7). Positive effect on biomass and N uptake have been reported by Hansen

378 and Djurhuus (1997). The absence of positive effects in the first years could be due to either a lack

379 of sensitivity of N uptake to N mineralization, or a lack of synchrony between extra mineralization

380 due to catch crops and crop N demand in the model. Since the residue decomposition model in

381 STICS has been successfully validated on decomposition of various catch crop residues in soil

382 (Justes et al., 2009), the first hypothesis seems the most appropriate. We also found that soil mineral

383 N was poorly simulated, although unbiased and better than reported by Houlès et al. (2004). In

384 contrast to another evaluation of STICS model (Sierra et al., 2003), soil water content at harvest

385 was not as well simulated, although it remained correct. In our study, drainage was overestimated

386 by 10 to 20%, as also reported by Schnebelen et al. (2004); however, we did not obtain a systematic

387 overestimation of N leaching which was correctly simulated. The simulated effects of catch crops

388 on leaching were well predicted in two sites out of three.

389 **5.2. N mineralization and storage in soil over 13-17 years**

390 The kinetics of net mineralization *in situ* was well simulated by the STICS model after calibration.

391 This result was obtained with standard parameterisation of soil mineralization at Thibie, while

392 modifications were needed on the two other sites to simulate well both mineralization and organic

393 N sequestration in soil. The dynamics of mineralization at Boigneville and Kerlavic were correctly

394 simulated by increasing the fraction of active organic matter in soil from 35% to 44% and 60%

395 respectively, indicating that this fraction could be dependent on soil characteristics, particularly on

396 previous land use history. According to models and authors, the active fraction can vary from 20-

397 40% (Ludwig et al., 2003; Ludwig et al., 2007) to 90% (ROTHC, Coleman and Jenkinson, 1996).

398 The large active fraction found at Kerlavic is attributed to the specific history of this site, with a

399 previous grassland. Extra N mineralization due to catch crops was well simulated by the model over

400 13-17 years after calibration. The hypotheses made about the importance of root biomass had a

401 significant impact on the simulated dynamics and its consistence with measured data. Indeed, we

17

402 had to consider a large root biomass of ryegrass (larger than measured at harvest) in order to

403 correctly simulate N dynamics at Kerlavic (Constantin et al., 2011). Roots could represent an

404 important contribution to C and N storage in soil (e.g. Balesdent and Balabane, 1996). The

405 importance of this phenomenon has not received much attention in STICS model for two reasons:

406 the lack of experimental data and the fact that the model has mainly been used in annual

407 simulations. In summary, STICS model thus parameterized was able to simulate correctly and the

408 effects of catch crop on N mineralization and sequestration in the mid-term and could be used to

409 extrapolate to the longer term.

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

411 The model predicted that under constant rotation and repeated catch crops, the annual

412 mineralization increased progressively and then stabilised (within 10%) after 23 to 45 years. The

413 former prediction was confirmed in two out three sites since significant cumulative effects were

414 observed at Thibie and Kerlavic during the first 15 years (Constantin et al., 2011). The annual extra

415 mineralization due to catch crops on year n originate both from fresh catch crop residues (grown in

416 year n-1) and from stabilized organic matter formed earlier during decomposition of the previous

417 catch crop residues (grown in years 1 to n). The fresh residues contribute positively or negatively to

418 this annual rate depending on their C:N ratio (e.g. Whitmore and Groot, 1997; Trinsoutrot et al.,

419 2000; Justes et al., 2009). The immobilisation of N due to the higher C:N ratio of ryegrass residues

420 explains the lower annual mineralization rate simulated over 60 years at Kerlavic (74%) than at the

421 two other sites (>100%). N immobilization occurs in soil during the first stages of decomposition, at

422 the expense of soil mineral N. Therefore the total amount of N which becomes stabilized exceeds

423 the amount of N contained in the crop residues. This is why the relative rate of mineralization (Mcc)

424 can be greater than 1 as mentioned previously. These high annual rates highlight the necessity of

425 considering the previous catch crop history when evaluating the annual effect of catch crops.

18

426 **5.4. N stock changes with continuous catch crops and effects of climate change**

427 The model also predicted that the N sequestered due to catch crops allowed maintaining the soil

428 organic matter level at steady state at two sites. At the third site (Kerlavic), repeated catch crops

429 limited but could not hamper the decline in SOM after grassland destruction. The range of decrease

430 at Kerlavic corresponded to the 30-50% decrease found after conversion of natural to agricultural

431 ecosystems over 50-100 years in temperate regions (Lal, 2008). The positive effect of catch crops

432 on N sequestration simulated by the model is in accordance with previous reports of positive effects

433 on N and C sequestration (Singh et al., 1998; Blombäck et al., 2003). In our simulations, climate

434 change led to a moderate increase in net N mineralization and reduction in soil organic N, which

435 agrees with previous results for soil organic carbon (Hungate et al., 2009). In fact, the climate

436 change involves two opposing effects: an increase in mineralization rate and an increase in SOM

437 humification due to higher crop biomass and C return (Lal, 2008). The steady state obtained after

438 23-45 years with continuous catch crops was reached when the inputs in soil humified matter were

439 equal to the outputs, meaning that the annual input of humified N due to catch crops (N of residues

440 + N immobilised from the soil) was equal to the extra annual mineralization. The steady state

441 occurred at a lower level when catch crop frequency declined due to smaller N inputs. When catch

442 crops were abandoned, the extra soil organic N progressively decreased to become negligible after

443 60 years. This decline was also simulated by the FASSET model in Danish conditions when catch

444 crops were stopped after 30 years (Bernsten et al., 2006). It occurred at a slower rate: nearly 20% of

445 extra N sequestered remained in the soil 75 years after ceasing catch crops, while only 6-8%

446 remained after 60 years in our simulations.

447 **5.5. Catch crop efficiency in decreasing leaching and fertilisation**

448 The reduction in nitrate leaching simulated by the model over the long-term confirmed that

449 fertilisation rate needs to be adjusted after a few years to maintain the efficiency of the catch crops

450 to reduce N leaching. The decrease in N fertilisation rate by 20-24 kg ha^{-1} yr^{-1} to maintain crop

19

451   biomass production at the level of the control was similar to the reduction of 15-27 and 23 kg ha^{-1}

452   yr^{-1} estimated in previous studies after 19 to 25 years of repeated catch crops (Hansen et al., 2000;

453   Berntsen et al., 2006). It allows compensating for the increase in net N mineralization with repeated

454   catch crops; when the annual mineralization rate reaches a steady state, the fertilisation rate does not

455   have to be reduced further. The decrease in catch crop efficiency for reducing nitrate concentration

456   in drained water can be expected at constant N fertilisation because of the enhanced mineralization

457   (Berntsen, 2006). The enhanced mineralization due to the extra organic N remaining in soil after

458   stopping catch crops resulted in greater amounts of N leached than in the control, confirming

459   previous findings (Thomsen and Christensen, 1999; Hansen et al., 2000). However, in our case this

460   phenomenon lasted much more than four years and nitrate leaching remained higher than in the

461   control during the whole simulation period, although with a progressive decrease. Overall catch

462   crops had a positive effect on N leaching over 60 years and their negative effects could be

463   minimised by adjusting the fertilisation rate to the higher mineralization, particularly during the first

464   years after stopping catch crops. In all cases, catch crops lead to slow down the nitrogen cascade

465   (Galloway et al., 2003). The 17-18% N leaching reduction when catch crop frequency was 33-50%

466   was slightly lower than the 23-28% found in other studies (Olesen et al., 2004; Beaudoin et al.,

467   2005). Our results indicate that, even with a low catch crop frequency, the fertilisation rate should

468   be decreased in the long term to maintain a good reduction in nitrate leaching. This is contradictory

469   with the hypothesis of MacDonald et al. (2005) that adjustments of fertiliser N recommendations

470   are not necessary in the case of small cover crops grown once every 3-4 years.

471

472   **6. Conclusions**

473   The crop-soil model STICS satisfactorily predicted crop and soil parameters in continuous

474   simulations over 15 years, confirming the robustness of the model which correctly reproduced the N

475   fate in three different pedo-climatic situations. A few parameters had to be calibrated because they

20

476   were not or could not be measured. Long-term simulations allowed us to determine the steady state

477   of net N mineralization and storage in soil due to repeated catch crops and confirmed the need to

478   adjust fertilisation rates when catch crops are grown repeatedly. The model simulated negative

479   effects of abandoning catch crops on N leaching, linked to changes in extra N in soil and extra

480   mineralization, years after catch cropping has ceased. The model outputs are logical with our

481   understanding of SOM turnover, although we cannot be sure of the intensity of the reduction in

482   catch crop efficiency with respect to nitrate leaching. The results presented here should be

483   compared with data from very long-term experiments to confirm these results. To obtain more

484   reliable simulations over the longer term, better data are needed on catch crop biomass, particularly

485   the root system, and the effects on nitrate leaching. Similarly, the active organic fraction should be

486   determined according to soil characteristics and previous land history. Long-term experiments and

487   simulation studies are complementary tools for defining sustainable agricultural practices.

488   7. Acknowledgements

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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.

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	M[a]	217	220	233	221	217	221
(mm)	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	M	44	44	36	42	39	43
(kg N ha^{-1})	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	M	8.1	10.4	10.2	9.0	9.4	10.1
(t DM ha^{-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	M	6.3	9.4	-	6.5	9.8	-
(t DM ha^{-1})	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	M	142	161	156	155	152	153
(kg N ha^{-1})	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	M	147	125	-	149	128	-
(kg N ha^{-1})	MD	-16	4	-	-26	-4	-
	RMSE	28	31	-	36	29	-
	EF	0.41	0.06	-	0.13	0.22	-
Drained water	M	152	130	593	148	107	563
(mm)	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	M	25	22	55	23	19	55
(kg N ha^{-1})	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.

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.
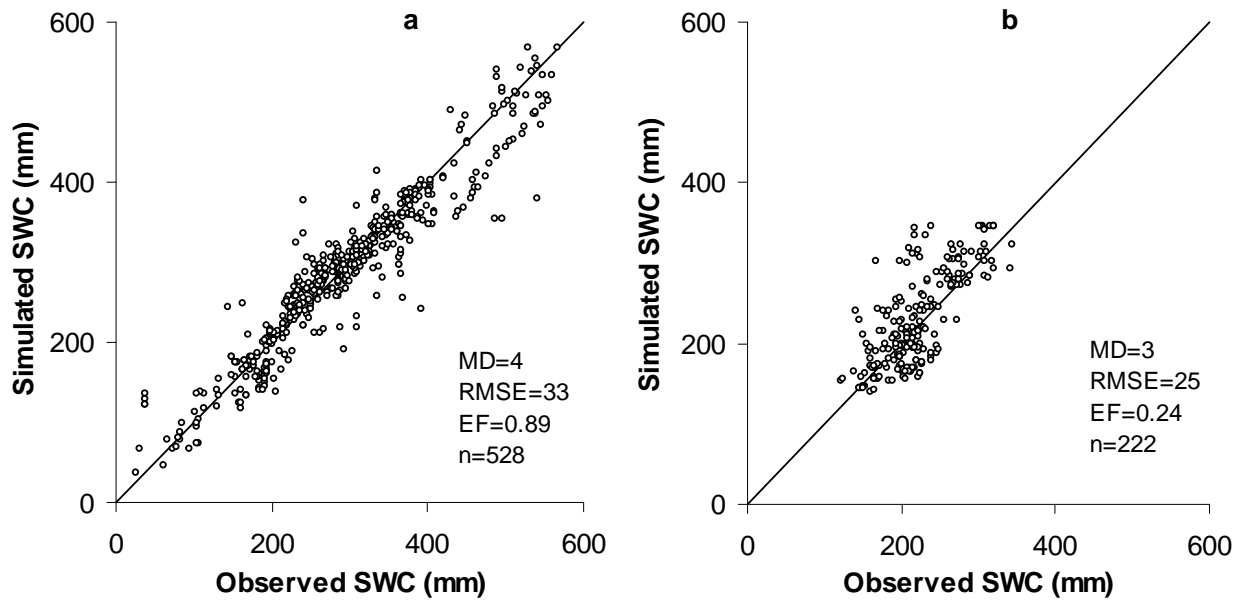
Figure 2 Observed and simulated kinetics of cumulative net N mineralization at Boigneville (a), Thibie (b) and Kerlavic (c), for scenarios S0 and S2 over 13-17 years in continuous simulations.
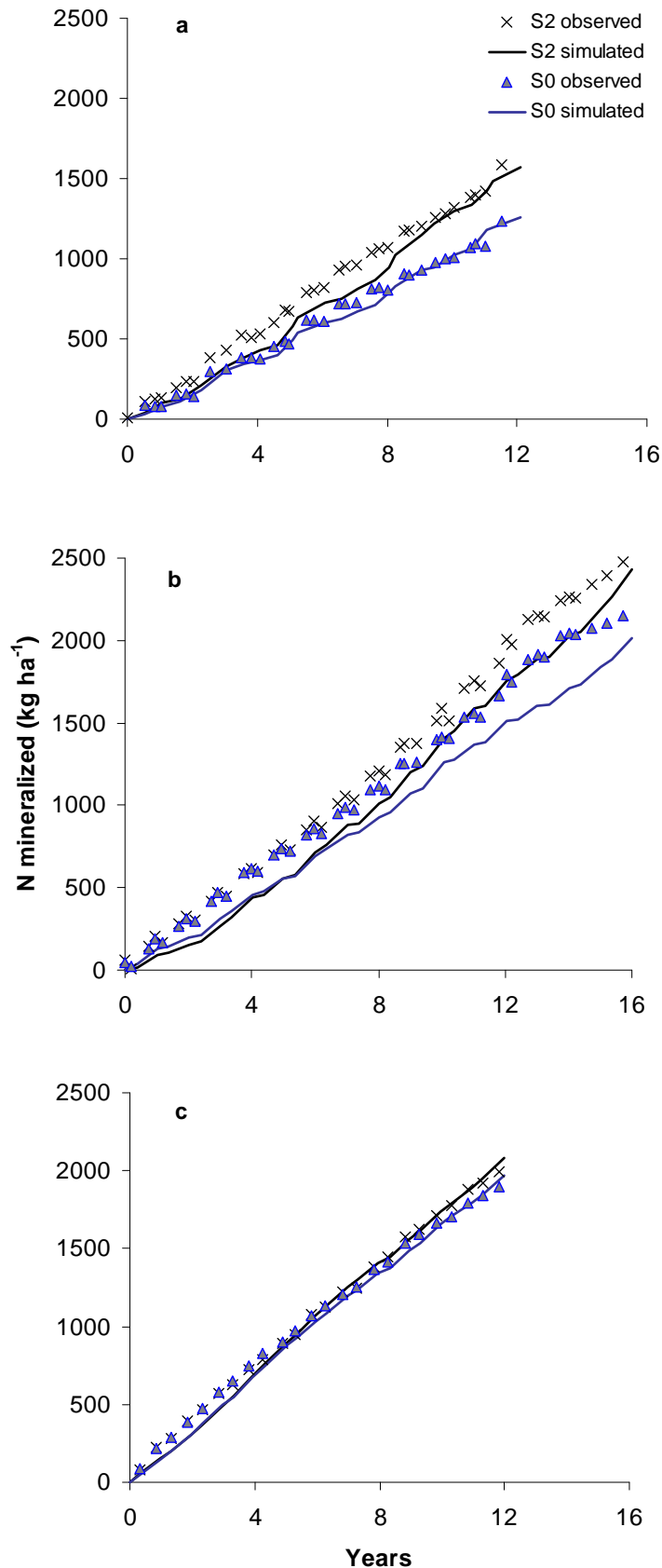
Figure 3 Kinetics of organic N sequestered in soil (ΔN stock) due to catch crops, simulated with four scenarios (continuous lines) at Boigneville (a), Thibie (b) and Kerlavic (c). The symbols represent the mean and confidence interval of the measured ΔN stock after 13-17 years (corresponding to scenario S3).
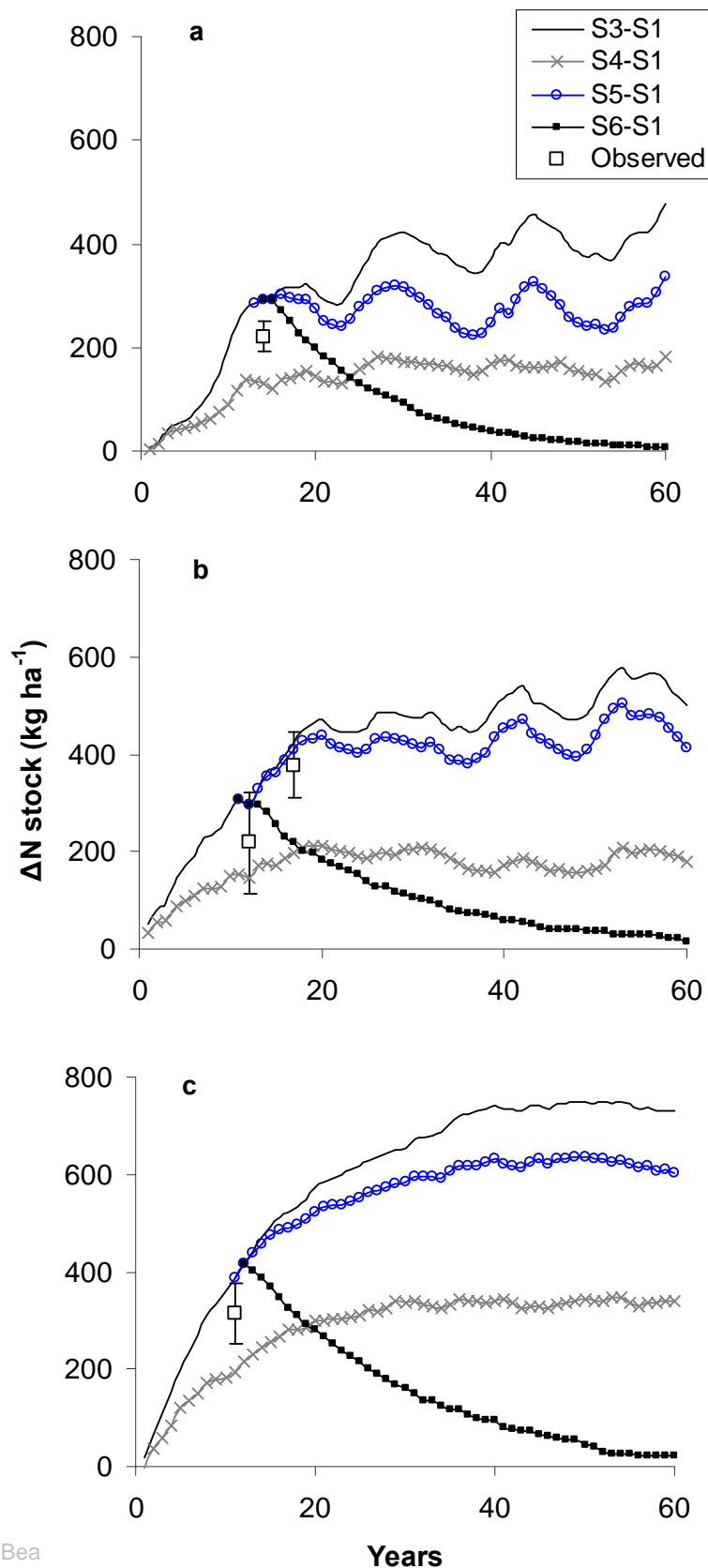
Constantin, J., Bea... (2012). Long-term nitrogen... model in a temperate... 10.1016/j.agee.2011.06.006

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.
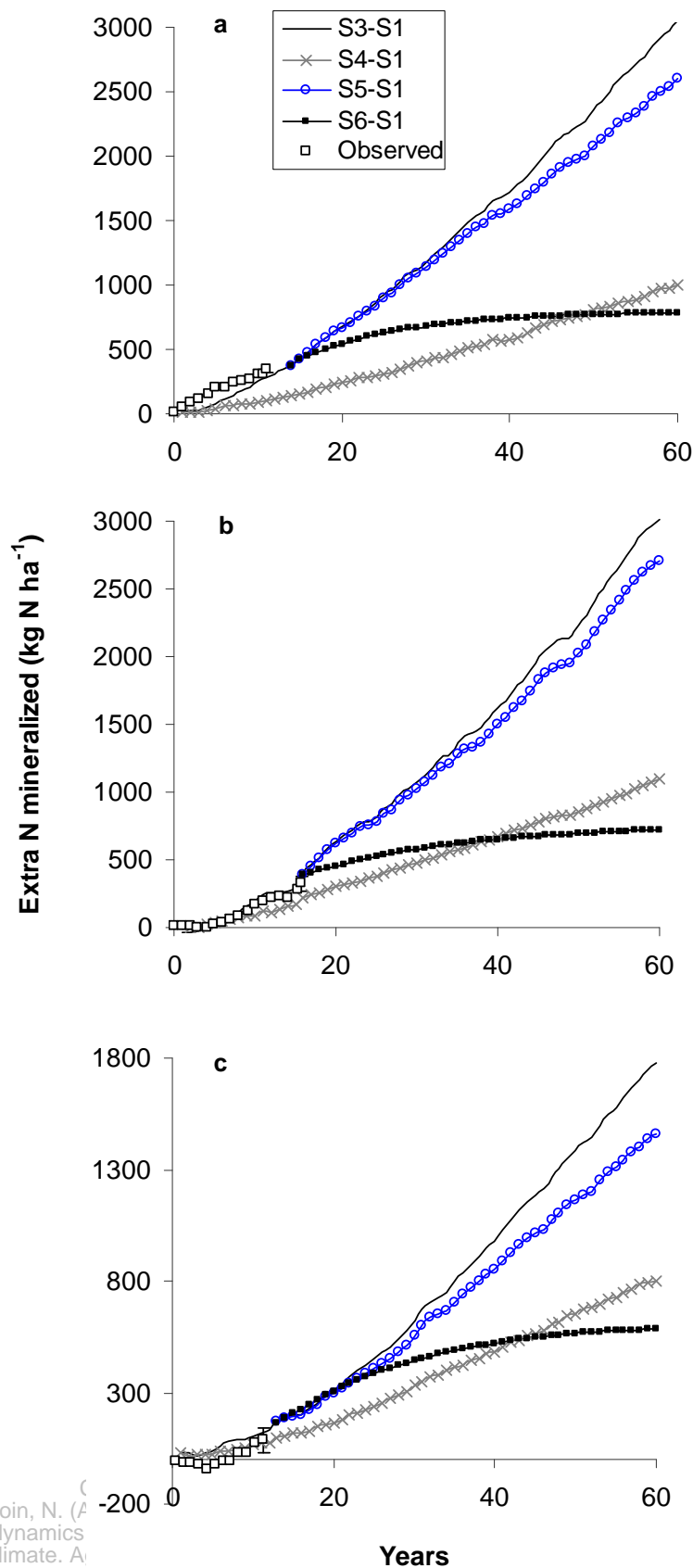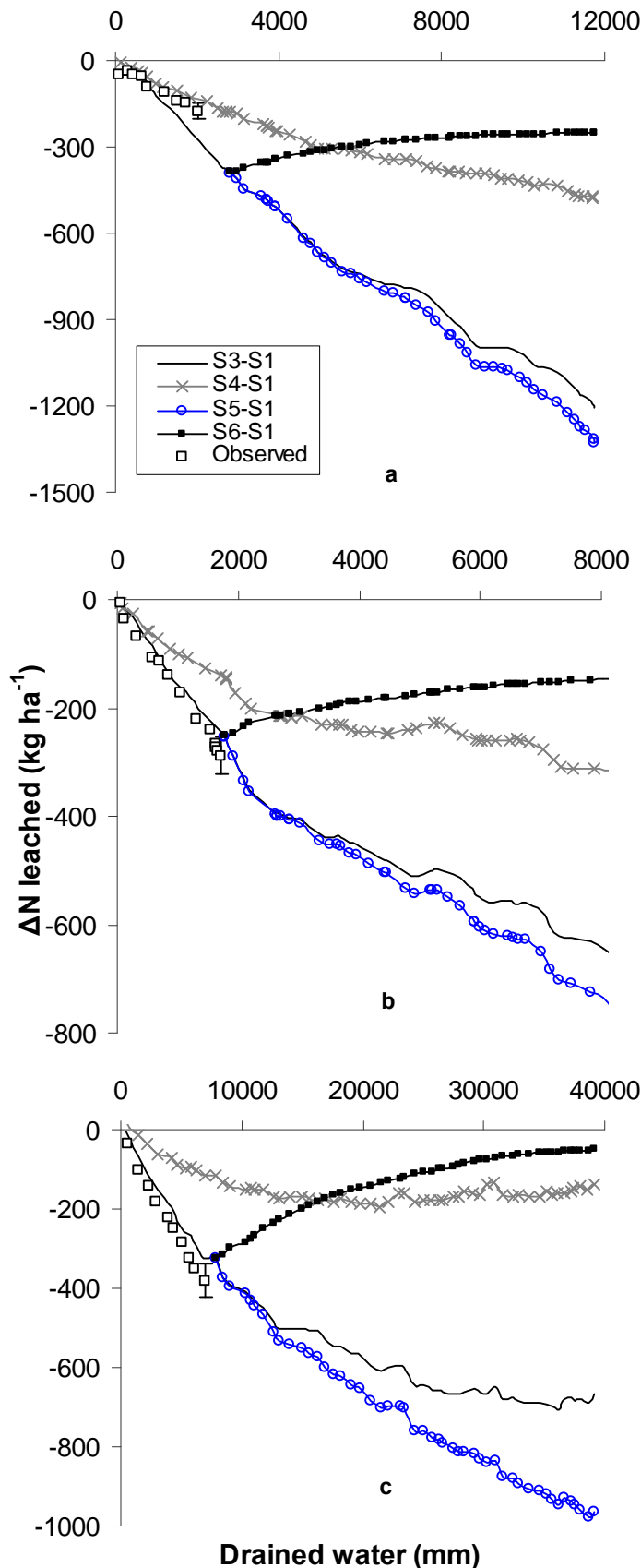
Figure 5 Evolution of the annual relative mineralization rate (M_{CC}) due to catch crops simulated over 60 years in scenarios S2 and S3 at Boigneville (a), Thibie (b) and Kerlavic (c). M_{CC} is the ratio between the extra N mineralized due to catch crops during year n and the N added to soil by catch crops during year n-1. Symbols are the values simulated by STICS; continuous lines are the fitted curves (exponential).
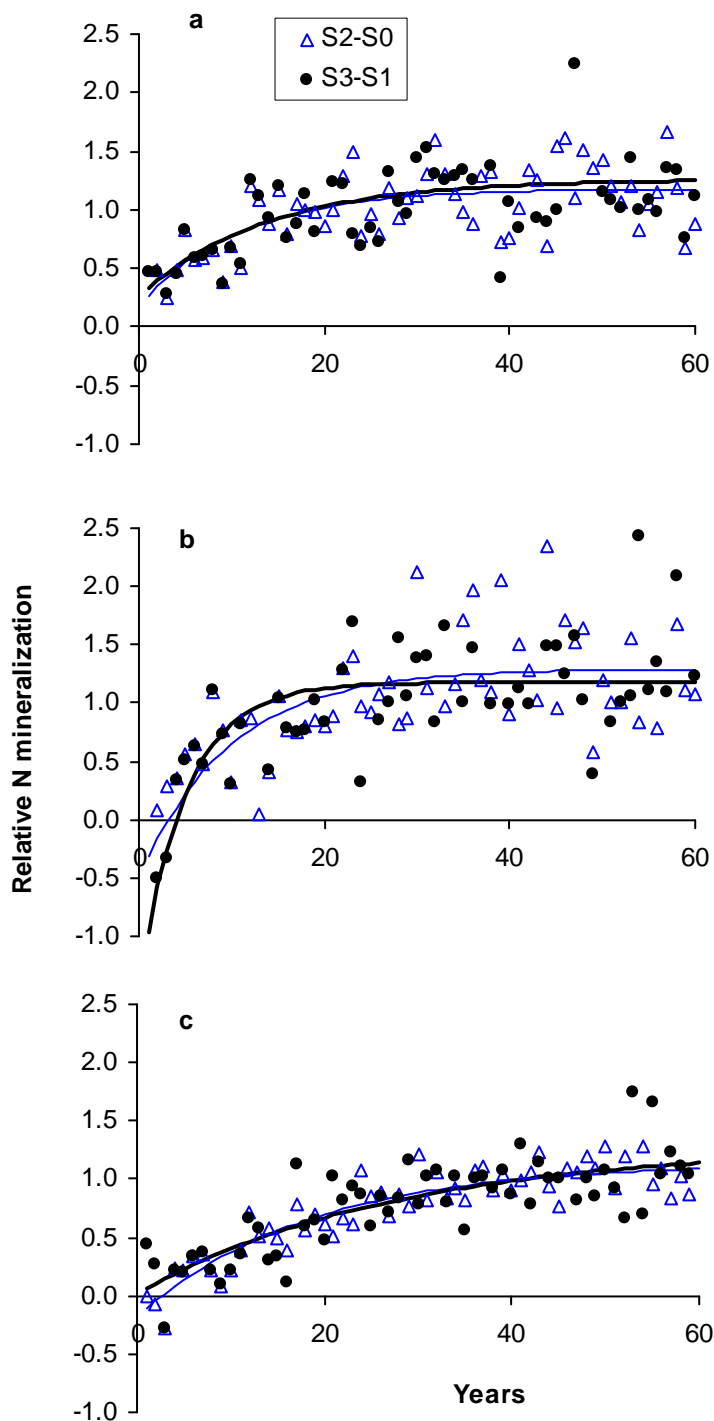
Figure 6 Cumulative extra N leached due to catch crops versus cumulative drained water, simulated over 60 years in scenarios S3-S6 at Boigneville (a), Thibie (b) and Kerlavic (c). The symbols represent the mean and confidence interval of the measured extra N leached (corresponding to scenario S3).

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