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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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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.

1. 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 13–24 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, 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.

2. Materials and methods

2.1. 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, and maize) and catch crops (mustard and 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 3–4 layers down to 90 or 120 cm. The catch crop database gathers experimental data obtained on three mid 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 3–10 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 characteristics, climate variables, crops, agricultural techniques, N fertilization 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).

2.2. 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

Table 1
Main characteristics of the three mid term experiments.

	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, and 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).