



MERCI: a simple method and decision-support tool to estimate availability of nitrogen from a wide range of cover crops to the next cash crop

Julie Constantin · Sébastien Minette ·
Gregory Vericel · Lionel Jordan-Meille ·
Eric Justes

Received: 30 January 2023 / Accepted: 6 September 2023 / Published online: 20 September 2023
© The Author(s) 2023

Abstract

Background and aims Cover crops can efficiently increase nitrogen (N) recycling in agroecosystems. By providing a green-manure effect for the next crop, they allow reduced mineral fertilisation. We developed a decision-support tool, called MERCI, to predict N available from cover crop residues over time, from a single measurement of fresh shoot biomass.

Methods We coupled a large experimental database from France with a simulation experiment using the soil-crop model STICS. More than 25 000 measurements of 74 species of cover crops as a sole crop or bispecific mixtures were collected. Linear regression

models, at the species, family or entire-database level depending on the data available, were built to predict dry biomass, N amount and C:N ratio. Dynamics of N mineralized and leaching from cover crop residues were predicted at 24 contrasting sites as a function of the biomass, carbon (C):N ratio and termination date. **Results** Correlations between fresh biomass, dry biomass and N amounts in experimental data were strong ($r = 0.80\text{--}0.96$), and predicted N amounts in fresh shoot biomass were relatively accurate. Percentages of N mineralized and leached simulated by STICS were explained mainly by the C:N ratio, site and number of months after termination, but to different degrees.

Conclusion MERCI is an easy and robust decision-support tool for predicting N release in the field, and could thus be adopted by advisors and farmers to improve management of nutrient recycling in temperate arable cropping systems.

Keywords Biomass · Green-manure · Carbon · Mineralization · STICS model

Responsible Editor: Martin Weih.

J. Constantin (✉)
Université de Toulouse, INRAE, UMR AGIR,
Castanet-Tolosan F-31320, France
e-mail: julie.constantin@inrae.fr

S. Minette
Chambre d'Agriculture Nouvelle-Aquitaine, Lusignan,
France

G. Vericel
Arvalis Institut du Végétal, Baziège, France

L. Jordan-Meille
UMR 1391 Bordeaux Sciences Agro-INRAE, Gradignan,
France

E. Justes
Persyst Department, CIRAD, Montpellier, France

Introduction

Cover crops are an interesting practice for designing more biodiversity-based cropping systems and moving toward agroecological systems (Duru et al. 2015). Buried in the soil at termination, they can provide a range of ecosystem services such as reduced

nitrate leaching (Constantin et al. 2010b; Thapa et al. 2018; Thomsen 2005), nitrogen (N) and sulphur (S) recycling (Couëdel et al. 2018; Tosti et al. 2012; Tribouillois et al. 2015a), reduced erosion during fallow periods, increased carbon (C) sequestration in soils (Launay et al. 2021; Poeplau and Don 2015), an improved greenhouse gas balance of cropping systems (Kaye and Quemada 2017; Tribouillois et al. 2018) and, when crucifer species are used, biofumigation effects to control pests and diseases (Couëdel et al. 2019). They can also provide a green-manure effect, allowing farmers to apply less mineral N fertiliser than when a bare soil precedes the main crop (e.g. Tonitto et al. (2006).

As cover crops take up N from the soil and can also input additional N through symbiotic N₂ fixation when legume species are used, they change N dynamics during the fallow period and for the next crop. The species and management chosen for cover crops have different effects on the N budget. For instance, the green-manure effect does not always occur; however, it can be favoured by combining legumes with non-legumes (Thorup-Kristensen et al. 2003; Tribouillois et al. 2015a) or through cover crop management, such as sowing and termination dates (Alonso-Ayuso et al. 2014). A wide range of species are available for cover crops, with a variety of characteristics, such as resistance to drought, biomass production potential, sensitivity to high temperatures for germination and growth, and N requirements (Tribouillois et al. 2015b, 2016). In temperate countries such as France, sowing dates usually range from July–October, while termination dates range from early October to late April. Depending on the species and dates of sowing and termination chosen, effects of cover crops on N dynamics and the availability of mineral N for the next cash crop can vary greatly.

Mineralisation rates of cover crop residues depend on crop characteristics such as the C:N ratio and thus may release mineral N immediately or immobilize soil mineral N for some time (Justes et al. 2009). In a soil incubation experiment, Justes et al. (2009) observed that net mineralization (i.e. gross mineralization minus immobilization) within 160 days equalled ca. 40% of the N in residues when the C:N ratio was 11.7 vs. nearly 20% of net immobilization (i.e. -20% of added organic N) when the C:N ratio was 31.3. Based on these data, Justes et al. (2009) developed a model to simulate dynamics of C and N mineralization for a

wide range of crop residues that included cover crops, and the model provided relatively accurate predictions. This model was integrated into the soil-crop model STICS (Brisson et al. 2002; Coucheney et al. 2015) to simulate mineralization of crop residues in the field as a function of climate, soil and management. STICS also predicts effects on N leaching, as it simulates components of the N budget. As N dynamics in soil are tedious and difficult to measure in the field, such models are useful for simulating dynamics of residue decomposition and mineralization and their influence on N dynamics and N release for the crop following cover crop termination (Justes 2017).

However, STICS remains too complex and difficult for non-experts to use, especially as a simple decision-support tool. Moreover, such process-based models need large amounts of data to simulate a given field (e.g. daily climate, detailed soil data), require some expertise to be used correctly and usually do not consider end-users (Constantin et al. 2015b; Prost et al. 2011). To design a decision-support tool, certain hybrid approaches can be useful in a wide range of situations for local stakeholders, such as agricultural advisors or farmers (Meunier et al. 2022). These hybrid approaches combine detailed process-based modelling with more empirical or statistical modelling in order to be easily usable in the field.

Given potentially significant effects of cover crops on N availability for the next cash crop, the objective of this study was to develop a simple and robust decision-support tool to quantify dynamics of N release for the next crop that can be applied to a wide range of cover crop species and types of management and that requires few input data that are as easy to collect as possible. To reach this goal, the method developed consisted of coupling a large experimental database on cover crops with statistical modelling and data predicted by a process-based model from a single input datum: a simple sample of fresh shoot (i.e. above-ground) biomass at cover crop termination.

Materials and methods

Approach developed to estimate N release for the next cash crop

The general approach coupled field and simulated experiments to estimate, from a cover crop's fresh

biomass at termination, the N available for the next cash crop over time. The four main steps were the following:

- (1) Build a large database of many cover crop species, as a sole crop and in species mixtures, with contrasting climates, soils and management.
- (2) Predict shoot and root dry biomass, N and C contents and C:N ratio from fresh shoot biomass.
- (3) Quantify N mineralization and nitrate leaching from cover crop residues using the STICS soil-crop model for a variety of climates, soils (type and depth) and crop management practices.
- (4) Predict N available from cover crop residues over time for the next crop for 6 months after cover crop termination and burial in the soil.

The complete approach was integrated into the decision-support tool, called MERCI (Method to Estimate N Release from Cover crop Introduction) (Fig. 1).

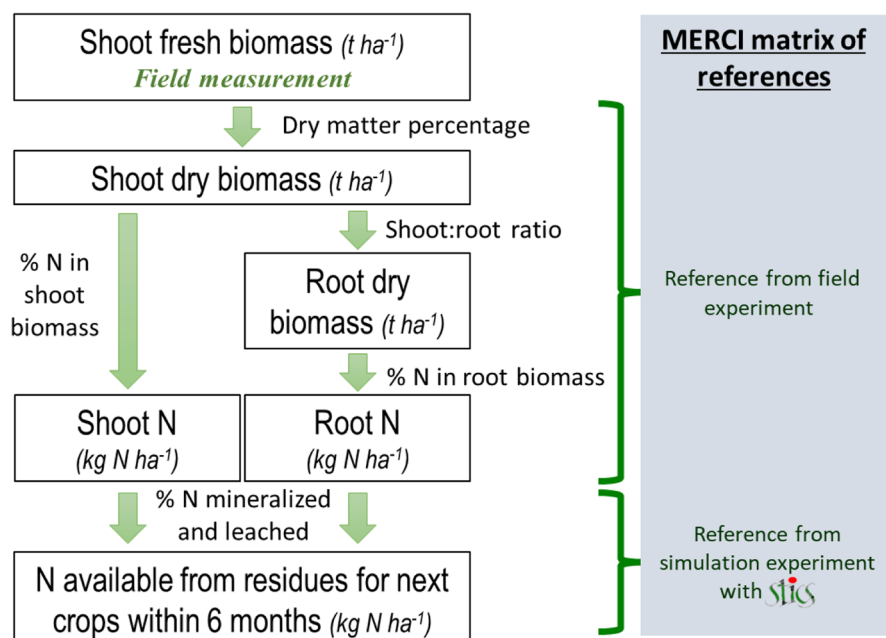
Cover crop database

Collecting as much data as possible from 48 research and development partners, we built a large database of cover crop experiments throughout France from 1982 to 2020 (Fig. 2a). The data came from French

regions with large areas of annual cropping systems. Data availability also depended on each partner's resources and the location of experimental units in France. Nevertheless, the data covered a wide variety of climates and soils encountered in French agriculture, which more generally represent conditions of temperate countries in western and southern Europe (Metzger et al. 2005).

The data covered a wide range of cover crop species and management. A total of 949 “site × year” combinations and 8 749 situations (i.e. measurements of a given species on a specific date), mainly from conventional agricultural systems, throughout France were collated, covering 78 species of cover crops from seven botanical families (34% Brassicaceae, 33% Fabaceae, 25% Poaceae, 6% Hydrophyllaceae and 1% or less each Asteraceae, Polygonaceae and Linaceae). Species in 59% of situations were a sole cover crop, while 41% were in a species mixture, usually of two species (only 2% of mixtures had 3–8 species). The sowing, emergence (if available) and measurement dates during cover crop growth or at termination were recorded in the database. The sowing dates in the database ranged from 15 June to 1 November, while measurement dates (at termination or before) ranged from 13 September to 26 April for 98% of situations. The data of interest were fresh and dry biomasses as well as C and N concentrations in shoots and roots.

Fig. 1 General methodology of the MERCI (Method to Estimate N Release from Cover crop Introduction) decision-support tool to predict nitrogen (N) released from cover crop residues for a given species



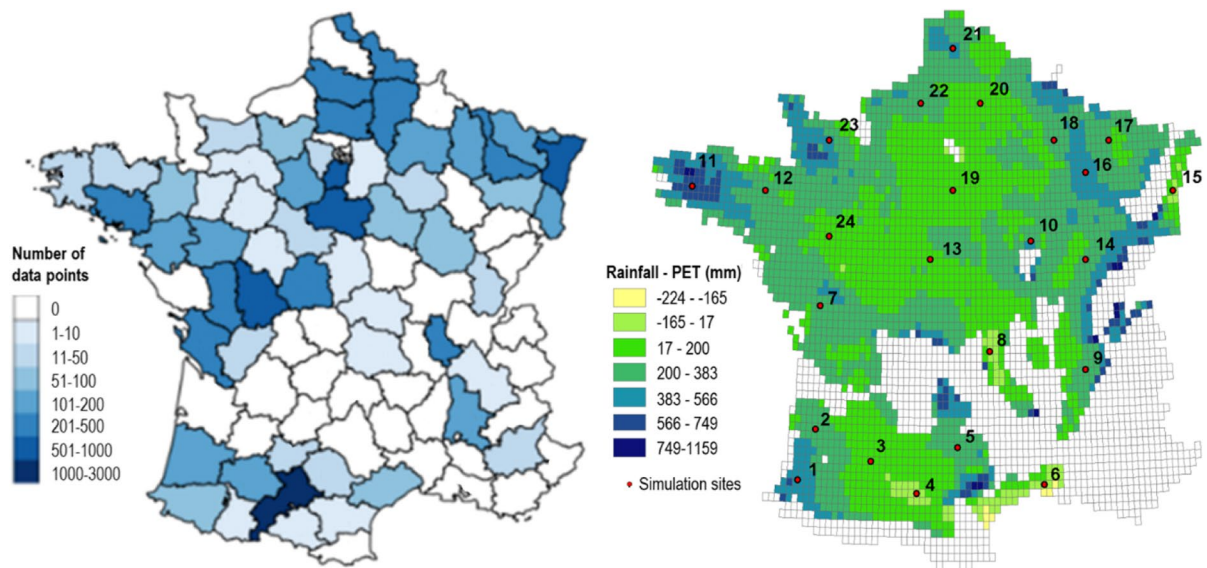


Fig. 2 Maps with (on the left) number of experimental data points by French department and (on the right) simulation sites and rainfall minus potential evapotranspiration (PET) during the main cover crop growing period (August–March)

Data were most common for the dry biomass, N concentration and fresh biomass of shoots, followed by C concentrations of shoots, while data for root biomass were generally scarcer (Table 1). Some botanical families were represented more often, with ca. 5 400 to ca. 10 100 data points each for Brassicaceae, Fabaceae and Poaceae vs. less than 300 each for Asteraceae, Linaceae and Polygonaceae. Hydrophyllaceae was intermediate, with ca. 1 400. In total, the cover crop database used to create MERCI contained more than 25 000 measurements of cover crops.

Overview of the STICS soil-crop model

We used the STICS soil-crop model (version 9.0) to simulate the percentage of cover crop residues mineralized and leached over time after termination. STICS simulates dynamics of water, N and C in the soil-crop system, under climate, soil, crop and crop-management conditions at a daily time-step (Brisson et al. 1998, 2008). STICS simulations of soil water and mineral N dynamics under bare soil have been calibrated and tested for many crops, including cover

Table 1 Number of data in the cover crop database by botanical family and crop part (shoot or root)

| Number of species | | Brassicaceae | Fabaceae | Poaceae | Hydrophyllaceae | Asteraceae | Linaceae | Polygonaceae | Total |
|-------------------|---------------|--------------|----------|---------|-----------------|------------|----------|--------------|--------|
| | | 11 | 32 | 23 | 1 | 5 | 1 | 1 | 74 |
| Shoot | Dry biomass | 2 960 | 2 787 | 1 939 | 501 | 107 | 23 | 70 | 8 387 |
| | Fresh biomass | 1 797 | 1 115 | 1 009 | 304 | 68 | 20 | 42 | 4 355 |
| | Carbon | 1 027 | 1 183 | 366 | 122 | 11 | 2 | 17 | 2 728 |
| | Nitrogen | 2 441 | 2 585 | 1 846 | 404 | 92 | 13 | 64 | 7 445 |
| Root | Dry biomass | 859 | 150 | 126 | 20 | 11 | 1 | 4 | 1 171 |
| | Carbon | 291 | 44 | 19 | 14 | 4 | 1 | 4 | 377 |
| | Nitrogen | 726 | 144 | 104 | 17 | 4 | 1 | 4 | 1 000 |
| Total | | 10 101 | 8 008 | 5 409 | 1 382 | 297 | 61 | 205 | 25 463 |

crops, throughout France (Coucheney et al. 2015; Yin et al. 2020). STICS has shown a good ability to predict these two variables, with a high accuracy for water and reasonably good accuracy for N, with a Nash-Sutcliffe efficiency coefficient (which ranges from $-\infty$ (prediction no better than observed means) to 1 (perfect prediction) of 0.90 and 0.56, respectively. Specific studies have been performed with STICS to predict crop residue decomposition for mature crop and a wide range of cover crop residues, with a variety of species and C:N ratios, which yielded satisfactory predictions of C and N mineralization (Constantin et al. 2015a; Justes et al. 2009; Nicolardot et al. 2001). STICS's ability to predict drainage and N leaching has also been evaluated, with satisfactory predictions for situations with and without cover crops (Constantin et al. 2012; Jégo et al. 2008; Schnebelen et al. 2004).

Experimental design for simulations

To simulate N mineralization from cover crop residues and N leaching after cover crop termination, we used the 24 sites across France that Constantin et al. (2015a) had previously selected. These sites cover a wide range of climate conditions in the main cropping areas of the country, particularly during the fallow period from August–April, based on mean temperature and on rainfall minus potential evapotranspiration over several years (Fig. 2b). We selected 2–4 of the most common soils in the region around each site that had contrasting soil available water capacity (67–327 mm), based on the French Geographic Soil Database at 1:1 000 000 scale (v1–21 December 1998. INRA, US 1106 Infosol, Orléans, France).

STICS simulated bare soil with or without cover crop residues from 2006 to 2026 using the RCP 8.5 climate scenario from DRIAS (Météo France, <http://www.drias-climat.fr/>) to represent the current and near-future climate of France and its inter-annual variability. The simulations were initialized on seven termination dates (every month from 15 October to 15 April) with three amounts of total (shoot+root) biomass (2, 4 and 8 t ha⁻¹) and seven C:N ratios (7.5, 12.5, 17.5, 22.5, 30, 40, 50) of cover crop residues, which were always buried in the soil. No species-specific information was needed, as STICS simulates N mineralization of crop residues based mainly on their C:N ratio and age (mature or immature). We simulated a baseline situation without cover crop residues

to assess potential supplementary N leaching due to cover crop residues that could particularly occur for low C:N ratios (<15; Justes et al. 2009).

For each termination date, initial soil water and mineral N content were the same for simulations with and without cover crop residues. Initial soil mineral N was 20 kg N ha⁻¹ from 0 to 90 cm in every simulation, assuming good N uptake by the cover crops. For initial soil water content, we simulated a cover crop of white mustard and Italian ryegrass from 1 August for each year (2006–2026) per soil and site to generate an initial water content consistent with the climate of the site on each of the seven termination dates. For each of these termination dates, we used the mean soil water content per soil layer to initialize the simulations of decomposition and mineralization of cover crop residues over time.

Predicting dry biomass, N content and the C:N ratio of cover crops at termination from experimental data

To estimate the shoot and total dry biomass, N content and C:N ratio from a simple measurement of fresh shoot biomass by species on a 1 m² quadrat, we first analysed correlations within the experimental database (*PerformanceAnalytics R package*). We also quantified the percentage of variance explained by available variables (e.g. botanical family, species as a sole cover crop or in a mixture, sowing and termination dates, duration of crop development) and quantitative data that were strongly correlated ($r > 0.51$) with the variable to predict. Depending on the results, we built specific meta-models by botanical family and species to predict the total biomass at termination and its total N concentration, and thus its N amount. When many data were available for a given species or family, the relation used to predict the shoot N amount was also refined at the species level and by class of dry shoot biomass (0–1, 1–2, 2–3, 3–4 or more than 4 t ha⁻¹). The percentage of C in shoots and roots was estimated as the mean in the experimental database by species or botanical family, depending on data availability. It was then used to calculate the C:N ratio of cover crops at termination, which STICS needed as input data to predict N mineralization and leaching. For species mixtures, each species was assessed independently to predict the dry biomass, N content and C:N ratio of its shoots and roots at termination.

Predicting N mineralized and leached from cover crop residues over time with STICS

N available from cover crops to the next crop was estimated using STICS predictions, shoot and root N amounts and the C:N ratio of residues of each species estimated during the previous step. First, the percentage of N mineralized from cover crop residues after termination ($Nmin_p$) was calculated monthly over 6 months based on STICS predictions of crop residue decomposition and mineralization (variable $Qminr$, in kg N ha^{-1}) divided by the initial N amount in residues ($Nres$):

$$Nmin_p = \frac{Qminr}{Nres}$$

The amount of N leached from cover crop residues was calculated as the nitrate-N leached under cover crop residues ($Nleach_{CC}$) minus that under a bare soil ($Nleach_{BS}$) initialized with the same soil water and N contents. N leaching means that N has leached below the soil depth reachable by roots, between 0.5 and 1.4 m depending on the region, and is lost for the crop. The percentage of N leached from cover crop residues ($\Delta Nleach_p$) was then calculated by dividing this difference by the initial N amount in residues:

$$\Delta Nleach_p = \frac{Nleach_{CC} - Nleach_{BS}}{Nres}$$

This calculation was performed by site, soil, year, termination date of the simulated cover crop, class of dry shoot biomass and C:N ratio of the cover crop residues. Then, over the 20 simulated years, we calculated the mean percentage of N that mineralized and was leached from the cover crop every month for 6 months.

Predicting N availability for the next crop by combining experimental and simulated data

The N available after 6 months was calculated by combining experimental data for N amounts and C:N ratios in cover crop residues with simulated N mineralization and leaching:

$$Nmin = Nres_{CC} \times Nmin_p - Nres_{CC} \times \Delta Nleach_p$$

with $Nres_{CC}$ the N in the cover crop residues at termination, calculated during the previous step from

experimental data from the simple fresh biomass measurement in the field; $Nmin_p$ and $\Delta Nleach_p$ are the percentage of N mineralized and N leached from cover crops predicted by STICS within the same termination date range and C:N ratio class as predicted by the experimental data and considering the nearest climate site simulated. Seven C:N ratio classes (i.e. 5–10, 10–15, 15–20, 20–25, 25–35, 40–50 and 50 or more) were represented in simulations by seven C:N ratios (i.e. 7.5, 12.5, 17.5, 22.5, 30, 40 and 50, respectively). Seven termination classes (i.e. before October, November, December, January, February, March and after April) were represented in simulations by seven termination dates (i.e. 15 October, 15 November, 15 December, 15 January, 15 February, 15 March and 15 April, respectively).

The calculation was performed independently for the shoots and roots of each species. Their N availability (N mineralized from cover crop residues minus N leached from them) was then summed by month for 6 months after the termination date to calculate the total amount of N from the cover crops available for the next crop.

Statistical analysis

To estimate the accuracy of estimates of the C:N ratio and total N content of cover crop residues based on fresh biomass in the database, we used three complementary statistical criteria: root mean square error (RMSE), mean deviation (MD) and the Nash-Sutcliffe efficiency coefficient (EF):

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

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

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

with E_i the estimated value, O_i observed value, \bar{O} the mean of the observed values and n the number of values.

Analysis of variance (ANOVA) were performed on the experimental and simulation results to estimate the percentage of variance explained by the factors for each variable of interest, using R software (<https://cran.r-project.org>). For the experimental database, the factors tested were species, botanical family, cover

crop in a species mixture or not, growing duration and French region to explain dry shoot biomass, total dry biomass and N in shoots and roots. Depending on the variable explained, measured fresh shoot biomass and dry shoot or root biomass were also used. For the simulation database, we tested the site, soil, cover crop biomass at termination, C:N ratio, termination date and number of months since termination as factors to explain the percentage of N mineralized and N leached from cover crop residues.

Results

Description of the cover crop experimental database

The experimental database covered a wide range of shoot biomass, reaching almost 100 t ha⁻¹ in fresh and 12 t ha⁻¹ in dry biomass (median=9.1 and 1.4 t

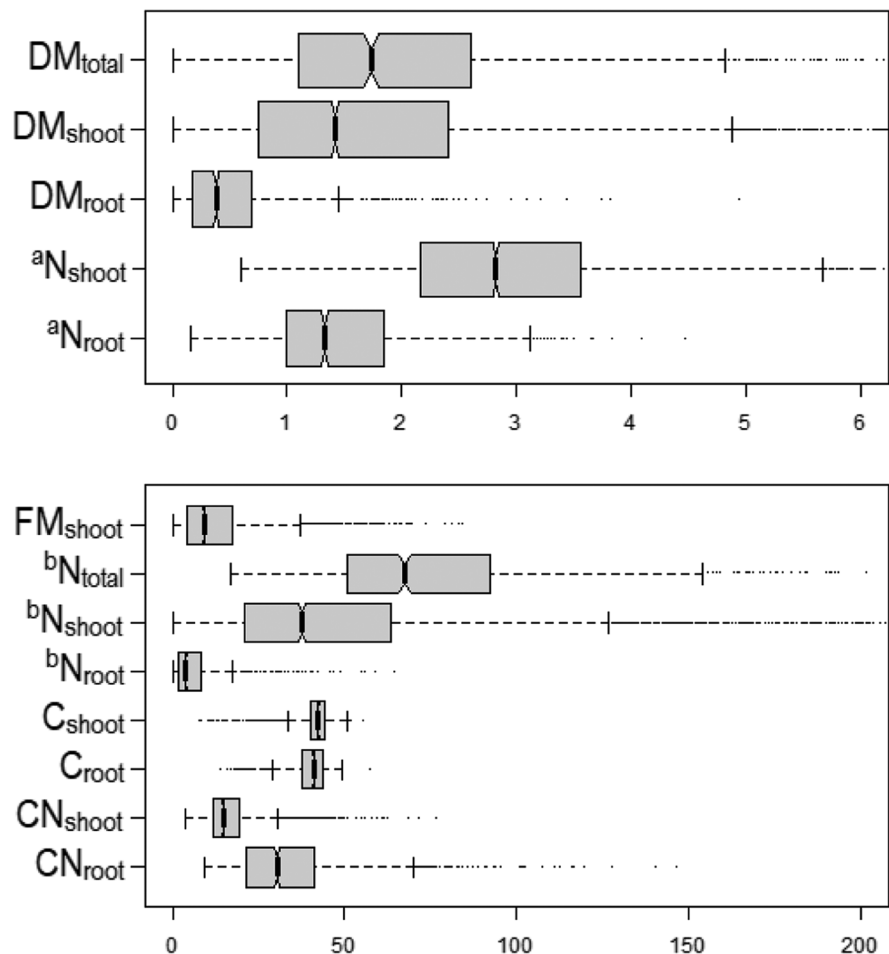
ha⁻¹, respectively) (Fig. 3). The corresponding shoot N amount reached 300 kg ha⁻¹ but usually ranged from ca. 130 to 200 kg ha⁻¹. For the situations in which roots had been measured and analysed, median total dry biomass and N amounts were 1.7 t ha⁻¹ and 67 kg ha⁻¹, respectively. C shoot and root contents were similar (usually ca. 40 and 43%, respectively). As N content in roots was lower than that in shoots, the median C:N ratio of roots was twice that of shoots (30 vs. 15, respectively).

As sample sizes differed among variables, it was difficult to compare shoots and roots since data were not necessarily on the same experiments or fields.

Predicting dry biomass and N content based on experimental data

Analysis of the experimental database showed strong and significant correlations between fresh shoot

Fig. 3 Range of variables in the entire cover crop database for shoot, root and total concentration or amount depending on the variable. DM and FM mean dry and fresh biomass (in t ha⁻¹), respectively, C means carbon (%), N means nitrogen (a in % and b in kg N ha⁻¹) and CN means the C:N ratio (no unit). Whiskers equal 1.5 times the interquartile range (i.e. 25th to 75th percentile)



biomass, dry shoot biomass and total dry biomass, confirming the relevance of using fresh shoot biomass to estimate dry biomass in MERCI (Fig. 4). Dry root biomass was also correlated significantly with dry shoot biomass and total dry biomass, but less strongly. The correlation between N amount and biomass was somewhat weaker, but remained significant for shoots, roots and total biomass and total N in the plant. Although the correlation between fresh shoot biomass and total N in the plant had fewer data points, it was relatively strong ($r=0.80$).

ANOVA showed that dry shoot biomass was explained mainly by fresh shoot biomass (76.0%), followed by species (4.2%), botanical family (2.0%) and growing duration (1.7%). Total dry biomass was explained mainly by dry shoot biomass (92.0%), followed by species (2.2%), while dry root biomass was explained by dry shoot biomass (32%), species (20%) and botanical family (6%). As a result, depending on data availability, models were made by species, by botanical family or all families in the entire database

combined. Linear regressions to predict dry shoot biomass from fresh biomass varied (Table 2). As the 'a' coefficient for the entire database was 0.14, the mean water content of cover crops was 86%. This coefficient was somewhat lower for Brassicaceae and Hydrophyllaceae and higher for Fabaceae, Poaceae, Linaceae and Polygonaceae and resulted in higher R^2 , except for Hydrophyllaceae. The mean percentage of roots estimated by the linear regression between dry shoot biomass and total dry biomass was 31% and ranged from 10 to 43%, with the highest percentages for Poaceae. R^2 ranged from 0.90 to 0.98, except for Linaceae (as the database contained only one value).

ANOVA showed that dry biomass explained 66–77% of the variance in N amount. Species and botanical family explained 2–5% of the N amount variables, except for the total N amount, which was explained more by species (12%). The mean N amount in dry shoot biomass in the entire database was 26.5 kg N t^{-1} (Table 2). It was highest in Fabaceae (33.6 kg N t^{-1}), as expected with legumes, due to their

Fig. 4 Correlation matrix with (top-right) correlation coefficients and (bottom-left) scatterplots between variables and (middle) histograms of each variable. Variables are the fresh shoot biomass (FM_{shoot}); shoot, root and total dry biomass (DM_{shoot} , DM_{root} and DM_{total} , respectively); and shoot, root and total N in the plant (N_{shoot} , N_{root} and N_{total} , respectively). All correlations were significant ($p < 0.001$)

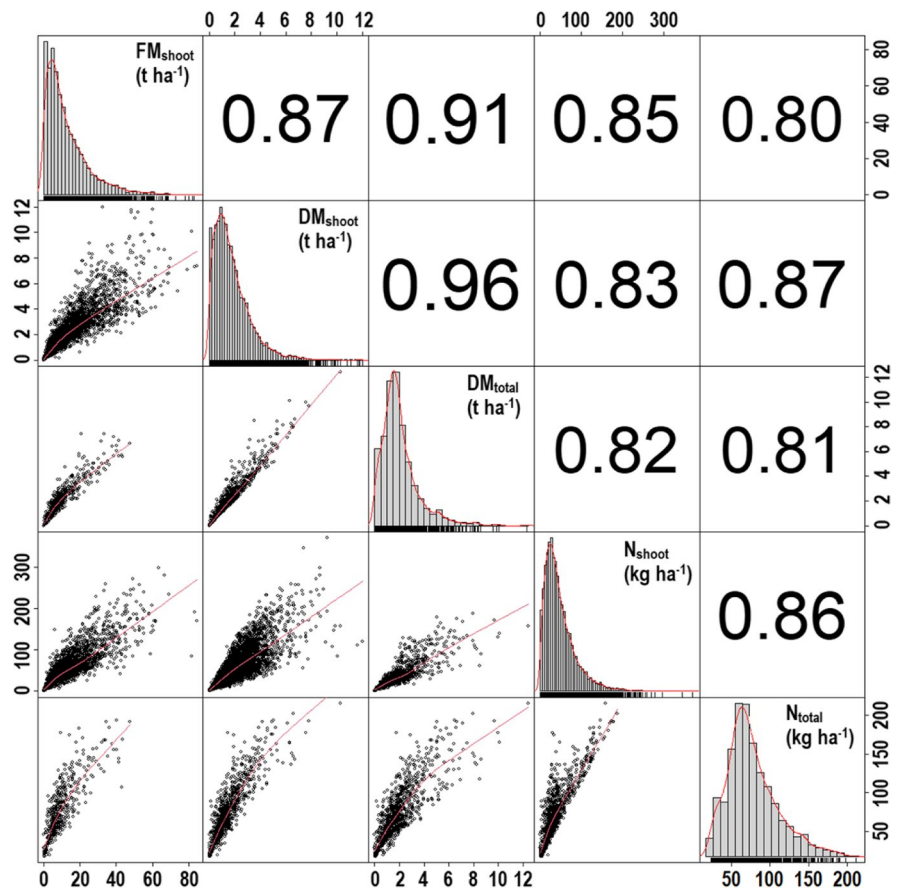


Table 2 Linear regression equation by botanical family (and associated R^2) used to predict dry shoot biomass (DM_{shoot}) from fresh shoot biomass (FM_{shoot}), predict total dry biomass(DM_{total}) or shoot N amount (N_{shoot}) from dry shoot biomass, and predict root N amount (N_{root}) from dry root biomass (DM_{root})

| | $DM_{shoot} = a \times FM_{shoot}$ | | $DM_{total} = a \times DM_{shoot}$ | | $N_{shoot} = a \times DM_{shoot}$ | | $N_{root} = a \times DM_{root}$ | |
|-----------------|------------------------------------|-------|------------------------------------|-------|-----------------------------------|-------|---------------------------------|-------|
| | a | R^2 | a | R^2 | a | R^2 | a | R^2 |
| Brassicaceae | 0.13 | 0.77 | 1.33 | 0.92 | 25.3 | 0.69 | 14.2 | 0.88 |
| Fabaceae | 0.15 | 0.86 | 1.15 | 0.96 | 33.6 | 0.86 | 24.7 | 0.96 |
| Poaceae | 0.19 | 0.81 | 1.43 | 0.90 | 21.0 | 0.67 | 9.7 | 0.91 |
| Hydrophyllaceae | 0.10 | 0.74 | 1.21 | 0.94 | 23.6 | 0.61 | 13.9 | 0.99 |
| Asteraceae | 0.14 | 0.83 | 1.24 | 0.98 | 18.1 | 0.76 | 19.9 | 0.89 |
| Linaceae | 0.17 | 0.90 | 1.17* | NA | 21.6 | 0.92 | 15.7* | NA |
| Polygonaceae | 0.20 | 0.66 | 1.10 | 0.98 | 17.7 | 0.83 | 16.2 | 0.99 |
| All | 0.14 | 0.76 | 1.31 | 0.92 | 26.5 | 0.69 | 13.3 | 0.86 |

DM and FM are in $t\ ha^{-1}$ and N is in $kg\ N\ ha^{-1}$. * Coefficient obtained from only one value

symbiotic N_2 fixation. It was lowest for Polygonaceae and Asteraceae ($18\ kg\ N\ t^{-1}$). The N amount of the other families ranged from 21 to $25\ kg\ N\ t^{-1}$ (Table 2). Root N amount ($13.3\ kg\ N\ t^{-1}$) was half that of shoot N amount ($26.5\ kg\ N\ t^{-1}$). Shoot N amount had the same trend for Fabaceae and was lowest for Poaceae ($9.7\ kg\ N\ t^{-1}$). Shoot N for Asteraceae, Linaceae and Polygonaceae was estimated from only 1–4 measurements depending on the family but seemed consistent with those of the other botanical families.

Linear regression models based were generally more accurate when they were built by botanical family than based on the entire database (Table 3). However, even predictions based on the entire database were good,

with EF of the calculation steps ranging from 0.69 to 0.92, except for the prediction of dry root biomass from dry shoot biomass, which had a lower EF (0.3) and a low RMSE ($4\ kg\ N\ ha^{-1}$). MD was low for all variables, with three of the five equal to 0. RMSE was 0.4 – $0.9\ t\ ha^{-1}$ for predictions of dry biomass and 4 – $21\ kg\ ha^{-1}$ for predictions of N variables. When shoot N was estimated directly from fresh shoot biomass, EF was nearly the same as when it was predicted from dry shoot biomass (0.68 vs. 0.69, respectively). RMSE and MD were slightly higher in this case, but only by $2\ kg\ N\ ha^{-1}$, meaning that MERCI estimates well N content in the total biomass of cover crop residues from fresh shoot biomass. Predictions of root N directly from fresh shoot

Table 3 Statistical criteria of the calculation steps of MERCI using experimental data: root mean square error (RMSE), mean deviation (MD) and the Nash-Sutcliffe efficiency coefficient (EF). Dry shoot biomass (DM_{shoot}) from fresh shoot biomass (FM_{shoot}); total dry biomass (DM_{total}), dry root biomass(DM_{root}) and shoot N amount (N_{shoot}) from dry shoot biomass; and root N amount (N_{root}) from dry root biomass (DM_{root}). Shoot and root N was also estimated from fresh shoot biomass only

| | | Predicted variable | | | | | | |
|-------------------------------------|------|----------------------------------|----------------------------------|---------------------------------|----------------------------------|---------------------------------|----------------------------------|---------------------------------|
| | | DM_{shoot} ($t\ ha^{-1}$) | DM_{total} ($t\ ha^{-1}$) | DM_{root} ($t\ ha^{-1}$) | N_{shoot} ($kg\ ha^{-1}$) | N_{root} ($kg\ ha^{-1}$) | N_{shoot} ($kg\ ha^{-1}$) | N_{root} ($kg\ ha^{-1}$) |
| No. observations | | 4356 | 1171 | 1171 | 7085 | 1006 | 3124 | 466 |
| Variable used to predict | | FM_{shoot} ($t\ ha^{-1}$) | DM_{shoot} ($t\ ha^{-1}$) | | DM_{shoot} ($t\ ha^{-1}$) | | FM_{shoot} ($t\ ha^{-1}$) | |
| Coefficient for the entire database | MD | -0.2 | 0.0 | 0.0 | -2 | 0 | -5 | -2 |
| | RMSE | 0.9 | 0.4 | 0.4 | 21 | 4 | 23 | 8 |
| | EF | 0.72 | 0.92 | 0.30 | 0.69 | 0.74 | 0.68 | 0.25 |
| Coefficient by botanical family | MD | -0.1 | 0.0 | 0.0 | -2 | 0 | -5 | -2 |
| | RMSE | 0.8 | 0.4 | 0.4 | 19 | 4 | 20 | 8 |
| | EF | 0.78 | 0.93 | 0.38 | 0.77 | 0.79 | 0.75 | 0.25 |

biomass were slightly less accurate than those directly from dry root biomass but remained satisfactory. Moreover, the roots of cover crops contained less N than the shoots. Predicting the N amount from fresh biomass in cover crops was also limited by the number of data, as not all variables were measured in all samples.

The results were the same when the regression models were built by botanical family, with more accurate predictions. EF generally increased slightly, while MD and RMSE decreased.

For N in plant, the ‘*a*’ coefficient, representing the proportion of N in dry shoot biomass, was generally higher when biomass was low, due to the phenomenon of N dilution. For instance, from each of the three most common botanical families in the database, we selected the dominant species: white mustard, bristle oat and common vetch. We evaluated the estimates made at the species level and then those that considered biomass classes (data not shown). Species-level estimates were slightly more accurate for bristle oat and common vetch but remained the same for white mustard. Considering N dilution by biomass class increased EF by 0.10, decreased RMSE by 2 and decreased MD by 1 kg N ha⁻¹ for bristle oat, while vetch and white mustard evaluations remained the same.

Predicting C concentrations based on experimental data

The C concentration in shoots was generally higher than that in roots and ranged from 39.6 in Hydrophyllaceae to 47.6. in Linaceae. The C concentration in roots of Poaceae (32.9%) was lower than those of the other families, and the mean for the entire database was less than 40% against 41.4% in shoots (Table 4).

Table 4 Mean concentrations (%) of carbon (C) in shoots and roots by botanical family and in the entire database

| | Shoot C (%) | Roots C (%) |
|-----------------|-------------|-------------|
| Brassicaceae | 40.6 | 40.9 |
| Fabaceae | 42.1 | 36.0 |
| Poaceae | 42.0 | 32.9 |
| Hydrophyllaceae | 39.6 | 41.4 |
| Asteraceae | 42.1 | 40.6 |
| Linaceae | 47.6 | 43.0 |
| Polygonaceae | 42.7 | 40.8 |
| All | 41.4 | 39.9 |

Predicting N mineralized and leached from cover crop residues based on simulation data

As expected given STICS equations, ANOVA showed that the percentage of N mineralized was explained mainly by the C:N ratio of the residues (71%), followed by the site (20%) and number of months of N mineralization since termination (3%) (total: 94%). The percentage of N leached from residues was also explained by the C:N ratio, site and number of months, but to a lesser degree (20%, 10% and 7%, respectively). N mineralization from cover crops increased as C:N ratio decreased, from net N mineralization after 6 months when the C:N ratio was less than 22.5 to net N immobilization after 6 months when the C:N ratio usually exceeded 30 (Fig. 5a).

For every site, C:N ratios greater than 22.5 had the highest variability in mineralized N (data not shown). This higher variability was due to the contrasting amounts of simulated residues (2–8 t ha⁻¹) with low N concentration but approximately the same amount of N in the soil. In these situations, larger amounts of biomass led to more N immobilization (i.e. mineralization below 0%) because of the amount of residues to decompose. This is also explained by the low amount of N in the residue, used as denominator to calculate the percentage of N mineralized. In parallel, compared to N leaching under bare soil, N leaching from cover crop residues increased below a C:N ratio of 22.5 and decreased above this ratio, but it had high variability (Fig. 5b).

The percentage of N leached from cover crop residues after 6 months generally varied more among sites than the percentage of N mineralized did (Table 5). The latter depended mainly on the C:N ratio, varying among sites by only 4% points with C:N ratios below 40 and by 5 and 8% points with C:N ratios of 40 and 50, respectively. Standard deviations were also similar among sites and tended to increase as the C:N ratio increased: from 2 to 5% points with a C:N ratio of 7.5 to 8–15% points with a C:N ratio of 50. The percentage of N leached from cover crop residues tended to decrease as the C:N ratio increased, as net immobilization of soil mineral N occurred, but it varied greatly among sites, particularly for the lowest and highest C:N ratios. For instance, 7–33% of N in cover crop residues was leached among sites with a C:N ratio of 7.5, while the percentage ranged from –3% to -1% with a C:N ratio of 22.5.

Fig. 5 Percentage of N mineralized and leached from cover crop (CC) residues depending on their C:N ratio (7.5, 12.5, 17.5, 22.5, 30, 40 or 50) and duration since termination (1–6 months), all sites, soils, biomass classes and termination days and the 20 years combined. Whiskers equal 1.5 times the inter-quartile range (i.e. 25th to 75th percentile). Negative values indicate N immobilization

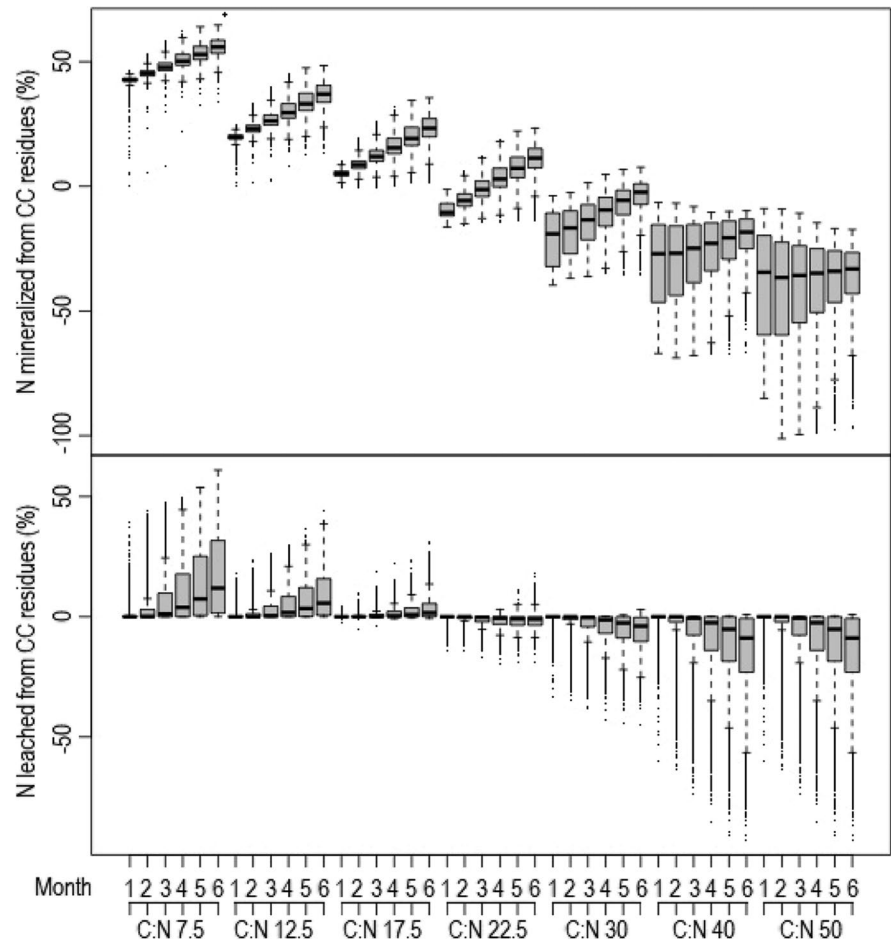


Table 5 Example of six contrasting sites for the mean percentage of N mineralized (N_{min_p}) and N leached (ΔN_{leach_p}) from cover crop residues after 6 months

| Prediction | C:N ratio | Site 1 | Site 4 | Site 7 | Site 11 | Site 15 | Site 20 |
|----------------------|-----------|----------|---------|----------|----------|----------|----------|
| N_{min_p} | 7.5 | 59 (5) | 58 (3) | 57 (3) | 56 (2) | 57 (5) | 56 (4) |
| | 12.5 | 41 (6) | 39 (4) | 39 (3) | 37 (3) | 38 (6) | 37 (5) |
| | 17.5 | 28 (6) | 26 (4) | 25 (4) | 24 (3) | 24 (6) | 24 (5) |
| | 22.5 | 14 (7) | 13 (4) | 12 (4) | 10 (3) | 11 (7) | 10 (6) |
| | 30 | -2 (7) | -2 (6) | -2 (5) | -4 (5) | -3 (8) | -6 (7) |
| | 40 | -20 (8) | -18 (7) | -19 (7) | -19 (7) | -19 (8) | -25 (11) |
| | 50 | -37 (10) | -34 (8) | -34 (8) | -34 (9) | -34 (10) | -42 (15) |
| ΔN_{leach_p} | 7.5 | 33 (14) | 7 (8) | 18 (17) | 27 (17) | 7 (9) | 18 (15) |
| | 12.5 | 18 (9) | 3 (4) | 9 (9) | 14 (10) | 4 (5) | 9 (8) |
| | 17.5 | 8 (6) | 1 (2) | 4 (5) | 6 (5) | 1 (2) | 3 (4) |
| | 22.5 | -2 (4) | -1 (1) | -2 (3) | -3 (3) | -1 (2) | -3 (3) |
| | 30 | -11 (8) | -3 (4) | -6 (7) | -9 (8) | -3 (5) | -8 (8) |
| | 40 | -27 (19) | -5 (9) | -14 (16) | -20 (17) | -6 (9) | -18 (20) |
| | 50 | -27 (19) | -5 (9) | -14 (16) | -20 (17) | -6 (9) | -18 (20) |

Standard deviations due to soil, initial biomass, termination day and year are indicated between brackets. See Fig. 2 for site locations

Percentage of N availability over time from cover crop residues

To predict the percentage of N availability over time, MERCI calculated the percentages of N mineralized and N leached as a function of the termination date class and C:N ratio predicted from the measurement of fresh shoot biomass in the field for each species and part. In MERCI, the percentage is applied to the N amount predicted by the linear regressions built from the experimental database for each part of each species. Applied on cover crops with measured N total (962 cases) from the experimental database, we found that the cover crop effect on N availability was in average at 23 kg ha⁻¹ over six month, with a range between -20 to +80 kg N ha⁻¹. In 90% of the situations, this N availability ranged between 10 and 40 kg N ha⁻¹.

The calculated percentage of N availability on the experimental database ranged from -30 to +60% and was mainly due to the mineralization levels from residue, between -31 and +60%, the percentage leached being lower, between 0 and 50% with an average at 6% (Fig. 6). As expected, N availability percentage was higher for Fabaceae due to lower C:N ratio and higher mineralized N percentage. These results led

to average N availability between 22 and 24 kg N ha⁻¹ depending on the family, with a range by family of 45 kg N ha⁻¹ for the lowest value in Hydrophyllaceae and 101 kg N ha⁻¹ for the highest one in Brassicaceae.

Discussion

MERCI: a simple and robust decision-support tool to predict nutrient availability for a wide range of cover crops

This study developed the decision-support tool MERCI (<http://www.methode-merci.fr>), which estimates N availability from cover crop residues for a wide range of species and botanical families, as sole crops or in a mixture. Its large database provides reference data for the biomass production and N concentration of 74 species, despite having less data for roots due to the difficulty of collecting them in the field. For species with few data (less than 7 by variable), predictions are based on its botanical family or the entire-database, despite decreased accuracy, as done by Meunier et al. (2022). To our knowledge, MERCI has no equivalent in the literature, especially one built from such a large database.

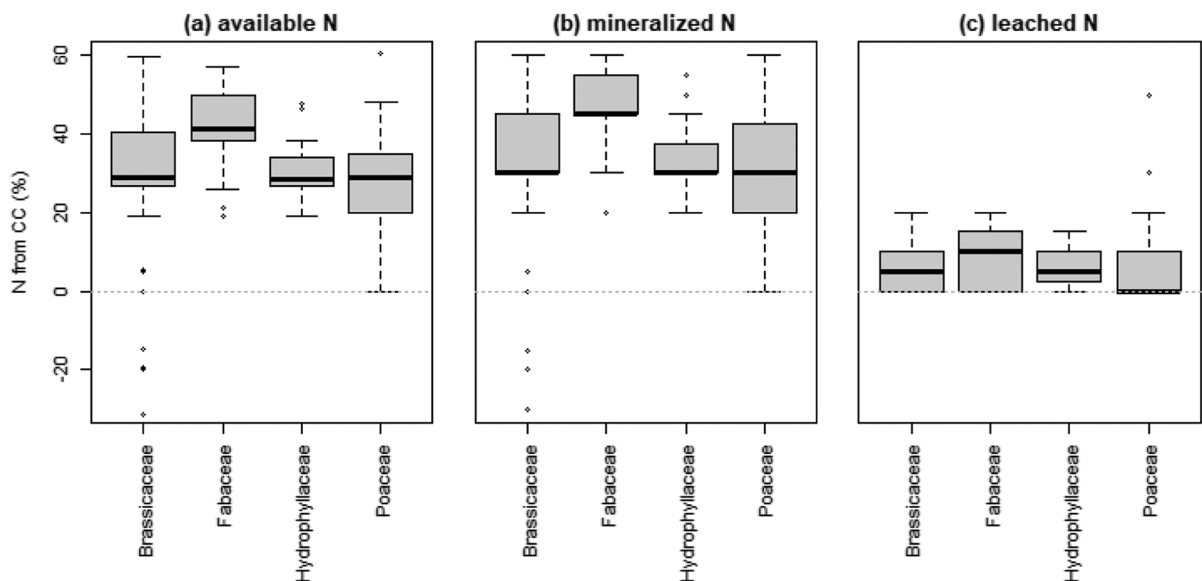


Fig. 6 N availability over 6 months (a), mineralized (b) and leached N (c) from the cover crop residue after termination, by botanical family, calculated on the N total measurement from the experimental database (962 measurements)

Many studies have been performed to estimate or measure N release from cover crops in specific situations (Hansen et al. 2021; Tonitto et al. 2006; Wittwer et al. 2017), but they have not developed models to estimate N release easily in order to adapt N fertilization for the next crop, considering end-users, as recommended by Prost et al. (2011).

Coupling an experimental database with simulation by a crop model has been used in previous studies, and was found satisfactory for developing decision-support tools (Meunier et al. 2022; White et al. 2017). STICS predictions of crop residue mineralization have been validated for the soils and climates used in the simulation experiment (e.g. Constantin et al. 2011; Coucheney et al. 2015; Jégo et al. 2008; Yin et al. 2020), which increased confidence in its predictions of N mineralization and nitrate leaching. As expected and generally known, the C:N ratio was a good proxy for mature and immature residue decomposition and N residue mineralization (Nicolardot et al. 2001; Tosti et al. 2012; White et al. 2017), and climate influenced the amount of nitrate leached, with high variability among years (Di and Cameron 2002; Thapa et al. 2018). It was also consistent to predict net N immobilization when cover crops had a C:N ratio greater than approximately 25 (Redin et al. 2014; Tosti et al. 2014). Using predictions of a dynamic soil-crop model helped to build a large table of references with dynamics of N availability that is useful for synchronizing the latter with N requirements of the next cash crop by choosing an appropriate termination date and/or species.

The correlation between fresh and dry shoot biomass was strong, and mean crop water content ranged from 10 to 20% among the families, which is similar to those observed in previous studies of specific species (Balodis et al. 2011; Monzerrat Ramírez-Olvera et al. 2018). Unexpectedly, water content in the entire plant was not really explained by the cover crop's growing period duration or termination date, perhaps because all cover crops in the database were terminated before reaching the physiological stages of maturity and senescence, which provokes a decrease in water content.

The percentage of root biomass in total biomass was consistent with the literature, with higher percentages for Poaceae species (Redin et al. 2018; Sievers and Cook 2018; Thorup-Kristensen 2001).

The percentage was slightly lower than those in studies of wheat or maize, likely because these studies measured mature crops, while cover crops are often terminated when still immature. The root system of young crops is still developing to support future shoot growth, which explains their higher percentage of root biomass. This highlights the importance of considering roots to fully evaluate effects of cover crops on nutrient cycles and C storage, particularly when aerial biomass is exported (Launay et al. 2022).

N amounts acquired by cover crops were also consistent, with higher N content usually found in legumes due to symbiotic N₂ fixation (Tonitto et al. 2006; Tribouillois et al. 2015b) and N dilution observed when biomass was higher (Colnenne et al. 1998; Debaeke et al. 2012; Zhao et al. 2018). The relation between dry shoot biomass and N amount showed more variability but remained satisfactory for predicting the latter, especially when enough data were available for a given species. Adding classes of biomass to consider N dilution improved predictions for some species, but not by much, as N often limits growth of cover crops. This may have been due to the small range of biomass of cover crops in the database, given their short growing period and the scarcity of data for many species.

N availability for the next crop estimated on the MERCI experimental database ranged from −20 to 80 kg N/ha. In most cases, the effect was between 10 and 40 kg N ha^{−1} with higher percentages for legume cover crops. It is consistent with previous studies that found N release from cover crops of 10–56 kg N ha^{−1} depending on cover crop species (Hansen et al. 2021) and of 28 against 60 kg N ha^{−1} for cereal rye against vetch (Singh et al. 2020). Associated impact on mineral N fertilization reduction was estimated by several authors that quantified it between 0 and 87 kg N ha^{−1} (Andraski and Bundy 2005; Fontaine et al. 2020), that is consistent with the range of N availability estimated in the MERCI tool.

Accuracy was generally higher when many data points were available for a given species, but MERCI remained sufficiently robust and accurate to estimate the N amount from fresh shoot biomass at the family level, or from the entire database for species with few data points or a rare botanical family. This approach provided high flexibility depending on the data available, as well as initial estimates for new species, for which measurements remain rare.

Limits and possible extensions of MERCI

Uncertainties in MERCI were quantified for the estimation steps using the experimental database, while for STICS predictions of N mineralized from cover crop residues, the evaluation of RMSE have been made in previous publications. For STICS predictions of N leaching, some experimental data were evaluated, but it is difficult to quantify its uncertainty because it is difficult to measure experimentally. Consequently, it would be interesting to assess MERCI fully, from measurement of fresh biomass to predictions of N over time and other nutrient availability for the next crop based on field data from a variety of soil, climate and cover crop management conditions. This evaluation would require specific experiments with detailed monitoring of N dynamics after the termination date, particularly in the soil.

We decided to sum the species and their parts at the end of the calculation for several practical reasons. For one, doing so provided the contribution of each species to the availability of N and other nutrients to the next crop. Second, if shoots of cover crops are exported for energy or forage, the method remains easily applicable for estimating the influence of roots alone on nutrients, as shoots and roots are calculated independently. Conversely, it assumes that shoots and roots do not interact strongly after burial in the soil or during decomposition. Third, the method allows users to add more species to a mixture easily and to run MERCI for mixtures that contain more than two species. However, the addition of more species should be evaluated to ensure the relevance of MERCI for multispecies mixtures, as only 2% of mixtures in the experimental database had more than two species. Finally, the method considers mineralization of the N in cover crop residues that have been buried. According to the literature, burying crop residues mineralizes their N less slowly than leaving them on the soil surface and induces less N immobilization in the soil (Abiven and Recous 2007; Chaves et al. 2021; Li et al. 2013). Keeping shoots and roots separate in MERCI allows this effect to be simulated by modifying the N mineralization of only the shoots of each cover crop species and could be useful to assess N dynamics in conservation agriculture systems.

The concept of N dilution was considered to attempt to increase the accuracy of N predictions from dry biomass. Classes of dry biomass were used to represent

N dilution, but doing so requires much more data on a wide range of biomass for a given species. This requirement rendered application of this concept to the entire database difficult, and prediction accuracy did not always increase. Addition of new data to the experimental database should indicate whether these biomass classes are justified, depending on the increase in accuracy for most species. Use of MERCI will help to guide its development to simultaneously increase its accuracy and adoption by advisors and farmers.

To date, the method has been developed and applied only for temperate climates and a range of soils that correspond to the high variability of soils encountered in Western Europe. As STICS is used to predict N release and availability, MERCI's domain of validity is that of STICS, and future extensions of STICS should enable MERCI to be applied to a wider range of situations. STICS is now calibrated for soils and climates that are representative of much of Europe, but also some from North America (Jégo et al. 2010; Nendel et al. 2022; Yin et al. 2016).

Moreover, estimating the percentage of N available depends on the nearest simulated site, of which France has only 24. Like soil type and depth, climate can vary greatly over short distances, especially rainfall, and influence the associated risks of N leaching (Di and Cameron 2002). As shown, the percentage of N mineralized was less sensitive to the site or the year, while N leaching was highly sensitive to it and varied greatly by year, as generally recognized (Beaudoin et al. 2005; Constantin et al. 2015a). This potential for N leaching could varied even more in irrigated systems as compared to rainfed ones, depending on water management strategies. Given these elements, one improvement could be to analyse the climate of the site of interest to choose the most similar site in the simulation, particularly in rainfall. Choosing the simulated site well could allow N leaching from cover crops to be predicted more accurately without greatly modifying prediction of the percentage of N mineralized. A future version of MERCI could also consider the probability of rainfall during the 6 months after termination of cover crop to estimate nitrate leaching from mineralization of cover crop residues more accurately. More generally, a better characterization of the climate years and risks of occurrence for some rainfall events after cover crop termination could help to obtain better predictions of cover crops effects, particularly on region with high risk and variability in N leaching.

The database contains few data on roots in general, increasing uncertainties for N predictions and more data could help predict root N more accurately. Nevertheless, N in roots is a relatively small percentage of total N, so its uncertainty has less influence than that of shoots, except for exported residues. Nevertheless, even with an accuracy of 25% (RMSE as a percentage of the mean), MERCI is useful for advisors and farmers to predict N availability for the next cash crop and potentially adjust N fertilization in consequences, as no such tool was previously available for end-users.

Implications for N mineral fertilization and climate change mitigation

While MERCI estimates N release from cover crops after termination as a function of soil and climate, it is not sufficient for calculating the influence of cover crop on mineral N fertilization. Analysing soil mineral N at sowing of the next crop is crucial for doing so, in addition to MERCI's predictions of N mineralization of cover crop residues. Soil mineral N at sowing combined with MERCI estimation of N release from the same date should be used to better calculate the amount of mineral fertiliser to apply depending on crop requirements, using N-budget approaches such as that of COMIFER (Meynard et al. 2002).

As shown by our results, pre-emptive competition for N for the next crop is possible, particularly with late termination, N immobilization due to a high C:N ratio and a dry context (Thorup-Kristensen et al. 2003). With low drainage during winter, cover crops take up soil mineral N that would have remained completely available for the next crop and then release no more than 50 to 65% of it (Hansen et al. 2021; Justes et al. 2009). In this particular context, growing a large amount of cover crop biomass with a high C:N ratio and late termination could decrease N availability when the next crop needs a large amount of N to grow. In consequences, N fertilization could increase in the short term. However, using cover crops for several years in cropping systems could increase soil organic matter and basal soil N mineralization, leading to lower fertiliser requirements, estimated at 15–27 kg N ha⁻¹ yr⁻¹ after 15 to 25 years of cover crops (Berntsen et al. 2006; Constantin et al. 2012; Hansen and Djurhuus 1997). Adapting cover crop management, such as the duration of growing period and the use of species mixtures, especially including

legumes, should help avoid pre-emptive competition and lead to a green-manure effect, thus decreasing fertiliser requirements (Tosti et al. 2014; White et al. 2017). Between decreasing N leaching and increasing N input through symbiotic N₂ fixation, cover crop mixtures with legumes and non-legume crops could help increase N cycling in agroecosystems (Abdalla et al. 2019; Tribouillois et al. 2015a), and MERCI could help make choices that optimize the N management of arable cropping systems, by testing different scenarios of cover crop management (species and termination dates). Future extension of MERCI could included the same kind of predictions for others nutrients such as P, K, S and Mg for a better cycling of nutrients in cropping systems.

Finally, better consideration of cover crop N inputs to decrease the use of mineral N fertilisers decreases environmental impacts by decreasing CO₂ and N₂O emissions of fertilisers when applied in the field, even though cover crops slightly increase N₂O emissions compared to those of a bare soil in some cases (Abdalla et al. 2019; Basche et al. 2014; Kaye and Quemada 2017). It also mitigates climate change impacts, as less mineral fertiliser produced with the Haber-Bosch process, which has a high energy cost, is used. As MERCI estimated the total amount of C in cover crop residues, it is also simple to estimate C storage in the soil due to cover crops using a simple humification coefficient, estimated in the literature to range from 0.25 to 0.28 (Constantin et al. 2010a; Poeplau and Don 2015), which provides an initial estimate of the contribution of cover crops to sequestering C in the soil and mitigating CO₂ emissions.

Conclusion

We developed the simple decision-support tool MERCI to estimate N availability from cover crop residues to the next cash crop; it requires only measured fresh shoot biomass for each of the species grown in the cover crop. MERCI, available on a website for end-users such as farmers and agricultural advisors, is easy to apply and robust, as it has been validated for a wide range of species and temperate conditions. MERCI is useful for considering the green-manure effect of cover crops and optimizing N recycling in agroecosystems. It results in less use of mineral N fertilisers, which have negative

environmental impacts, particularly through their production. By highlighting potential positive agronomic effects, MERCI promotes the use of cover crops, which can provide several other ecosystem services. MERCI estimated N well, but it should be evaluated under more conditions, for species mixtures with more than two species and for more nutrients with new data in order to develop more agroecological cropping systems.

Acknowledgements We thank all partners and providers of data for the MERCI experimental database (<https://methode-merci.fr/partenaires>), as well as the following partners for financial support: Chambre Régionale d'Agriculture Nouvelle Aquitaine, Arvalis Institut du végétal, Bordeaux Science Agro and INRAE. This study was financially supported by the French Ministry of Agriculture in the MERCI Project (AAP 775 CasDAR 2018).

Data Availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request and subject to partner agreement. Only aggregated data will be available.

Declarations

Competing interest The authors have no relevant financial, non-financial or competing interests to disclose.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abdalla M, Hastings A, Cheng K, Yue Q, Chadwick D, Espenberger M, Truu J, Rees RM, Smith P (2019) A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Glob Chang Biol* 25:2530–2543. <https://doi.org/10.1111/gcb.14644>
- Abiven S, Recous S (2007) Mineralisation of crop residues on the soil surface or incorporated in the soil under controlled

- conditions. *Biol Fertil Soils* 43:849–852. <https://doi.org/10.1007/s00374-007-0165-2>
- Alonso-Ayuso M, Gabriel JL, Quemada M (2014) The kill date as a management tool for cover cropping success. *PLoS ONE* 9:e109587. <https://doi.org/10.1371/journal.pone.0109587>
- Andraski TW, Bundy LG (2005) Cover crop effects on corn yield response to nitrogen on an irrigated sandy soil. *Agron J* 97:1239–1244. <https://doi.org/10.2134/agronj2005.0052>
- Balodis O, Bartuševis J, Gaile Z (2011) Biomass yield of different plants for biogas production. In: *Proceedings of the 8th International Scientific and Practical Conference. Environment Technology Resources* 1:238. <https://doi.org/10.17770/etr2011vol1.884>
- Basche AD, Miguez FE, Kaspar TC, Castellano MJ (2014) Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. *J Soil Water Conserv* 69:471–482. <https://doi.org/10.2489/jswc.69.6.471>
- Beaudoin N, Saad JK, Van Laethem C, Machet J, Maucorps J, Mary B (2005) Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. *Agric Ecosyst Environ* 111:292–310. <https://doi.org/10.1016/j.agee.2005.06.006>
- Berntsen J, Olesen JE, Petersen BM, Hansen EM (2006) Long-term fate of nitrogen uptake in catch crops. *Eur J Agron* 25:383–390. <https://doi.org/10.1016/j.eja.2006.07.006>
- Brisson N, Launay M, Mary B, Beaudoin N (2008) Conceptual basis, formalisations and parameterization of the STICS crop model. *Éditions Quae*, 2008
- Brisson N, Mary B, Ripoche D, Jeuffroy M-H, Ruget F, Nicoullaud B, Gate P, Devienne-barret F, Recous S, Tayot X, Plenet D, Cellier P, Machet J, Marc J, Delécolle R (1998) STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* 18:311–346
- Brisson N, Ruget F, Gate P, Lorgeou J, Nicoullaud B, Tayot X, Plenet D, Jeuffroy M-H, Bouthier A, Ripoche D, Mary B, Justes E (2002) A generic model for simulating crops and their water and nitrogen balances. II. Model validation for wheat and maize. *Agronomie* 22:69–92. <https://doi.org/10.1051/agro>
- Chaves B, Redin M, Giacomini SJ, Schmatz R, Léonard J, Ferchaud F, Recous S (2021) The combination of residue quality, residue placement and soil mineral N content drives C and N dynamics by modifying N availability to microbial decomposers. *Soil Biol Biochem* 163:108434. <https://doi.org/10.1016/j.soilbio.2021.108434>
- Colnenne C, Meynard JM, Reau R, Justes E, Merrien A (1998) Determination of a critical nitrogen dilution curve for winter oilseed rape. *Ann Bot* 81:311–317. <https://doi.org/10.1006/anbo.1997.0557>
- Constantin J, Le Bas C, Justes E (2015a) Large-scale assessment of optimal emergence and destruction dates for cover crops to reduce nitrate leaching in temperate conditions using the STICS soil – crop model. *Eur J Agron* 69:75–87. <https://doi.org/10.1016/j.eja.2015.06.002>
- Constantin J, Willaume M, Murgue C, Lacroix B, Therond O (2015b) The soil-crop models STICS and AqYield predict yield and soil water content for irrigated crops equally well with limited data. *Agric for Meteorol Meteorol* 206:55–68. <https://doi.org/10.1016/j.agrformet.2015.02.011>

- Constantin J, Beaudoin N, Launay M, Duval J, Mary B (2012) Long-term nitrogen dynamics in various catch crop scenarios: test and simulations with STICS model in a temperate climate. *Agric Ecosyst Environ* 147:36–46. <https://doi.org/10.1016/j.agee.2011.06.006>
- Constantin J, Beaudoin N, Laurent F, Cohan J, Duyme F, Mary B (2011) Cumulative effects of catch crops on nitrogen uptake, leaching and net mineralization. *Plant Soil* 341:137–154. <https://doi.org/10.1007/s11104-010-0630-9>
- Constantin J, Mary B, Laurent F, Aubrion G, Fontaine A, Kerveillant P, Beaudoin N (2010a) Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agric Ecosyst Environ* 135:268–278. <https://doi.org/10.1016/j.agee.2009.10.005>
- Constantin J, Mary B, Bruno, Mary B, Laurent F, Aubrion G, Fontaine A, Kerveillant P, Beaudoin N (2010b) Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture, Ecosystems and Environment* Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen le. <https://doi.org/10.1016/j.agee.2009.10.005>
- Coucheney E, Buis S, Launay M, Constantin J, Mary B, García de Cortázar-Atauri I, Ripoche D, Beaudoin N, Ruget FF, Andrianarisoa KS, Le Bas C, Justes E, Leonard J (2015) Accuracy, robustness and behavior of the STICS v-8 soil-crop model for plant, water and nitrogen outputs: evaluation over a wide range of agro-environmental conditions. *Environ Model Softw* 64:177–190. <https://doi.org/10.1016/j.envsoft.2014.11.024>
- Couëdel A, Alletto L, Justes É (2018) Crucifer-legume cover crop mixtures provide effective sulphate catch crop and sulphur green manure services. *Plant Soil* 426:61–76. <https://doi.org/10.1007/s11104-018-3615-8>
- Couëdel A, Kirkegaard J, Alletto L, Justes É (2019) Crucifer-legume cover crop mixtures for biocontrol: toward a new multi-service paradigm. *Adv Agron* 157:55–139. <https://doi.org/10.1016/bs.agron.2019.05.003>
- Debaeke P, van Oosterom EJ, Justes E, Champolivier L, Merrien A, Aguirrezabal LAN, González-Dugo V, Massignam AM, Montemurro F (2012) A species-specific critical nitrogen dilution curve for sunflower (*Helianthus annuus* L.). *F Crop Res* 136:76–84. <https://doi.org/10.1016/j.fcr.2012.07.024>
- Di HJ, Cameron KC (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr Cycl Agroecosyst* 64:237–256. <https://doi.org/10.1023/A:1021471531188>
- Duru M, Therond O, Martin G, Martin-Clouaire R, Magne MA, Justes E, Journet EP, Aubertot J-N, Savary S, Bergez J-E, Sarthou J-P (2015) How to implement biodiversity-based agriculture to enhance ecosystem services: a review. *Agron Sustain Dev* 35:1259–1281. <https://doi.org/10.1007/s13593-015-0306-1>
- Fontaine D, Eriksen J, Sørensen P (2020) Cover crop and cereal straw management influence the residual nitrogen effect. *Eur J Agron* 118:126100. <https://doi.org/10.1016/j.eja.2020.126100>
- Hansen EM, Djurhuus J (1997) Yield and N uptake as affected by soil tillage and catch crop. *Soil Tillage Res* 42:241–252
- Hansen V, Eriksen J, Jensen LS, Thorup-Kristensen K, Magid J (2021) Towards integrated cover crop management: N, P and S release from aboveground and belowground residues. *Agric Ecosyst Environ* 313:107392. <https://doi.org/10.1016/j.agee.2021.107392>
- Jégo G, Martínez M, Antigüedad I, Launay M, Sanchez-Perez J-M, Justes E (2008) Evaluation of the impact of various agricultural practices on nitrate leaching under the root zone of potato and sugar beet using the STICS soil-crop model. *Sci Total Environ* 394:207–221. <https://doi.org/10.1016/j.scitotenv.2008.01.021>
- Jégo G, Pattey E, Bourgeois G, Morrison MJ, Drury CF, Tremblay N, Tremblay G (2010) Calibration and performance evaluation of soybean and spring wheat cultivars using the STICS crop model in Eastern Canada. *F Crop Res* 117:183–196. <https://doi.org/10.1016/j.fcr.2010.03.008>
- Justes E (2017) Conclusions and Outlook. In: Justes E (ed) *Cover crops for sustainable farming*. Springer Netherlands, Dordrecht, pp 83–88. https://doi.org/10.1007/978-94-024-0986-4_4
- Justes E, Mary B, Nicolardot B (2009) Quantifying and modelling C and N mineralization kinetics of catch crop residues in soil: parameterization of the residue decomposition module of STICS model for mature and non mature residues. *Plant Soil* 325:171–185. <https://doi.org/10.1007/s11104-009-9966-4>
- Kaye JP, Quemada M (2017) Using cover crops to mitigate and adapt to climate change. A review. *Agron Sustain Dev* 37. <https://doi.org/10.1007/s13593-016-0410-x>
- Launay C, Constantin J, Chlebowski F, Houot S, Graux A-I, Klumpp K, Martin R, Mary B, Pellerin S, Therond O (2021) Estimating the carbon storage potential and greenhouse gas emissions of french arable cropland using high-resolution modeling. *Glob Chang Biol* 1–41. <https://doi.org/10.1111/gcb.15512>
- Launay C, Houot S, Frédéric S, Girault R, Levavasaur F, Marsac S, Constantin J (2022) Incorporating energy cover crops for biogas production into agricultural systems: benefits and environmental impacts. A review. *Agron Sustain Dev* 8:42–57
- Li LJ, Han XZ, You MY, Yuan YR, Ding XL, Qiao YF (2013) Carbon and nitrogen mineralization patterns of two contrasting crop residues in a Mollisol: Effects of residue type and placement in soils. *Eur J Soil Biol* 54:1–6. <https://doi.org/10.1016/j.ejsobi.2012.11.002>
- Metzger MJ, Bunce RGH, Jongman RHG, Múcher CA, Watkins JW (2005) A climatic stratification of the environment of Europe. *Glob Ecol Biogeogr* 14:549–563. <https://doi.org/10.1111/j.1466-822X.2005.00190.x>
- Meunier C, Alletto L, Bedoussac L, Bergez JE, Casadebaig P, Constantin J, Gaudio N, Mahmoud R, Aubertot JN, Celette F, Guinet M, Jeuffroy MH, Robin MH, Médiène S, Fontaine L, Nicolardot B, Pelzer E, Souchère V, Voisin AS, Rosiès B, Casagrande M, Martin G (2022) A modelling chain combining soft and hard models to assess a bundle of ecosystem services provided by a diversity of cereal-legume intercrops. *Eur J Agron* 132:126412. <https://doi.org/10.1016/j.eja.2021.126412>
- Meynard JM, Cerf M, Guichard L, Jeuffroy MH, Makowski D (2002) Which decision support tools for the environmental management of nitrogen? *Agronomie* 22:817–829. <https://doi.org/10.1051/AGRO:2002064>
- Monzerrat Ramírez-Olvera S, Trejo-Té llez I, García-Morales L, Antonio S, Pérez-Sato J, Gómez-Merino FC (2018) Cerium enhances germination and shoot growth, and

- alters mineral nutrient concentration in rice. <https://doi.org/10.1371/journal.pone.0194691>
- Nendel C, Reckling M, Debaeke P, Schulz S, Mohnicke MB, Fronzek S, Hoffmann M, Jakšić S, Kersebaum C, Kopyra AK, Schoving C, Stella T, Battisti R (2022) Future area expansion outweighs increasing drought risk for soybean in Europe. *Glob Chang Biol* 00:1–19. <https://doi.org/10.1111/gcb.16562>
- Nicolardot B, Recous S, Mary B (2001) Simulation of C and N mineralisation during crop residue decomposition: a simple dynamic model based on the C : N ratio of the residues. *Plant and Soil* 228:83–103. <https://doi.org/10.1023/A:1004813801728>
- Poelau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agric Ecosyst Environ* 200:33–41. <https://doi.org/10.1016/j.agee.2014.10.024>
- Prost L, Cerf M, Jeuffroy M-H (2011) Lack of consideration for end-users during the design of agronomic models. A review. *Agron Sustain Dev* 32:581–594. <https://doi.org/10.1007/s13593-011-0059-4>
- Redin M, Recous S, Aita C, Chaves B, Pfeifer IC, Bastos LM, Pilecco GE, Giacomini SJ (2018) Root and shoot contribution to carbon and nitrogen inputs in the topsoil layer in no-tillage crop systems under subtropical conditions. *Rev Bras Cienc do Solo* 42. <https://doi.org/10.1590/18069657RBCS20170355>
- Redin M, Recous S, Aita C, Dietrich G, Skolaude AC, Ludke WH, Schmatz R, Giacomini SJ (2014) How the chemical composition and heterogeneity of crop residue mixtures decomposing at the soil surface affects C and N mineralization. *Soil Biol Biochem* 78:65–75. <https://doi.org/10.1016/J.SOILBIO.2014.07.014>
- Schnebelen N, Nicoullaud B, Bourennane H, Couturier A (2004) The STICS model to predict nitrate leaching following agricultural practices. *Agronomie* 24:423–435. <https://doi.org/10.1051/agro>
- Sievers T, Cook RL (2018) Aboveground and Root decomposition of cereal Rye and hairy vetch cover crops. *Soil Sci Soc Am J* 82:147–155. <https://doi.org/10.2136/sssaj2017.05.0139>
- Singh G, Dhakal M, Yang L, Kaur G, Williard KWJ, Schoonover JE, Sadeghpour A (2020) Decomposition and nitrogen release of cover crops in reduced- and no-tillage systems. *Agron J* 112:3605–3618
- Thapa R, Mirsky SB, Tully KL (2018) Cover crops reduce Nitrate leaching in Agroecosystems: A Global Meta-Analysis. *J Environ Qual* 47:1400–1411. <https://doi.org/10.2134/jeq2018.03.0107>
- Thomsen IK (2005) Nitrate leaching under spring barley is influenced by the presence of a ryegrass catch crop: results from a lysimeter experiment. *Agric Ecosyst Environ* 111:21–29. <https://doi.org/10.1016/j.agee.2005.05.001>
- Thorup-Kristensen K (2001) Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? *Plant Soil* 230:185–195
- Thorup-Kristensen K, Magrid J, Jensen LS, Magid J, Jensen LS, Magrid J, Jensen LS, Magid J, Jensen LS (2003) Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Adv Agron* 79:227–302. [https://doi.org/10.1016/S0065-2113\(02\)79005-6](https://doi.org/10.1016/S0065-2113(02)79005-6)
- Tonitto C, David MB, Drinkwater LE (2006) Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. *Agric Ecosyst Environ* 112:58–72. <https://doi.org/10.1016/j.agee.2005.07.003>
- Tosti G, Benincasa P, Farneselli M, Pace R, Tei F, Guiducci M, Thorup-Kristensen K (2012) Green manuring effect of pure and mixed barley – hairy vetch winter cover crops on maize and processing tomato N nutrition. *Eur J Agron* 43:136–146. <https://doi.org/10.1016/j.eja.2012.06.004>
- Tosti G, Benincasa P, Farneselli M, Tei F, Guiducci M (2014) Barley–hairy vetch mixture as cover crop for green manuring and the mitigation of N leaching risk. *Eur J Agron* 54:34–39. <https://doi.org/10.1016/j.eja.2013.11.012>
- Tribouillois H, Cohan J-P, Justes E (2015a) Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: assessment combining experimentation and modelling. *Plant Soil* 401:347–364. <https://doi.org/10.1007/s11104-015-2734-8>
- Tribouillois H, Fort F, Cruz P, Charles R, Flores O, Garnier E, Justes E (2015b) A functional characterisation of a wide range of cover crop species: growth and nitrogen acquisition rates, leaf traits and ecological strategies. *PLoS ONE* 10:1–17. <https://doi.org/10.1371/journal.pone.0122156>
- Tribouillois H, Constantin J, Justes E (2018) Cover crops mitigate direct greenhouse gases balance but reduce drainage under climate change scenarios in temperate climate with dry summers. *Glob Chang Biol* 24:2513–2529. <https://doi.org/10.1111/gcb.14091>
- Tribouillois H, Dürr C, Demilly D, Wagner M, Justes E (2016) Determination of Germination response to temperature and water potential for a wide range of cover crop species and related functional groups. *PLoS ONE* 11:e0161185. <https://doi.org/10.1371/journal.pone.0161185>
- White CM, DuPont ST, Hautau M, Hartman D, Finney DM, Bradley B, LaChance JC, Kaye JP (2017) Managing the trade off between nitrogen supply and retention with cover crop mixtures. *Agric Ecosyst Environ* 237:121–133. <https://doi.org/10.1016/j.agee.2016.12.016>
- Wittwer RA, Dorn B, Jossi W, van der Heijden MGA (2017) Cover crops support ecological intensification of arable cropping systems. *Sci Rep* 7:1–12. <https://doi.org/10.1038/srep41911>
- Yin X, Beaudoin N, Ferchaud F, Mary B, Strullu L, Chlébowski F, Clivot H, Herre C, Duval J, Louarn G (2020) Long-term modelling of soil N mineralization and N fate using STICS in a 34- year crop rotation experiment. *Geoderma* 357:113956. <https://doi.org/10.1016/j.geoderma.2019.113956>
- Yin X, Kersebaum K-C, Kollas C, Manevski K, Baby S, Beaudoin N, Ozturk I, Gaiser T, Wu L, Hoffmann M, Charfeddine M, Conradt T, Constantin J, Ewert F, Garcia de Cortazar-Atauri I, Giglio L, Hlavinka P, Hoffmann H, Launay M, Louarn G, Manderscheid R, Mary B, Mirschel W, Nendel C, Pacholski A, Palosuo T, Ripoche-wachter D, Rötter RP, Ruget F, Sharif B, Trnka M, Ventrella D, Weigel H-J, Olesen JE, Christian K, Öztürk I, Ho M, de Cortázar-Atauri I, Ho H (2016) Performance of process-based models for simulation of grain N in crop rotations

across Europe. *Agric Syst* 154:63–77. <https://doi.org/10.1016/j.agsy.2017.03.005>

Zhao B, Ata-Ul-Karim ST, Duan A, Liu Z, Wang X, Xiao J, Liu Z, Qin A, Ning D, Zhang W, Lian Y (2018) Determination of critical nitrogen concentration and dilution curve based on leaf area index for summer maize. *F Crop Res* 228:195–203. <https://doi.org/10.1016/j.fcr.2018.09.005>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.