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PRIMARY RESEARCH ARTICLE

Estimating the carbon storage potential and greenhouse gas emissions of French arable cropland using high-resolution modeling

Camille Launay^{1,2}  | Julie Constantin¹  | Florent Chlebowski³ | Sabine Houot⁴  |
 Anne-Isabelle Graux⁵  | Katja Klumpp⁶  | Raphaël Martin⁶  | Bruno Mary³ |
 Sylvain Pellerin⁷ | Olivier Therond⁸ 

¹Université de Toulouse, INRAE, UMR AGIR, Castanet-Tolosan, France

²INRAE, DEPE, Paris, France

³BioEcoAgro Joint Research Unit, INRAE, Université de Liège, Université de Lille, Université de Picardie Jules Verne, Barenton-Bugny, France

⁴Université Paris-Saclay, INRAE, AgroParisTech, UMR Ecosys, Thiverval-Grignon, France

⁵INRAE, Institut Agro, UMR PEGASE, Saint-Gilles, France

⁶Université Clermont Auvergne, INRAE, VetAgroSup, UMR UREP, Clermont-Ferrand, France

⁷INRAE, Bordeaux Sciences Agro, UMR ISPA, Villenave d'Ornon, France

⁸Université de Lorraine, INRAE, UMR LAE, Colmar, France

Correspondence

Julie Constantin, INRAE, UMR AGIR, F-31320 Castanet-Tolosan, France.
 Email: julie.constantin@inrae.fr

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Abstract

Many studies have assessed the potential of agricultural practices to sequester carbon (C). A comprehensive evaluation of impacts of agricultural practices requires not only considering C storage but also direct and indirect emissions of greenhouse gases (GHG) and their side effects (e.g., on the water cycle or agricultural production). We used a high-resolution modeling approach with the Simulateur multiDisciplinaire pour les Cultures Standard soil-crop model to quantify soil organic C (SOC) storage potential, GHG balance, biomass production and nitrogen- and water-related impacts for all arable land in France for current cropping systems (baseline scenario) and three mitigation scenarios: (i) spatial and temporal expansion of cover crops, (ii) spatial insertion and temporal extension of temporary grasslands (two sub-scenarios) and (iii) improved recycling of organic resources as fertilizer. In the baseline scenario, SOC decreased slightly over 30 years in crop-only rotations but increased significantly in crop/temporary grassland rotations. Results highlighted a strong trade-off between the storage rate per unit area ($\text{kg C ha}^{-1} \text{ year}^{-1}$) of mitigation scenarios and the areas to which they could be applied. As a result, while the most promising scenario at the field scale was the insertion of temporary grassland ($+466 \text{ kg C ha}^{-1} \text{ year}^{-1}$ stored to a depth of 0.3 m compared to the baseline, on 0.68 Mha), at the national scale, it was by far the expansion of cover crops ($+131 \text{ kg C ha}^{-1} \text{ year}^{-1}$, on 17.62 Mha). Side effects on crop production, water irrigation and nitrogen emissions varied greatly depending on the scenario and production situation. At the national scale, combining the three mitigation scenarios could mitigate GHG emissions of current cropping systems by 54% (-11.2 from the current $20.5 \text{ Mt CO}_2\text{e year}^{-1}$), but the remaining emissions would still lie far from the objective of C-neutral agriculture.

KEYWORDS

cover crops, cropping system, large scale, organic fertilization, STICS model, temporary grasslands

1 | INTRODUCTION

The 2018 IPCC Special Report stressed the need to achieve global carbon (C) neutrality by 2050 (Hoegh-Guldberg et al., 2018) to limit the global temperature increase to 1.5°C above pre-industrial levels. This ambitious objective is now a benchmark in national, European and international climate policies. Achieving C neutrality requires both (1) drastically reducing CO₂ emissions from the use of fossil fuels and deforestation, and emissions of other greenhouse gases (GHGs; CH₄ and N₂O), mainly from agriculture and (2) increasing C storage, mainly by changing land use and land cover but also by developing agricultural and forestry practices that promote C storage in soils and woody biomass (Watson et al., 2000).

At the global scale, the stock of soil organic C (SOC) to a depth of 2 m is ca. 2400 Gt C, which is three times the amount of C in the atmosphere (800 Gt C). The ratio of annual anthropogenic emissions of CO₂ from fossil-fuel combustion (9.6 Gt C year⁻¹) to SOC stock (2400 Gt C) is ca. 4‰, suggesting that an increase in SOC stock of 4‰ per year would theoretically offset these emissions (Minasny et al., 2017, 2018). This rough assessment led to the emergence of the “4 per 1000” initiative, a multi-stakeholder platform to increase SOC storage through sustainable practices. The initiative aims to quantify the key contribution of SOC storage to climate change mitigation, soil fertility and food security as well as the many constraints that limit SOC storage (e.g., pedoclimatic characteristics, land use, change in land management and cover). Moreover, the initiative clarified that the simplified 4‰ target is an aspirational goal with much uncertainty about what can be achieved in specific regions or countries (Chenu et al., 2019; Minasny et al., 2018; Rumpel et al., 2020; see <https://www.4p1000.org>).

As a result of the 4‰ initiative, many studies have assessed the potential of agricultural practices to increase SOC. Assuming a target of 3.5 Gt C year⁻¹ for the 4‰ initiative, Zomer et al. (2017) estimated that “croplands worldwide could sequester between 0.90 and 1.85 Gt C year⁻¹, that is, 26%–53% of the target” in the top 0.3 m of soils. Several meta-analyses of cropping systems have shown the ability of key agricultural practices to favor SOC storage. For example, the meta-analysis of Poeplau and Don (2015) showed that cover crops, when their residues are always left in the field, increased SOC in the topsoil (0–0.22 m deep) by a mean of 320 kg C ha⁻¹ year⁻¹ in a temperate climate. Likewise, inserting grasslands into crop rotations was highlighted to have potentially positive impacts on SOC storage (Franzuebbers et al., 2014; Johnston et al., 2017; Lemaire et al., 2015). The mitigation potential of these management practices is now well recognized. In addition, even if application of animal manure is not a mitigation practice, it is an excellent way to increase SOC stock locally. A meta-analysis of application of animal manure (Maillard & Angers, 2014) indicated that it increased SOC by 311 kg C ha⁻¹ year⁻¹ in the topsoil (0–0.3 m deep) compared to application of only mineral fertilizer when applied for a mean of 18 years. In cases where the organic material applied is not from agricultural origin (e.g., green waste, municipal waste, sewage sludge), C storage

is also a C sequestration. For example, regular application of compost from different non-agricultural sources has been shown to increase SOC in the topsoil (0–0.29 m deep) by up to 500 kg C ha⁻¹ year⁻¹ in a temperate climate (Peltre et al., 2012).

In contrast, there is less consensus about other agricultural practices, such as no-till (Bossio et al., 2020). The meta-analysis of Haddaway et al. (2017) showed that in boreo-temperate regions, C stock increased under no-till in the topsoil (0–0.3 m) but not in the entire soil profile. Ogle et al. (2019) highlighted the large uncertainties in the effect of no-till on SOC storage and concluded that “no-till may be better viewed as a method for reducing soil erosion, adapting to climate change, and ensuring food security” rather than mitigating GHG emissions. Finally, the results obtained in long-term experiments in France (Dimassi et al., 2013, 2014; Mary et al., 2020) indicate that there is no benefit of reduced tillage and even no-till on SOC sequestration in the 0–0.4 m layer.

When considering the potential of agricultural practices, some authors emphasized that C storage implies nitrogen (N) and phosphorus storage as well, due to the stoichiometric constraints of organic matter (Bertrand et al., 2019; Guenet et al., 2020; Spohn, 2020; van Groenigen et al., 2017). Care must be taken in managing N not to create a surplus between inputs and exports that could increase N₂O emissions (Guenet et al., 2020). If N input by mineral fertilizers is increased, indirect CO₂ emissions from the energy used to produce the fertilizers must also be taken into account (Schlesinger, 2000). It is therefore necessary to also consider direct and indirect GHG emissions to have a complete view of impacts of agricultural practices on the GHG balance in cropping systems. Other issues, such as water resources, N-related impacts (e.g., nitrate leaching, ammonia volatilization) and production levels, would also need to be considered to avoid major hidden side effects (“hidden costs” of Lal, 2004a, 2004b) when implementing practices to mitigate climate change.

Although reviews and meta-analyses provide important information about potential effects of agricultural practices on SOC storage, they do not quantify changes in SOC stock in a region or country, nor estimate effects of their combination. Indeed, SOC storage and direct and indirect GHG emissions depend greatly on local pedoclimatic and cropping systems characteristics. In their recent review of SOC-based climate strategies, Bossio et al. (2020) claim that “for agriculture and grassland pathways, future work should disaggregate mitigation accounting to specific activities each with their own mitigation estimates, trade-offs and cobenefits.”

Representing the heterogeneity of production systems in a region or country is one of the main methodological challenges when attempting to estimate the balance between SOC storage and GHG emissions of agriculture (Lal, 2004a, 2004b). The use of cropping system models along with databases that cover the heterogeneity of production systems forms the basis for addressing this challenge (e.g., Liu et al., 2011; Tribouillois et al., 2018). In addition, a model-based approach has the advantage of being able to simulate both climate change and cropping system scenarios (e.g., Tribouillois et al., 2018). Due to a dearth of data and modeling issues (Brilli et al., 2017; Rosenzweig et al., 2013), however, few studies have

applied this approach to large spatial (km^2 resolution) and temporal scales (several decades) to estimate the past, current and/or potential balance between SOC storage and GHG emissions (see e.g., Liu et al., 2011).

The aims of our study were to use a model-based approach at a high spatial resolution (km^2) for all cropland area in France to estimate the (i) SOC storage potential of current cropping systems, (ii) potential additional SOC storage of mitigation scenarios entailing agricultural practices assumed to increase SOC storage, (iii) total GHG balance of these cropping systems and (iv) effects of adopting of these agricultural practices on yield and water and N cycles.

2 | MATERIALS AND METHODS

2.1 | Modeling approach

We used the high-resolution modeling approach to quantify the SOC storage potential under current cropping systems in France (the "baseline scenario") and under cropping systems with alternative agricultural practices used to store more C ("mitigation scenarios"). We first described the current cropping systems (rotations and crop management) and the associated pedoclimatic conditions as finely as possible. Then, based on a literature review, we selected a number of practices to store SOC (mitigation scenarios) according to their SOC storage potential and the ability to simulate them with the selected crop model. We used the soil-crop model *Simulateur multIdisciplinaire pour les Cultures Standard* (STICS) (Brisson et al., 1998, 2003), which has been calibrated and evaluated for a wide range of cropping systems, soils and climates in France (Constantin et al., 2012; Coucheney et al., 2015; Graux et al., 2020; Yin et al., 2020), to simulate water, N and C balances at the field scale in all the scenarios. Simulation inputs and outputs are available at <https://doi.org/10.15454/LV9ZRW>.

2.2 | Crop model

Simulateur multIdisciplinaire pour les Cultures Standard is a process-based ecosystem model that simulates daily interactions between water, C and N cycles as a function of crop species, management (i.e., sowing, N fertilization, irrigation, tillage, harvest, residue management) and pedoclimate characteristics (daily weather, clay content, organic N content and C:N ratio of topsoil, water retention properties of the soil profile).

In the STICS version used (v. 2114), biological activity and thus SOC mineralization is assumed to occur only in the topsoil (0–30 cm). SOC is divided into four pools: organic inputs (organic fertilizers and crop residues), microbial biomass, active SOC (called "humus") and inert SOC. The decomposition of the first three pools follows a first-order kinetics, with a potential decomposition rate modulated by the environmental conditions, particularly soil temperature and soil water content. Substrate decomposition results in C mineralization (CO_2 emission) and microbial assimilation depending on a microbial

yield rate. N fluxes (immobilization and mineralization) are driven by C fluxes and the C:N ratio of the organic pools. The parameters of the organic residues decomposition module have been calibrated using long-term incubations in the laboratory (Justes et al., 2009). The decomposition rate of organic residues can be limited by lack of mineral N, as well as the N immobilization process. The decomposition rate of the active pool depends on soil properties (clay, organic N and CaCO_3 contents, pH and C:N ratio), as established by Clivot et al. (2017) and climate (soil temperature and water content). The proportion of stable SOC varies with crop history from 40% under permanent grassland to 65% under permanent arable cropping. This version of STICS also simulates grassland management practices such as recovery of vegetative growth after cutting and animal manure deposition on soil during grazing (Graux et al., 2020; Strullu et al., 2020). A more detailed description of the model is provided in SM1.

The accuracy of STICS's predictions has been evaluated for several major crops, including cereals, oilseed and protein crops, cover crops (ryegrass, mustard), forages and sugar beets, for more than 1800 production situations throughout France (Coucheney et al., 2015). These situations varied in management, N fertilization (mineral or organic), irrigation (irrigated or rainfed), crop cultivars and periods of tillage, sowing and harvest. Coucheney et al. (2015) validated STICS for a wide range of pedoclimatic conditions, ranging from oceanic to Mediterranean or semi-continental climates and from clay to sandy soils with contrasting available water and organic matter contents. They studied 10 STICS predictions of biomass, yield, water balance and N balance, and classified eight of them as satisfactory, good or very good. The AMG model, on which C dynamics in STICS is based, has been evaluated positively for several cropping systems in 16 long-term (14–168 years) field experiments with mineral (9) or organic (7) fertilization (Levasseur et al., 2020; Saffih-Hdadi & Mary, 2008). It estimated SOC changes accurately, with a mean rRMSE of only 3.9% (Saffih-Hdadi & Mary, 2008). Both STICS and AMG made good predictions of changes in SOC stocks in very long-term experiments (Farina et al., 2020). STICS could also well simulate cover crop effects on SOC stocks and associated changes in N mineralization in three long-term experiments in France (Constantin et al., 2012) and four long-term experiments in Switzerland and Denmark (Autret et al., 2020). Finally, STICS has estimated well key environmental variables such as nitrate leaching and N_2O emissions (Constantin et al., 2012; Plaza-Bonilla et al., 2017; Vuichard et al., 2016).

2.3 | Current cropping systems: Baseline scenario

2.3.1 | Pedoclimatic units

To represent the diversity of pedoclimatic zones in mainland France, soil mapping units (polygons) of the 1:1,000,000 French soil map (Figure 1b; Jamagne et al., 1995) and 8 km \times 8 km SAFRAN climate grids (Figure 1a; Durand et al., 1993) were spatially intersected to identify 30,966 pedoclimatic units (PCUs), which had a mean area

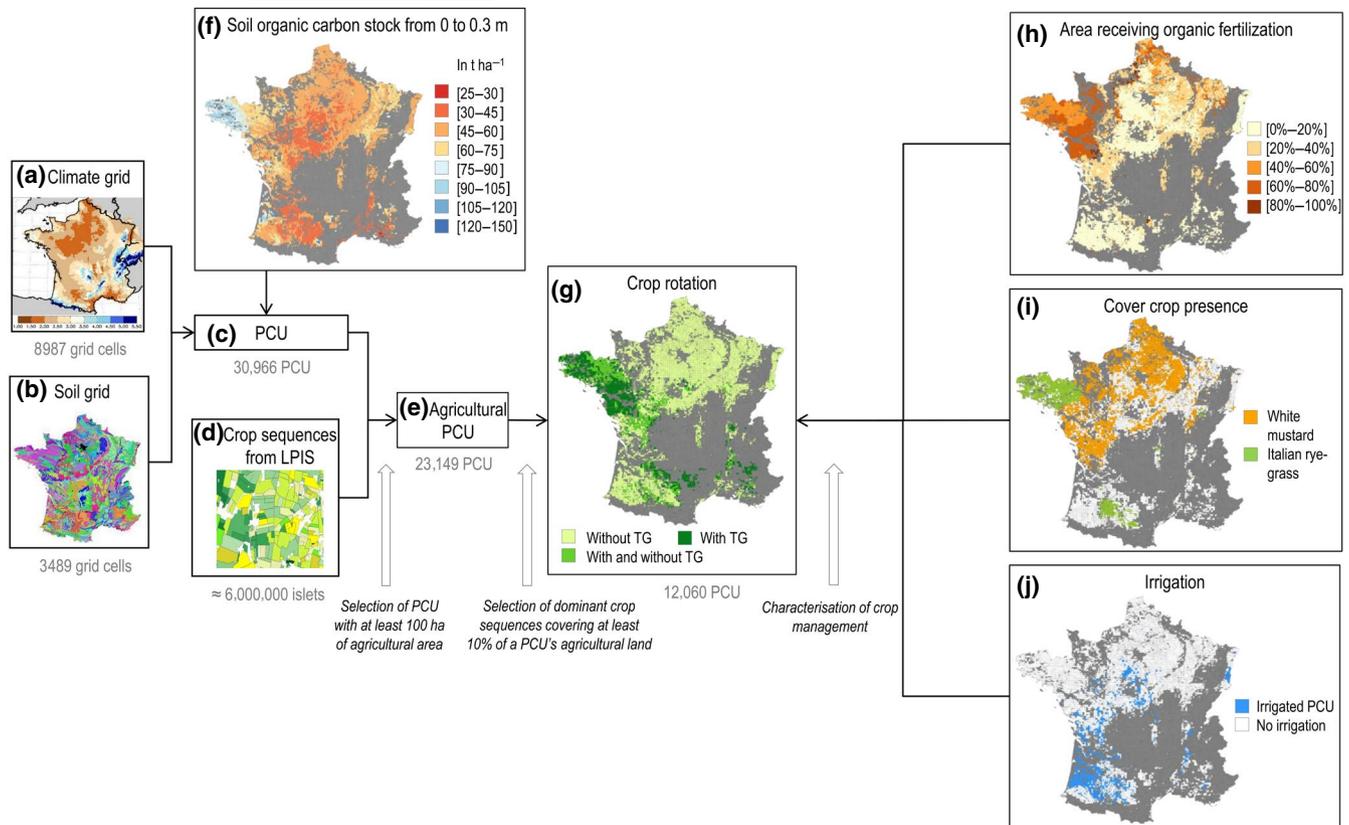


FIGURE 1 The workflow developed to represent current cropping systems in France. (a) The climate grid is crossed with (b) the soil grid to provide (c) the spatial simulation units, that is, the pedoclimatic units (PCU). (d) The Land Parcel Identification System (LPIS) is used to filter (e) the agricultural PCU and determine (g) the dominant crop sequences per PCU with and without temporary grasslands (TG). (f) An initial organic carbon stock is allocated to each PCU. The crop management is constructed for each crop rotation according to (h) fertilization practices, (i) winter fallow management practices and (j) irrigation practices found in France. Only the three main irrigated crops in France (maize, wheat and sunflower) were considered irrigated in the simulations [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1111/gcb.15512)]

of 17.72 km² (Figure 1c). We then selected the 23,149 PCUs with more than 100 ha of agricultural area (Figure 1e) according to the French Land Parcel Identification System (Figure 1d), which represented 27.29 Mha, that is, 97% of the agricultural area (annual and perennial crops + grasslands + market gardens + fallow land). We selected those that had arable crops and temporary grasslands on at least 10% of the agricultural area, which yielded 12,060 PCUs that covered 84% of French cropland. Since spatial distribution of soil types within each soil mapping unit is unknown, they were selected in decreasing order of percentage until they covered at least 70% of the area, which resulted in one to three soils per soil mapping unit.

2.3.2 | Initial SOC and nitrogen stocks

Initial SOC stock in the topsoil was estimated from soil data at a 90 m × 90 m resolution (Mulder et al., 2016). These detailed soil data were aggregated into the PCUs by calculating the mean SOC stock of the 90 m × 90 m pixels in each PCU that had crops as the land use (Figure 1f) and applied to the entire PCU. Topsoil organic N content was calculated from the bulk density of this layer by assuming a constant C:N ratio of 11 (Kirkby et al., 2011).

2.3.3 | Crop rotations and cultivars

To identify the main crop rotation(s) per PCU, we used the crop rotation database developed by the French National Research Institute for Agriculture, Food and Environment (INRAE; Leenhardt et al., 2012). We selected one dominant crop-only rotation if it covered more than 50% of the PCU's agricultural area. If not, we selected the two largest crop-only rotations per PCU that each covered at least 10% of the PCU's area. We also selected a crop/temporary grassland rotation if it covered at least 10% of the PCU's area (Figure 1g). Ultimately, we selected 71 crop-only and 274 crop/temporary grassland rotations for the 12,060 PCUs, which yielded 18,593 rotation × PCU combinations. These rotations, covering 4.79 Mha, were considered to represent well the 18.35 Mha of arable crops and temporary grasslands in France. Accordingly, the results were directly extrapolated using a cross product.

Based on these rotations and the crops calibrated in STICS, the crop species simulated were grain and silage maize, winter wheat, rapeseed, sugar beet, sunflower, winter and spring pea, and temporary grasslands. For maize, we adapted the precocity of cultivars to each PCU growing-degree days available between sowing and harvest. For the other crops, we chose the most common cultivar in

France available in STICS. Parameters of the grass species of temporary grasslands already calibrated in STICS were adapted to simulate species like tall fescue (*Festuca arundinacea*) and orchard grass (*Dactylis glomerata*).

2.3.4 | Crop management

We used the Agricultural Practices Survey conducted in 2006 and 2011 by the Ministry of Agriculture, Agri-Food and Forestry for ca. 14,000 fields throughout France to determine crop management. Since the data are available and considered representative at the administrative region level (NUTS II; Eurostat, 2018), we used the median of observations per arable crop and administrative region for sowing and harvest dates, mineral or organic fertilizer dose (Tables S1 and S2), dates of mineral N fertilization, percentage of the crop with organic N fertilization (Figure 1h), type (cattle manure, pig slurry or sugar beet vinasse) and frequency of organic N fertilization, and frequency of tillage. Characteristics of these organic fertilizers are shown in Table S3.

Organic fertilization

Since both mineral and organic N fertilizers could be applied in each NUTS II region, but their spatial locations were unknown, they were simulated for each rotation as either mineral-only or both mineral and organic fertilization (hereafter, “mineral” and “organic,” respectively) when some crops of the rotation were fertilized with organic N in the region. Mineral fertilization was used to supplement organic fertilization to maintain the same yields as for crops with mineral fertilization.

To quantify straw exportations from fields, we assumed that 1 t of fresh matter (FM) of straw was necessary to produce the bedding of 4.3 t FM of solid cattle manure, based on the French grey literature. To have enough straw to produce the amount of solid manure applied at the regional scale, straw was first exported from cereals in rotations that received organic fertilization and then, from those that received mineral fertilization, first in the same region and, if necessary, in neighboring ones.

Cover crops

In accordance with the French application of European Union Nitrate Directive, cover crops were included in rotations in PCUs located in Nitrate Vulnerable Zones in 2012. The Nitrate Vulnerable Zones are defined as “areas of land which drain into polluted waters or waters at risk of pollution and which contribute to nitrate pollution” (91/676/EC). They were sown before spring crops, except when the previous crop was grain maize or sugar beet, after which the soil was left bare. Cover crop species (white mustard or Italian ryegrass) and dates of sowing and destruction by soil tillage were defined per region based on the Agricultural Practices Survey (Figure 1i).

Irrigation

Irrigation was limited to crops and PCUs where the Land Parcel Identification System indicated that it was the dominant practice

(Figure 1j). Since irrigation practices depend greatly on the yearly climate, it was simulated using the automatic irrigation module of STICS (Brisson et al., 2009) for the main irrigated crops in France (i.e., maize, winter wheat and sunflower). Maize was irrigated to meet 85% of maximum evapotranspiration throughout its growing cycle while sunflower and winter wheat were irrigated only around their flowering.

Temporary grasslands

Temporary grassland management was provided by Graux et al. (2020) and based on the definition of 30 grassland management types in France. A dominant grassland management type was assigned to each PCU if it covered more than 50% of the PCU area, otherwise two dominant management types were selected. Management descriptions included grassland uses (number and timing of hay or silage cut(s) and/or grazing periods) and N fertilization practices (timing and amount). Grassland use ranged from extensive (one cut or four grazing periods per year) to intensive management (up to four cuts and 10 grazing periods per year; Figure S1). Unlike in the study of Graux et al. (2020), N fertilization could be mineral or organic. Data on organic fertilizer type and doses were extracted from the Agricultural Practices Survey. Organic fertilization was applied once every 3–4 years if grassland was exclusively grazed, once every 2 years if grassland was cut late and once per year if grassland was cut early (Chambres d'agriculture d'Auvergne, 2016). Following French regulations, N fertilization of the crop following a temporary grassland was reduced by 60 kg N ha⁻¹ year⁻¹ if the duration of the grassland was 3 years or less, and by 100 kg N ha⁻¹ year⁻¹ if the duration was 4 years. The crop following grassland was not fertilized if the grassland duration was 5 years or longer.

2.4 | Mitigation scenarios to increase SOC storage

Based on the literature review, we identified three mitigation scenarios: (i) spatial and temporal expansion of cover crops, (ii) spatial insertion and temporal extension of temporary grasslands (two sub-scenarios) and (iii) improved recycling of organic resources as organic fertilizer. These scenarios were simulated separately and in combination. When combined, scenarios were implemented for a given PCU and cropping system only when they were compatible, which led to a patchwork of scenarios (three, two or one) among PCUs and cropping systems. If two scenarios were not compatible, the one that stored the most SOC, based on single-scenario results, was simulated.

2.4.1 | Cover crop expansion

The first scenario (“cover crop”) consisted of maximizing soil coverage both spatially and temporally to increase C returns to the soil. In nitrate vulnerable zones, cover crops already grown were continued until 1 month before the sowing of the next spring crop instead of November in most regions. They were also added during short fallow periods of at least 2 months and incorporated in soil just before sowing the winter crop. In other PCUs, cover crops were included during

all fallow periods of at least 2 months, except after sugar beet with late harvest date that does not allow good sowing conditions. The same destruction rule as in the nitrate vulnerable zones was applied. Italian ryegrass was sown during long fallow periods followed by a spring crop, except after grain maize where fababean was sown while vetch was sown during short fallow periods followed by a winter crop. In irrigated PCUs, cover crops were irrigated at sowing if necessary to ensure emergence and growth. Overall, 96% of the simulated arable land was concerned by this scenario, either by temporal expansion of current cover crops (17% of area) or insertion of new cover crops in the rotation (57% of the area), or by both (26% of the area). N fertilization in this scenario remained the same as that in the baseline scenario (i.e., no consideration of the potential green manure effect of cover crops).

2.4.2 | Temporary grassland expansion

The second scenario ("temporary grasslands") was composed of two practices (sub-scenarios): temporal extension and spatial insertion into crop rotations. Grasslands less than 3 years old were extended to 3 years, while grasslands 3 or 4 years old were extended to 5 years. Furthermore, in all crop rotations that included silage maize, the silage maize was replaced by a 3-year grassland. For silage maize monocrops, they were replaced by rotations of 3 years of silage maize followed by 3 years of grassland. These new temporary grasslands were managed according to the dominant grassland management type of the PCU. Following these rules, the duration of 89% of current temporary grasslands was extended, and new temporary grasslands were inserted into 6% of arable crop rotations.

2.4.3 | Improved recycling of organic resources

In the third scenario ("improved recycling"), we applied amounts of organic fertilizers not currently applied on agricultural land (i.e., those currently disposed of using other treatments). Since French agriculture already recovers well all livestock manure and waste and by-products from agri-food industries, the scenario focused on applying organic fertilizers from urban activities: home-sorted and market bio-waste, green waste and sewage sludge not already composted (Solagro - INDDIGO, 2013). Based on expert opinion of the French Agency for Environment and Energy Management (personal communication), we assumed that 50% of home-sorted bio-waste could be collected and 100% of market bio-waste; 50% of these bio-wastes being composted with green waste and 50% treated by anaerobic digestion (100% in densely populated areas). We also assumed that all sewage sludge was composted. According to French data per region (Solagro - INDDIGO, 2013), we estimated a new resource of 7.73 Mt FM of compost and 4.29 Mt FM of digestate. Their characteristics are described in Table S3. These new resources were applied randomly in rotations that did not receive organic fertilization in the baseline scenario. Mineral fertilization of these crops was reduced to keep the N-use efficiency of input at the same level. On rapeseed

or winter wheat, 15 t FM ha⁻¹ of compost was applied in late summer while 25 m³ FM ha⁻¹ of digestate was applied at the sowing of a cover crop or in spring before sowing maize or sunflower. Compost and digestate were applied on average every 2 or 3 years depending on crop rotations on 7% of the area of simulated rotations.

2.5 | Simulations and extrapolation

Five scenarios were simulated to estimate SOC storage and GHG balance in current and alternative cropping systems: baseline (18.35 Mha), cover crop (96% of the baseline area, 17.62 Mha), temporary grassland (31%, 5.69 Mha; 4.64 Mha of expanded duration and 0.68 Mha of insertion), improved recycling (7%, 1.28 Mha) and the combination of the three mitigation scenarios (99%, 18.16 Mha). A simulation corresponded to a combination of (1 rotation with its management) × 1 PCU × 1 soil × 30-year climate. The baseline and mitigation scenarios required 62 694 and 175 030 simulations, respectively, over 32 years (1980–2013). The first 2 years were used only to initialize soil mineral N and water contents according to agro-pedoclimatic conditions. Yearly outputs were then analyzed for 1984–2013 and averaged over the 30 years. They included crop yields, SOC storage to a depth of 0.3 m, soil N mineralization, N₂O and NH₃ emissions, drainage and nitrate leaching. Crop yields predicted in the baseline scenario were compared to national references to ensure that they were accurate. Results expressed at a spatial scale larger than those of the production situations were calculated by averaging results of the situations weighted by their areas.

2.6 | C storage and GHG balance

For each scenario, mean annual SOC storage was calculated as the initial SOC stock minus final SOC stock, divided by the 30 years of simulation. For a given PCU, the same initial SOC stock, defined as described in Section 2.3.2, was used for all scenarios. The additional SOC storage achieved in each mitigation scenarios was calculated as its final SOC stock minus that of the baseline, only for the areas where cropping systems had changed.

Since STICS simulates SOC dynamics in the topsoil ($\Delta\text{SOC}_{0-0.3}$, kg C ha⁻¹ year⁻¹), we used the linear regression model of Balesdent et al. (2018) to estimate the SOC storage of the entire soil profile ($\Delta\text{SOC}_{0-\text{depth}}$, kg C ha⁻¹ year⁻¹) when SOC in the topsoil increased. This regression allows estimating the ratio of new C in the 0.3–1.0 m layer to the new C in the 0–1.0 m layer ($R_{0.3-1.0}$) according to soil cover types. For cropland the regression is (Equation 1):

$$R_{0.3-1.0} = 0.30907 + 0.00381 \times \text{MAT} + 0.000638 \times \text{Clay} - 0.0996 \times \text{P:PET}, \quad (1)$$

with MAT the mean annual temperature (°C), Clay the topsoil clay content (%) and P:PET the ratio of annual precipitation to evapotranspiration.

To account for the specific soil depths of our study, $R_{0.3\text{-depth}}$ was proportionally estimated according to $R_{0.3\text{-}1.0}$ (Equation 2).

$$R_{0.3\text{-depth}} = \frac{\min(\text{depth} - 0.3; 0.7) \times R_{0.3\text{-}1.0}}{0.7}. \quad (2)$$

Finally, we estimated the SOC storage of the entire soil profile (Equation 3).

$$\Delta\text{SOC}_{0\text{-depth}} = \frac{\Delta\text{SOC}_{0\text{-}0.3}}{1 - R_{0.3\text{-depth}}}. \quad (3)$$

Without other hypotheses, when SOC in the topsoil decreased, we assumed that SOC in the subsoil (>0.3 m deep) did not change.

We calculated the annual in-field GHG emission balance ($\text{GHG}_{\text{balance}}$, $\text{kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$) according to Autret et al. (2019):

$$\text{GHG balance} = 296 \times \frac{44}{28} (\text{direct N}_2\text{Oe} + \text{indirect N}_2\text{Oe}) - \frac{44}{12} \Delta\text{SOC}_{0\text{-depth}},$$

with direct N_2Oe the amount of N_2O emitted from the soil ($\text{kg N}_2\text{O-N ha}^{-1}\text{ year}^{-1}$), and indirect N_2Oe the amount of N_2O emitted throughout the N cascade through NH_3 volatilization and nitrate leaching ($\text{kg N}_2\text{O-N ha}^{-1}\text{ year}^{-1}$).

Direct N_2O emissions were simulated by STICS and averaged over 30 years. Indirect N_2O emissions were estimated using emission factors defined by the IPCC (De Klein et al., 2006): 1% of the N from fertilizers that volatilizes being transformed into N_2O and 0.75% of the leached N being transformed into N_2O throughout the N cascade in groundwater, rivers and estuaries. Emissions at the system boundary, the off-field GHG balance (GHG_F balance), was calculated by adding the amount of CO_2 emitted during fertilizer production ($\text{kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$), which equaled the amount of mineral N fertilizer applied per ha times an emission factor of $5.34\text{ kg CO}_2\text{e kg}^{-1}$ of N for ammonium nitrate. In the improved recycling scenario, since the newly available green waste was also returned to the ground in the baseline scenario (albeit outside agricultural fields), we corrected the amount of additional C storage in the simulations with compost application proportionally to the amount of C from green waste (i.e., 74% of total additional C) to calculate GHG_F balance. Since CO_2 emissions induced by field operations (agricultural machines) have much less impact than the other sources considered (Autret et al., 2019; Ferlicoq et al., 2017), and the necessary data were not available, they were ignored.

2.7 | Statistical analysis

A generalized linear model was built to determine the influence of pedoclimatic and management factors on changes in SOC stock in the baseline scenario (using the *stats* package of R version 3.5.3). In addition, ANOVA was performed to identify the management

factors that influenced additional SOC storage in each mitigation scenario.

3 | RESULTS

3.1 | C storage and GHG balance in the baseline scenario

The SOC stock in the topsoil was estimated to increase over 30 years by a mean of $51\text{ kg C ha}^{-1}\text{ year}^{-1}$, but with a high SD (± 263 ; Table 1). Over the entire soil depth, changes in SOC stock represented an increase of $80 (\pm 305)\text{ kg C ha}^{-1}\text{ year}^{-1}$ (i.e., $295\text{ kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$ extracted from the atmosphere). Despite this SOC storage, SOC in 55% of the simulated area decreased over time. Since cropping systems emitted $637 (\pm 478)\text{ kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$ through N_2O emissions, they remained a net GHG source of $342 (\pm 1276)\text{ kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$. This balance was three times as high ($1119 \pm 1430\text{ kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$) when off-field emissions of mineral fertilizer production were included. At the national scale (18.35 Mha), the predicted GHG_F balance represented emission of $20.5\text{ Mt CO}_2\text{e ha}^{-1}\text{ year}^{-1}$ to the atmosphere over 30 years.

Soil organic C storage and GHG balance differed greatly between crop/temporary grassland and crop-only rotations (1.22 and 3.57 Mha simulated, respectively; Table 1). Crop/temporary grassland rotations stored $370 (\pm 278)\text{ kg C ha}^{-1}\text{ year}^{-1}$, while crop-only rotations released $59 (\pm 160)\text{ kg C ha}^{-1}\text{ year}^{-1}$. With inclusion of off-field emissions, the first one extracted $812\text{ kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$ while the second one emitted $1784\text{ kg CO}_2\text{e ha}^{-1}\text{ year}^{-1}$ to the atmosphere.

The high spatial resolution of the simulations highlighted regional differences that influenced results (Figure 2a). SOC storage potential was positive in the northwest of France, relatively neutral in the east and center but negative in the far East, due to higher initial C stock and absence of cover crops during the winter fallow (Figure 1). Areas of SOC storage overlapped well locations of crop/temporary grassland rotations.

The generalized linear models revealed a significant effect of pedoclimatic factors and management practices for both crop-only and crop/temporary grassland rotations ($p < 2.10^{-16}$; Tables S4 and S5). Soil pH, frequency of cover crops in the crop rotation and the proportion of grassland years in the crop/temporary grassland rotation had the strongest effects. Other pedoclimatic factors (e.g., clay, CaCO_3 and initial SOC contents; mean annual temperature; precipitation minus potential evapotranspiration) also had significant effects on SOC storage potential. These factors and pH are in the equations that STICS uses to predict organic matter decomposition.

3.2 | C storage and GHG balance in mitigation scenarios

The mitigation scenarios differed greatly in additional annual SOC storage per ha (Table 2) and the area concerned (Figure 2b–f). The cover crop scenario which covered the largest area (96% of French

TABLE 1 Mean annual soil organic C storage (Δ SOC), direct and indirect N_2O emissions (N_2O_e) and greenhouse gas (GHG) balances of current crop rotations simulated over 30 years. Values are provided for rotations with and without temporary grassland (TG), cover crops (CC) and with mineral-only fertilization (mineral N) or mineral and organic fertilization (organic N). On-field and off-field GHG balances correspond to emissions without (GHG) and with emissions of mineral fertilizer production (GHG_F), respectively. Positive SOC storage corresponds to compensated and thus negative CO_2 emissions. Standard deviations are given in parentheses

Rotation	C storage		Nitrogen loss			GHG balance			
	Δ SOC 0–0.3 m	Δ SOC 0–depth	Direct N_2O_e	Volatilization	Leaching	CO_2 emissions from soil	Total N_2O_e	GHG balance	GHG_F balance
	kg C ha ⁻¹ year ⁻¹		kg N ha ⁻¹ year ⁻¹			kg CO ₂ e ha ⁻¹ year ⁻¹			
All	51 (263)	80 (305)	1.0 (0.8)	7.6 (5.8)	39 (23)	-295 (1118)	637 (387)	342 (1276)	1119 (1430)
Crop-only	-59 (160)	-48 (177)	1.1 (0.8)	8.6 (5.6)	44 (24)	177 (649)	703 (417)	880 (809)	1784 (821)
With CC	-61 (168)	-52 (182)	1.1 (0.8)	8.2 (4.8)	37 (21)	190 (667)	680 (404)	869 (860)	1685 (856)
Without CC	-58 (153)	-46 (173)	1.1 (0.9)	8.9 (5.9)	48 (24)	169 (634)	719 (421)	888 (762)	1847 (767)
Organic N	-47 (170)	-57 (190)	1.1 (0.8)	9.2 (6.2)	47 (25)	208 (697)	718 (407)	927 (834)	1782 (854)
Mineral N	-90 (149)	-61 (164)	1.1 (0.9)	7.9 (4.8)	39 (22)	223 (601)	683 (427)	905 (785)	1806 (788)
Crop/TG	370 (278)	453 (335)	0.7 (0.4)	4.8 (6.1)	27 (16)	-1661 (1228)	441 (224)	-1220 (1266)	-812 (1260)
With CC	401 (293)	484 (345)	0.7 (0.4)	4.3 (5.1)	25 (15)	-1773 (1265)	434 (201)	-1339 (1293)	-905 (1280)
Without CC	342 (267)	426 (328)	0.7 (0.4)	5.2 (6.5)	28 (16)	-1561 (1203)	447 (236)	-1113 (1246)	-728 (1247)
Organic N	500 (296)	547 (359)	0.7 (0.4)	4.8 (6.8)	28 (16)	-2007 (1316)	446 (225)	-1561 (1359)	-1161 (1360)
Mineral N	358 (244)	511 (365)	0.7 (0.4)	3.7 (5.4)	22 (15)	-1872 (1338)	420 (215)	-1453 (1368)	-993 (1357)

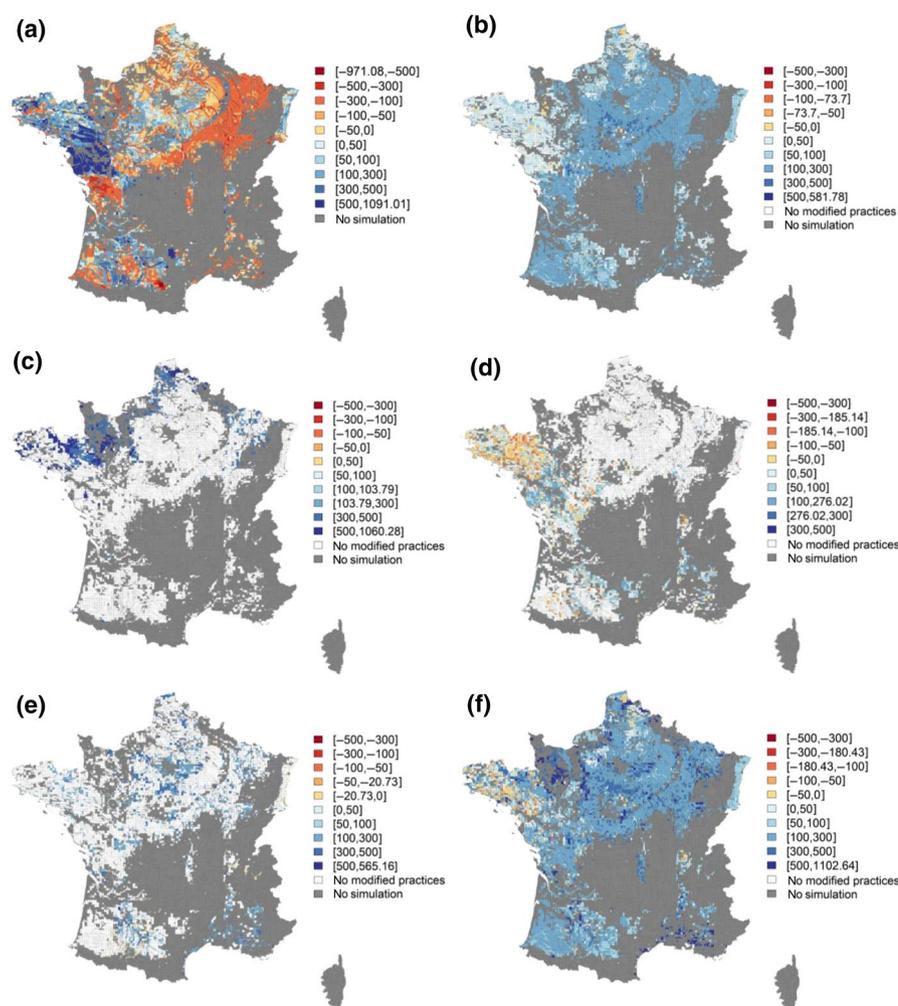


FIGURE 2 Maps of (a) annual soil organic carbon (SOC) storage in the baseline scenario and (b–f) additional SOC storage in mitigation scenarios (kg C ha⁻¹ year⁻¹) in the topsoil (0–0.3 m deep) in cropping systems simulated over 30 years with Simulateur multidisciplinaire pour les Cultures Standard. Additional SOC storage potential relative to the baseline scenario when implementing mitigation (sub-) scenarios: (b) cover crop insertion, (c) insertion of temporary grasslands instead of silage maize, (d) extension of temporary grassland duration, (e) improved recycling of organic resources and (f) consistent combination of these mitigation (sub-) scenarios when possible at the cropping system scale. SOC, soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Mean annual soil organic C storage (Δ SOC), direct and indirect N_2O emissions (N_2O_e) and greenhouse gas (GHG) balances of scenarios simulated over 30 years. For each scenario, results are shown only for the rotations that changed from the baseline scenario (and for the same rotations in the baseline scenario). GHG_F and GHG balances are balances with and without emissions of mineral fertilizer production, respectively. C in organic matter moved on-farm and not newly stored in the “improved recycling” scenario was subtracted from the off-field GHG_F balance (see text). Standard deviations are given in parentheses

(Sub-)scenario	C storage	Nitrogen loss			GHG balance			
	Δ SOC 0–0.3 m kg C ha ⁻¹ year ⁻¹	Direct N_2O_e kg N ha ⁻¹ year ⁻¹	Volatilization	Leaching	CO ₂ emissions from soil kg CO ₂ e ha ⁻¹ year ⁻¹	Total N_2O_e	GHG balance	GHG _F balance
Cover crop expansion								
Mitigation	169 (234)	1.1 (0.8)	7.7 (6.2)	36 (24)	-788 (1023)	672 (386)	-116 (1174)	674 (1282)
Baseline	38 (253)	1.0 (0.8)	7.8 (5.8)	40 (23)	-241 (1071)	641 (387)	399 (1227)	1189 (1371)
Difference	131	0.1	0.1	-4	-547	31	-515	-515
Insertion of temporary grasslands								
Mitigation	390 (299)	0.7 (0.4)	6.4 (4.9)	29 (16)	-1737 (1280)	457 (241)	-1280 (1340)	-863 (1422)
Baseline	-76 (190)	1.0 (0.6)	7.7 (5.4)	38 (21)	248 (737)	632 (335)	880 (820)	1676 (847)
Difference	466	-0.3	-1.3	-9	-1985	-175	-2159	-2538
Extension of temporary grassland duration								
Mitigation	399 (279)	0.6 (0.4)	4.4 (5.9)	20 (13)	-1797 (1236)	368 (197)	-1429 (1254)	-1128 (1236)
Baseline	371 (279)	0.7 (0.4)	4.7 (5.9)	27 (16)	-1666 (1232)	441 (223)	-1225 (1269)	-815 (1262)
Difference	28	-0.1	-0.3	-7	-131	-73	-204	-313
Improved recycling								
Mitigation	195 (242)	1.2 (0.8)	8.4 (6.0)	58 (31)	-931 (1078)	801 (421)	-130 (1236)	1322 (670)
Baseline	-38 (199)	1.0 (0.7)	7.7 (5.0)	39 (21)	80 (832)	635 (364)	715 (994)	1522 (1086)
Difference	233	0.2	0.7	19	-1011	165	-846	-201
Combined scenarios								
Mitigation	236 (269)	1.0 (0.8)	7.5 (6.2)	35 (26)	-1086 (1188)	621 (406)	-465 (1334)	499 (1487)
Baseline	51 (264)	1.0 (0.8)	7.6 (5.8)	39 (23)	-298 (1118)	638 (386)	340 (1275)	1116 (1428)
Difference	184	0	-0.1	-4	-788	-16	-805	-617

arable land) had a relatively low additional C storage potential per ha (131 kg C ha⁻¹ year⁻¹ in the topsoil). Additional SOC storage in the cover crop scenario ranged from small (+38 kg C ha⁻¹ year⁻¹), for situations that already had cover crops in the baseline scenario, to large (+169 kg C ha⁻¹ year⁻¹), in areas where cover crops were inserted. In northwestern and northern France, cover crops were already present in most rotations (Figure 2b) and rotations with grasslands or sugar beet limit the ability to insert new ones. In the southwest or far east, additional cover crops can be inserted into the maize monocrops. Finally, in the rest of France, new cover crops may be inserted during the short summer fallow. The main drivers of the additional SOC storage in this scenario were the frequency of insertion of cover crops and the additional biomass they produced (38% and 25% of variance explained, respectively; Table S6).

In the temporary grasslands scenario, the grassland insertion sub-scenario which has the lowest area concerned (6% of arable land in France) had the highest additional C storage potential per ha (466 kg C ha⁻¹ year⁻¹). On average, production situations in the concerned area changed from a decrease in SOC (-76 kg C ha⁻¹ year⁻¹) in the baseline scenario to SOC storage (+390 kg C ha⁻¹ year⁻¹; Table 2), due

to more C inputs to the soil from grassland than from the silage maize it replaced. Since temporary grassland replaced only silage maize, only some areas were involved, mainly in northwestern France (Figure 2c). In contrast, the sub-scenario of an increase in temporary grassland duration, covering 25% of arable land in France yielded mixed results, with one-third of the area with negative or no additional SOC storage and two-thirds of the area with small mean additional SOC storage, leading to a mean positive effect of +28 kg C ha⁻¹ year⁻¹ (Figure 2d). These results can be explained by the baseline crop/temporary grassland rotations already having a high rate of SOC storage (371 kg C ha⁻¹ year⁻¹) and an increase in their frequency from 50% of the years to only 60%.

The improved recycling scenario which covered a much smaller area (7% of arable land in France) was also effective, with higher additional C storage than the cover crop scenario (233 kg C ha⁻¹ year⁻¹; Table 2). Its SOC storage depended greatly on the type of organic product applied (64% of variance explained; Table S7), compost resulting in more SOC stored than digestate.

Finally, annual SOC storage decreased over time, in all mitigation scenarios, being 23%–40% lower over 30 years than over the first 10 years of simulations (Table S8; Figure S2).

Total N₂O emissions decreased in the grassland insertion and extension sub-scenarios while they increased slightly in the cover crop scenario, despite a decrease in the indirect emissions. They increased more strongly in improved recycling scenario, in both direct and indirect emissions (Table 2). On average, the grassland insertion sub-scenario decreased N₂O emissions the most, while the improved recycling scenario increased it the most ($-175 \text{ kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ vs. $+165 \text{ kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, respectively).

The grassland insertion, grassland extension and cover crop scenarios, by shortening fallow periods and increasing plant uptake of soil mineral N, decreased nitrate leaching (-8.3 , -7.2 and $-4.1 \text{ kg N-NO}_3^- \text{ ha}^{-1} \text{ year}^{-1}$, respectively), despite an increase in soil organic matter and N mineralization over time (Figure S2). In contrast, the improved recycling scenario increased nitrate leaching greatly ($+19.8 \text{ kg N-NO}_3^- \text{ ha}^{-1} \text{ year}^{-1}$; $+51\%$).

Since grasslands are usually fertilized less than arable crops, their insertion or extension reduced the amount of N fertilizer applied at the rotation scale and thus denitrification, nitrification and volatilization. Replacing mineral by organic fertilizer in the improved resources scenario had the same effect. Then, GHG emissions from mineral fertilizer production decreased by 379, 109 and 44 $\text{kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, respectively, while they did not change in the cover crop scenario since mineral fertilization was not adapted.

Overall, the absolute GHG balance was better in all mitigation scenarios than in the baseline scenario. For on-field emissions only, the mean GHG balance was negative for all mitigation scenarios (i.e., C sink at the field scale). The grassland insertion sub-scenario, which had the highest SOC storage potential, remained the best compared to the baseline scenario ($-2159 \text{ kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$; Table 2). It was followed by the improved recycling, cover crop and grassland extension (sub-)scenarios (-846 , -515 and $-204 \text{ kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, respectively). When including off-field emissions due to mineral fertilizer production, only the grassland insertion sub-scenario remained a C sink; the other two became C sources that increased GHG emissions. Correcting for the effects of already returned organic matter that was moved on-farm in the improved recycling scenario decreased its potential to reduce GHG emissions. Consequently, it avoided only the emission of $201 \text{ kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ compared to the baseline scenario while ignoring emissions during composting.

The scenarios were ranked differently regarding the national potential for reducing GHG emissions. The cover crop scenario had the highest mitigation potential compared to the baseline scenario ($9.1 \text{ Mt CO}_2\text{e year}^{-1}$), followed by the grassland insertion, grassland extension and improved recycling (sub-)scenarios (2.8 , 1.5 and $0.3 \text{ Mt CO}_2\text{e year}^{-1}$, respectively).

3.3 | Combining the three mitigation scenarios

Consistent combination of the three mitigation scenarios resulted in mean additional C storage of $+184 (\pm 179) \text{ kg C ha}^{-1} \text{ year}^{-1}$ (Table 2).

We observed synergistic, additive and antagonistic (or less than additive) effects depending on the combinations of practices (Figure 3). Combining the cover crop and improved recycling scenarios revealed synergy, with more C stored than the sum of the individual scenarios, since digestate applied on cover crops increased their biomass and C return to the soil. Combining the grassland scenario with others had no synergistic effect, since increasing their proportion decreased the frequency of cover crops and new organic fertilizer applications, which resulted in lower C storage than the sum of the individual scenarios.

Considering total N₂O emissions and SOC storage over the entire soil profile, the GHG emission balance decreased by $805 \text{ kg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$ compared to the baseline scenario and reached $859 \text{ kg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$ when including mineral fertilizer production. By also excluding C not sequestered but simply displaced in the improved recycling scenario part of the combination, the difference with the baseline decreased to $617 \text{ kg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$ (Table 2). Compared to the baseline scenario, the national potential for decreasing GHG emissions with the combination of all three scenarios was $11.2 \text{ Mt CO}_2\text{e year}^{-1}$, which was the best scenario for improving the GHG balance of current cropping systems.

3.4 | Yield and water and mineral nitrogen consumption

Depending on the crop and mitigation scenario, mean yield changed by -26% to $+18\%$ (Table S9). The improved recycling scenario increased

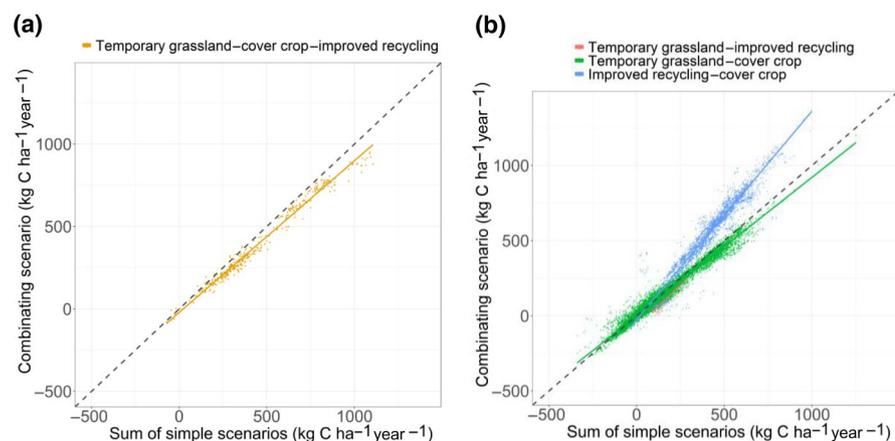


FIGURE 3 Predicted additional soil organic carbon (SOC) storage from the combination of scenarios as a function of the sum of additional SOC storages of these scenarios. Each point corresponds to a simulated cropping system. (a) All three scenarios were combined when possible; if not, (b) they were combined in compatible pairs. Points above the dashed 1:1 line indicate synergistic effects [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Absolute amounts and relative changes in parenthesis of the mean annual quantity of mineral fertilizers applied, evapotranspiration and irrigation from the baseline scenario to the mitigation (sub-)scenarios over the area concerned by each

(Sub-)scenario	Mineral fertilization (kg N ha ⁻¹ year ⁻¹)	Evapo-transpiration (mm year ⁻¹)	Irrigation (mm year ⁻¹)
Baseline	139	436	66
Cover crop expansion	0 (0%)	56 (13%)	53 (79%)
Insertion of temporary grassland	-70 (-47%)	43 (10%)	-68 (-60%)
Extension of temporary grassland duration	-20 (-25%)	14 (3%)	-7 (-25%)
Improved recycling	-9 (-6%)	8 (2%)	-1 (-1%)
Combination of all scenarios	-12 (-9%)	56 (13%)	47 (71%)

the yield of all crops, slightly for grain and silage maize and peas and by 8%–12% for other crops and temporary grasslands. In the grassland insertion sub-scenario, the yield of some crops following the new grassland decreased (by 16% and 26% for wheat and sunflower, respectively), while those of other crops increased (by 10% and 14% for sugar beet and spring pea, respectively). In contrast, the grassland extension sub-scenario had little effect on wheat and sunflower yields, a stronger positive effect on sugar beet yield (+18%) but a negative effect on spring pea yield (-11%). The cover crop scenario had little effect on most crop yields, except for rapeseed (+8%) and silage maize (-7%).

The scenarios investigated also influenced annual evapotranspiration and irrigation (Table 3). In response to the longer duration of soil cover, mean evapotranspiration increased by 13% and 10% in the cover crop and in the grassland insertion (sub-)scenarios, respectively. It was influenced less by the grassland extension (+3%) and improved recycling (+2%) (sub-)scenarios. On average, irrigation increased in the cover crop scenario (53 mm), decreased in the grassland insertion and extension sub-scenarios (-68 and -7 mm, respectively) and changed little in the improved recycling scenario. Quantifying irrigation on main crops and cover crops separately showed that half of the increase in irrigation in the cover crop scenario is due to the possibility to irrigate the cover crops for emergence. The other half of the increase occurs on the main irrigated crops: maize, sunflower and wheat.

Impacts of scenarios on N fertilization were related to the assumptions used in each scenario: no change in the cover crop scenario and a decrease in both the grassland insertion and extension (-47% and -25%, respectively) and the improved recycling scenario (-6%).

4 | DISCUSSION

4.1 | Carbon storage in the baseline scenario

Consistent with previous studies, current cropping systems showed a slight decrease in SOC over 30 years in crop-only rotations (Ceschia et al., 2010; Ciais et al., 2010; Clivot et al., 2019) while SOC increased in crop/temporary grassland rotations (Franzluebbers et al., 2014; Johnston et al., 2017; Singh & Lal, 2005; Smith et al., 1997; van Eekeren et al., 2008; Vertès et al., 2007; Vertès & Mary, 2007). The slightly negative mean effect

of cover crops on SOC in crop-only rotations was related to their low frequency in cropping systems that decreased SOC while they were not included in grain maize monocrops, with large C input into soils. This result was probably due more to the cropping systems than the cover crops. Nevertheless, the off-field GHG_F balance was better with cover crops than without. In crop/temporary grassland rotations, the effect of cover crops was more as expected, with an increase in SOC, albeit small, due to the low frequency and biomass of cover crops in these rotations. The increase in SOC with organic fertilization was small due to straw being exported from cropping systems to produce manure while straw was rarely exported from cropping systems with mineral-only fertilization. The difference in their GHG_F balances was also small, related to higher volatilization and leaching and little reduction in mineral fertilization, since organic fertilization is often applied with a low frequency.

As mentioned in other studies, we observed an impact of soil and climate characteristics on C storage (Bai et al., 2019; Chenu et al., 2019). Involved in the protection of organic matter and the activity of microorganisms, some soil properties such as clay content, pH, temperature or moisture influence the accumulation of C in the soil. Clay content had a positive impact while pH had a negative one on C storage in the simulations but the influence of climate is less obvious. Higher temperatures may be correlated with faster decomposition of organic matter (Bai et al., 2019) but they may also be correlated with higher plant biomass production (Gottschalk et al., 2012) leading to higher C inputs into soils. This raises the question of the influence of climate change (rising temperature and CO₂ concentration, modification of precipitation) to predict the new balance between C input and output.

4.2 | Carbon storage in the mitigation scenarios

The mitigation scenarios show that it is possible to increase SOC storage significantly without completely redesigning current cropping systems. However, there is a trade-off between the storage rate per unit area (kg C ha⁻¹ year⁻¹) and the area on which scenarios can be applied. While the most promising scenario to store SOC at the field scale was grassland insertion, at the national scale, it was by far cover crop expansion.

Our simulated SOC dynamics generally agreed with results from the literature. The mean SOC storage of $466 \text{ kg C ha}^{-1} \text{ year}^{-1}$ for grassland insertion was similar to that in other studies, which ranged from 100 to $800 \text{ kg C ha}^{-1} \text{ year}^{-1}$ (Conant et al., 2001; Kätterer et al., 2008; Watson et al., 2000). The small effect of temporal extension was related to the high initial proportion of grassland in rotations (50%), which already increased C storage (Franzluebbers et al., 2014). Improved recycling had a strong potential to store C in the topsoil ($233 \text{ kg C ha}^{-1} \text{ year}^{-1}$), as shown in the literature (Levavasseur et al., 2020; Maillard & Angers, 2014; Peltre et al., 2012).

In the cover crop scenario, SOC increased by a mean of $131 \text{ kg C ha}^{-1} \text{ year}^{-1}$ while the meta-analysis of Poeplau and Don (2015) showed a mean of $320 \text{ kg C ha}^{-1} \text{ year}^{-1}$. The smaller effect may be explained by the nature and durations of cover crops. The use of legume and non-legume mixtures, later destruction and fertilization could enhance this potential by increasing biomass production (Alonso-Ayuso et al., 2014; Kaye & Quemada, 2017; Marsac et al., 2019). Indeed, the synergistic effect between cover crops and improved recycling increased up to more than 50% the C storage confirming the hypothesis of Bai et al. (2019). Finally, our modeling approach enabled us to represent specific characteristics of production situations (crop rotation, management and pedoclimate) in France and provided detailed SOC storage potential in them.

As well known and shown in our simulations, SOC does not increase linearly and may decrease over decades (Bossio et al., 2020; Chenu et al., 2019; Figure S2). Over longer time horizons, systems will probably reach a new steady state at which no more C is stored. Maintaining the accumulated SOC requires that the mitigation strategy be applied continually or even adapted to climate change (Bossio et al., 2020).

4.3 | GHG balance in the baseline and mitigation scenarios

In the baseline scenario, crop-only rotations were a net source of GHG while crop/temporary grassland rotations were a net sink on average. However, since the area of the former is three times that of the latter, it resulted in a net emission of $20.5 \text{ Mt CO}_2\text{e year}^{-1}$ over the 18.35 Mha of arable area in France.

All mitigation scenarios had a positive effect on GHG balances. The cover crop and improved recycling scenarios increased N_2O emissions with the increase in SOC stocks as reported in Guenet et al. (2020) but not to the point of offsetting C sequestration. These two scenarios remained sources of GHG while the grassland scenario became a sink. At the national scale, the combination of scenarios could mitigate GHG emissions by 54% (-11.2 from the current $20.5 \text{ Mt CO}_2\text{e year}^{-1}$), but it did not allow C-neutral agriculture. Moreover, these estimates are conservative, since emissions from certain activities (e.g., composting, fuel combustion during field operations) could not be included in this study and can be not anecdotal. For example, McGill et al. (2018) demonstrated that the

groundwater-fed irrigation, present in some of our crop systems, degraded the GHG balance despite a gain in C storage due to the fuel consumption of the pumps, the degassing of dissolved GHG from irrigation water and the increase in soil N_2O emission (which is considered into our study).

4.4 | Trade-offs and synergies

For crops whose yields are strongly sensitive to N availability (e.g., rapeseed, sugar beet), all scenarios had a positive effect (Table S7). For less sensitive crops (e.g., wheat, sunflower, pea), the effect depended on the scenario and probably greatly on the production situation. For crops whose yields are strongly sensitive to water availability (e.g., maize), increasing soil cover by inserting cover crops and grassland may decrease soil water availability during crop growth (Meyer et al., 2020) and water drainage that supplies groundwater, which could be an issue in some arid regions (Meyer et al., 2019). This kind of trade-off effect can be reduced by managing cover crops to decrease evapotranspiration, such as by applying mulch (Kaye & Quemada, 2017). In regions with water shortages, irrigation of cover crops during the low-water period may amplify conflicts over water use (Martin et al., 2016; Murgue et al., 2016). Finally, while a risk of intensification of input use was identified (van Groenigen et al., 2017), our results highlight that it may be possible to increase SOC storage without increasing mineral fertilization and even when decreasing it by ca. 9% (Table 3).

As well known, expanding cover crops and grassland decreases nitrate leaching (Autret et al., 2019; Constantin et al., 2010; Vertès et al., 2007). As shown, however, increasing organic fertilization can increase nitrate leaching and volatilization and thus deteriorate water and air quality (Bergström & Kirchmann, 2006; Huang et al., 2017; Reidy et al., 2008). To limit these negative impacts, fertilization management strategies can be developed, by decreasing N input to adapt to the increased soil organic matter, and using better equipment to decrease volatilization (Häni et al., 2016).

Finally, it is crucial to highlight that the increase in SOC may improve soil physical (e.g., structure, available water capacity), chemical (e.g., N supply) and biological fertility (e.g., pest suppression, bioturbation; Bender et al., 2016; Bossio et al., 2020; El Mujtar et al., 2019; Lal, 2016). Thus, in the improved recycling scenario, applying organic matter on arable land instead of other types of areas (e.g., grass strips along roads) may increase certain agronomic benefits.

4.5 | Strengths and limits of the modeling approach

Our simulations assessed fine-scale effects of differences in pedoclimate and cropping systems in France for multiple interdependent biophysical issues related to climate change (SOC dynamics and GHG emissions on-field and off-field), agriculture (yields) and

the environment (nitrate leaching, NH_3 volatilization and water use). Several main limits of this approach can be identified, however. While fertilization has strong direct and indirect impacts on C dynamics, GHG emissions and N-related pollution, STICS could not simulate such adaptation at such a large scale. With an adaptation to the spatiotemporal requirements of crops as much as possible (e.g., precision farming), nitrate leaching and NH_3 volatilization could probably be decreased or avoided, especially in the improved recycling scenario (Herrmann et al., 2017; Huang et al., 2016; Milliron et al., 2019). It would also improve the use of green manure effects of cover crops by decreasing mineral N fertilization (Tonitto et al., 2006).

The positive effect of soil cover on albedo and thus climate regulation was not considered in this study. According to the literature, this effect, which is equivalent to a mitigation potential of $159 \text{ kg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ in Europe (Carrer et al., 2018), should improve the GHG balance of scenarios that extend the duration of soil cover in rotations (cover crop and grassland scenarios; Song, 1999; Wang & Davidson, 2007) for most soils.

We estimated the SOC storage potential in subsoils (>0.3 m) using the relationship of Balesdent et al. (2018). Results indicated little contribution of subsoils to changes in the total SOC stock. However, the same relationship was used in all mitigation scenarios, even though those that inserted grasslands or cover crops might have input more C into subsoils from roots than the improved recycling scenario (Ward et al., 2016).

Finally, mitigation scenarios did not consider strong adaptation of rotations, such as inserting legumes to reduce use of mineral N fertilizers, as in conservation or organic agriculture. Such deep redesign of current simplified and input-based agricultural systems into "biodiversity-based" systems remains a challenge for farms, agronomic research and modeling approaches (Duru et al., 2015; Therond et al., 2017).

5 | CONCLUSION AND PERSPECTIVES

Finally, despite effective increased SOC storage and improved GHG balance, all of the mitigation scenarios investigated, even when consistently combined, did not create C-neutral agriculture. The high-resolution modeling approach showed that current systems, although storing a small amount of C in soils on average, were strong sources of GHG. It enabled us to investigate trade-offs and synergies between climate change mitigation, yield and environmental issues, which highlighted the potential emerging issue of water as a limited resource and a factor that limits biomass production strongly. We highlighted some key management issues to explore to improve GHG balance while protecting the environment. The first one is decreasing fertilization as soil organic matter mineralization increases. The second one is choosing more adapted cover crop species and applying organic resources on them to achieve synergic effects. The last one is improving management of cover crops and temporary grasslands to decrease

water consumption and irrigation. However, redesigning cropping systems might lead to stronger effects and side effects (e.g., market, subsidies) that would need to be assessed. Finally, harvesting biomass of cover crops and grasslands to produce energy (e.g., through anaerobic digestion) could provide both an opportunity to expand the duration and/or areas on which these crops are grown and to provide renewable energy (e.g., biogas) to replace fossil energy but the advantages and disadvantages of using crop biomass to produce renewable energy or to store more C in agricultural soils should be assessed in detail.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in "Stocker du carbone dans les sols fran ais: quel potentiel au regard de l'objectif 4 pour 1000 et   quel c ot ?" at <https://doi.org/10.15454/LV9ZRW>.

ORCID

Camille Launay  <https://orcid.org/0000-0002-2362-7071>

Julie Constantin  <https://orcid.org/0000-0001-9647-5374>

Sabine Houot  <https://orcid.org/0000-0001-7297-7038>

Anne-Isabelle Graux  <https://orcid.org/0000-0002-4707-7844>

Katja Klumpp  <https://orcid.org/0000-0002-4799-5231>

Rapha el Martin  <https://orcid.org/0000-0001-8778-7915>

Olivier Therond  <https://orcid.org/0000-0003-0191-3509>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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