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RESEARCH ARTICLE

Energy cover crops for biogas production increase soil organic carbon stocks: A modeling approach

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Abstract

Energy cover crops for biogas production through anaerobic digestion (AD) are inserted between two primary crops. They replace either bare soil or non-harvested cover crops, and their management is usually intensified to produce more biomass. They allow the production of renewable energy as well as digestate, used as an organic fertilizer, without directly competing with food production. Because of the increased biomass production and export and of the return of a digested biomass to the soil, the impact of energy cover crops on soil organic carbon (SOC) is questioned. The objective of this paper was to study the difference in SOC stocks induced by the introduction of energy cover crops for AD coupled with the application of the resulting amount of digestate. We used the AD model Sys-Metha combined with the soil C model AMG to simulate SOC stocks for 13 case studies in France, with scenarios comparing different inter-crop management practices, with or without cover crops, harvested or not. Our results indicated that the higher biomass production of energy cover crops (from 6.7 to 11.1 t DM ha^{-1}) in comparison with nonharvested cover crops (2 t DM ha^{-1}) or bare soil led to higher humified C input (belowground input and digestate), despite the high C fraction exported in AD. This resulted in an increase in SOC stocks in comparison with nonharvested cover crops or bare soil (from 0.01 to 0.12 t C ha^{-1} $year^{-1}$ over 30 years). The uncertainties in the model parameters did not modify these results. However, in the case of equal biomass production between energy cover crops and nonharvested cover crops, SOC stocks would be lower with energy cover crops.

KEYWORDS

AMG, anaerobic digestion, arable crops, biogas, cover crop, France, modeling, SOC, Sys-Metha

1 | INTRODUCTION

The production of cover crops for anaerobic digestion (AD) and biogas production is promoted in various countries to increase renewable energy production (Marsac et al., 2019; Molinuevo-Salces et al., 2013; Riau et al., 2021; Szerencsits et al., 2016). Energy cover crops are grown between two primary crops, instead of bare soil or a nonharvested cover crop. In contrast to dedicated energy crops, cover crops do not theoretically compete directly with food production and do not lead to indirect land use changes that can increase the global warming potential of AD (Styles et al., 2015). Compared with bare soils, cover crops are known to promote soil organic carbon (SOC) storage (Poeplau & Don, 2015). In the case of energy cover crops, different changes could impact SOC storage. Most of the aboveground biomass of the energy cover crop is harvested, leading a priori to a smaller aboveground C input. However, biomass production from energy cover crops is usually higher than that from nonharvested cover crops, due to a longer cultivation period and an intensification of their management, for example, the use of digestate or mineral fertilizer and chemical weeding (Bacenetti et al., 2014; Marsac et al., 2019; Szerencsits et al., 2016). This increase in biomass production includes higher belowground C inputs (roots and rhizodeposit), since belowground biomass increases with aboveground biomass (Bolinder et al., 2007). During AD, an important fraction of harvested biomass is digested and converted into biogas (CO_2 and CH_4), but a residual and variable fraction of C remains in the digestate, depending on the type of digested biomass (Thomsen et al., 2013). C from digestates is usually considered more resistant to decomposition than C from plant materials (Béghin-Tanneau et al., 2019; Chen et al., 2012; Thomsen et al., 2013). The importance of the recalcitrance of organic matter for C sequestration in the long term is questioned in the literature. Biotic and abiotic stabilization are thought to be more important for long-term C sequestration (Dignac et al., 2017; Dungait et al., 2012), whatever the chemical recalcitrance of added organic matter. However, different authors have shown that the higher the recalcitrance of exogenous organic matter is, the higher the SOC stocks in the long term (decades) after repeated applications (Gerzabek et al., 1997; Levavasseur et al., 2020). Owing to the changes induced by energy cover crops on C inputs, both in terms of quantity and quality, some questions arose regarding the effects of energy cover crops on SOC. SOC increase is indeed known for decades to increase soil chemical, physical and biological fertility, leading to higher productivity (Oldfield et al., 2020). SOC could also play a role in climate change mitigation, as proposed by the 4 per 1000 initiative (Minasny et al., 2017), even if it is strongly debated because of the increased demand for nutrients associated with SOC storage for stoichiometric concerns, the time-constrained capacity of soils to store C, and possible trade-offs with an increase in other soil GHG emissions (N_2O and CH_4; Baveye et al., 2018). Long-term experiments in the field are the reference method to study the effects of agronomic practices on SOC storage. However, due to the delay in obtaining significant results and the associated costs and workload, long-term experiments are limited to the study of few practices. Moreover, in the specific case of energy cover crops, an additional difficulty in studying their effect on SOC storage is how to design an experiment in which the digestate applied to soil would exactly correspond to the quantity and quality of digestate that could be produced only from the harvested energy cover crop. For all these reasons, modeling can be a relevant alternative. Soil-carbon models have already often been used to study prospective scenarios of agronomic practices (Bleuler et al., 2017; Mondini et al., 2018; Saffih-Hdadi & Mary, 2008). The simulation of various climate, soil and cropping system conditions with the soil C model is also easily affordable. In addition, the AD model can simulate the behavior of biomass C during AD and digestate storage before its application to soils (Bareha et al., 2021; Batstone et al., 2002). Thus, chaining an AD model and a soil C model should enable us to answer the question on the effect on SOC stocks of the insertion in cropping systems of energy cover crops and of the application of the corresponding digestate amount on soils.

The objective of this paper was to study the differences in SOC stocks induced by the introduction of energy cover crops for biogas production through AD, including the application of the resulting digestate. The study was based on the combination of an AD model and a soil C model to simulate SOC stocks for different case studies with energy cover crops in France.

2 | MATERIALS AND METHODS

2.1 | General approach

The general approach of the study followed four main steps (Figure 1):

1. The definition of case studies describing soil, climate, and cropping systems, for both a no-AD scenario (either bare soil or nonharvested cover crop depending on the most common farmer practices in the considered case study) and an AD scenario. In particular, the potential biomass production of crops, nonharvested cover crops and energy cover crops harvested for biogas

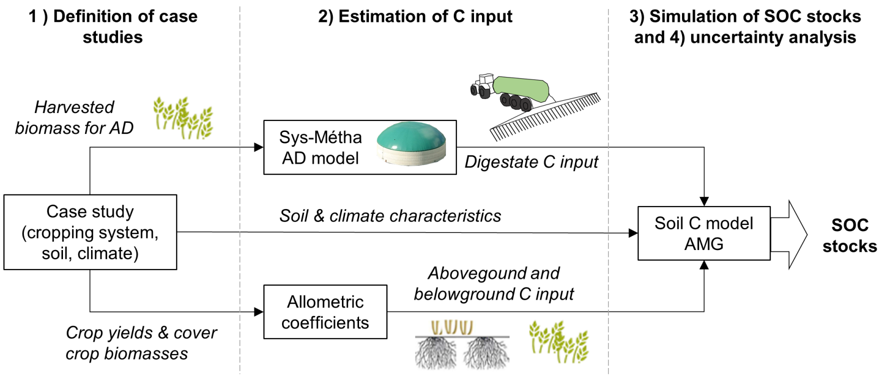

FIGURE 1 Conceptual diagram of the methodology. AD, anaerobic digestion; SOC, soil organic carbon.

production was defined, as well as the impact of energy cover crops on the following primary crop.

2. The estimation of C input to soil for each case study. C input consisted of nonharvested biomass (total aboveground biomass or aboveground residues, roots and rhizodeposit) and digestate. Nonharvested biomass was estimated using allometric coefficients (Bolinder et al., 2007; Clivot et al., 2019) while the Sys-Metha model (Bareha et al., 2021) was used to predict the C quantity in digestate in the AD scenario.
3. The prediction with the AMG model (Clivot et al., 2019) of SOC stocks in the case studies, either with (AD) or without (no-AD) cover crop harvested for biogas production and the application of the resulting quantity of digestate.
4. An uncertainty analysis of the SOC stock predictions.

2.2 | Definition of case studies

Each case study corresponded to a soil type, a climate and a cropping system and included two scenarios: a no-AD scenario with bare soil or a nonharvested cover crop (depending on the considered case study) and an AD scenario with an energy cover crop harvested for AD and the application of the resulting amount of digestate. Each case study was designed with local experts based on real-life situations and local codesign workshops during the RECITAL program (Southwest, West, Rhône-Alpes). These case studies were representative of Ile-de-France (Paris area), Southwestern France, Rhône-Alpes (central to Southeastern France) and Western France (Figure S1). They represented four contrasting areas in terms of climates and cropping systems (Table 1, detailed information in Tables S1–S3). Soils were mainly luvisols because luvisols are one the main soil type in France and because energy cover crops are often cultivated in fertile soils as luvisols are.

In the no-AD scenarios, nonharvested cover crops were inserted before spring crops, such as grain maize (*Zea mays*), sunflower (*Helianthus annuus*), sugar beet (*Beta vulgaris*) and soybean (*Glycine max*). However, we did not consider nonharvested cover crops after a crop harvested late in autumn (e.g., grain maize), as they are usually absent. This corresponds to the regulations in most areas in France for limiting nitrate leaching during winter in compliance with the European nitrates directive (EU Commission, 1991). However, in the southwestern region, no cover crop is usually inserted before spring crops to allow early soil tillage of clayey soils before winter (no cover crop was, thus, considered in the southwestern no-AD scenarios). Nonharvested cover crops are usually not inserted during late summer/early autumn before winter crops such as winter wheat (*Triticum aestivum*), winter barley (*Hordeum vulgare)* or rapeseed (*Brassica napus*) and soil usually remains bare (no cover crop before winter crops in the no-AD scenarios). According to Soleilhavoup and Crisan (2021), mustard (*Sinapis alba*) is the dominant nonharvested cover crop in France, and its mean aboveground biomass production is approximately 2 t DM ha^{-1}. It is typically sown from mid-August to mid-September and terminated from November to January. The usually low biomass production of nonharvested cover crop is confirmed by the figures given in Constantin et al. (2010) or Thapa et al. (2018).

In the AD scenario, two types of energy cover crops could be inserted in the crop rotation and replaced either bare soil or a nonharvested cover crop, leading to four contrasting situations:

- a summer energy cover crop sown after the harvest of a primary crop in early summer (e.g., winter barley, pea) and harvested in autumn before the sowing of a winter crop (e.g., winter wheat), replacing bare soil,
- a summer energy cover crop sown after the harvest of a primary crop in early summer (e.g., winter barley, pea) and harvested in autumn before the sowing of a spring crop in early spring (e.g., sugar beet), replacing a nonharvested cover crop,
- a winter energy cover crop sown in autumn and harvested in spring, before a spring crop sown in late spring (e.g., grain maize), replacing a nonharvested cover crop,

TABLE 1 Main characteristics of the case studies. (CC) represents the period between two primary crops during which a cover crop may be inserted. The yield of nonharvested cover crops corresponds to total aboveground biomass, while that of energy cover crops correspond to harvested aboveground biomass. Köppen–Geiger climate classes are indicated in brackets (Beck et al., 2018)

ID	Region	Climate	Soil type	Crop rotation	Cover crop in the no-AD scenario	Cover crop type in the AD scenario
1	Ile-de-France	Oceanic (Cfa)	Luvisol	Rapeseed—winter wheat—(CC)—grain maize—winter wheat	Mustard: 2 t DM ha^{-1}	Winter cereal (mainly winter barley): 10 t DM ha^{-1}
2				Rapeseed—winter wheat—winter barley—(CC)—winter wheat	None	Silage maize: 6 t DM ha^{-1}
3				Rapeseed—winter wheat—winter barley—(CC)—sugar beet—winter wheat	Mustard: 2 t DM ha^{-1}	Silage maize: 6 t DM ha^{-1}
4	Southwest	Ocenaic to Mediterranean (Cfa to Cfb)	Luvisol	(CC)—grain maize—grain maize	None	Oat: 7 t DM ha^{-1}
5				(CC)—grain maize—soybean	None	Oat: 7 t DM ha^{-1}
6			Calcosol	(CC)—sunflower—winter wheat	None	Triticale: 7 t DM ha^{-1}
7				(CC)—grain maize—sunflower—winter wheat	None	Triticale: 7 t DM ha^{-1}
8				Sunflower—winter barley—(CC)	None	Sorghum: 6 t DM ha^{-1}
9	Rhône-Alpes	Semicontinental (Cfa to Dfb)	Luvisol	(CC)—grain maize—grain maize	None	Rye: 7 t DM ha^{-1}
10				(CC)—grain maize—winter wheat	Mustard: 2 t DM ha^{-1}	Rye: 7 t DM ha^{-1}
11				(CC)—grain maize—soybean—winter wheat—winter barley	Mustard: 2 t DM ha^{-1}	Rye: 7 t DM ha^{-1}
12	West	Oceanic (Cfa)	Cambisol	(CC)—grain maize—winter wheat	Mustard: 2 t DM ha^{-1}	Rye: 7 t DM ha^{-1}
13				(CC)—grain maize—winter barley	Mustard: 2 t DM ha^{-1}	Sorghum: 6 t DM ha^{-1}

Abbreviation: AD, anaerobic digestion.

- a winter energy cover crop sown in autumn and harvested in spring, before a spring crop sown in late spring (e.g., grain maize), replacing bare soil.

Summer energy cover crops were maize or sorghum (*Sorghum bicolor*), sown at the end of June to the beginning of July and harvested in mid-October. Winter energy cover crops were winter barley, rye (*Secale cereal*), oat (*Avena sativa*) or triticale (×*Triticosecale* Wittm. ex A. Camus), sown in late September to mid-October and harvested in the beginning of May to mid-May. Local experts defined the reference yields of energy cover crops based on farmer surveys and field experiments (Carton et al., 2022; Marsac et al., 2019). Yields of winter energy cover crops were higher in the Ile-de-France region due to the highly fertile soil, usually a longer cultivation period and an increased use of fertilizers and pesticides. Each AD scenario also considered the application of digestate. The exact digestate C input resulting from the AD of the energy cover crop was computed with Sys-Metha (Section 2.3.2). Typically, an energy cover crop yield of 7 $t\,DM\,ha^{-1}$ (with 20% DM content) corresponded approximately to a digestate application of 35 $m^3\,ha^{-1}$ once in the rotation, which was a classical application rate (Levavasseur et al., 2022). Alternative lower and higher application rates of digestate were considered in the uncertainty analysis (Section 2.5) to explore the effect of a discrepancy between fields producing energy cover crops and fields where digestate was applied. Wet mesophilic digestion with an absence of phase separation and an uncovered storage of raw digestate were considered in the AD scenario, as typical AD of energy cover crops operated (Levavasseur et al., 2022). Except for the insertion of energy cover crops and the application of digestate, no modification of the cropping system was considered in the AD scenario. However, as suggested by some authors (Graß et al., 2013; Marsac et al., 2019), a possible yield decrease of the primary crop following a winter energy cover crop was considered in response to decreased water and mineral N reserves and a shorter cultivation period (Section 2.5). For each ton per hectare of winter energy cover crop higher than 5 $t\,DM\,ha^{-1}$, we considered an additional 4% yield loss of the following primary crop. For example, it led to a 40% yield loss for a yield of winter energy cover crop equal to 15 $t\,DM\,ha^{-1}$. We tested alternative values in uncertainty analysis (see Section 2.5).

In both the no-AD and AD scenarios, all residues from the primary crops were considered returned to the soil. A yearly soil tillage up to 25 cm was considered (leading to a uniform distribution of modeled SOC at the tillage depth).

2.3 | Estimation of C input

2.3.1 | Nonharvested biomass

Allometric coefficients proposed in Clivot et al. (2019) were used to compute aboveground and belowground C input from crop yields (Table S4).

$$C_{crop\_AG} = Y \times \frac{1 - HI}{HI} \times 0.44, \quad (1)$$

$$C_{crop\_BG} = 1.65 \times \frac{Y}{SRR \times HI} \times \left(1 - \beta^{depth}\right) \times 0.4, \quad (2)$$

where $C_{crop-AG}$ represents the aboveground C input from a crop, Y represents the crop dry matter yield, HI is the harvest index (grain to aboveground biomass ratio), 0.44 is the C content of aboveground biomass (in $g\,g^{-1}$ DM), $C_{crop-BG}$ is the belowground C input on the considered soil depth from a crop, 1.65 is a multiplication coefficient to consider rhizodeposit C input, SRR is the shoot:root ratio (SRR), β is a crop-specific parameter related to the root distributions, depth is the considered soil depth, and 0.4 is the C content of belowground biomass (in $g\,g^{-1}$ DM),

For summer energy cover crops, the parameters of silage maize were used for both silage maize and sorghum for simplicity purposes. Silage maize coefficients from Clivot et al. (2019) were used, except for the HI, which was considered equal to 90% (instead of 96%). For winter energy cover crops, a high uncertainty concerning the SRR of immature cereals used as energy cover crops existed. Mature cereals harvested for grain had an SRR from 6 (winter wheat) to 9 (winter barley) in AMG (Clivot et al., 2019). However, Marsac et al. (2019) reported some high root biomass for winter energy cover crops (triticale, barley and oat), leading to an SRR between 3 and 4. The fraction of root biomass relative to the total biomass decreases with crop maturity (Baret et al., 1992), leading to a lower SRR for energy cover crops harvested immature. Due to this uncertainty and for simplicity purposes, we retained a common parameterization for all winter energy cover crops, with an intermediate SRR (6), and tested the effect of this uncertainty (see Section 2.5), as well as that on the HI (equal to 0.9 by default).

2.3.2 | Digestate input

The harvested energy cover crop biomass was converted into the quantity of C using a C content of 0.44 $g\,g^{-1}$ dry biomass (Clivot et al., 2019). We used the formalisms and the database of the Sys-Metha model (Bareha et al., 2021) to estimate on average the remaining amount of C in the digestate after the AD of the energy cover crop and the storage of the digestate (mean estimation for all case studies). Sys-Metha is a simple mass balance tool used to predict carbon and nitrogen fluxes in AD systems. It is composed of an exhaustive substrate database and of three submodels related to AD, phase separation of digestate and digestate storage. Input data are the main digester characteristics and the digester feedstock. To estimate the proportion of C from the energy cover crop remaining in the raw digestate after AD ($\%C_{dig}$), we applied the formula:

$$\%C_{dig} = \left(1 - \%C_{biodegradable} \times AD_{yield}\right) \times \left(1 - \%C_{loss\ storage}\right) \quad (3)$$

where $\%C_{biodegradable}$ is the organic carbon biodegradability of the energy cover crop (in % of cover crop C), AD_{yield} is a multiplication factor depending on hydraulic retention time in the digester, and $\%C_{loss\ storage}$ is the loss during digestate storage.

We considered biogas plants with a hydraulic retention time greater than 100 days (Levavasseur et al., 2022), leading to an AD yield of 105% in Sys-Metha. $\%C_{loss\ storage}$ was equal to 8% for raw digestate. According to the type of cover crops (cereals only), $\%C_{biodegradable}$ varied between 62 and 85%. This finally led to a $\%C_{dig}$ between 10% and 32%. We, thus, considered a mean $\%C_{dig}$ equal to 20%, also in accordance with the study of Thomsen et al. (2013). We tested alternative values in uncertainty analysis (see Section 2.5). We also approximated the performance of Sys-Metha for the prediction of $\%C_{dig}$ by simulating biogas plants with a majority of cover crops in their feedstock reported in Levavasseur et al. (2022). The comparison between predicted and measured digestate C content is reported in Figure S2. The relative bias (11%) and the relative root mean square error (24%) supported the possible use of Sys-Metha to estimate $\%C_{dig}$ and the uncertainty range tested.

Finally, we did not explicitly simulate C loss during ensiling before AD. However, Teixeira Franco et al. (2016) reported some organic matter losses during ensiling of approximately 10%. We, thus, considered that they are included in the uncertainty tested around the reference value of $\%C_{dig}$.

2.4 | SOC modeling

2.4.1 | General description of AMG

AMG is a soil-carbon model dedicated to the prediction of SOC stock evolution in cropping systems at the yearly time step. It has been developed for more than 20 years (Andriulo et al., 1999). AMGv2, the version used in this study, is fully described in Clivot et al. (2019). It uses a simple representation of SOC, with three C pools: a pool including C inputs from crop residues, roots and exogenous organic matter (e.g., manure, digestates, composts), an active C pool and a stable C pool. A fixed proportion (h) of the C inputs is allocated to the active pool. The remaining fraction ($1-h$) is considered mineralized as CO_2 in the year following application. Aboveground crop residues, roots and exogenous organic matter are each characterized by the specific h parameter (called the humification coefficient). The active C pool decomposes according to first-order kinetics with a rate constant k affected by the climate (mean annual water balance and air temperature) and soil characteristics (clay and carbonate contents, pH and C:N ratio of the total SOM). The stable C pool is taken to be inert during the simulated period. The performances of AMGv2 for predicting SOC stocks have been found to be satisfying in various climate, soil and cropping system conditions (Clivot et al., 2019) and with exogenous organic matter application (Levavasseur et al., 2020). In these latter studies, the simulation error was found to be similar to the standard deviation of SOC measurements in long-term experiments (3 $t\,C\,ha^{-1}$).

2.4.2 | AMG calibration

In this study, all the default parameters of AMGv2 for active carbon mineralization and humification coefficients of crop residues and roots were used (Clivot et al., 2019). The initial proportion of soil stable carbon was also kept as default, i.e., 65%, corresponding to a long-term period of arable crops without exogenous organic matter application.

Digestates from cover crops were not calibrated in AMG. Levavasseur et al. (2020) proposed using the I_{ROC} indicator (indicator of residual organic carbon in soils) to determine the humification coefficient of exogenous organic matter (including digestates) in AMG. I_{ROC} has been proposed by Lashermes et al. (2009) and is determined from the biochemical fractions of the digestates (Van Soest & Wine, 1967) and the proportion of carbon in the digestate that is mineralized during a very short incubation (3 days). I_{ROC} has been defined as a predictor of C remaining from exogenous organic matter after long-term incubation with soil under controlled conditions. We, thus, used the mean I_{ROC} value (0.5) of the raw digestates of cover crops reported in Levavasseur et al. (2022). The uncertainty concerning this value was also tested (Section 2.5).

To interpret the simulated SOC stocks, the mean yearly humified C input was computed from C inputs (Section 2.3) and humification coefficients (Table S4):

$$C_{hum} = \frac{1}{n} \sum_{i=1}^{n} \left(C_{crop_{AG},i} \times H_{crop_{AG},i} + C_{crop_{BG},i} \times H_{BG} + C_{cover\ crop_{AG},i} \times H_{cover\ crop_{AG},i} + C_{cover\ crop_{BG},i} \times H_{BG} + C_{dig,i} \times H_{dig} \right), \quad (4)$$

where C_{hum} is the mean yearly humified C input (in $t\,C\,ha^{-1}$), n is the crop rotation duration (in years), $C_{crop\_AG,i}$ is the aboveground C input from crop in year i, $H_{crop\_AG,i}$ is the humification coefficient of aboveground residues of crop in year i, $C_{crop\_BG,i}$ is the belowground C input from crop in year i, H_{BG} is the humification coefficient of belowground residues of crops, $C_{cover\ crop\_AG,i}$ is the aboveground C input from (energy) cover crop in year i, $H_{cover\ crop\_AG,i}$ is the humification coefficient of aboveground biomass (or residues) of (energy) cover crop in year i, $C_{cover\ cop\_BG,i}$ is the belowground C input from (energy) cover crop in year i, $C_{dig,i}$ is the C input from digestate in year i, and H_{dig} is the humification coefficient of digestate.

2.4.3 | Input data

For each case study, C input (Section 2.3) and soil and climate characteristics (Section 2.2) were used as input data in AMG. In addition to the reference C input, we tested alternative C input from cover crops to study its effect on SOC stocks: from 0 to 5 $t\,DM\,ha^{-1}$ for nonharvested cover crops and from 0 to 15 $t\,DM\,ha^{-1}$ for energy cover crops.

For all case studies, we considered an initial SOC stock of 50 $t\,C\,ha^{-1}$ over 0–25 cm, which roughly represented an average SOC stock in arable fields in France (Pellerin et al., 2020). Owing to the formalism of AMG, the difference in simulated SOC stocks between the no-AD and AD scenarios is not impacted by this initial SOC stock value. SOC stocks were simulated over 30 years for each case study for the no-AD and AD scenarios, with past average yearly climate data (1981–2010). The difference in simulated SOC stocks after 30 years between the AD and no-AD scenarios was computed for each case study. Thirty years were simulated to consider the dynamics of C storage following a change in cropping systems (Pellerin et al., 2020).

2.5 | Uncertainty analysis

We tested the effect of the main uncertainties associated with the key parameters related to the AD scenario in our modeling approach: the HI and the SRR of the energy cover crop, the yield loss of the primary crop following the winter energy cover crop (Y_{loss}), the proportion of C remaining in the digestate after AD ($\%C_{dig}$), the proportion of digestate returned to soil (P_{dig}) and the humification coefficient of digestate (H_{dig}). For each parameter, a minimum-maximum range was defined according to the variability reported in the reference publications (Table 2) and/or according to authors' expertise and farmer surveys. To compare the effect of uncertainty over all the case studies, we computed the relative difference between the AD scenarios with the alternative parameter value and the AD scenarios with the reference parameter value of the difference in SOC stocks between the AD and no-AD scenarios (Relative ΔSOC):

$$\text{Relative } \Delta SOC = \frac{\left(SOC_{30,AD\ alt} - SOC_{30,no\ AD}\right) - \left(SOC_{30,AD\ ref} - SOC_{30,no\ AD}\right)}{\left(SOC_{30,AD\ ref} - SOC_{30,no\ AD}\right)}, \quad (5)$$

where $SOC_{30,AD\ alt}$, $SOC_{30,AD\ ref}$, and $SOC_{30,no\text{-}AD}$ are the simulated SOC stocks after 30 years in the AD scenario with the alternative parameter value, in the AD scenario with the reference parameter value and in the no-AD scenario, respectively.

3 | RESULTS

3.1 | Detailed results for case Study 1: Winter energy cover crop in rapeseed-wheat-maize-wheat rotation in Ile-de-France

Case Study 1 was chosen as an example to illustrate the detailed results. Detailed results for the other case studies are given in Figures S3–S5.

3.1.1 | Humified C input

The mean yearly humified C input (C_{hum}) was mainly driven by aboveground and belowground primary crop residues in both the AD and no-AD scenarios (Figure 2), with 1.18 and 1.13 $t\,humified\,C\,ha^{-1}\,year^{-1}$, respectively. The slight decrease in the AD scenario corresponded to the decrease in the grain maize yield following the winter energy cover crop. Despite the harvest of most aboveground biomass of the energy cover crop, the humified C input from the cover crop was higher in the AD scenario

TABLE 2 Alternative values tested for key parameters in the uncertainty analysis: Harvest index (HI) and the shoot:root ratio (SRR) of the energy cover crop, the yield loss (in % of reference yield) of the primary crop following winter energy cover crop for a cover crop yield above 5 tDM ha^{-1} (Y_{loss}), the proportion (in %) of C remaining in the digestate after anaerobic digestion (%C_{dig}), the proportion (in %) of digestate returned to soil (P_{dig}) and the humification coefficient of digestate (H_{dig})

Parameter	Reference value	Alternative values	Source
HI	0.9	{0.6, 0.95}	Clivot et al. (2019) Marsac et al. (2019)
SRR	6 (winter energy cover crop) 5.6 (summer energy cover crop)	{−50%, 50%} in comparison with reference values	Clivot et al. (2019) Marsac et al. (2019)
Y_{loss}	4%	{2%, 8%}	Marsac et al. (2019) + farmer survey
%C_{dig}	20%	{10%, 30%}	Bareha et al. (2021)
P_{dig}	100%	{0%, 200%}	Assumption
H_{dig}	0.5	{0.3, 0.7}	Levavasseur et al. (2022)

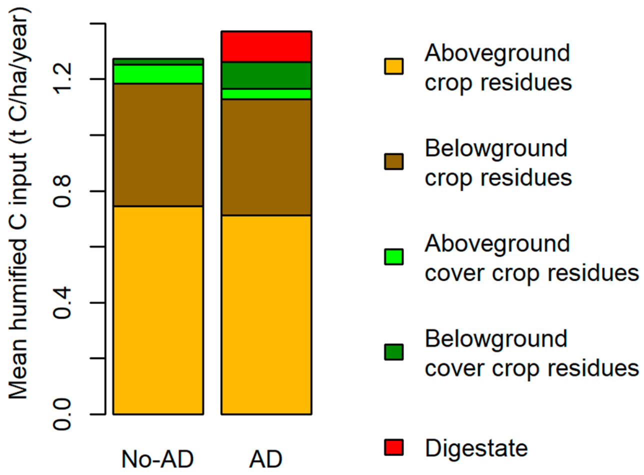

FIGURE 2 Mean yearly humified C input for the first case study. AD, anaerobic digestion.

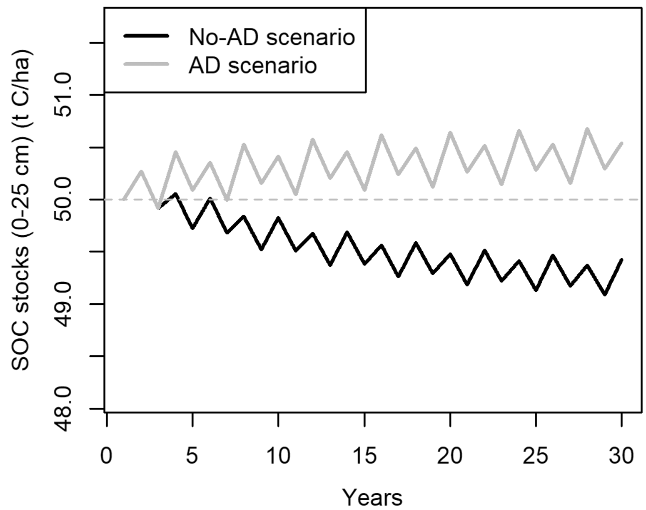

FIGURE 3 Simulated SOC stock (0–25 cm) evolution for the first case study for the no-AD and AD scenarios. AD, anaerobic digestion; SOC, soil organic carbon.

than in the no-AD scenario with the mustard cover crop (0.13 and 0.09 t humified C ha^{-1} year^{-1}, respectively) due to higher belowground C inputs. Finally, with the addition of digestate, the total C_{hum} input was higher in the AD scenario than in the no-AD scenario (1.37 and 1.27 t humified C ha^{-1} year^{-1}, respectively).

3.1.2 | SOC stock evolution

The SOC stocks slightly increased in the AD scenario, whereas they slightly decreased in the no-AD scenario (Figure 3). After 30 years, the simulated SOC stocks were 49.4 and 50.5 t C ha^{-1} in the no-AD and AD scenarios, respectively, while they both started at 50 t C ha^{-1}.

3.1.3 | Influence of cover crop yield

Simulated SOC stocks after 30 years increased with increasing aboveground biomass of cover crops (Figure 4) in both scenarios. In the AD scenario, the increased rate of SOC stocks decreased when the cover crop total biomass was higher than 5.5 tDM ha^{-1} (i.e., 5 tDM ha^{-1} harvested with HI = 0.9) due to the increasing yield loss of the following primary crop.

For the same cover crop biomass, simulated SOC stocks were higher for the no-AD scenario. For example, for the reference biomass production of the nonharvested cover crop (2 tDM ha^{-1}), the simulated SOC stocks were 49.4 and 48.9 t C ha^{-1} for the no-AD and AD scenarios, respectively. To reach the same SOC stocks as the no-AD scenario with its reference cover crop biomass, a total aboveground biomass of energy cover crop higher than 4.1 tDM ha^{-1} (yield of 3.7 tDM ha^{-1} with HI = 0.9) would be needed in the AD scenario of this first case study. The reference total aboveground biomass production of the energy cover crop (11.1 t DM ha^{-1} for a yield of 10 tDM ha^{-1} and HI = 0.9) was far higher than this latter threshold. On the other hand, to reach the same SOC stocks as the AD scenario with its reference energy cover crop biomass, a biomass production of nonharvested cover crops higher than 4.3 t DM ha^{-1} would be needed in the no-AD scenario. This biomass was largely higher than the reference biomass production of the nonharvested cover crop (2 t DM ha^{-1}).

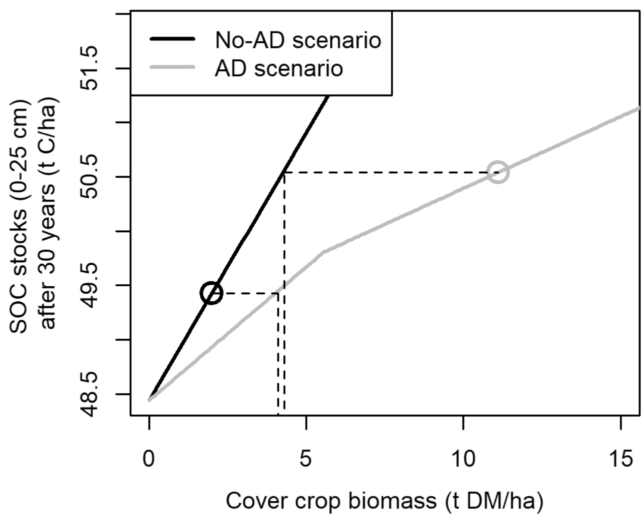

FIGURE 4 Simulated SOC stocks after 30 years (0–25 cm) for the first case study and the no-AD and AD scenarios. The points represent the simulated SOC stocks for the reference cover crop aboveground biomass, while the lines represent the simulated SOC stocks for the variable cover crop aboveground biomass. The total aboveground biomass was considered: The reference energy cover crop yield of 10 t DM ha^{-1} corresponded to a total aboveground biomass of 11.1 t DM ha^{-1} (HI = 0.9). Dotted lines are plotted to ease the determination of the minimum biomass required to reach the same SOC stocks between the two scenarios. AD, anaerobic digestion; HI, harvest index; SOC, soil organic carbon.

3.2 | Carbon storage for all case studies

The humified C input C_{hum} was higher in the AD scenario than in the no-AD scenario for all case studies (Table S5), with an increase varying from 0.04 (Case Study 3) to 0.31 t humified C ha^{-1} year^{-1}(Case Studies 5 and 6). Consistently, the simulated SOC stocks were higher in the AD scenario than in the no-AD scenario for all case studies (Figure 5). The mean yearly SOC increase over 30 years in the AD scenarios compared with the no-AD scenarios was equal to 0.06 t C ha^{-1} year^{-1} and ranged from 0.01 to 0.12 t C ha^{-1} year^{-1}. For an initial SOC stock of 50 t C ha^{-1}, this represented a mean yearly SOC increase of 1.3‰ (from 0.3‰ to 2.4‰). It was maximal for Case Study 6 with a high frequency of insertion of winter energy cover crop (every 2 years), in replacement of a bare soil, and in clayey calcareous soil (associated with a lower SOC mineralization rate in AMG). It was minimal in Case Study 3 with an insertion of a summer energy cover crop every 5 years in replacement of a nonharvested cover crop.

For case studies in which the energy cover crop replaced bare soil (2, 4, 5, 6, 7, 8, and 9), the energy cover crop and its resulting digestate induced an increase in SOC stocks as soon as biomass was produced, while the energy cover crop yield had to be higher than 3.8 t DM ha^{-1} on average when the energy cover crop replaced nonharvested cover crop (Figure S6). To reach the same SOC stocks as the AD scenarios with their reference energy cover crop yield, the biomass of the nonharvested cover crop had to be higher than 3.4 t DM ha^{-1} on average (Figure S7).

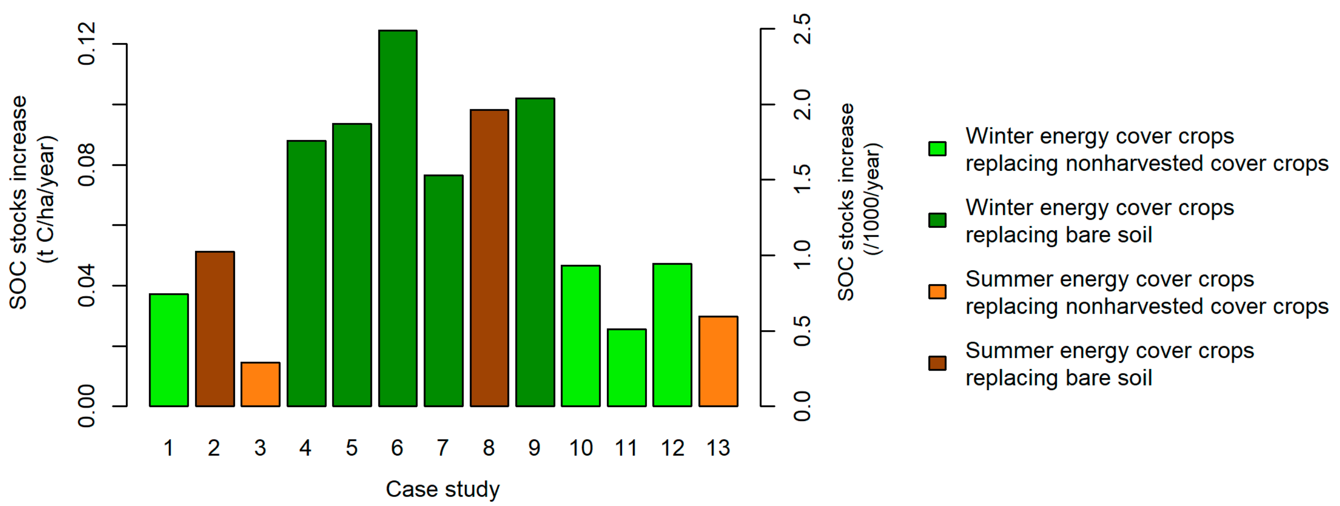

FIGURE 5 Mean yearly SOC increase over 30 years (0–25 cm) for AD scenarios compared with no-AD scenarios for each case study. The SOC increase expressed per 1000 (right *y*-axis) corresponds to the ratio between the SOC increase in t C ha^{-1} year^{-1} (left *y*-axis) and the initial SOC stock (50 t C ha^{-1}). AD, anaerobic digestion; SOC, soil organic carbon.

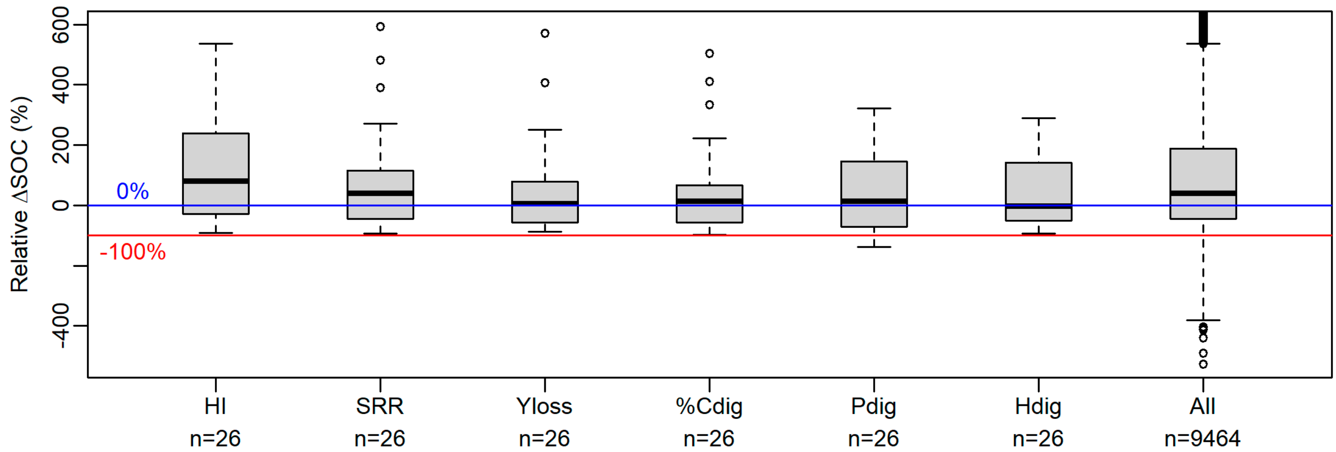

FIGURE 6 Simulated difference in SOC stocks between AD and no-AD scenarios with alternative parameter values relative to the simulated difference in SOC stocks between AD and no-AD scenarios with the reference parameter values (Relative ΔSOC). Each boxplot represents the distribution of simulated values for all case studies together according to the different parameter values. %C_{dig}, C remaining in digestate; All, all uncertainties together; H_{dig}, humification coefficient of the digestate; HI, harvest index; P_{dig}, proportion of digestate returned to soil; SRR, shoot:root ratio; Y_{loss}, yield loss of the primary crop following winter energy cover crop. A Relative ΔSOC lower than −100% indicates a decrease in SOC stocks in comparison with the non-AD scenario. Very few data are higher than 600% (577 over 9620), and the *y*-axis is cut to 600% to improve the visibility. AD, anaerobic digestion; SOC, soil organic carbon.

3.3 | Uncertainty analysis

Most parameter uncertainties had strong effects on the difference in SOC stocks between the AD and no-AD scenarios (Figure 6). However, only the lack of digestate returned to soil ($P_{dig} = 0$) could imply the absence of SOC stock increases in comparison with the no-AD scenarios (i.e., a Relative ΔSOC lower than −100%). In contrast, a lower HI could imply a strong increase in Relative ΔSOC (e.g., third quartile equal to 216%). Combining all uncertainties together, only 9% of simulated Relative ΔSOC was lower than −100% and corresponded in most cases to simulation without digestate application (7% of simulated Relative ΔSOC). The other cases corresponded to simulations combining most hypotheses unfavorable to the AD scenario, for example, high HI, SRR and Y_{loss}, and low H_{dig} and %C_{dig}. Finally, with digestate returned to soil and the reference energy cover crop yields, the AD scenarios increased SOC stocks compared with the no-AD scenarios, almost regardless of the considered uncertainties.

4 | DISCUSSION

4.1 | Drivers of SOC storage with energy cover crops

The insertion of energy cover crops and the restitution of digestate allowed an increase in SOC stocks in all our case studies, representing various soil, climate and cropping system conditions in France (Figure 5). This SOC stock increase was due to the increased biomass production of the cover crop that led to an increased C input. C input increased thanks to increased belowground cover crop biomass and digestate application, despite the harvest of aboveground cover crop residues and potential decrease in primary crop residues. This result is consistent with Chenu et al. (2019), suggesting that increasing C inputs is probably the best option to increase SOC stocks. In cases where energy cover crops replaced bare soil, the SOC stock increase was even higher due to an additional source of C input (cover crop and digestate; Table S5; Figure 5). The increase in cover crop biomass in the AD scenarios is consistent with the objectives of farmers who seek to maximize biomass production for AD. In contrast, various barriers (e.g., cost, labor, weed control) constrain the development of nonharvested cover crops (Hijbeek et al., 2019), leading to low biomass when inserted only to comply with regulations. The typical produced biomass of nonharvested cover crops in France reported in Soleilhavoup and Crisan (2021), thus, appeared too low to reach the same SOC storage as that of energy cover crops.

In the case of energy cover crops having the same yield as cover crops, our simulation study indicated lower SOC stocks due to their harvested part. This result was consistent with that of Thomsen et al. (2013), who found a slightly lower long-term C retention in soil after digestion of cattle feed (mixture of 60% silage maize, 21% alfalfa and 18% rapeseed cake) than for raw feed (12% and 14%, respectively). Despite using the same proportion of C remaining after AD, our study considered a higher humification of crop residues, which could exacerbate the simulated SOC decrease with energy cover crops in comparison with non-harvested cover crops in the case of equivalent biomass production.

In addition to increased C input, the insertion of energy cover crops modified the quality of C input. More belowground residues and the application of digestates characterized the AD scenarios. Roots and organic amendments in general are known to contribute more to SOC than aboveground residues (Kätterer et al., 2011). Accordingly, the humification coefficient of digestates was equal to 0.5 in comparison with 0.2 to 0.3 for aboveground crop residues and 0.4 for roots (Clivot et al., 2019) in our study. The increased recalcitrance of C after AD, thus, contributed to the increase in SOC storage: humified C input from digestate represented from 43% to 71% of increasing C inputs according to the considered case studies (Table S6). However, the increased recalcitrance could not compensate the C losses during AD in the case of equivalent biomass production. Belowground inputs of cover crop represented from 29% to 42% of the increasing C inputs.

4.2 | Uncertainty in SOC storage

In addition to cover crop yields and the return of digestate to soil, the HI and the SRR of cover crops were key parameters to explain SOC storage in our study. The HI can be measured relatively easily (e.g., Marsac et al., 2019); the uncertainty in its value could, thus, be limited in the future. SRR is more difficult to estimate, and only a few measures exist regarding energy cover crops. Moreover, Taghizadeh-Toosi et al. (2016) argued that the proportional relationship between belowground residues and yield with the use of SRR (Bolinder et al., 2007) was not reliable. They proposed using fixed belowground C inputs specific to crop species. Baret et al. (1992) showed that the root biomass fraction exponentially decreased with crop development, which should be considered to estimate the belowground C input of immature crops such as energy cover crops. Because of the higher humification coefficient of belowground crop residues in comparison with aboveground residues, the uncertainty in this C input is important to limit. The ratio used in AMG to estimate exudate C and dead root C from root C (0.65) was also taken from Bolinder et al. (2007). It was determined for mature cereal crops, and its usage for immature crops such as cover crops could be questioned. The work of Swinnen et al. (1994) suggests that the proportion of dead root and exudate C relative to belowground C could be lower for immature crops. Pausch and Kuzyakov (2018) also suggested that this ratio could be lower even for mature crops. This could have led to an overestimation of belowground C from cover crops in our study.

Beyond the uncertainty in the parameters related to our modeling approach, some uncertainties more related to the processes of SOC storage were not addressed in our study. AMG is a simple C model that does not consider the recent advances concerning the process governing SOC storage, e.g., organomineral interactions and accessibility to microbial decomposers (Schmidt et al., 2011). AMG also does not consider variable priming effects depending on the type of added organic matter, whereas Béghin-Tanneau et al. (2019) showed a positive priming effect with raw silage in opposition to a negative priming effect with digested silage in laboratory conditions. However, in field conditions, Cardinael et al. (2015) indicated an absence of an impact of the priming effect on long-term SOC stocks between processed (composted straw) and fresh organic matter (straw). More broadly, despite its simple formalism, AMG was found to have good performance for predicting SOC stocks for various conditions of soil, climate and cropping systems (Clivot et al., 2019; Levavasseur et al., 2020).

To confirm these simulation results, some well-designed long-term experiments in various conditions of soil and climate should be implemented, which would imply a comparison of bare soil, cover crops and energy cover crops, combined with the application or not of digestate (ideally from the digestion of cover crops only). Monitoring of cover crop aboveground and belowground biomass, as well as of SOC stocks, could confirm our simulation results, limit the uncertainty pointed out in our study, and address the relative role of aboveground, belowground and digestate contributions to SOC storage in these emerging systems.

4.3 | Feasibility and comparison to the potential of other practices

To our knowledge, our study is the first to focus on the effects of the AD of cover crops on SOC stocks while considering realistic cropping systems. In the literature, the effects of AD (in general, not only of cover crops) have been only slighlty studied except under laboratory conditions. Wentzel et al. (2015) showed no differences between fields fertilized with raw or digested slurry. Moinard (2021) also showed a slight decrease in SOC stocks at the farm scale after the AD of cattle effluents (without external waste import in AD) by using a modeling approach. Globally, this highlighted the lack of studies focusing on the effects of AD on SOC stocks at the cropping system or farm scales.

Launay et al. (2021) studied the potential SOC storage related to various agricultural practices in France. At the field scale, cover crop temporal expansion and/or insertion (in comparison with bare soil), temporary grassland insertion or improved recycling of organic wastes (0.13, 0.47 and 0.23 t C ha^{-1} $year^{-1}$, respectively) were more promising than the insertion of energy cover crops (our study, 0.06 t C ha^{-1} $year^{-1}$ on average). However, most of our case studies showed SOC stock increases similar to those in the cases of temporal expansion only of cover crops in the study of Launay et al. (2021) (0.04 t C ha^{-1} $year^{-1}$). In comparison with the study of Lugato et al. (2014) at the European scale, the insertion of energy cover crops had a comparable potential than the return of crop residues or reduced tillage (0.04 t C ha^{-1} $year^{-1}$) but again a lower potential than the insertion of cover crops or temporary grasslands (0.11 t C ha^{-1} $year^{-1}$). In addition to the potential at the field scale, potential deployment at wider scales must be considered. For example, energy cover crops could be less constrained than the expansion of temporary grasslands (limited to cattle breeding areas) or the recycling of organic wastes (most of them are already recycled). In comparison with nonharvested cover crops, they provide an additional source of income for the farmer so they might be more likely to be implemented. The prospective study of Ademe (2018), thus, planned the production of 50×10^6 t DM of energy cover crops in France in 2050. However, water availability and the vegetation period specific to each area are key issues to consider (Graß et al., 2013) in the ability to sustain both the energy cover crop yield and the following primary crop yield. Another limit to consider in the deployment of energy cover crops is the potential competition with forage production or grazing of cover crops in breeding areas, which represents up to 23% of cover crop areas before silage maize in France (Soleilhavoup & Crisan, 2021).

Our study focused on SOC storage, whereas the insertion of an energy cover crop raises many other questions that should also be assessed (Launay et al., 2022). First, even if SOC stocks increased, the quality of C input was modified, which could modify the soil biology (Chen et al., 2012). Second, the increase in biomass production with energy cover crops required more inputs (e.g., fertilizers, pesticides, water, field work). These increased resource uses, as well as the insertion of the energy cover crop itself, modified N dynamics, GHG emissions, run-off and soil erosion, etc., and would require a multicriteria assessment. Esnouf et al. (2021) performed a life cycle assessment of AD based mainly on energy cover crops. Most of the studied impacts were improved with the insertion of energy cover crops and a limited use of chemical input (pesticides, mineral fertilizers) and no irrigation. However, no yield loss of the crop following an energy cover crop was considered, preventing indirect land use changes, which was a key feature in the sustainability of AD in the study of Styles et al. (2015).

Finally, our study considered some theoretical case studies with the AD of cover crops only but without any changes in the cropping systems, with the exception of the insertion of energy cover crops. We made this simulation choice to study the specific effect of the AD of cover crops on SOC stocks. In reality, cover crops are almost always digested with other substrates (Levavasseur et al., 2022), leading to imports of nutrients on farms that strongly modify C and N fluxes (Moinard, 2021). Changes in crop rotations could also occur to favor primary crops with a shorter cultivation period and allow the insertion of more energy cover crops. Carton et al. (2022) showed for example that some farmers replaced winter wheat by winter barley (with an earlier harvest) to increase the cultivation period of silage maize as a summer energy cover crop. These additional changes should also be studied in a broader assessment of AD.

5 | CONCLUSION

Our modeling study indicated that the insertion of energy cover crops for AD in cropping systems increased SOC stocks in comparison with nonharvested cover crops or bare soil (0.06 t C ha^{-1} $year^{-1}$ on average). SOC storage was driven by the increased biomass production of energy cover crops in comparison with nonharvested cover crops (from 4 to 9 t DM ha^{-1}) or bare soil, leading to increased C input (belowground and digestate; from 0.03 to 0.3 t humified C ha^{-1} $year^{-1}$), despite high C export in AD to produce biogas. However, in the case of equal biomass production between energy cover crops and nonharvested cover crops, SOC stocks would be lower with energy cover crops despite the higher recalcitrance of digestate C. In addition to the effects on SOC stocks, a multicriteria assessment should be performed to consider other impacts induced by the intensification of energy cover crop cultivation (e.g., use of fertilizers, irrigation, impacts on the following primary crop) and by the diversification of cropping systems induced. To study these additional effects and confirm our simulation results on SOC stocks, long-term experiments should be implemented to disentangle the effects of aboveground and belowground cover crop biomass and digestate.

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CONFLICT OF INTEREST

The authors have no relevant financial or nonfinancial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study areopenly available in: The Agreste database at https://agreste.agriculture.gouv.fr/agreste-web/disaron/Chd2009/detail/ (main crop yield, nonharvested cover crop biomass). The Meteo France database at https://meteofrance.com/climat/normales/france (climatic data). The Carton et al. (2022) report at https://agriculture.gouv.fr/performances-agronomiques-et-environnementales-de-la-methanisation-agricole-sans-elevage-analyse (energy cover crop management and biomass, humification coefficient ofdigestate). The Opticive project report at https://librairie.ademe.fr/dechets-economie-circulaire/3993-opticive.html (energy cover crop management and biomass, energy cover crop root biomass). The Sys-Metha database at https://entrepot.recherche.data.gouv.fr/dataset.xhtml?persistentId=doi:10.15454/U4S6OF (C losses during anaerobic digestion).

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SUPPORTING INFORMATION

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