The crop residue conundrum: maintaining long-term soil organic carbon stocks while reinforcing the bioeconomy, compatible endeavors?

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Abstract

Crop residues are key to supply carbon to the bioeconomy without interfering with food security. However, it is often suggested to export no more than half of this potential to ensure the maintenance of soil organic carbon (SOC) stocks. In this study, we challenge this idea by assessing how the residues use for the bioeconomy is intertwined with the maintenance of long-term SOC stocks, and thus the amount that can safely be harvested. We considered the coproduct return to the soil from five bioeconomy scenarios: i) pyrolysis biochar, ii) gasification biochar, iii) hydrothermal liquefaction hydrochar, iv) anaerobic digestion digestate, and v) lignocellulosic ethanol molasses. To compare the long-term SOC changes from these scenarios against a business-as-usual (BAU) scenario, in which crop residues are left unharvested, we developed an original framework coupling a SOC model with a bioeconomy module, that we applied at high spatial resolution to cover over 60,000 combinations of crop rotations and pedoclimatic units over France, for 2020–2120. The SOC model was adapted to consider the recalcitrance to degradation of each coproduct, while the bioeconomy module determines the share of carbon from the crop residues allocated to the coproducts. Our results show that crop residues could be completely harvested if biochar from pyrolysis or gasification is returned to soils, with SOC expected to double as compared to the BAU scenario. Replacing crop residues with hydrochar was shown to increase SOC stocks in 87% of the areas (max + 8%), while the digestate scenario predicted minor SOC increases in 50% of the areas (max + 0.76%) and decreases in 40% of the areas (min − 4%). The molasses scenario yielded SOC losses in all the areas and is thus not recommended as a C maintenance strategy. Excluding these, an additional amount of 60.4–191 PJ of crop residues (use-dependent) could be available for the French bioeconomy in comparison to applying a universal removal rate of 31.5%.

1. Introduction

Crop residues are a key feedstock to supply non-fossil carbon (C) to the future bioeconomy. In Europe alone, a theoretical potential of 3800 PJ y^{-1} (Hamelin et al., 2019) were estimated; equivalent to the gross annual electricity generation of France and Germany combined (BP, 2021). Crop residues include a variety of streams; such as (i) dry stalks and leaves of cereal and (ii) oilseed crops, and (iii) stems and leaves from tubers. These streams are leftover from harvest operations and thus not a primary economic product (Karan and Hamelin, 2021). This biomass is key for the bioeconomy, as it is widely available in large quantities, at low costs, and with short harvest times, besides not directly competing with food security (Sadh, 2018; Swain et al., 2019). Current uses of crop residues include animal fodder and bedding, mushroom production, mulch to preserve soil moisture, among others (Hamelin et al., 2019; Scarlat et al., 2019).

When left unharvested, crop residues can contribute to soil organic carbon (SOC) and play a key role for the long-term quality, nutrient balance, and agronomic functions of soils. Increasing removal rates reduce the soil organic matter inputs, which creates a tradeoff between the crop residue use for the bioeconomy and SOC stocks maintenance (Blanco-Canqui, 2013; Morais et al., 2019).

Various studies suggested limiting the removal to rates between 15 and 60% of the theoretical harvesting potential (depending on the crop type), due to technical and environmental constraints (Fischer et al., 2010; Haase et al., 2016; Monforti, 2015; Panoutsou and Kyriakos, 2021; Scarlat et al., 2019). These restrictions significantly reduce the supply of renewable carbon from crop residues to the bioeconomy.

Bioeconomy processes convert biomass into a main product, while the more degradation-resistant fraction remains a coproduct. Coproducts can be applied to the soils as exogenous organic matter (EOM) to maintain or improve the SOC stocks (Cayuela et al., 2010). EOM is a heterogeneous material and can be composed of recalcitrant and labile fractions. The labile fractions tend to be mineralized fast (i.e. as CO_2 emissions) after the first couple of years following soil application, while the recalcitrant fractions exhibit longer mean residence times (MRT; (Lehmann et al., 2015)), promoting SOC storage (Bera et al., 2019; Lehmann et al., 2015). SOC stock evolution depends on the applied coproduct as well as the site-specific conditions and cropping systems (i.e. a combination of soil properties, climate, crop rotations and other management practices). Spatially explicit considerations are thus needed in order to address the conundrum between long-term SOC storage and the supply of a renewable C feedstock to the bioeconomy.

Some soil C models can simulate long-term SOC dynamics considering different cropping systems and climate (Smith et al., 2020). Organic matter decomposition involves complex processes influenced by the biomass characteristics, eventual stabilization treatment and/or recalcitrance degree, pedoclimatic conditions, and interactions with the soil microbiota, among others. An accurate prediction of the coproducts carbon persistence in soils is therefore challenging (Lehmann et al., 2020; Mondini et al., 2017). Some soil models have been adapted or parameters have been proposed, to simulate the return of bioeconomy coproducts into soils. This includes, for instance, RothC (Lefebvre et al., 2020; Woolf and Lehmann, 2012), Century (Dil and Oelberman), APSIM (Archontoulis et al., 2016), and EPIC (Lychuk et al., 2015) for biochar. For digestate, CTOOL (Hansen et al., n.d.), AMG (Levavasseur et al., 2020), CANDY (Witing et al., 2018), and RothC (Mondini et al., 2017) have been adapted. RothC (Mondini et al., 2017) has also ben adapted to consider bioethanol coproducts, such as the non-fermentable residue. BioEsoil, a tool based on RothC, evaluates the effect of residues from bioenergy processes (i.e., gasification and incineration) on soil organic matter (Bonten et al., 2014). However, these studies have been location- and coproduct-specific, limited to very specific simulation parcels, due to the scarcity of data and modeling issues to cover high spatial resolutions and temporal scales. To date, only a few studies have used a soil model that includes different EOM inputs coupled with large-scale spatial information, as in Mondini et al. (2018), where eight types of EOMs were simulated at the scale of entire Italy.

The effect of crop residues harvesting and their use in the bioeconomy on long-term SOC stocks has been explored in Hansen et al. (2020), where the authors found that as an average for Danish soils, the straw that can be harvested for pathways involving no C return is 26% of what can be harvested if the digestate is returned to soils. Yet, the Hansen et al. (2020) assessed only one bioeconomy conversion pathway and used a rather coarse spatial representation of Danish croplands limited to two types of crop rotations and three types of soils. Similarly, Woolf and Lehmann (2012) predicted that applying biochar to soils could increase SOC stocks by 30–60% in 100 years while removing 50% of crop residues for bioenergy in three specific locations in Colombia, Kenya, and the USA.

To our knowledge, no study has addressed the effect on SOC stocks from crop residue removal and C return to the soil from various bioeconomy conversion pathways. In this work, we challenge the idea that the biomass potential from crop residues must be limited by a given removal rate, to maintain organic carbon in arable soils. Instead, we propose that such potential is deeply intertwined with the use of the biomass within the bioeconomy. This is based on the rationale that many technologies involve a potential carbon return to soils as a coproduct more recalcitrant to degradation than the original raw biomass.

Thus, this study aims to (i) further understand the cause-effect link between the “C-neutral harvest” of crop residues (defined below) and their usage within the bioeconomy, and (ii) address how this differs among the major existing bioeconomy pathways where a C return to the soil is possible. To this end, we modeled, as an illustrative case study, the SOC evolution of all arable topsoils topsoil (0–30 cm) in France, with and without crop residues harvest for different bioeconomy pathways. The term “C-neutral harvest” is herein employed to designate situations where the long-term (here defined as 100 y) SOC stocks of a given bioeconomy management do not decrease, in comparison to a reference situation where crop residues are incorporated into soils. It encompasses a similar vision to what previous studies referred to as “sustainable harvest” (Scarlat et al., 2019) but is more explicit on what it covers (quantification of SOC stocks only) and what it disregards (e.g. other aspects of long-term sustainability such as biodiversity or soil fertility).

2. Materials And Methods

We propose a modeling framework to assess the long-term SOC stock effects of crop residues usage for different bioeconomy technologies, considering different management practices on arable topsoils. It quantifies the amount of harvestable crop residues that can be removed from fields for bioeconomy, while an alternative coproduct is returned to meet the condition of maintaining or even increasing the SOC stock levels, as compared to a reference situation, where residues are left on the field. The bioeconomy scenarios considered here include pyrolysis, gasification, hydrothermal liquefaction (HTL), anaerobic digestion (AD), and lignocellulosic bioethanol (2GEtOH) production.

The framework is based on spatially explicit high-resolution data on climate, soil, and agricultural practices of specific units of metropolitan France and a SOC model that simulates the SOC stock changes in cropping systems receiving coproduct inputs with specific recalcitrance properties. The temporal scope is 100 years, over the years 2020–2120.

The state of C in arable soils, agricultural practices, soil, and climate at the beginning of the time scope is here referred to as the initial conditions. Two developments over the time scope are considered: (i) a business as usual (BAU) scenario reflecting current practices, where part of the harvestable crop residues (ca. 46%; details in SI1.2) are already being exported for livestock (as bedding and fodder) and the rest is left on fields, and (ii) a bioeconomy scenario which is similar to BAU, except that the share of straw left on fields is harvested, used in the bioeconomy (five distinct bioeconomy scenarios being independently considered), and partly returned to fields as a bioeconomy coproduct. The BAU scenario is thus a measure-stick against which the bioeconomy scenarios are contrasted. For these six future developments (i.e., BAU and the five bioeconomy scenarios), the long-term changes in SOC stocks are determined, as further described in section 2.4.

The soil physicochemical properties and the future meteorological variables assumed (further detailed in sections 2.2 and 2.4) are the same for the BAU and bioeconomy scenarios. Similarly, the same rotations, farming management practices (section 2.2), and crop yields (SI1) are repeated cycle after cycle. The impact on crop yields from changing the raw biomass to stabilized EOM (Oldfield et al., 2019) was excluded to emphasize the effect of crop residue removal alone. The technical harvestable rate and amount of crop residues already used for livestock are crop dependent (SI1) and are assumed to remain constant during the modeling timeframe.

The structure of the framework consists of four main modules (Fig. 1), further detailed in the subsequent subsections: description of the simulation units (Module 1), definition of the bioeconomy scenarios, carbon conversion from residues to coproducts and recalcitrance of coproducts (Module 2), modeling SOC stock changes and collecting related input data (Module 3), and sensitivity analysis (Module 4). The process was automated using R (R Core Team, 2021); the scripts and data used are available in https://doi.org/10.48531/JBRU.CALMIP/AUEEEJ

2.1 Module 1: Spatially explicit data

The aim of Module 1 is to define representative simulation units (SU) for the studied case, reflecting the variety of soils, climates, crop rotations, and farming practices in a spatially explicit manner.

Module 1 is entirely building upon the study of Launay et al. (2021), launched within the frame of the French efforts within the international 4p1000 initiative (“4p1000”), acknowledged as the most comprehensive and updated spatially explicit representation of cropping systems in France. Launay et al. (2021) defined a set of fundamental concepts briefly described as follows.

Pedoclimatic units (PCU) are defined as a unique combination of soil properties (coarse fraction, clay content, pH, etc.) and meteorological variables (temperature, precipitations, and potential evapotranspiration) (French climate and soils types are specified in SI1.1). When found on arable lands, these are referred to as agricultural PCU (APCU). French APCUs combine soil mapping units (1:1000000; Jamagne et al., 1995) and the French SAFRAN climate grids (8x8 km; Durand et al., 1993) with identified crop rotations per PCU retrieved from the French Land Parcel Identification System (Leenhardt et al., 2012; Levavasseur et al., 2015). A total of 12,060 APCUs with more than 100 ha of agricultural area, where at least 10% of it has arable crops and/or temporary grasslands, were identified. The selection represents 84% of the French cropland.

The crop rotations selected in Launay et al. (2021) include 12 different crops, temporary grasslands, and cover crops (further detailed in SI1.2). Winter wheat is the most representative crop, providing 65% of the available residual biomass (dry matter). Crop rotations cover 4.79 Mha and were judged to be a fair representation of the 18.35 Mha of French arable crops and temporary grasslands in 2006–2012. Farming practices —involving organic fertilization, cover crops, irrigation, tillage, and current use of crop residues— were determined from a survey conducted by the Ministry of Agriculture, Agri-Food, and Forestry over the period 2006–2011 (Graux et al., 2020; Lafargue, 2013).

The combination of APCUs, crop rotations, and farming practices yielded 62694 simulation units (SI1.1). Further details on the crop rotation and yields are presented in SI1.2.

2.2 Module 2: Bioeconomy scenarios

This module describes the five bioeconomy scenarios. All the bioeconomy scenarios involve two key parameters to answer the research questions of this study, namely (i) the amount of C from the harvested crop residues (of a given SU; Fig. 1) that will end up in the coproducts returned to fields and (ii) the C recalcitrance to degradation of this coproduct. The former is hereafter referred to as carbon conversion (Cc) and the latter as carbon recalcitrance (Cr). The recalcitrance represents the most stable biochemical fraction of organic products. Here, it is the fraction of the coproduct that cannot be readily mineralized and which decomposes slower than the more labile fraction of the organic coproduct. The labile fraction is assumed to be entirely processed by soil microorganisms within about one year. The Cc and Cr of a coproduct depend on the feedstock and process conditions.

Thermochemical processes, such as gasification, pyrolysis, and HTL, exposing biomass to elevated temperatures for long times, coproduce biochar with more aromatic compounds than for low temperatures and short times, thus the former is related to high degrees of recalcitrance (Han et al., 2020; He et al., 2018; Wang et al., 2016). Various studies determined that the recalcitrant fraction of biochar exhibits MRTs from decades to millennia (Lehmann et al., 2015; Zimmerman and Gao, 2013). HTL, which is carried out at lower temperatures than pyrolysis and gasification, using relatively wet feedstock, produces a less recalcitrant char than pyrolysis. Gasification, which employs higher temperatures than HTL and pyrolysis, yields a char with a higher degree of stability than pyrolysis char.

In this work, we only considere the return of the char produced in each thermochemical technology, and other coproducts generated (e.g., tar, ashes) are excluded. To avoid confusion between the coproducts assessed in each scenario, we refer to pyrolysis, gasification, and HTL char as pyrochar, gaschar, and hydrochar, respectively.

Biochemical processes, such as alcoholic fermentation and anaerobic digestion, are carried out using microorganisms and lower temperatures than thermochemical technologies. The outputs of AD are biogas and digestate, while alcoholic fermentation produces bioethanol and a residue that is often separated into a lignin-rich solid and a liquid fraction known as molasses. The solid coproduct is typically used for energy production. Therefore, for the biochemical pathways, we consider only digestate (from AD) and molasses (from 2GEtOH production) as EOMs. The carbon stability and soil MRT of molasses and digestate are considered lower than for chars (Table 1).

The Cr and Cc considered herein stem from a comprehensive compilation and data reconciliation of over 400 incubation assays, field trials, and modeling experiments involving a wide variety of feedstock, including crop residues, as detailed in Andrade et al. (*submitted*). To the extent possible, the Cc and Cr values used herein were derived from studies involving straw-like feedstock. Table 1 summarizes the Cc and Cr values considered, along with the identification of the coproduct returned to fields and the other products generated during the conversion process, for each scenario. The bioeconomy conversion pathways are further described in SI1.3.

Table 1
Overview of the bioeconomy scenarios considered in the study, and implications in terms of the Cc (Carbon conversion) and Cr (Carbon recalcitrance) parameters. MRT: Mean Residence time, DM: dry matter, n/a: not applicable

Scenario	Process Conditions	Co-product returned to soil	Other products generated[a]	Cc[b]	Cr[b]	MRT[c]	Key process reference[h]
				%	%	Years	
BAU	Crops residues left on soil	None	None	n/a	n/a	n/a	(Launay et al., 2021)
Pyrolysis[d]	350–700°C, from seconds to 2h, typically fed with a biomass DM > 90%	Pyrochar[e]	**Bio-oil**, non-condensable gases	44 [34–54]	95 [90–99]	> 100	(Ippolito et al., 2020; Joseph et al., 2021; Lehmann et al., 2015)
Gasification	600–1200°C dry gasification. 300–550°C hydrothermal gasification, typically fed with a DM > 90%	Gaschar	**Syngas**, tar, ashes	20 [14–25]	95 [90–99]	> 100	(Molino et al., 2018; Ventura et al., 2019; Watson et al., 2018)
Hydrothermal Liquefaction[f]	180–400°C, use of K_2CO_3 catalyst to enhance bio-oil production; typically fed with a DM < 20%	Hydrochar	**Bio-oil**, non-condensable gases	31 [12–45]	83 [80–96]	< 26	(Malghani et al., 2015; Watson et al., 2020)
Anaerobic[g] Digestion	Mesophilic conditions (30–50°C). 1–3 months. Typically, wet digestion, with DM in the digester < 35%	Digestate	**Biogas**	33 [30–40]	68 [58–77]	< 26	(Hamelin et al., 2014; Sarker et al., 2019)Zhang et al2021

Scenario	Process Conditions	Co-product returned to soil	Other products generated[a]	Cc[b]	Cr[b]	MRT[c]	Key process reference[h]
				%	%	Years	
Lignocellulosic ethanol	Pretreatment, acid and enzymatic hydrolysis, fermentation *S. cerevisiae, purification by* distillation. The effluent is separated into a solid fraction and liquid molasses	Molasses	**Ethanol**, solid fraction	24 [18–30]	45 [28–60]	< 26	(Swain et al., 2019; Tonini et al., 2016; Wietschel et al., 2021)

[a] The main product considered to drive the investment in this bioeconomy scenario, under the specified conditions, is indicated in bold; [b] Cc: C fraction of initial crop residue transferred to the co-product returned to fields, Cr: C fraction of the co-product allocated to the stable biochemical fraction. The values presented herein are averages from Andrade et al. (*submitted)*, based on a compilation of 124, 33, 97, 99, and 51 records, for pyrochar, gaschar, hydrochar, digestate, and molasses, respectively. Ranges in brackets represent quartiles 1 and 3; [c] The MRT allows to define the SOC fraction of the soil model to allocate the Cr fraction. The soil model used in this study considers that EOMs with MRT of the Cr fraction higher than the modeling timeframe are inert, thus any coproduct with an MRT longer than 100 years is virtually inert. EOMs with Cr fractions exhibiting MRT of 7–26 years are considered to be slowly mineralized (Clivot et al., 2019) in the soil model (see section 2.3). [d] Pyrolysis can be classified as fast (300–500°C, seconds of retention time) or slow (500–700°C, minutes to hours). Slow conditions tend to favor the production of biochar, whereas the fast process is optimal for bio-oil production. From an economic standpoint, the pyrolysis scenario in this study aims to maximize the bio-oil yields, thus the process conditions of the studies included are those of a fast process, when possible (Ippolito et al., 2020). [e] Also commonly referred to as biochar. [f] The use of catalysts, specially K_2CO_3 accelerates the water gas shift reaction in low temperatures HTL processes, which yields higher rates of bio-oil (targeted product) than hydrochar. The use of catalysts tends to be more common (Mathanker et al., 2021), therefore, the Cc and Cr values stem from such process conditions. [g] Some simulation units involve the use of manure as organic fertilizer. For these, we did not consider this manure to be digested, to keep the focus on the impacts from crop residues. Cc accounts only for the C from crop residues transferred to the digestate. [h] Only key references mentioned, the full compilation of reviewed studies is presented in Andrade et al (*submitted*).

2.3 Module 3: SOC Model

Module 3 describes the SOC model used, and the adaptations considered in this study, as well as how the bioeconomy scenarios have been compared with the BAU scenario.

2.3.1 AMG model: Overview

For both BAU and bioeconomy scenarios, the evolution of topsoil organic C stocks (0–30 cm) was simulated with the AMGv2 SOC model, detailed in Clivot et al. (2019). AMG is a French SOC model, first described in Andriulo et al. (1999), which simulates the carbon dynamics of agricultural topsoils at an annual timestep. The model successfully predicted the changes in SOC stocks of various cropping systems under different pedoclimatic conditions in France and Europe (Clivot et al., 2019; Farina et al., 2020; Saffih-Hdadi and Mary, 2008) and has notably been calibrated for 26 EOM types (Levavasseur et al., 2020). AMG splits the organic matter (OM) into three different pools (shown as boxes in Fig. 2). The fresh OM inputs from above- (crop residues) and below- (crop roots and root exudates) ground plant compartments, as well as inputs from EOM (e.g., manure, bioeconomy coproducts), represent the fresh organic matter (FOM) pool, which is assumed to be annually decomposed (Fig. 2a). The C in the FOM pool is labeled as C_{FOM}. The proportion of C_{FOM} incorporated into the active SOC pool (C_A) is determined by a retention coefficient (*h*). The fraction of C_{FOM} that does not enter C_A (1-h) is mineralized as CO_2. The C_A pool is affected by the mineralization process following first-order kinetics with a *k* mineralization rate. The stable SOC pool (C_S), sets 65% of the initial SOC by default as inert during all the simulations for sites with an arable land history (Clivot et al., 2019).

2.3.2 Model input data

AMG minimum input data comprises crop rotations, climate, soil physicochemical properties, initial SOC stocks, and farming practices (including the maximal soil tillage depth, irrigation water amounts, EOM inputs, and crop residue management). Crop rotation information includes annual yield, moisture content of the harvested product, harvest indexes (HI), and C allocation coefficients determining the proportion of C in the harvested product (RP), above-ground residues (RS), root C (RR), and extra-root C (RE) (Fig. 1). It also includes the fraction of residues that can be technically harvested, per crop type.

HI and allocation coefficients were used as set in the method proposed for calculating C inputs for AMGv2 (Clivot et al., 2019), themselves adapted from Bolinder et al. (2007). The technically harvestable fraction for each crop was also taken as defined in the proposed method (further details in Table SI1.1) and varies from 55–91%. Meteorological data comprises the mean annual air temperature and the annual water balance, the latter being determined as the difference between the water inputs (accumulated precipitations and irrigation) and potential evapotranspiration. In this study, the spatially explicit meteorological data were retrieved, for years 2020 to 2100, from SICLIMA (DRIAS, last updated May 2013), for the RCP4.5 climate trajectory (Representative Concentration Pathway; IPCC, 2021), downscaled by the model CNRM-CERFACS-CM5/CNRM-ALADIN63. These projections were not available beyond 2100. For the period from 2101 to 2120, average values from the last decade (i.e., from 2091 to 2100) were used.

Soil-related data include initial SOC stocks, pH, bulk density, coarse fraction, clay content, C:N ratio, and $CaCO_3$ content. Initial SOC stocks were retrieved from Mulder et al. (2016) and used as processed in Launay et al. (2021) to correspond to the APCU resolution, while the other soil parameters were retrieved from Jamagne et al. (1995). AMG also requires information regarding farming practices, as detailed in Module 1.

Defult h values (FOM-dependent) given in AMG for crop residues and non-coproduct EOMs (e.g. animal manure) were used (Clivot et al., 2019; Levavasseur et al., 2020), while for the bioeconomy coproducts were determined individually. The actual mineralization rate (k) of the active SOC pool, which depends on environmental response functions, is calculated for each year and each situation as defined in Clivot et al. (2019).

2.3.3 AMG adapted for bioeconomy processes

We adapted the calculation method for C inputs and the model to include the Cc and Cr values of pyrochar, gaschar, hydrochar, digestate, and lignocellulosic ethanol molasses. The adapted version of AMG allows determining the SOC evolution of the different bioeconomy scenarios by deriving retention coefficients from Cr values. The C input from the coproducts is determined using the initial C in the crop residues and the Cc coefficient.

We grouped the Cr values per coproduct as highly recalcitrant (pyrochar and gaschar) and less recalcitrant (hydrochar, digestate, and molasses), to define the C retention into the soil associated to each coproduct. The recalcitrance and the MRT values in Table 1 were used to set the *h* coefficient per coproduct and allocate the C among the soil pools (C_A or C_S), respectively. Two retention coefficients were defined to differentiate between the fraction integrating the active pool (h_a) and the stable pool (h_s).

For the highly recalcitrant coproducts with MRTs longer than the modeling timeframe, the Cr fraction (95%; Table 1) was considered virtually inert and was directly allocated into the stable pool as h_s (Fig. 2b), while the labile fraction was assumed to be entirely lost as CO_2 and no h_a was considered. For the less recalcitrant coproducts hydrochar, digestate, and bioethanol molasses, we assumed that the labile fraction (1-Cr; 17%, 32%, and 36%, respectively) was mineralized in the first year and the remaining recalcitrant fraction corresponded to h_a (here equivalent to Cr) and was fully allocated to the active pool (Fig. 2a). The derived h_a coefficient for the digestate (0.68) is close to the value of 0.65 proposed in Levavasseur et al. (2020). No reference allowing for similar comparison was found for the other studied coproducts. The adaptation of AMG for the bioeconomy is further detailed in SI1.4.

2.3.4 AMG output analysis

The difference in changes of SOC stocks between a given bioeconomy scenario and the BAU was determined based on Eq. 1.

$$\Delta SOC_{bio-BAU}(\%) = \frac{SOC_{fbio} - SOC_{fBAU}}{SOC_{fBAU}} \quad \text{Eq. 1}$$

where $\Delta SOC_{bio-BAU}$ (%) is the percent change in SOC by shifting from BAU to bioeconomy, SOC_{fbio} corresponds to the SOC stocks at the end of the simulation, f, (here f = year 100) for the bioeconomy scenario, and SOC_{fBAU} is the SOC stocks at the end of the simulation for the BAU scenario.

Positive values of $\Delta SOC_{bio-BAU}$ represent an increase in SOC stocks for the bioeconomy scenarios as compared to the BAU scenarios, while negative values reflect SOC losses from shifting to the bioeconomy.

For a given scenario (BAU or bioeconomy), the change in SOC stocks over 100 years was calculated as the final SOC stock minus the initial SOC, as shown in Eq. 2.:

$$\Delta SOC_{0-100_i}(\%) = \frac{SOC_{100i} - SOC_0}{SOC_0} \quad \text{Eq. 2}$$

where ΔSOC_{0-100i} (%) is the percent change of SOC stocks from the initial conditions (year 2020) until the end of the simulation (year 2120); SOC_0 corresponds to the initial SOC stocks and SOC_{100i} to the final SOC stocks (after 100 years), per scenario *i*.

The difference between the scenarios BAU and bioeconomy was calculated at a national scale as the total net SOC change for all the APCUs areas (Eq. 3).

$$Total national \Delta SOC net = \sum_i^j \left(SOC_{bio} - SOC_{BAU}\right)_j * PondCoef_{SU_j x APCU_i} * S_{APCU_i} \quad \text{Eq. 3}$$

Total national ΔSOC net (in t C) is the sum of the difference between the SOC stocks under the bioeconomy scenario and BAU scenarios at the year 2120 per SU, times the ponderation coefficient ($PondCoef_{SUxAPCU}$) of the SU surface in the APCU surface, times the surface of the APCU (S_{APCU}). The total APCU surface is 14.9 Mha but after the selection criteria in Module 1 and SI1.1, only 3.5 Mha were included in the SUs. $PondCoef_{SUxAPCU}$ corresponds to the weight of a SU area in each APCU and allows to scale the SOC change per SU to the APCU scale (j = identity of the SU within a given APCU, i = identity of the APCU).

2.5 Module 4: Sensitivity Analysis

SOC stock changes are influenced by the characteristics and amount of the carbon inputs (Keel et al., 2017). We performed a sensitivity analysis (SA) on the key parameters governing the amount of C returned to the soil contributing to SOC, namely Cc and Cr. As shown in Table 1, both Cc and Cr can vary within ranges conditioned by the process performance (itself depending on the specific process conditions) and the type of assay used to determine it (affecting Cr only). These ranges were retrieved from our review (Andrade et al. *submitted*). Here, we use the first and third quartiles of Andrade et al. (*submitted*) to set "low" and "high" levels for Cc and Cr, for all coproducts (Table SI1.2). Combinations of low, mean, and high Cc and Cr were tested, for a total of 8 new sets of Cc and Cr combinations per scenario.

Since the long-term recalcitrance behavior of biochar is poorly understood due to a lack of long-term experimental evidence in comparison to reported half-lifetimes ranging from decadal- to millennial-scales (Woolf et al., 2021; Zimmerman, 2010), an additional SA was performed on the procedure used to partition Cr within AMG SOC pools. It was performed for the pyrolysis scenario as a representative case of a highly recalcitrant EOM. In the initial method (section 2.3.3), we considered the recalcitrant fraction completely inert during the simulation and fully allocated it to the C_S pool. Yet, various studies suggest that the recalcitrant fraction may not be completely inert but follow a very slow decay rate (Han et al., 2020; Joseph et al., 2021). Therefore, an alternative partition of the recalcitrant fraction between C_A and $C_{S,}$was considered. To this end, we considered a remaining C fraction of 75% after 100 years, meaning that 25% of the initial C is mineralized during the timeframe (Andrade et al., *submitted*, Woolf et al., 2021). From the 25%, a fraction corresponds to a very labile fraction readily mineralized in the first year (4%) while the remaining corresponds to the mineralizable recalcitrant fraction which is allocated to the C_A pool to be slowly mineralized. More details are provided in SI1.5. The values for pyrochar covered those found in the literature and suggested by the IPCC (2019), which proposes that around 80% of C in biochar remains after 100 years for pyrolysis temperatures of 450–600°C. Table SI1.2 summarizes all the combinations explored for the SA.

An excessive application of biochar may be toxic for soil microbiota, which may reduce plant growth (Joseph et al., 2021) and increase CH_4 and CO_2 emissions (Zhang et al., 2020). To avoid this negative effect, a last SA was performed to explore the effects of exporting all the available harvestable crop residues followed by the return of a lower amount of coproduct than the generated. Accordingly, an extra scenario was modeled, limiting the soil application rate of pyro- and gaschar to not exceed a total of 50 Mg C ha^{-1} regularly applied over 100 years, as suggested by Woolf et al. (2010) to allow char storage in the soil and ensure positive or neutral effects on plant yields. The analysis of alternative storage options for the portion of char not returned to the soil is out of the scope of this work.

Finally, for occurrences where $\Delta SOC_{bio-BAU}$ (Eq. 1) was negative, the portion of retrieved residues from fields was decreased in steps of 25% from its initial 100% value until 0%. These iterations were performed only for scenarios showing negative $\Delta SOC_{bio-BAU,}$ to identify possible compromises between bioeconomy exports and SOC maintenance.

3. Results

3.1 BAU scenario

The BAU scenario predicted a potential decrease of the topsoil SOC stocks by a mean of 2% (Table 2) in the APCUs over 100 years, which represents a C loss of 18 Mt C at the French national scale. Approximately 63% of the simulated areas predicted SOC stocks decrease over 100 years, with a maximum decrease of 27% in some APCUs. APCUs with SOC stock increases may raise their levels by up to 85%, mainly in the Central and Western regions (Fig. 3).

3.2 Bioeconomy scenarios: 100% export over 100 years

Crop residues are already exported for other services in 10% of the areas, making them unavailable for the bioeconomy. Therefore, these areas did not present any change in the bioeconomy scenarios as compared to the BAU scenario. At the national level, the SOC building-up potential over 100 years of each bioeconomy scenario varies greatly; it ranges from − 34.9 (molasses) to 774.2 Mt C (pyrochar) (Table 2), a 22-fold difference, reflecting the importance of the coproducts' Cc and Cr parameters, among others.

The highest additional SOC storage, as compared to BAU, was observed for pyrochar application (+ 105.5%), while the highest SOC loss was associated with molasses return (-4.4%) (Table 2). It should be highlighted, however, that these decreases and increases are highly variable across the country (Fig. 4), reflecting the large variety of underlying pedoclimatic conditions and cropping practices. This applies for both the BAU (Fig. 3) and bioeconomy scenarios (Fig. 4). Among others, the Southwest of France tends to exhibit the largest SOC changes (both positive and negative) among the different scenarios, while the SOC changes in the northwest tend to be lower (Fig. 4, SI2).

The pyrolysis and gasification scenarios predicted enhanced SOC levels in all the APCUs after 100 years, with the highest potential for SOC sequestration in the Southwestern and Central regions (Fig. 4. a,c). For pyrolysis, SOC stocks increased by over 100% in 57% of the country (Table S2.1), with a national mean SOC stock increase of 105% (+ 774 Mt C, Table 2). For the gasification scenario a mean national increase of 43% (+ 316 Mt C, Table 2) was expected. In 85% of the modeled areas, the consecutive application of gaschar could potentially increase SOC stocks by approximately 80%, as compared to BAU (max + 178%) (Table S2.1; Table S2.4).

The return of hydrochar is shown to ensure soil C sequestration in 88% of the areas (Table S2.4), with a maximum increase of 4%. At national scale, this scenario represents an average SOC change of 1.1% and a total additional C storage of 8.9 Mt C (Table 2). Unlike pyrolysis and gasification, this scenario indicates potential C losses (up to − 1.8%). Digestate may contribute to build up SOC stocks in the North-central area of France, with predicted losses in the Southwestern and Northern regions. With digestate, SOC stocks are shown to slightly increase (max 0.8%) in 50% of the simulated areas (Table 2). Despite the potential SOC storage in this scenario, a mean loss of 0.1% in SOC stocks is expected at a national scale over the timeframe compared to the BAU scenario. For the molasses, the expected SOC stocks after 100 years are lower than in the BAU scenario by a mean of 4.4% at a national scale, representing a potential soil C loss of 35 Mt C (Table 2). The results indicate relative SOC reductions up to 14%, with the highest losses in the Southwest, Northern, and Northeast regions.

For the scenarios depicting SOC losses (i.e., HTL, AD, and 2GEtOH) exporting rates were re-adjusted (75%, 50%). Decreases in the exporting rates did not influence the overall percentage of areas affected (Table S2.1), thus no lower exporting values were tested. However, the export rate reduction resulted in a lower national SOC loss compared with the 100% export rate for all the remodeled scenarios (Table S2.2).

3.3 Sensitivity Analysis

The SA allowed to evaluate the uncertainty of the potential national SOC changes at the year 2120 to variability of the Cc and Cr coefficients relative to the mean coefficient value(Fig. 5).

For the pyrolysis scenario, the different combinations of Cc and Cr coefficients affected the additional SOC stocks ranging between − 29% and + 30%, equivalent to 549 Mt C and 1009 Mt C (Table S2.3), at a national level. An one-at-a-time (OAT) test showed the SOC results to be apparently more sensitive to Cc, ranging between − 25% and + 25%, while Cr ranged between − 6% and + 5%.

The additional SOC stocks for all the SA tested in the gasification scenario varied by -40% to + 36% from that obtained using the mean coefficients, equivalent to 187–431 Mt C. Cr variability contributed to SOC changes between − 6% and + 5%, while Cc alone affected the results from − 36% to + 30%. From these results, it is observed that Cc has the greatest influence on the pyrolysis and gasification scenario, one reason being the greater range of values compared to Cr (Fig.S4, Fig.S6).

For the low recalcitrance scenarios, the uncertainty of the coefficients caused results to vary from C losses to potential additional C storage. The HTL scenario result is affected by -4.8% to + 7.6%. High Cc values, for any given Cr, predict C sequestration in areas that would potentially lose SOC stocks with the mean coefficients. The opposite was observed for low Cc values, which resulted in SOC losses for all the APCUs (Fig. S7). Due to the diverse possible conditions of the HTL technology, the Cc coefficients in this scenario were tested for a broader range (0.12–0.45), which produced a higher effect for Cc than for Cr.

The national SOC change ranges from − 16 MtC to + 24 MtC for the different coefficients in the AD scenario, representing changes of -2 to 3%. The combination of high Cc and Cr resulted in SOC losses in only 0.2% of the simulated areas, compared to 40% for the mean values of the parameters (Table S2.1). Similarly, lower Cc and Cr values result in SOC stocks decreasing in all the areas (Fig S8). For the molasses scenario, the combination of maximum and minimum values of Cc and Cr represented a SOC stocks variation of -61–48% (Table S2.3) from the values obtained for the mean parameters, with losses observed in all the APCUs.

The Cr partitioning between the C_A and the C_S pools of AMG (Pyrolysis 2) resulted in cumulated additional SOC stocks of 617 Mt C compared to the BAU scenario, by the year 2120 (Table S2.2). This represents a difference of -21% in comparison to a 100% C allocation of the recalcitrant pyrochar to the C_S pool only, with variabilities in the SOC stock results ranging from − 39% to -10% for all the SA coefficient combinations (Table S2.3). Albeit the net additional C stored differed for the two Cr allocation methods, the trend observed was the same, with expected SOC increases in all the APCUs. For the Pyrolysis 2 scenario, 36% of the areas predicted SOC increases above 100% (Fig. S5).

If all the harvestable crop residues are exported for pyrolysis or gasification, but only 50 t C ha^{-1} are regularly recycled to the soils throughout the 100 years to avoid the toxic effects of excessive char application, no SOC decreases are observed as a result, on all the APCU.

Table 2
National 100 y SOC changes from BAU to bioeconomy ($\Delta SOC_{bio-BAU}$), in total Mt C and %, at an exporting rate of 100%, at year 2120. Values in % are provided as national averages of all APCUs.

Bioeconomy scenarios	**Total national $\Delta SOC_{bio-BAU}$**[b]	**Min**[d]	**Max**[d]	**Average national $\Delta SOC_{bio-BAU}$**[e]	**σ**[c]	**Min**[d]	**Max**[d]
	(Mt C)			**(%)**			
BAU[a]	-17.8	-0.1	0.1	-2.2	14.8	-27.0	84.9
Pyrolysis	774.2	0.0[f]	0.5	105.5	69.3	0.1	409.2
Gasification	315.6	0.0[f]	0.2	43.3	29.3	0.1	177.2
HTL	8.9	0.0[f]	0.0[f]	1.1	0.8	-1.8	4.1
AD	-0.8	-0.0[f]	0.0[f]	-0.1	0.4	-3.5	0.7
2G Ethanol	-34.9	-0.0[f]	0.0[f]	-4.4	2.9	-14.2	-0.0[f]
[a]BAU scenario corresponds to ΔSOC_{0-100}. Initial SOC stocks: 797 Mt C.							
[b]Sum of all the modeled APCUs							
[c]Standard deviation							
[d]Minimum and maximum $\Delta SOC_{bio-BAU}$ reported over all APCU							
[e]Average SOC change for all the modeled APCUs							

[f]Value is not zero. More decimals included in Table SI2.2

4. Discussion

4.1 Long term spatially-explicit co-products potential for SOC stocks

The business as usual (BAU) scenario reflecting current practices predicted a slight average decrease (2% for 100 years) of topsoil organic C in the simulated areas, which is consistent with the potential prolongation of average decreases in SOC stocks observed over the past decades in temperate croplands in France, Belgium and

Germany (Clivot et al., 2019; Goidts and van Wesemael, 2007; Meersmans et al., 2011; Steinmann et al., 2016). The simulated decrease is however lower than that of 14% obtained by Riggers et al. (2021) in German croplands with a multi-model ensemble for the same climate projection (RCP 4.5) and unchanged (current) C inputs for the 2014–2099 period. The BAU scenario predicted SOC losses in around 63% of all simulated areas (Fig. 3), which is in line with the trends observed in Launay et al. (2021), where SOC decreases on 55% of the simulated areas (STICS model) were observed after 30 years. The regional differences observed can be explained by the influence of the initial SOC stocks, climate, soil and cropping system characteristics.

Results differed considerably among the recalcitrance groups (high and low) because the adapted AMG allocates the recalcitrant C as inert for the highly recalcitrant coproducts whereas it is allocated to the decomposable active pool for the less recalcitrant coproducts. The steady state normally faced in the active pool is never attained in the stable one, allowing the high recalcitrant products to continue building up SOC stocks in the long-term.

In a C-neutral harvesting context, 100% of the harvestable crop residues can be exported for bio-oil or syngas production by pyrolysis or gasification, respectively. Pyrolysis results do compare to those of previous studies. For instance, Lefebvre et al. (2020) reported a 127% SOC increase in 20 years in sugarcane fields by replacing sugarcane bagasse and trash with the biochar produced. Woolf and Lehmann (2012) found that the export of 50% of maize residues for biochar production, with the subsequent addition of biochar to soils, can increase the SOC stocks by 30–60% over 100 y.

The AD scenario projected a negligible SOC stock increase (up to 0.7%) in in 50% of the modeled areas and small SOC losses (up to 4%) in the remaining 40% (the remaining 10% being areas where crop residues are already exported for other uses). Evidence suggests that anaerobic digestion does not modify the characteristics of the biomass stable C remaining in the digestate (Möller, 2015), thus the long-term effect on SOC stocks is often not significant. This was also reported in (Thomsen et al., 2013). Bodilis et al. (2015) observed a slight decrease in the SOC stocks after digestate application in French croplands, as compared to undigested biomass using AMG. On the contrary, Mondini et al. (2018) reported a 2-fold SOC increment after digestate application on Italian lands, compared to undigested crop residues using a modified version of RothC.

The difference between the raw and digested residual biomass lies in the labile C fraction. The removal of the labile fraction reduces CO_2 emissions from digestate compared to the raw feedstock. Besides C, bioavailable nutrients are concentrated in digestate, often in a form that is more assimilable for plants, which makes it an attractive fertilizer (Wentzel et al., 2015). Using digestate as fertilizer can offset the emissions incurred by mineral fertilizer production and application (Reibel, 2018), though excessive application could increase N emissions (ADEME et al., 2018). Areas depicting SOC decreases should therefore be analyzed in detail to determine whether other benefits (energy and nutrient recovery) are worth taking the risk of losing soil C.

The SOC stocks decreased in all the APCUs in the 2GEtOH scenario, which reflects the changed lignin condensation of the biomass exerted by the chemical and enzymatic treatments, allowing the soil microorganisms to decompose the coproducts at a faster rate (Bera et al., 2019; Cayuela et al., 2014, 2010). It is associated with increased microbial activity, which may improve fertility and plant growth (Alotaibi and Schoenau, 2011). Nevertheless, soil application of molasses has been associated with negative impacts on the soil characteristics (e.g., increased salinity and electrical conductivity) and increased GHG emissions in comparison to untreated biomass (Bera et al., 2019; Cayuela et al., 2010). Our results suggest to not exchange the crop residues provision to soils with bioethanol coproducts, if the objective is to prevent SOC losses. More research is required to understand the recalcitrance properties and C content of bioethanol coproducts and harness its potential as a soil amendment.

4.2 Crop residues potential for bioeconomy

In France, it is suggested to limit the harvest of cereal straw to leave a share of 41–96% of the technically harvestable residues on the soil, to preserve its agronomic functions (France Agrimer, 2020). Similarly, ADEME (2018) determined that by 2050, only 21% of crop residues could be mobilized for the specific needs of biogas production, due to agronomical soil functions and issues related to a competitive use. Our results suggest that these thresholds may be too stringent for a C-neutral harvesting context, even for anaerobic digestion, where a 75% harvest (and return) rate implies SOC losses below 1% in 37.5% of the areas (maximum loss of 2.6%, in 2.5% of the areas).

In fact, considering the results of this study, the harvest potential is 100% (of the technically harvestable feedstock not already used), unless the residues are to be used for bioethanol (0% removal). If, to be conservative, we consider export rates of 0% only in the areas where SOC losses are observed with anaerobic digestion and HTL, a reduction of the corresponding crop residue potential of 80% and 3% would be observed, respectively (based on 2021, where the non-exported harvestable crop residues totaled 30.4 Mt dry matter). Comparing this with the potential resulting from applying a generic 68.5% limit (middle of the above range suggested for France) of residues to be left on land, it involves that between 4 (anaerobic digestion) and 11 (pyrolysis, gasification) Mt dry matter of additional crop residues are obtained by applying our framework. This corresponds to 149–279 PJ y^{-1} (for a low heating value of 17.5 GJ t^{-1} DM), the equivalent of the gross electricity generation in Greece and Austria, respectively.

Current French cropping systems must increase the C inputs by 42% on average to reach the 4‰ target (Martin et al., 2021), while recent works predict a required increase of 283% for Germany (Riggers et al., 2021). However, a decreasing SOC stocks trend under a BAU scenario has been identified in this work and others (Launay et al., 2021; Martin et al., 2021). In this context, the management of crop residues, allowing to increase SOC stocks as in the biochar scenarios (pyrochar, gaschar, and hydrochar) and partially in the digestate scenario, are alternatives towards the 4‰ goals.

4.3 Strengths and limitations

The scarcity and high variability of data regarding the coproducts C recalcitrance, and the challenge of representing long-term effects on real environments based on short-term laboratory studies require caution in the analysis of the results. The main conclusions do not regard the absolute values predicted but the trends related to the sensitivity of the model to the parameters. We tested a wide range of plausible values for the key parameters, so the conclusions drawn for each technology can provide insightful decision support with regards to the crop residues potential for bioeconomy.

Our results partially show the bioeconomy cause effect link between the usage of the crop residues and its exporting potentials, with different long-term SOC stocks predictions among scenarios. Using coproducts as EOMs inputs to the soil are expected to modify soil physical, chemical, and biological characteristics in diverse ways. These soil changes can be i) altered net primary production (NPP) due to changes in the amount and quality of input C and nutrients, ii) addition of extra organic compounds to the soils, iii) soil microbiota adaptation to utilize the C in the coproducts (this C being structurally different to the one in plant residues) (Hansen et al., 2017; Oldfield et al., 2019). An excessive application of bioeconomy coproducts may alter soil functions which could in turn have some environmental impacts. Moreover, the C in the raw biomass is readily available while in the stabilized or recalcitrant matter the C may be unavailable for microorganisms, which could affect soil functioning and fertility. The SA demonstrated that the 100% of the crop residues can be exported to increase the bioeconomy provision while at the same time restraining the possible negative effects of biochar, by limiting the application, without affecting the SOC stocks.

Other limitations can be identified in the adapted model and the case studied herein. Changes in soil fertility induced by the coproducts addition were not considered, as well as the potential changes in soil structure and quality (Drosg et al., 2015; Joseph et al., 2021) due to limitations of the model. Besides, nitrogen dynamics (i.e., nitrate leaching and NH_3 emissions) and atmospheric emissions were not evaluated. It was beyond the scope of this work to analyze the overall life cycle effects of the different bioeconomy strategies (i.e. accounting for the substituted energy and products by the main bioeconomy products), here focusing on SOC changes only. Similarly, how to prioritize the distribution of each specific crop residues to each bioeconomy technology. These considerations, however, need to be assessed in future studies to have a holistic understanding of the environmental impacts of exporting crop residues for each technology.

The fine granularity of the simulation units assesses the differences among the French croplands, predicting spatially explicit SOC evolutions under each bioeconomy scenario. This approach allows locating areas where coproducts application can build up SOC stocks. Thus, the model can be used to provide advice for resources management for bioeconomy development in specific locations. The framework developed and the modeling approach can be replicated for other regions at different scales, even with less specific granularity to evaluate the development of crop-based bioeconomy technologies.

The future climate trajectory followed the RCP4.5, however, results may vary for different future climate trajectories. In fact, Mondini et al., (2018) modeled the SOC evolution of Italian croplands amended with 8 different EOMs under 12 different climate scenarios, reporting a coefficient of variation ranging from 1.2 to 4.3%. The present study considers unchanged cropping systems and crop yields throughout the 100 years. The impact of this hypothesis could be challenged in future work by e.g. using (ADEME et al., 2018) projections of cropping systems in France, namely one complying with the Factor 4 initiative, and another prolonging the current trends. Factor 4, a national strategy that aims to divide GHG emissions by a factor of 4 by 2050, envisions better agricultural practices and less livestock while the current trends would lead to higher yields for grass, cereal-, and oleaginous crops. These changes in the cropping systems may affect the SOC dynamics and the ability to export crop residues.

We assumed that all cover crops are maintained on soils and all temporary grasslands are exported, while currently ca. 50% of cover crops and 11% of temporary grasslands are being collected at a national scale for anaerobic digestion (ADEME et al., 2018). This surplus provision of digested feedstock may improve the results obtained for the AD scenario. Moreover, we only considered the changes in recalcitrance for the crop residues digested and not for the co-substrate used. Around 50% of the simulation units involve the presence of manurea besides other organic amendments which wthat could be co-digested, resulting in C inputs decrease but C recalcitrance improvements.

Finally, it should be noted that the SOC losses observed for hydrochar, digestate, and molasses could be compensated if coupled with other strategies, such as: i) redistribution of coproduct from areas showing increased SOC stocks, ii) introduction of specific cover crops, iii) changes in farming management, iv) mix of bioeconomy coproducts return. This was however beyond the study scope.

Conclusions

This study demonstrated that, to maintain long-term SOC stocks, the harvesting potential of crop residues is influenced by the process for which the biomass is destined and is spatially explicit. The partial return of the crop residues C to soils as stabilized coproducts was shown to maintain and even increase SOC stocks, in comparison to the levels achieved by just leaving the residues on soils, allowing to provide a greater amount of feedstock to bioeconomy. The study thus confirmed that current practices blindly limiting the potential of crop residues to a stringent threshold unfairly deprive the bioeconomy from an important amount of biomass.

Pyrochar and gaschar were shown, when used as soil C input in exchange for crop residues, to increase SOC stocks in all the French croplands modeled. The HTL scenario predicted SOC stocks increases for 87% of the areas, with a slight loss for the croplands located in the North. The results also indicated that minor SOC gains can be expected through exchanging raw residues for digestate, but only in 50% of the areas, while slight losses were observed on the remaining areas. On the other hand, exporting C from crop residues to be compensated with molasses return was shown to lead to clear losses of SOC stocks, on all areas.

By adapting the soil carbon model AMG to consider the recalcitrance of returned bioeconomy coproducts, this study provides an operational tool that can guide, for any region, future decisions on the use of crop residues for bioeconomy. However, more research is required regarding recalcitrance, especially of bioethanol coproducts and gasification char, for which studies are scarce and the understanding of the C stability and MRT effects on SOC evolution remain an issue.

Declarations

Competing interests: The authors declare no competing interests.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in "TBI - Toulouse Biotechnology Institute - T21018" at https://doi.org/10.48531/JBRU.CALMIP/WYWKIQ.

SUPPORTING INFORMATION

Supportig Information to this study is presented in the SI1 and SI2 files.

Statement: At this moment the work of Andrade et al. is submitted and under revision

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Figures

Figure 1

Spatially explicit modeling framework, as applied to France, to quantify the long-term SOC difference between crop residues left on land and their harvest for 5 distinct bioeconomy pathways, with return of the coproduct.

[a] Jamagne et al., 1995

[b] Based on Durand et al., 1993 after adaptation of Launay et al., 2021

[c] https://www.geoportail.gouv.fr/donnees/registre-parcellaire-graphique-rpg-2010

[d] Leenhardt et al., 2012

[e] http://agreste.agriculture.gouv.fr/enquetes/pratiques-culturales/2006

[f] http://agreste.agriculture.gouv.fr/recensement-agricole-2010/

[g] Graux et al., 2020

[h] Launay et al., 2021

[i] Mulder et al., 2016

[j] CNRM-CERFACS-CM5–CNRM/ALADIN 63. Model GCM / RCM – correction ADAMONT. Institution: Méteo-France/CNRM, http://www.drias-climat.fr/

PET: Potential Evapotranspiration

RP: Relative Carbon allocation coefficient for the agricultural product

RR: Relative Carbon allocation coefficient for roots

RS: Relative Carbon allocation coefficient for straw or any post-harvest residue

RE: Relative Carbon allocation coefficient for extra root material

BAU: Business as Usual

SOC: Soil organic carbon

STICS: Soil-crop model used in Launay et al., (2021)

DRIAS: Spatially explicit database for France projections of climate scenarios

SAFRAN: Spatially explicit database for France climate

Figures legend: Cylinders: database, parallelogram: data input, rectangle: process, rectangle with inner bars: process containing more processes, curved bottom rectangle: manually input data sets, rounded rectangle: output

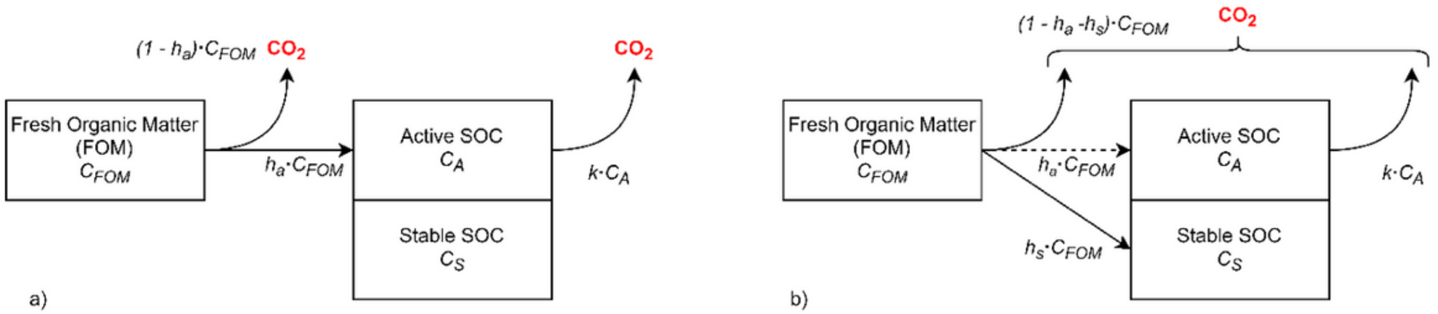

Figure 2

AMGv2 configuration implemented in this study (adapted from Clivot et al., 2019): a) AMG v2 (for all streams but pyro- and gaschar), and b) adaptation of AMGv2 (for pyro- and gaschar). FOM: fresh organic matter, C_{FOM}: carbon in the fresh organic matter, $h_a.C_{FOM}$: fraction of C_{FOM} allocated to the active pool C_A, $h_s.C_{FOM}$: fraction of C_{FOM} allocated into the stable pool C_S, h_a: retention coefficient integrating a fraction of FOM into the active pool, h_s: retention coefficient integrating a fraction of FOM into the stable pool, k: mineralization rate constant, dotted line: FOM fraction allocated to the active SOC pool (see section 2.5).

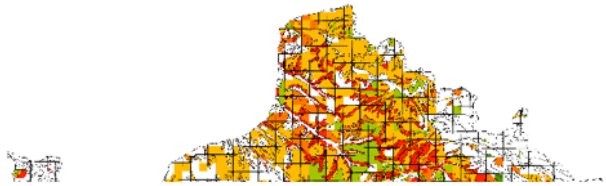

Figure 3

Predicted long-term soil organic carbon (SOC) stocks for the BAU scenario at year 2120

Figure 4

Spatially explicit soil organic carbon (SOC) stocks relative to the BAU scenario (year 2120) if the available harvestable crop residues are used for bioeconomy ($\Delta SOC_{bio\text{-}base}$ %) a) Pyrolysis (with C_S pool of AMG only; default), b) pyrolysis (with C_A and C_S pool of AMG; sensitivity), c) gasification, d) HTL, e) anaerobic digestion, f) lignocellulosic ethanol. White grids were not included in the simulations.

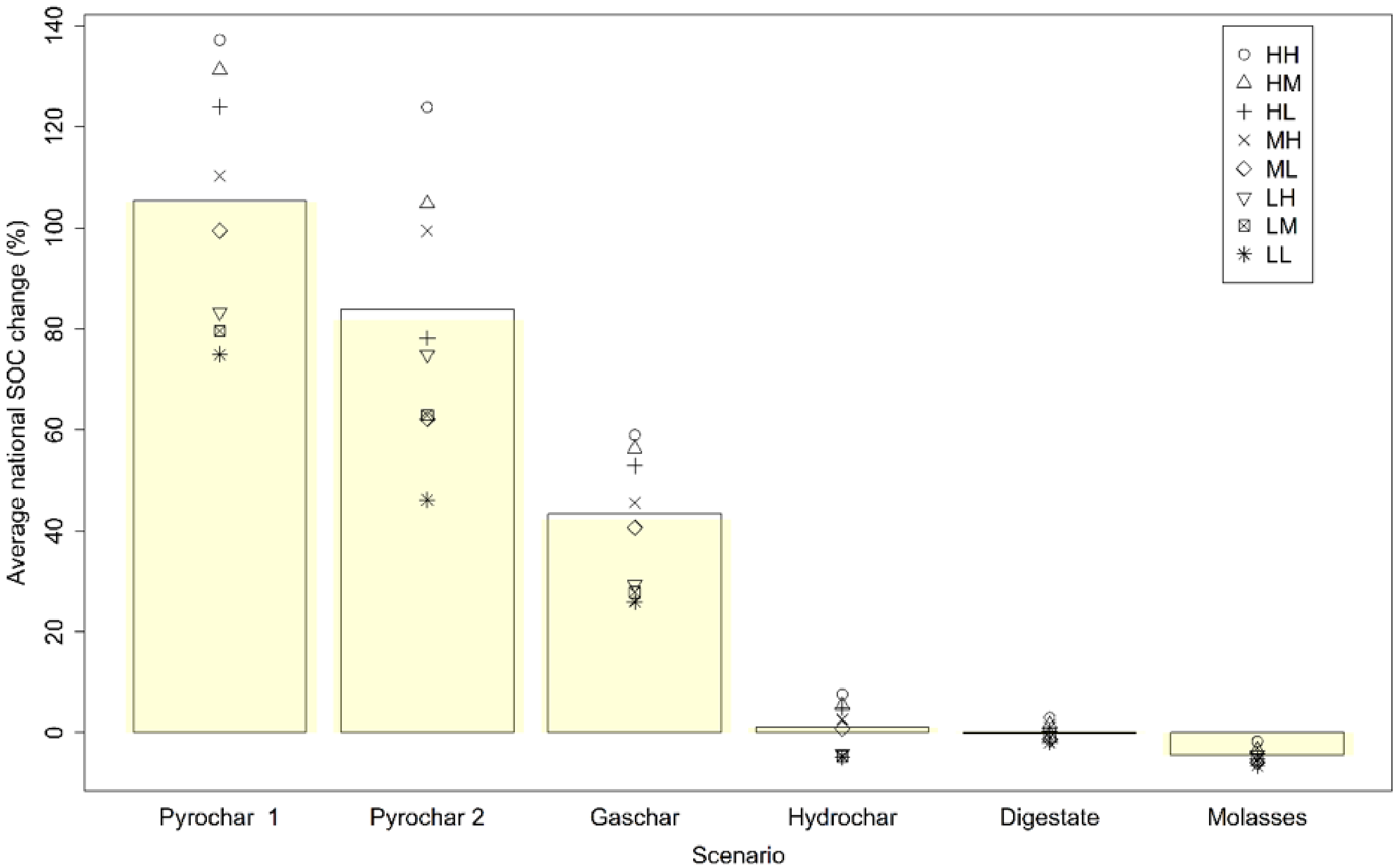

Figure 5

Sensitivity analysis describing a combination of low (L), mean (M), and high (H) Cc and Cr values for each bioeconomy scenario, with an extra scenario for pyrolysis (Pyrochar2) considering an alternative method to partition the recalcitrant fractions into SOC pools in AMG. The bars show the MM (Cc+Cr) value while yellow shades represent the average of all 9 points (SOC at year 2120; in comparison to BAU) for the different Cc and Cr combinations in a given scenario.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Andradeetal.CaseModelingSI1.pdf
- Andradeetal.CaseModelingSI2.xlsx