Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways

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Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways

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Abstract

Agricultural crop residues represent a significant part of the biomass potentially available for renewable energy systems. Sustaining soil organic carbon (C) is a common limiting factor applied to the biophysically available resource to determine crop residues potential for bioenergy. Studies quantifying this potential have so far largely considered crop biomass to produce renewable energy as being independent from the energy conversion pathway. However, the conversion method has great influence on how much C in crop residues can be returned back and retained in soils. Here, we applied the C-TOOL soil C model for two extreme conversion pathways of agricultural straw management in terms of C returned back to soils, using Denmark as a case study. Those were anaerobic digestion, involving the return of recalcitrant C to fields, and combustion, involving no C returns to agricultural fields. Danish agriculture was represented by six different soil-cropping schemes units on which our two extreme bioenergy pathways were modelled. We applied a premise that for a given geographical unit, the same long-term soil C level needs to be achieved under these extreme bioenergy scenarios; therefore, we identified how much straw could be removed from agricultural fields in each case while maintaining equal soil organic carbon (SOC) levels. We found that at the scale of the whole country, only 26% of the straw potential can be harvested for use in combustion to maintain in average long-term SOC at the same level as it would have been with the anaerobic digestion scenario. Thus, consideration for the biomass conversion pathway is important when identifying agricultural residue potentials for energy conversion while ensuring that SOC level is not compromised.

KEYWORDS
biomass potential, C-TOOL, energy conversion pathway, energy system analyses, soil carbon

1 | INTRODUCTION

In the search for fossil-free sources of carbon (C), biomass stands out as an attractive alternative C feedstock, and

agricultural residues are expected to play a major role for multiple bio-economy purposes (Bentsen & Felby, 2012; Elbersen, Startisky, Hengeveld, Schelhaas, & Naeff, 2012; Hamelin, Borzęcka, Kozak, & Pudełko, 2019) and for

sustainable bioenergy production (Larsen et al., 2017). Agricultural residues also play a major role in preserving long-term soil quality, in particular as they are a key input of C and other nutrients to the soils, with resulting impacts on net greenhouse gas emissions (Smith, Soussana, et al., 2019; Stockmann et al., 2013). Maintaining soil quality is essential for securing the needed increase in agricultural productivity to sustain food supply and sourcing the biomass needed for substituting carbon in fossil fuels for materials and energy (Keesstra et al., 2016). It thus becomes a key issue to identify and geo-localize how much of these residues can be harvested for sourcing energy systems and other parts of the bio-economy without compromising the long-term soil quality.

The challenge of recycling crop residues to maintain soil quality was acknowledged by Scarlat, Martinov, and Dallemand (2010) in a literature review on the sustainable removal rate of agricultural residues in Europe and North America (Scarlat et al., 2010). Their results suggested sustainable rates of residue removal that vary between 15% and 60% for cereal straw, 30% and 60% for sunflower straw and 30%–50% for rapeseed straw. Spöttle et al. (2013) determined a country-specific sustainable removal rate for some European countries, which varied between 33% for Hungary and 50% for France (Spöttle et al., 2013). Additionally, Haase, Rösch, and Ketzer (2016) established a residue removal restriction as a function of the soil organic carbon (SOC) in the topsoil in their high resolution study (1 km × 1 km grid cells) for five European regions (Haase et al., 2016). This translated to a fixed harvest limit corresponding to 20%–60% of the total residues; the lower limit was for topsoil with less than 2% SOC content. Monforti et al. (2015) simulated scenarios for the whole of Europe until 2050 with future climate projections using the same spatial resolution as Haase et al. (2016), and they reported that the maximum sustainable residual removal potential was in average 43% of the theoretical potential while preserving the soil C levels of 2012; however, this sustainable rate of residue removal varied among EU regions (Monforti et al., 2015). Based on simulations with the CENTURY model, Scarlat, Fahl, Lugato, Monforti-Ferrario, and Dallemand (2019) recently estimated the average annual sustainable potential of available agricultural residues

at ca. 149 Mt DM over the whole of Europe. However, their simulations of SOC stocks (excluding pastures) showed that SOC tended to decrease in some regions, even without crop residues removal. In these regions, leaving all crop residues on land was shown insufficient for improving or even maintaining SOC, and the authors concluded that additional analyses and measures are needed to improve SOC stocks while considering agricultural residues as an energy source (Scarlat et al., 2019).

Although these studies represent notable advances in acknowledging the importance of identifying a limit to the amount of harvestable agricultural residues, they suffer from critical shortcomings. A major shortcoming of previous studies is that the agricultural system, and thus the harvestable amount of agricultural residues and subsequent effect on soil quality, is treated in isolation from the biomass conversion systems. However, the amount of agricultural residues that can be harvested without compromising soil quality evidently depends on the conversion pathway for these residues. Some pathways will in fact imply a return of a significant portion of the C and nutrients (e.g. nitrogen [N], phosphorus and potassium) in residual biomass to the soil, while others, as we detailed in this study, imply no return of the C and nutrients to cultivated soils. Moreover, the nature of the organic C returned from some conversion pathways, notably anaerobic digestion for biogas conversion, is changed towards being more resistant to decomposition, and it may thus be retained in soils for longer time than fresh crop residues (Thomsen, Olesen, Henrik, Sørensen, & Christensen, 2013). Figure 1 illustrates the carbon flows from alternative energy conversion pathways of agricultural residues and their inputs to soil C.

In the transition towards renewable energy, energy system experts and decision-makers strive to optimize the energy system design and the use of renewable feedstock (Breum et al., 2019; Capros et al., 2016). Future energy mix studies (Bentsen, Nilsson, & Larsen, 2018; Venturini, Pizarro-Alonso, & Munster, 2019) display a variety of system design scenarios, including some highly bioenergy dependent ones. Yet, all these scenarios assume a static quantity of agricultural residues available for the energy system—independent of how the resource is handled subsequent to the energy conversion.
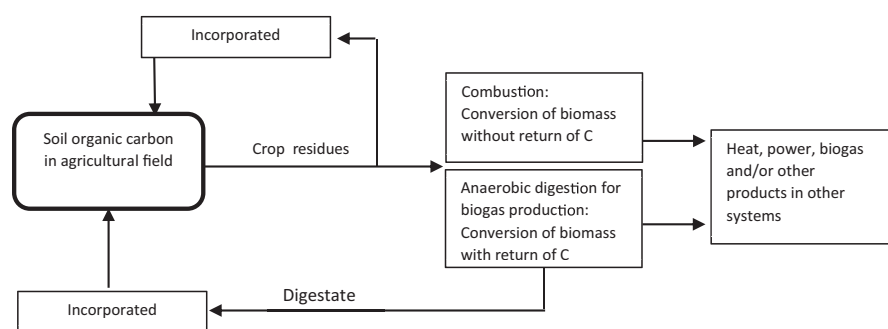

FIGURE 1 Agricultural crop residues can be incorporated directly in the soil or used in different energy systems. Some conversion pathways (here anaerobic digestion) will imply a return of C to the fields while others (here combustion) will not

Hence, there might be a significant difference in how much agricultural crop residue is available for energy use, if SOC maintenance is considered among the optimization criteria.

In this study, we hypothesize that the type of energy conversion pathway greatly influences the long-term SOC content of agricultural soils. We further assume that an additional objective of the bioenergy policy must be to ensure that SOC content is maintained by returning a sufficient amount of C through organic residues to the soil. Therefore, we aim to uncover whether the objective of ensuring a certain long-term SOC level should inherently be decisive for how much straw can be sourced from agriculture for energy production.

For that, we considered a case study for the harvest of crop residues involving two energy conversion pathways, that is, two extreme approaches in terms of the carbon returned to the soils: (A) high C return bioenergy strategy conversion where crop residues are used for biogas production (with return of C in the digestate) to agricultural soils and (B) zero C return bioenergy strategy conversion where crop residues are used for combustion, whether to produce heat or combined heat and power. These were selected as extreme cases to illustrate our methodological approach. Other examples of C return bioenergy strategies could have been selected, such as bio-oil production from pyrolysis with the return of biochar to soils or bio-ethanol production with the return of the molasses co-product to soils (Smith, Nkem, et al., 2019; Tonini, Hamelin, & Astrup, 2016), etc. Thus, our focus was on the agricultural field and the differences induced by bioenergy strategies in terms of long-term SOC content of soils, whereas understanding the implications of the energy services produced was outside the scope of the study. In other words, we focused only on exploring the unexplored causal link between the bioenergy use of crop residues and long-term SOC levels of agricultural fields. Similarly, the purpose of the study was not to identify a threshold limit of SOC to maintain for a sustainable long-term agriculture. Such thresholds are complex to define and depend among other aspects on soil type, cropping system and climate (Merante et al., 2017).

To address the above-mentioned hypothesis and pursue the aim of the study in a concrete real-life location, the geographical scope was confined to one national case study with high data availability, namely Denmark, using the whole of Denmark and detailed geo-localized data on Danish soil types (clay content), farm types (pig farms, cattle farms, cash crop farms and other) and cropping schemes. Finally, the long-term temporal scope was chosen to 300 years. This duration was considered necessary for exploring the quite slow developments towards steady-state SOC balance and yet sufficient to reveal the difference between the reached steady-state conditions in the scenarios being compared.

2 | MATERIALS AND METHODS

The study applied a carbon modelling approach to the case of straw management for agricultural fields in Denmark. The carbon flows considered are illustrated in Figure 1. The actual crop distribution in Denmark for 2014 on three soil types (Adhikari, Minasny, Greve, & Greve, 2014; Taghizadeh-Toosi, Olesen, et al., 2014) was used as the basis for defining the available straw potential for bioenergy. The analysis was constrained to two farming systems, namely arable (cash crop) and pig farming, since these were the only cropping systems considered to have available excess straw for bioenergy (Taghizadeh-Toosi & Olesen, 2016), that is, not already demanded for other purposes. A total of six soil–farm combinations, or units, were therefore considered. Two different bioenergy scenarios were tested: (A) a high C return bioenergy scenario, where carbon in the anaerobically digested straw is returned to agricultural soils as digestate and (B) a zero C return bioenergy scenario with combustion of straw and thus no return of carbon to soils. Scenarios are compared for their long-term SOC stock, here defined as 300 years. To achieve equivalency in the SOC stock after 300 years, the long-term SOC for Scenario A was established for six representative soil–farm combinations found in Denmark, and the amount of straw that could be removed in Scenario B to achieve a similar long-term SOC was calculated by iteration. It must be noted that those scenarios do not represent the current straw and manure management practices in Denmark. Thus, the current agricultural practice includes mostly field application of manure as raw manure, although approximately 20% of manure is currently digested. There is currently little straw used for anaerobic digestion, but a sizable fraction of the straw is used for combustion (Bentsen et al., 2018).

2.1 | Soil carbon modelling

The SOC modelling was performed with C-TOOL (Taghizadeh-Toosi, Christensen, et al., 2014). As plants grow and absorb atmospheric C through photosynthesis, they produce a main harvestable yield (e.g. grain, seed, tuber), and a second harvestable part (e.g. cereal and oilseed straw). They further generate non-harvestable aboveground biomass (e.g. chaff, leaves, stubble and the straw that cannot be picked up by the harvesting machinery) and non-harvestable belowground C deposition (e.g. root and rhizodeposition). This repartition of C among these various crop parts is illustrated in Figure 2. In addition to the main crops, cover crops (sometimes also referred to as catch crops) were also included in the model, as Danish regulations require that cover crops are included in the crop rotation to reduce nitrate leaching. Cover crops (e.g. perennial ryegrass, oilseed radish) are grown to capture soil mineral N during the autumn period and are typically left unharvested.

An added effect of cover crops is that they contribute with organic matter input for the build-up of aboveground and belowground soil C (Figure 2) and also add organic N through biological N-fixation, if the cover crop includes legume species (Li, Petersen, Sørensen, & Olesen, 2015). Similarly, the C share of animal manure applied to soil (Figure 2) as organic fertilizer is an additional C flow considered in this study, whether in its raw or digested form.

C-TOOL simulates medium- to long-term changes in SOC content of agricultural soils. Figure 3 summarizes the SOC flows in C-TOOL. The model is described in detail in Taghizadeh-Toosi, Christensen, et al. (2014), and summarized herein. The model consists of three conceptual C pools in topsoil and subsoil, that is, C in fresh organic matter (FOM), carbon in humified organic matter and C in resilient organic matter. Carbon is endogenously modelled to move between the pools through decomposition and vertical transport down through the soil profile. Decomposition of SOC follows first-order reaction kinetics and depends on temperature and clay content. Through SOC decomposition, C is respired as carbon dioxide (CO_2).

The C input within C-TOOL is the annual amount of plant-C added to the topsoil and subsoil and manure-C added to the topsoil. C-TOOL handles the difference in decomposition rate of partly decomposed biomass (e.g. manure that is stored in slurry tank) by distributing a share of the C input directly to the humified organic matter pool (while the rest goes to the FOM pool; Figure 3; Taghizadeh-Toosi, Christensen, et al., 2014). Here, about 12% of C for normal raw (i.e. non-digested) manure is used that goes to humified pool. Besides the annual C input to soil, the model in C-TOOL requires information on soil clay content, C/N ratio of the soil and initial C content. Table 1 shows the values used for the three soil groups included in this study. We assumed no difference in these parameters across farming types (arable and pig farms).

For tractability reasons and to focus on the significance of the carbon return flow differences only, the initial soil C level was set to 1.5% for all soil types, the common C content of agricultural soils in Denmark. This further allows to simplify the model to focus on the significance of the differences in carbon return flows between the scenarios without too much interference with other variables. The initial soil parameterization for C-TOOL was based on Taghizadeh-Toosi and Olesen (2016). The C-TOOL model further requires input of average monthly air temperature, since the decomposition of organic carbon depends on temperature (Taghizadeh-Toosi & Olesen, 2016). The applied temperature dataset was taken as the average monthly temperature for Denmark for the period 1986–2005. These temperatures were increased by 1.3°C to reflect the increased temperatures by 2041–2060 under CMIP5 RCP4.5 (Jacob et al., 2014). This was not performed to study the effect of a changing climate on the SOC dynamics, but as an attempt to feed realistic input data into the model (likely more realistic than no change of temperature).
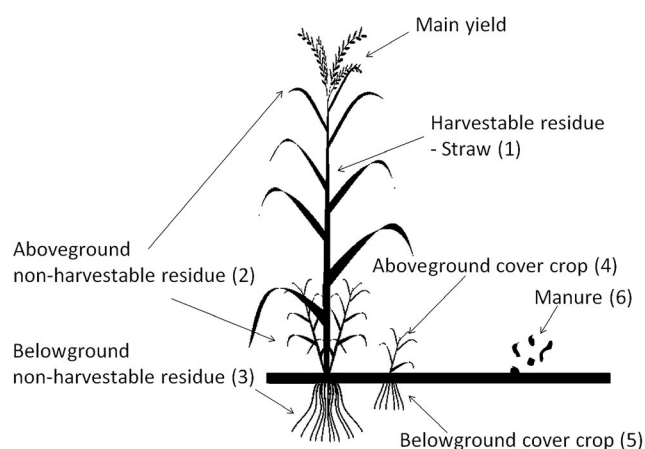

FIGURE 2 Key carbon plant compartments and inputs to soil included in the current analysis

TABLE 1 Soil parameters used for the parametrization of the model[a]

Soil type	Clay (%)	C/N ratio	Initial SOC (%)	Bulk density (Mg/m³)
Sand	5.0	13.6	1.50	1.42
Sandy loam	12.5	10.9	1.50	1.52
Loam	17.5	10.7	1.50	1.62

[a]Soil clay and carbon percentages and bulk density are based on dry weight (Adhikari et al., 2014; Taghizadeh-Toosi, Olesen, et al., 2014).
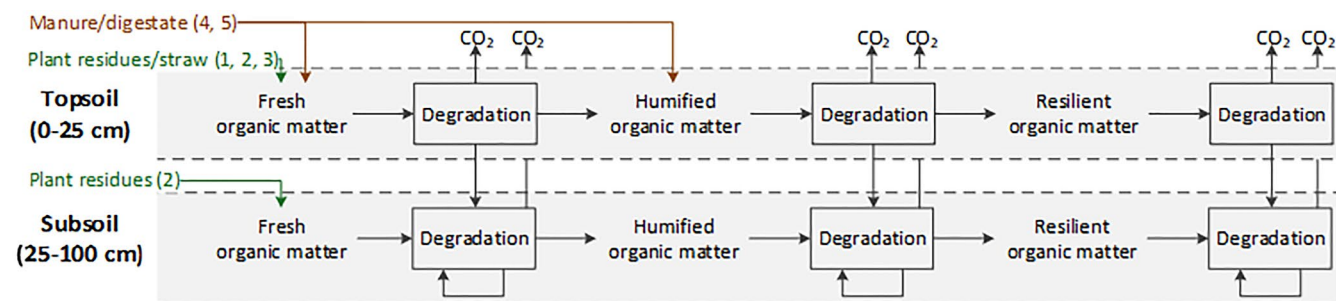

FIGURE 3 Soil organic carbon dynamics as modelled in C-TOOL. Numbers 1–5 refer to Figure 2

FIGURE 5 Representation of the six field units included in the study with the area they cover

TABLE 2 Crop rotations considered for the six field groups (from Taghizadeh-Toosi & Olesen, 2016)

Soil type	Year	Arable farm	Pig farm
Sand	1	Winter wheat	Winter oilseed rape
	2	Spring barley[a]	Winter wheat
	3	Spring barley[a]	Winter wheat
	4	Potato[a]	Spring barley[a]
	5	Spring barley	Spring barley[a]
Sandy loam	1	Winter wheat	Winter oilseed rape
	2	Sugar beet[a]	Winter wheat
	3	Spring barley	Winter wheat
	4	Winter wheat	Winter wheat
	5	Winter wheat	Spring barley[a]
Loam	1	Winter wheat	Winter oilseed rape
	2	Sugar beet[a]	Winter wheat
	3	Spring barley	Winter wheat
	4	Winter wheat	Winter wheat
	5	Winter wheat	Spring barley[a]

[a]The cover crop is incorporated in the soil in the same year as the main crop.

Fields associated with pig farming are considered to receive the maximally allowed pig manure inputs under Danish regulations, reflecting common practice in Danish pig farms. Pig manure is assumed to be handled as a liquid slurry, and very little straw is used in these manure management systems. It was assumed that manure was the only N source for these fields, and the amount of manure applied was therefore determined by the Danish N regulation for 2013–2014 (Plantedirektoratet, 2014), which specifies an N quota according to the type of crop and soil cultivated. Pig manure applied as slurry with 5.2% dry matter (DM), 3.97 kg N/Mg and 0.45 kg C/kg DM was considered, based on the Danish manure standard (Poulsen, 2013).

The crop rotations considered (Table 2) imply that straw is only produced from cereals and oilseed rape. Residues from potato and sugar beet were considered incorporated to the

soil, which is standard farm practice. An average straw DM content of 85% and a C content of 45% of the DM was used. The calculation for the yearly partition of C to the topsoil and subsoil for these six combinations of soil and farm types was based on the methodology presented in Taghizadeh-Toosi, Christensen, et al. (2014), based on allometric relations of C assimilation in aboveground and belowground crop parts. The crop yields that form the basis for these calculations were based on standard yields per crop group (Plantedirektoratet, 2014).
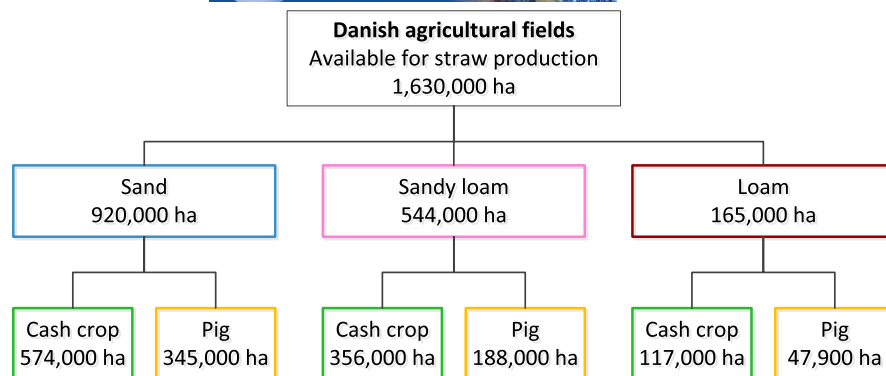
2.4 | Biomass scenarios and modelling rationale

Two ways of utilizing straw for energy in Denmark were compared:

1. Scenario *A* (high C return bioenergy strategy): All harvestable straw from a given field unit is used for anaerobic digestion to produce biogas, involving the partial return of the straw-C in digestate to the soil.
2. Scenario *B* (zero C return bioenergy strategy): All harvestable straw from a given field unit is used for combustion to produce heat and/or heat and power, without return of C to the soil.

In Scenario *A*, it was assumed that 60% of straw-C was converted to biogas (Hamelin, Naroznova, & Wenzel, 2014), implying that 40% of straw-C remained in the digestate and returned to the soil. For the pig farm, manure was considered to be applied in a digested form over the 300 year scope, considering that 50% of manure-C was converted to biogas (Hamelin et al., 2014). Though in practice, straw and manure are co-digested (which results in one digestate), the application of digestate was here modelled separately for each substrate, that is, as the C-portion stemming from straw digestion (here 153 kg C in the digestate per Mg fresh straw input to the digester) and the C-portion stemming from manure digestion (here 12 kg C in the digestate per Mg fresh manure input to the digester).

Most SOC models were developed in a time where the return of C inputs to soils from bioenergy pathways was not yet a concern. Therefore, C-TOOL, as most SOC models, does not directly allow to represent the potentially enhanced recalcitrance of digestate-C. However, as earlier described, C-TOOL can and does account for the difference in recalcitrance between raw manure and biomass, which here artificially distributes 12% of the C from manure inputs directly to the humified organic matter pool (while the rest goes to the FOM pool). To incorporate this effect for straw- and manure-digestates, the experimental results obtained by Thomsen et al. (2013) were used. They compared the C retention in soils for fresh and digested substrates. Thomsen et al. (2013) found that soils could retain 14% and 12% of the C after 20 years of incorporating feed/faeces and digested feed/faeces, respectively, based on the original C in the feed (Thomsen et al., 2013). Iterations were run in C-TOOL to determine the fraction of straw- and manure-digestates that should be considered for the amount of C being put directly in humified C pool to reproduce the results of Thomsen et al. (2013), considering the specific experimental conditions reported by the authors (e.g. clay content of 8%). Through this procedure, this fraction was found to be 36.7% for manure-digestate and 26.0% for straw-digestate.

In Scenario B, the harvestable straw from the field is not returned in any form; hence, only a certain portion of the straw can be removed so that the soil maintains the same C content as in Scenario A over 300 years. Quantifying this portion under a variety of representative field units is in fact the overall objective of this study.

Figure 6 illustrates the modelling rationale used to this end. It presents the retention of C from one hectare of winter wheat straw (1.8 Mg C/ha) on a loamy soil, over 300 years. The figure only presents the fate of the added C (C is added only once, namely at year 1) and not that of the existing SOC. Figure 6 shows that over time, the C from straw incorporated in the soil at year 1 is decomposed, and most of its C is emitted as carbon dioxide (CO_2) and lost from the soil (blue curve). When the same amount of straw is first harvested, then used for biogas as in Scenario A and partly returned as digested straw (orange curve), the C input to the soil at year 1 is significantly lower (0.71 Mg C/ha), since a part of the C is converted to biogas. As time progresses, however, the difference becomes smaller, because of the enhanced recalcitrance of the digestate-C returned to the soil. After 300 years, the difference between the curves is small, albeit non-null.

To ensure system equivalence between Scenarios A and B, the long-term SOC level of Scenario B must be kept equal to Scenario A. This rationale is used to determine how much straw can be removed in Scenario B. The black dotted curve of Figure 6 is obtained after iterations in C-TOOL and illustrates the amount of straw to incorporate in Scenario B to reach a SOC level almost equal, after
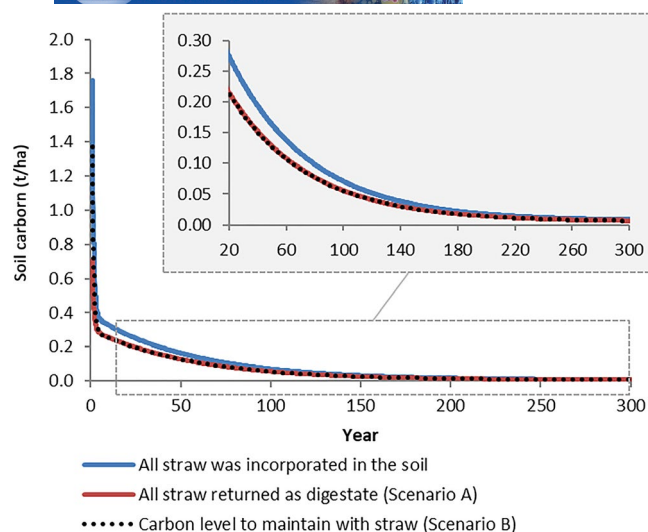

FIGURE 6 Simplified representation of the iterative modelling approach used: long-term soil C development following various winter wheat straw management in year 1, as modelled with C-TOOL. *Full blue curve*: all straw is incorporated; *Full orange curve*: all harvestable straw is used for biogas production, with the resulting digestate fully returned to the soil (Scenario A); *Dotted black curve*: the minimal amount of straw-C to incorporate at year 1 in a zero C return bioenergy conversion pathway such as combustion (Scenario B) to match the long-term soil organic carbon level of Scenario A

300 years, to the level of Scenario A. In the example shown here, 1.37 Mg C/ha of straw-C must be incorporated in year 1 in Scenario B to obtain a similar long-term SOC content as for Scenario A.

This logic was applied to the more complex systems modelled in this study, that is, based on the six soil–farm units considered (Figure 5; Table 2), the co-input of manure-C and considering the initial SOC content (Table 1). In other words, for each of the six soil–farm units considered herein, the amount of straw harvested in Scenario B was, through the use of C-TOOL, iteratively changed in order for Scenario B to match, at year 300, the SOC level of Scenario A. Therefore, the simulations were stopped when the difference between the SOC level of the two scenarios was less than 0.05% for the last 5 years of simulation.

3 | RESULTS

The current study modelled and compared extreme alternative pathways (Scenario A: biogas; Scenario B: combustion) for using straw for bioenergy production with regard to the amount of straw-C being returned to soils. The vision was to determine the maximal amount of straw that could be harvested for bioenergy in Scenario B to achieve the same long-term SOC as for Scenario A. The proportion varied between the various soil–farm units studied, but overall only 26% of straw could be removed for combustion (Table 3), showing that the

TABLE 3 Average annual straw potential (fresh weight with dry matter content of 85%) available for energy production on the six soil–farm groups included in the study under the condition that SOC remains the same in both scenarios. The last column (*B/A*) shows the percentage of straw available for energy use in Scenario *B* without C return to soil, for maintaining the same SOC level as in Scenario *A* with a partial return of straw-C as digestate

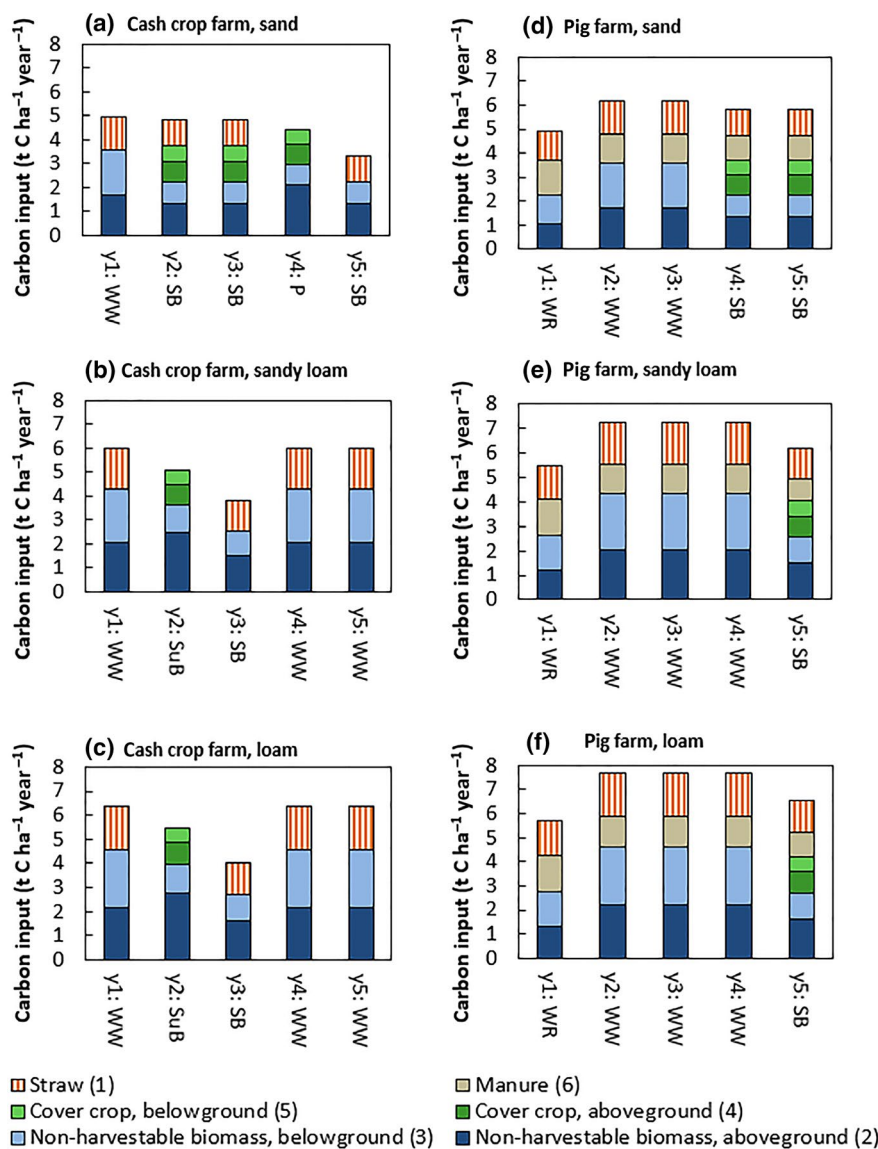| | | | Scenario | | | | |
| | | | *A* (with C return) | | *B* (without C return) | | *B/A* |
Farm type	Soil type	Total area (1,000 ha)	Mg ha^{-1} year^{-1}	Mt/year	Mg ha^{-1} year^{-1}	Mt/year	(%)
Arable	Sand	574	2.44	1.40	0.33	0.19	14
	Sandy loam	356	3.29	1.17	0.69	0.25	21
	Loam	117	3.50	0.41	0.84	0.10	24
Pig	Sand	345	3.23	1.11	1.05	0.36	32
	Sandy loam	188	4.01	0.76	1.67	0.31	42
	Loam	48	4.25	0.20	1.85	0.09	43
Total		1,628		5.05		1.30	26

FIGURE 7 Inputs of organic carbon to soil for the six field groups (a–f) related to the 5-year crop rotation applied in this study, prior to any straw harvest (P, potato; SB, spring barley; SuB, sugar beet; WR, winter oilseed rape; WW, winter wheat). Inputs related to main crop and cover crop are divided between aboveground and belowground inputs. Manure-C inputs consider raw manure

bioenergy conversion pathway plays a major role in shaping the bioenergy potential of agricultural residues, if maintaining long-term SOC is a sustainability decision criteria.

The estimated C inputs to soils in the six soil–farm units considered are shown in Figure 7. Crop yields were typically higher on loamy soils than on sandy soils, in particular for winter wheat. Carbon inputs from harvestable and non-harvestable crop residues were therefore higher on loamy soils (Figure 7). In general, autumn sown crops have greater yield and overall higher biomass production than similar spring sown crops because of their longer growth period. The amount of harvestable straw depended on the crop and soil type and varied between 1.09 and 1.79 Mg C ha^{-1} year^{-1}. The lowest straw production (and overall soil C input) was seen for spring barley on sandy soils, whereas the highest straw production was observed for winter wheat on loamy soils. In the years when cover crop was included, an extra C input of 1.5 Mg C ha^{-1} year^{-1} was added (Figure 7). On pig farms, manure as a C input constituted an input of 0.81–1.52 t C ha^{-1} year^{-1}. As shown in Figure 7, the proportion between straw (or harvestable aboveground residues) and the non-harvestable aboveground residues is comparable in all six soil–farm units, straw representing between 45% and 53% of the aboveground carbon.

4 | DISCUSSION

4.1 | Straw potential for bioenergy production involving no C returns to soils

The crop rotation as influenced by soil and farm type had some consequences for the potential of straw-C return to the soils. This is related to the nature and quantities of overall C inputs to the soil, including C inputs from roots, cover crops and manure, as shown in Figure 7. Table 3 shows, for the whole of Denmark, the available potential of straw for energy production calculated for each of the six field units in scenarios *A* and *B*, while Figure 8a,b illustrates the geospatial distribution of the straw potential in scenarios *A* and *B*.
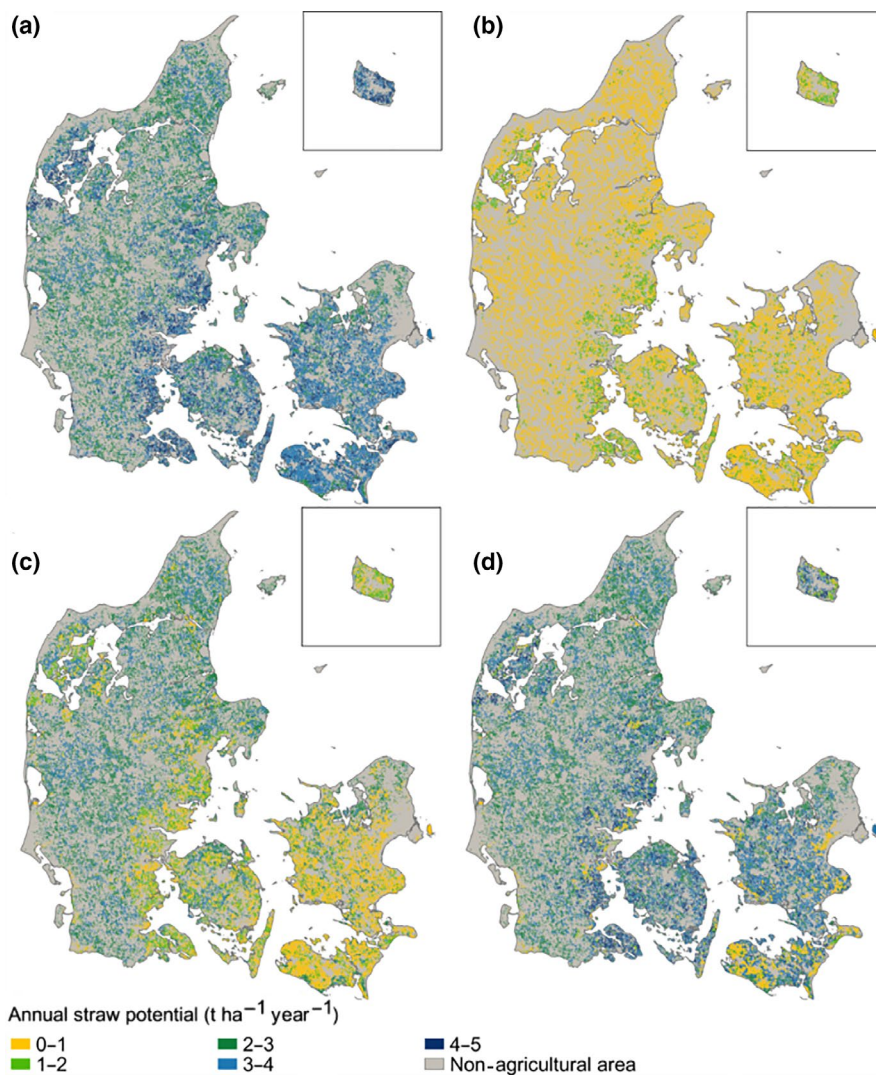
FIGURE 8 Spatial distribution of the annual straw potential for arable and pig farms in Denmark. (a) Scenario *A* (corresponds to all harvestable straw). (b) Scenario *B*—all soils must meet same soil organic carbon (SOC) as Scenario *A*. (c) Scenario *B*—sandy soils do not need to meet the same SOC as Scenario *A*. (d) Scenario *B*—sandy soils and sandy loams soils do not need to meet the same SOC as Scenario *A*

Annual straw potential (t ha^{-1} year^{-1})
- 0–1
- 1–2
- 2–3
- 3–4
- 4–5
- Non-agricultural area

As Table 3 illustrates, the additional manure-C input from pig farms, compared to arable farms, significantly influenced the difference in harvestable straw between scenarios *A* and *B*. For arable farms, the harvestable straw potential in Scenario *B* was estimated to be only 14%–24% (depending on soil type) of the potential in Scenario *A* for maintaining the same long-term SOC level. For pig farms, it was nearly twice as much, where 32%–43% of the harvestable straw could be removed in Scenario *B*, depending on soil type. This was mainly due to the return of C in manure on the pig farms, which allowed more straw removal from the system. Therefore, the higher the total input from other sources than straw, the smaller the significance of straw-C return after energy conversion.

Our modelling premise implies that all soil–farm units should, in Scenario *B*, meet the same long-term SOC level as Scenario *A*. Yet, this may be seen as too stringent. In fact, a previous study on the variability of SOC in Denmark between 1986 and 2009 (Taghizadeh-Toosi, Olesen, et al., 2014) showed a tendency for SOC on sandy soils to increase over time, as opposed to SOC on loamy soils that decreased over time. It was concluded to be due to the coinciding fact that grasslands and dairy farms were more abundant in the western parts of Denmark, where most of the sandy soils are located, and arable and pig farms are located in the eastern part of Denmark, where soils are dominated by sandy loam and loams. On the basis of this particular national context, it may be here considered that units on sandy soils can be little affected by eventual C returns from straw, if excess organic matter from the dairy farms are distributed to the arable and pig farms on these soils. In addition, soils with low clay content have less need for C input to meet requirements for suitable soil structure (Jensen et al., 2019). Therefore, all straw from these soils could be harvested without the obligation to match the long-term SOC observed when straw-C is partly returned to soils as digestate. This is shown in Figure 8c, which raises the total national potential of Scenario *B* by ca. 3-fold, namely from 1.30 to slightly above 3.0 Mt fresh straw per year. Extending this logic to sandy loam soils, the potential could reach up to 4.6 Mt fresh straw per year (Figure 8d) for Scenario *B*, which would then represent 90% of Scenario *A* potential.

It should be emphasized that these results consider an initial SOC concentration of 1.5% for all soils (Table 1), set for tractability reasons as earlier explained. In practice, the range of SOC concentrations could be between below 1% to more than 4% C all over Denmark (due to previous land use and soil management). Initial soil C concentration could have an overriding effect on the simulated scenarios of soil C contents; the lower initial SOC concentration level the higher SOC accumulated (Peltre et al., 2016). Yet, this would similarly affect both scenarios *A* and *B*. In consequence, although the absolute total straw potential in Scenario *A* or the potential of straw removal in Scenario *B* could be affected, the relative result at the national level, namely that only ca.

26% of the harvestable straw should be removed in Scenario *B*, is not likely to be significantly affected. Moreover, this effect is presumed to be negligible over the long time scope selected in this study.

4.2 | Implications for sustainable biomass use

Our results indicate that it would be possible to harvest four times more straw for energy conversion when using it for biogas with return of the residual, recalcitrant C in digestate, compared to using straw for energy conversion without any residual C return to the soil. In this study, we used the example of straw for biogas. Another possibility would be to pyrolyse the straw into a bio-oil fuel, while returning the C-rich biochar to soils, this C being potentially even more recalcitrant than the one from the digestate (Nguyen, Hermansen, & Mogensen, 2013).

Bioenergy pathways have a range of associated consequences on global environmental impacts or local ecosystems, spanning from effects on climate change, land use changes, to soil quality, which are not addressed here, being outside the analytical scope. However, our analyses do show that the energy conversion pathways without C return imply a much lower straw potential than pathways with C return to soils, in the perspective that both strategies should have the same long-term SOC level. In the perspective of greenhouse gas neutrality as, for example, announced by the European Green Deal, this implies that a much higher whole-system demand for the other non-fossil C-resources is then likely to be induced when selecting bioenergy strategies that do not return straw-C to soils.

Similarly, the identification of a specific sustainable threshold to be targeted for straw removal from agricultural lands in Denmark was not an objective of this study, which only focused on the long-term SOC content. In fact, even small changes in SOC can have disproportionally large impacts on soil quality and physical properties, such as aggregate stability and water infiltration rate, and these were not considered here. Nonetheless, our analysis of the interaction between long-term SOC and the type of bioenergy pathway straw undergoes revealed the methodological need to improve current energy system analysis models to include the affected agricultural system, including an indication of the soil quality of those agricultural fields (Merante et al., 2017; Oelofse et al., 2015).

Research has shown that the requirements for soil C to sustain ecosystem functions depend on soil and farming practices, and on which ecosystem services are in focus (Merante et al., 2017). An example is the soil structural stability, which is highly important for functions related to soil workability and hydrology. The ability of the soil to form aggregates and thus to enhance soil structural stability depends on its clay content, and the requirement for C to maintain a critical level of soil structural stability increases with clay content

(Jensen et al., 2019). Therefore, there may be potential to remove straw from sandy soils without sacrificing critical soil structural functions, and this would enhance the potential of straw for bioenergy on sandy soils as illustrated in Figure 8. However, other soil ecosystem functions will also be affected by straw removal, and there is a needed for a more complete assessment to address which straw bioenergy pathways would be long-term sustainable for different soil and farm types.

5 | CONCLUSIONS

We developed a dynamic and geo-localized approach to determine the influence of two energy conversion pathways of agricultural residues on long-term SOC development. The two energy conversion pathways were defined as Scenario A (high C return bioenergy strategy, here exemplified with the use of straw for biogas production with return of the digestate to soils) and Scenario B (zero C return bioenergy strategy exemplified with the use of straw for combustion). Our modelling approach aimed to maintain the same long-term SOC content under both scenarios. Though the approach was simplistic, it complements existing energy system analyses studies, which do not include SOC concerns. Our study shows that ensuring equal soil carbon contents when comparing two straw conversion pathways impacted greatly on the potential of straw biomass available for energy systems or other purposes in a future bio-economy. The requirement to maintain the SOC level in Scenario B equivalent to the level in Scenario A made an average of 26% (between 14% and 43% for the different soil and farm types) of the harvestable straw available for energy purposes in Scenario B compared to Scenario A. The differences in harvestable straw potential between scenarios A and B were higher on the fields with arable farming than on pig farms. Furthermore, the difference was higher on sandy soils than loamy soils. This was due to the difference in total C input, that is, the higher the input of C from other sources than straw, the lower the significance of straw inputs and differences between scenarios A and B. On the basis of our results, it is our claim that future renewable energy systems should be co-optimized in an integrated design of the energy and agricultural systems, to achieve a high synergy between the systems as well as a high availability of agricultural residues for bioenergy without jeopardizing long-term soil quality.

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