Ref. Ares(2021)4696580 - 21/07/2021

2021.04.28

Final 1

689229

Dynamic biogenic carbon model

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 689229.

DECISIVE

A DECENTRALISED MANAGEMENT SCHEME FOR INNOVATIVE VALORISATION OF URBAN BIOWASTE

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A Decentralised Management Scheme for Innovative Valorisation of Urban Biowaste

D3.2 - Dynamic biogenic carbon model

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<tr><td>Grant Agreement N°</td><td colspan="2">6689229</td><td></td></tr>
<tr><td>Acronym</td><td colspan="2">DECISIVE</td><td></td></tr>
<tr><td>Full Title</td><td colspan="2">A Decentralised Management Scheme for Innovative Valorisation of Urban Biowaste</td><td></td></tr>
<tr><td>Work Package (WP)</td><td colspan="2">3.1</td><td></td></tr>
<tr><td>Authors</td><td colspan="2">Klinglmair, M., Thomsen, M.</td><td></td></tr>
<tr><td>Document Type</td><td colspan="2">Report</td><td></td></tr>
<tr><td>Document Title</td><td colspan="2">Dynamic biogenic carbon model</td><td></td></tr>
<tr><td rowspan="4">Dissemination Level (mark with an “X” in the column to the far right)</td><td>CO</td><td>Confidential, only for partners of the Consortium (including the Commission’s Services)</td><td></td></tr>
<tr><td>PU</td><td>Public</td><td>X</td></tr>
<tr><td>PP</td><td>Restricted to other programme participants (including the Commission Services)</td><td></td></tr>
<tr><td>RE</td><td>Restricted to a group specified by the Consortium (including the Commission Services)</td><td></td></tr>
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ABSTRACT

Fertiliser derived from the organic fraction of household waste (OFHW), or food waste, is frequently discussed in terms of nutrient cycling and greenhouse gas emissions reduction through avoided mineral fertiliser production. An additional benefit lies in its potential for long-term biogenic carbon sequestration, and its potential for the design of organic fertilisers that optimally meet the nutrient demands of crops.

The DECISIVE concept proposes the anaerobic digestion of OFHW and (besides energy production from biogas) the use of digested OFHW on land. We present a dynamic model of the biogenic carbon (C) flows resulting from the diversion of biogenic C from a current, centralised, large-scale management system (such as incineration) to anaerobic digestion (AD) and use of the resulting organic fertiliser on agricultural land. The potential for soil carbon sequestration by applying fertilisers derived from agricultural residues and biowaste is observed by tracing the flows of biogenic carbon in several typical input feedstocks for AD. Specifically, the dynamic model addresses the contribution of OFHW to long-term carbon sequestration over a time span of 100 years, as compared to agricultural residues (manure and wheat straw) and sludge from AD units at urban wastewater treatment plants. In addition, the corresponding annual nutrient (N, P) and cadmium (as a food contaminant) loads to the topsoil are quantified.

The model is illustrated by a case study of diverting one-third of the OFHW produced in the area of North Zealand, Denmark, away from incineration. In the studied scenario, this fraction is co-digested with livestock manure and sewage sludge at biogas plants, with the digestate applied to agricultural land. At constant annual input rates and management practices, a diversion of 33% of OFHW would result in an increased organic carbon build-up in agricultural top soils of approximately 4%, over the current amounts applied, in a 100-year timeframe. The co-digestion of OFHW, moreover, adjusts the N:P ratio towards meeting plant nutrient demand, albeit without reaching an ideally high ratio, while the Cd loads from OFHW are well below regulatory limits in the modelled scenarios.

DOCUMENT HISTORY

Version	date	modification
Version 01	10/07/2020	First draft
Version 02	08/12/2020	Second draft after approval of the coordinator
Version 03	01/04/2021	Third draft implementing comments from TUUH reviewers
Version 04	01/04/2021	First release after approval by reviewers
Final version	28-04-2021	Approved by the coordinator Anne Trémier from Inrae

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Abbreviations

AD	anaerobic digestion
DM	dry matter
MSW	municipal solid waste
OFHW	organic fraction of household waste
WtE	Waste-to-Energy (waste incineration)

Executive Summary

In the context of a circular economy and sustainable production cycles, fertiliser derived from the organic fraction of household waste (OFHW) is frequently discussed in terms of nutrient cycling and reduction of greenhouse gas emissions through avoided fertiliser production. An additional benefit of applying OFHW-derived fertilizer to soil lies in its potential as an organic fertiliser and contributor to climate change mitigation by long-term sequestration of biogenic carbon. This report illustrates the relative ***impact of a central element of the DECISIVE solution***, i.e., the use of food-waste-derived fertiliser, on soil carbon restoration and nutrient recycling. It presents a modelling framework for quantifying the net potential for soil biogenic carbon sequestration (contributing to climate change mitigation) from applying a large portion of the organic fraction of household waste, or OFHW, on agricultural soil after anaerobic digestion. The model is illustrated, to aid practical application, by a case study from Denmark examining biogenic carbon flows resulting from anaerobic digestion and soil application of OFHW instead of incinerating this fraction with municipal solid waste.

We present a ***case study*** of diverting 33% of the OFHW produced in the Danish region of North Zealand away from incineration, and towards co-digestion with livestock manure and sewage sludge. The digestate is to be applied to agricultural land in the area. The case study observes the potential for long-term carbon sequestration by the application of fertilisers derived from agricultural residues (manure, wheat straw) and biowaste (sludge and OFHW) by tracing the flows and fate of biogenic carbon in these materials. We specifically address the contribution of co-digested OFHW over a time span of 100 years, as compared to other agricultural and biowastes as well as to OFHW incineration. In addition to biogenic carbon, nitrogen and phosphorus inputs corresponding to the carbon flows were examined, along with the associated cadmium loads to avoid the risk of adverse health effects.

OFHW is mainly made up of kitchen or food waste. In the ***reference scenario***, 100%, or 70 kilotons dry matter (DM; corresponding to 35.2 kilotons C) of OFHW are routed to incineration annually. 33% of OFHW (23 kilotons DM, or 11.7 kilotons C) are co-digested annually with either sewage sludge or manure in the ***alternative scenario***. The manure to be managed in the system amounts to 24.7 kilotons DM, or 10.5 kilotons C annually. Sludge production is 41.5 kilotons DM (20 kilotons C) per year, to be co-digested with OFHW as well. These values are set as constants throughout the timespan examined, assuming no change

At constant annual input rates and management practices, a diversion of 33% of OFHW to digestion and land application would ***result in an increased build-up of soil organic carbon*** of approximately 4% over the current amounts of biogenic carbon applied (through sludge and manure and returned to soil through crop residues) in the case study area. A diversion of 100% of OFHW to digestion would raise this contribution to 12%. The results, while showing the expected benefit of biogasification of OFHW over incineration in terms of climate change mitigation, point to a relatively minor role of OFHW compared to the other materials in the case study.

The application of digested OFHW to soil does not have a significant ***impact on a region's nutrient self-supply***; digestion and land application of 100% of OFHW would meet the plant phosphorus demand of 3.5% (2377 ha) of agricultural land in the case study area. The N:P ratio of OFHW does lift the N:P ratio of an input mix of OFHW, sludge, manure, and crop residues towards an ideal ratio of 6.5 for the area, albeit without reaching this value. The cadmium loads associated with using digested OFHW on agricultural soil, meanwhile, are no obstacle to adding digested OFHW to soil as a fertiliser.

The impact of OFHW-derived fertiliser, relative to other fertiliser inputs, is of course ***strongly dependent on the amount of suitable food waste feedstock*** in a given area. A larger urban agglomeration than Greater Copenhagen (as in this study), surrounded by less cropland, would conceivably result in a larger relative impact of OFHW-derived fertiliser due to a larger amount of OFHW and smaller recipient area. This would also likely increase the ratio of nutrient self-supply. The application of OFHW-based fertiliser, however, cannot be regarded as a cure-all for the case study region examined here, although it does contribute to beneficial outcomes regarding carbon sequestration, nutrient recirculation, and nutrient composition, while avoiding negative impacts from cadmium contamination.

Opportunities for net environmental and economic benefits of OFHW biogasification and land application are therefore likely to lie in combined soil carbon sequestration, nutrient cycling, and energy recovery.

1. Introduction

The challenge of a circular economy is the effective and sustained closing of multiple material cycles in a production system. The recycling and valorisation of household biowaste can contribute to the substitution of mineral fertiliser by returning nitrogen and phosphorus to agricultural soils, substitute fossil-based energy carriers by energy recovery from organic residues, avoid the high CO_2 footprint of the Haber-Bosch process for nitrogen fertiliser production, and sequester biogenic carbon contained in organic waste-based fertiliser products in agricultural soil. Trade-offs, however, exist with regard to the nutrient composition and fertilising value of the organic secondary fertilisers, and the global warming potential resulting from methane (CH_4) emissions from biogas production for energy use.

The DECISIVE project proposes a scenario in which food waste is separately collected, anaerobically digested, and recycled as an organic fertiliser. The advantage of applying biowaste-derived fertiliser to soil lies in the support of soil biological activity and nutrient cycling (Cayuela et al. 2010), and the restoration of soil carbon is all the more pertinent in light of forecasted negative net soil C fluxes in the next 100 years (Lugato et al. 2018). This report examines the effect of the DECISIVE approach of anaerobic digestion of food waste, and the land application of the resulting digestate, on the potential for long-term sequestration of biogenic carbon in soil as well as on the concomitant nutrient (nitrogen, phosphorus) and food contaminant (e.g. cadmium) loads.

To quantify the contribution of OFHW to soil organic carbon in this scenario, this report presents a dynamic model of the biogenic carbon stocks and flows in the system over a 100-year time horizon using the STELLA modelling software (version 1.9; https://iseesystems.com). The model quantifies only biogenic carbon stocks and flows and as such excludes indirect emissions, for example from energy consumption or transport. It covers biogenic carbon flow and stock dynamics in the waste management system, comprising organic household waste generation, production, consumption, storage processes, anaerobic digestion, and spreading on soil. Soil processes are modelled using an assumption of first order degradation kinetics, based on literature data for wastes and manures appropriate for an EU context with a temperate climate (Cayuela et al. 2010; Eklind and Kirchmann 2000; Thomsen et al. 2013).

The dynamic biogenic carbon model is accompanied by a quantification of the annual nitrogen and phosphorus loads via the organic fertilizers applied to soil, in order to determine to which extent the digestate-derived fertilisers can meet plant demand for N and P (Poulsen et al. 2019). In addition to carbon and nutrients, the cadmium load to soil was quantified, due to its diet-related health impacts (Pizzol et al. 2014; Marini et al. 2020). Cd is present in relatively high concentrations in mineral P fertiliser, but also in sewage sludge, manure, and food waste, albeit in lower concentrations (Jensen et al. 2015; Pizzol et al. 2014).

The model is illustrated by a case study from Denmark, where separate collection of the organic fraction of household waste (OFHW, primarily food waste, distinct from garden & park waste) plays a minor role at present. In the Danish area of North Zealand, the majority of OFHW is currently collected with residual waste and incinerated. We compared this current system to an alternative system in which a fraction of the food waste is diverted from incineration to anaerobic digestion and subsequent use of the digestate-based fertiliser on cropland. The case study traces the flows of biogenic carbon in OFHW throughout the system under study. A portion of the OFHW (33%) in the present catchment area of a WtE plant in North Zealand (Denmark) is assumed to be diverted to co-digestion at 8 sludge-based and 5 manure-based biogas plants (Thomsen et al. 2017). In the case study area, 132 kilotons (dry matter, DM) of OFHW are currently co-incinerated with municipal waste, and 24.7 kilotons (DM) of livestock manure, as well as 35.2 kilotons (DM) anaerobically digested sludge, are spread on agricultural land. The livestock manure produced is anaerobically digested in the alternative scenario, so that the OFHW diverted to anaerobic digesters is co-digested with either sewage sludge or manure.

2. Methodology

2.1. MODEL DESCRIPTION

The system was modelled in the Stella Professional software (version 1.9; iseesystems.com). Figure 1 shows a diagram of the modelled biowaste management system generated in Stella, with the different types of the model's elements.

The model only describes biogenic carbon (C) flows in the system, i.e. the carbon imported to the system via sewage sludge, manure, and the organic fraction of household waste (OFHW). These materials are eventually applied to soil, where the development of soil C stocks and mineralization of the added C amounts are modelled over a 100-year timeframe. Processes, stocks, and flows are modelled in kg C and calculated in intervals of 1 year. Annual N, P and Cd loads to soil are included in the model, while fate modelling in top soil was excluded for these elements.

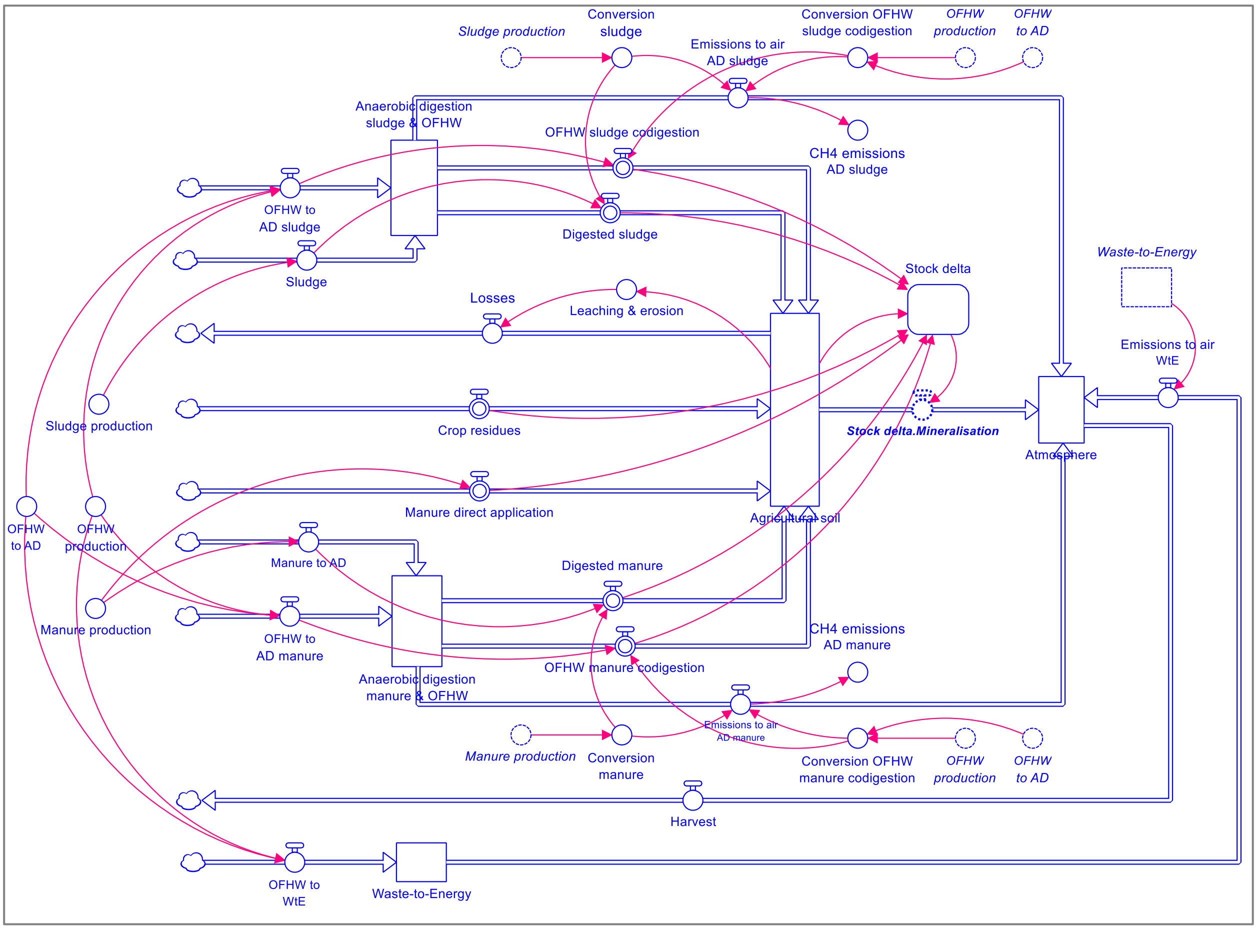


Figure 1. Diagram of the biogenic carbon flows as modelled in the STELLA software.

1) Processes indicate functional relationships (Seghetta et al. 2016) between stocks and represent substance flows inside the model. They are represented as arrows with a valve.
2) Parameters, or converters in the terminology of the Stella software, define processes (which in turn determine flows) or other converters. They are represented as blue circles.
3) Stocks are represented as rectangles, and are time-dependent. The time scale of the model was chosen as 1 year. None of the stocks contains C at year 0.
4) Connectors, shown as red arrows, represents a direct influence of one model component on another.

2.1.1. Processes and parameters

The model comprises 17 processes in total, defined by 16 parameters. The 17 modelled processes are described below, combined according to their functional roles and relationships as illustrated by the diagram in Figure 1, with their definitions given in Tables A1 and A2 in the appendix. Stocks are described in section 2.2.2.

OFHW, manure, and sludge production

The amounts of OFHW, manure, and sludge produced in an area under study are defined by the parameters (shown as blue circles on the left of Figure 1) denoted *sludge production*, *OFHW production*, and *manure production*. The fraction of OFHW to be diverted to anaerobic digestion is furthermore defined by the parameter called *OFHW to AD*.

Application on fields, crop uptake and soil C mineralization, harvest, crop residues

Since a part of the degradable organic matter in the respective feedstocks is already converted to methane during anaerobic digestion (Table 2), the ratio of degradable to recalcitrant C is lower in digested than in undigested manure, sludge, or OFHW. This can result in a larger fraction of the applied C to be stabilized in soil, with approximately twice as much C stabilized long-term for digested compared to undigested material, in the case of manure (Thomsen et al. 2013).

Table 1 gives an overview of the values used in this study to calculate the mineralization of organic carbon. The values were taken from literature describing C mineralization dynamics in agricultural soils in temperate climates, representative of the Danish situation (as such, they are not representative for the entire EU, and vary with geography and climate). For all materials applied in the case study, turnover rates *k* for fast- and slow-turnover C pools, applicable in the temperate-climate context of the north-western EU, were available. The humification coefficient h (Table 1) indicates the estimated fraction of recalcitrant organic matter remaining in soil (Cayuela et al. 2010).

The cumulative amount of the mineralisation of C added to soils in the form of digested OFHW, manure, digested manure, digested sewage sludge, and crop residues (straw, mainly wheat) left on or returned to fields is assumed to follow first-order kinetics (cf. Nielsen et al. 2019;Thomsen et al. 2013), as in Eq. 1:

$$C_m = \sum_{t=0}^{t=n} C_{input}[1 - \exp(-k * t)] \quad (1)$$

where C_m is the amount of C mineralised from time 0 to t, C_{input} is the size of the C pool from the input material at time 0, and k is the turnover rate of the C pool, with C_m for each input year and the amounts summed over the entire time frame examined.

If values for a two-pool model were available, the equation was adapted after Cayuela et al., (2010), with the pool of added degradable C divided into a fast-turnover and slow-turnover pool (Eq. 2):

$$C_m = \sum_{t=0}^{t=n} C_{input,k1}[1 - \exp(-k_1 * t)] + \sum_{t=0}^{t=n} C_{input,k2}[1 - \exp(-k_2 * t)] \quad (2)$$

where k_1 and k_2 denote fast and slow turnover rates, and $C_{input,k1}$ and $C_{input,k2}$ are the sizes of the corresponding C pools.

Table 1. Turnover rates for fast- and slow-turnover soil C pools, k_1 and k_2, of organic fertilizers applied to agricultural soils. The humification coefficient h (in % of total C applied), denotes the recalcitrant fraction of the applied C subject to humification and remaining in the soil.

	k_1 [yr^{-1}]	$t_{1/2,1}$ [yr]	k_2 [yr^{-1}]	$t_{1/2,2}$ [yr]	h [%]	Reference
Digested OFHW	32.85	0.021	10,95	0,063	48%	(Luxhøj et al. 2007)
	42% [a]		10% [a]			
Cattle manure	83.95	0.008	2,37	0,29	39%	(Cayuela et al., 2010)
	9% [a]		52% [a]			
Digested cattle manure	229.95	0.003	2,52	0,28	23%	(Cayuela et al., 2010)
	3% [a]		74% [a]			
Pig slurry	48.29	0.014	3,18	0,22	40%	(Cayuela et al., 2010)
	29% [a]		31% [a]			
Digested pig slurry	20.88	0.033	0,33	2,11	55%	(Cayuela et al., 2010)
	38% [a]		7% [a]			
Digested sludge [b]	32.85	0.021	10,95	0,063	48%	(Luxhøj et al. 2007)
	42% [a]		10% [a]			
Crop residues (straw)	72.09	0.010	0,99	0,70	67%	(Cayuela et al., 2010)
	5% [a]		28% [a]			

[a] Fractional amount of C in the rapid (k_1) and slow (k_2) turnover pools.
[b] Values for digested OFHW used as an approximation.

Compared to composting, which produces good quality soil improver and production of heat that is difficult to collect for use, anaerobic digestion results in the production of biogas containing mostly methane and carbon dioxide that is easy to collect and use for renewable energy production (Bátori et al, 2018), which is a key element in the DECISIVE solution. For this reason, we did not include composting in our study. Compost are considered a soil improver more than a fertiliser substitute, mainly used by farmers to build up soil organic matter and improve soil fertility (EIP-AGRI Focus Group, 2017). Digestate needs post-treatment due to the high water content among other issues (Zeng et al., 2016). Compost for sure has a higher content of effective organic carbon supporting the soil microbiology, but since focus of our study is compare the long-term soil carbon sequestration, fertilizer self-supply and potential trade-offs due to the present of Cd, we focus of combined biogas and organic fertilizer production.

Leaching and erosion

The total losses of C from added organic materials through leaching and erosion were estimated, based on Nielsen *et al.*, (2019), at 1% of added C.

Biogas plants and Waste-to-Energy plants

In the model, the losses of biogenic C to air from AD plants are determined by the parameters "Conversion sludge", "Conversion OFHW sludge co-digestion", "Conversion manure", and "Conversion OFHW manure co-digestion" for sludge- and manure-based biogas plants, respectively, whereas in the case of WtE these losses are a fixed fraction of the (static) OFHW input. These "conversion" parameters (see Table A2 in the Appendix) for the biogas plants define the conversion of the biogenic C in the various feedstocks to biogas as defined in Table 2, based on the feedstocks' CH_4 yields; these yields, usually reported in m^3/t DM input, were further converted to kg C to fit with the model's mass balance.

Losses of C through air emissions from the WtE facility and the manure-based and sludge-based biogas plants are based on the values reported by (Thomsen et al. 2017). The carbon loss to air from biogas plants (Table 2) was calculated based on equation 3:

$$C_{air,AD} = EF_{CH4-C} * V_{CH4} * \frac{M_C}{M_{CH4}} + \frac{0.65}{0.35} * V_{biogas} * \frac{M_C}{M_{CO2}} \qquad (3)$$

where the emission factor *EF* for methane losses from the biogas plant is 1.3% for sludge-based biogas plants and 4.2% for manure-based biogas plants (Nielsen et al., 2019). EF values were corrected for the ratio of CH_4 to CO_2 in biogas, here set at 0.35/0.65 (Mikkelsen et al. 2016). M_C/M_{CH4} and M_C/M_{CO2} denote the C content in CH_4 and CO_2, respectively.

2.1.2. Stocks

Stocks are defined by the processes and parameters that determine a stock's in- and outflows. As such, they consist of simple additions and subtractions, while the "mineralisation" process (Eqs. 1 & 2), for example, determines soil accumulation of biogenic C. The Anaerobic Digestion and Waste-to-Energy stocks do not accumulate C, P, or Cd over one year; their purpose is in linking processes, routing flows, and delivering output flows to be acted upon further by the processes for final disposal or treatment. Table A3 in the appendix gives the definition of the stocks used in the model.

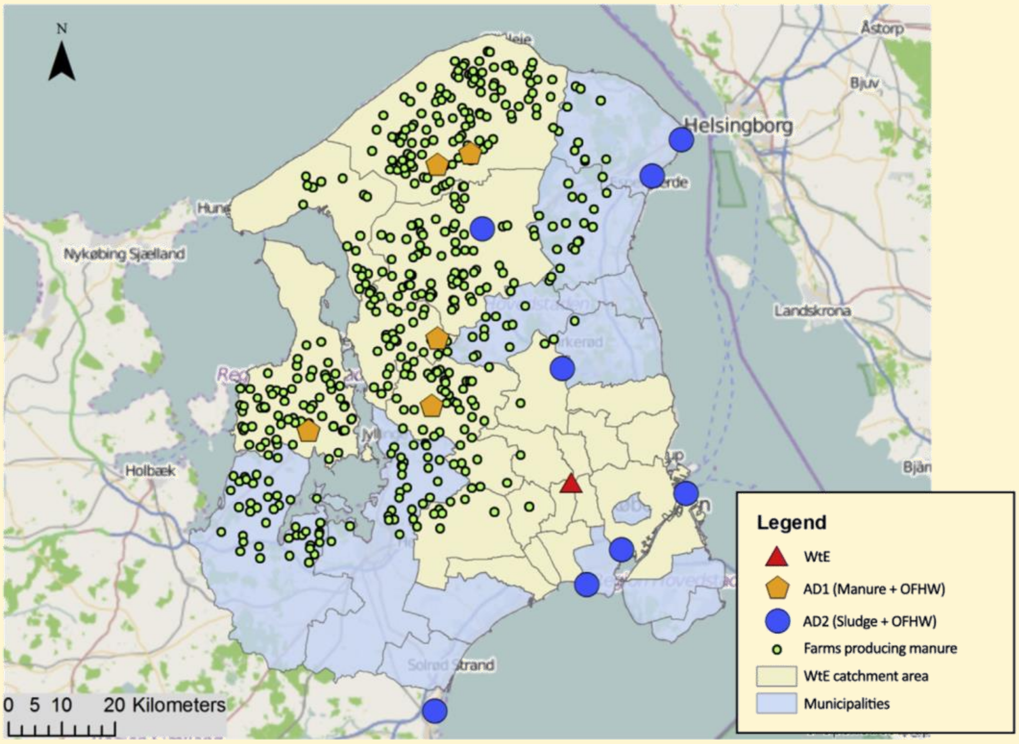
CASE STUDY: System description

OFHW is mainly made up of kitchen or food waste (Edjabou et al. 2016; Riber et al. 2009). In the *reference scenario*, 100%, or 70 kilotons dry matter (DM; corresponding to 35.2 kilotons C) of OFHW are routed to WtE annually. 33% of OFHW (23 kilotons DM, or 11.7 kilotons C) are co-digested annually with either sewage sludge or manure in the *alternative scenario*.

The **manure** to be managed in the system amounts to 24.7 kilotons DM, or 10.5 kilotons C (Thomsen et al. 2017) annually, of which 20.6 kilotons DM (8.7 kilotons C) are produced within sufficient proximity of AD plants to be co-digested with OFHW.

Sludge production is 41.5 kilotons DM (20 kilotons C) per year, to be co-digested with OFHW as well.

These values are set as constants throughout the timespan examined, assuming no change in e.g. demographics and agricultural practices, which would be beyond the scope of this study.



Overview of the case study area in North Zealand, Denmark, population approx. 1 037 000, agricultural area 68 608 ha (from Thomsen et al. 2017).

Amounts applied in the case study area (33% of OFHW diverted from incineration to AD; Thomsen et al. 2017).

Material	Biogenic C applied [kg C]
Digested OFHW	2 075 500
Cattle manure	1 358 280
Digested cattle manure	3 792 250
Pig slurry	405 720
Digested pig slurry	1 132 750
Digested sludge [b]	8 005 000
Crop residues (straw)	26 550 000

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3. Model output

3.1. BIOGENIC CARBON SEQUESTRATION

Thomsen et al. (2013) indicate that over a timespan of one year or longer, the decomposition and mineralisation of biomass added to soil differs little between fresh and digested plant biomass and manure.

CASE STUDY: Carbon sequestration from diverting one-third of OFHW to AD

Carbon from digested OFHW, in the scenario with 33% of OFHW diverted from incineration, approximately makes up an additional 4% over the sum of biogenic C from sludge, manure, and straw sequestered over a 100-year timeframe. If a theoretical 100% of OFHW in the case study area were to be diverted from incineration and used as fertiliser, this increase in biogenic C sequestration would amount to 12% over the amount already sequestered by the other input materials.

Due to the predominance of crop production in the case study area, and a correspondingly low livestock production (Rubæk et al. 2013), crop residues (mainly straw) form the most important fraction of the biogenic carbon accumulation in soil. While the absolute amounts of digested OFHW are small compared to the total amount of biogenic C stored in soil (Figure 2), it is worth noting that the recalcitrant fraction of digested OFHW is comparable to that of the other materials in this study (see Table 3). Accordingly, a similar fraction of the amount of OFHW applied remains in the soil in the long term, adding to the materials already applied to land..

The recalcitrant fractions of organic C, which make up between 23% and 67% of the total organic C in the materials applied here, remain in soil and decompose over decades or centuries (Thomsen et al. 2013), while the half-life times of the degradable fractions are considerably shorter that one year. Thus, these recalcitrant fractions are crucial for long-term organic C sequestration in soil.

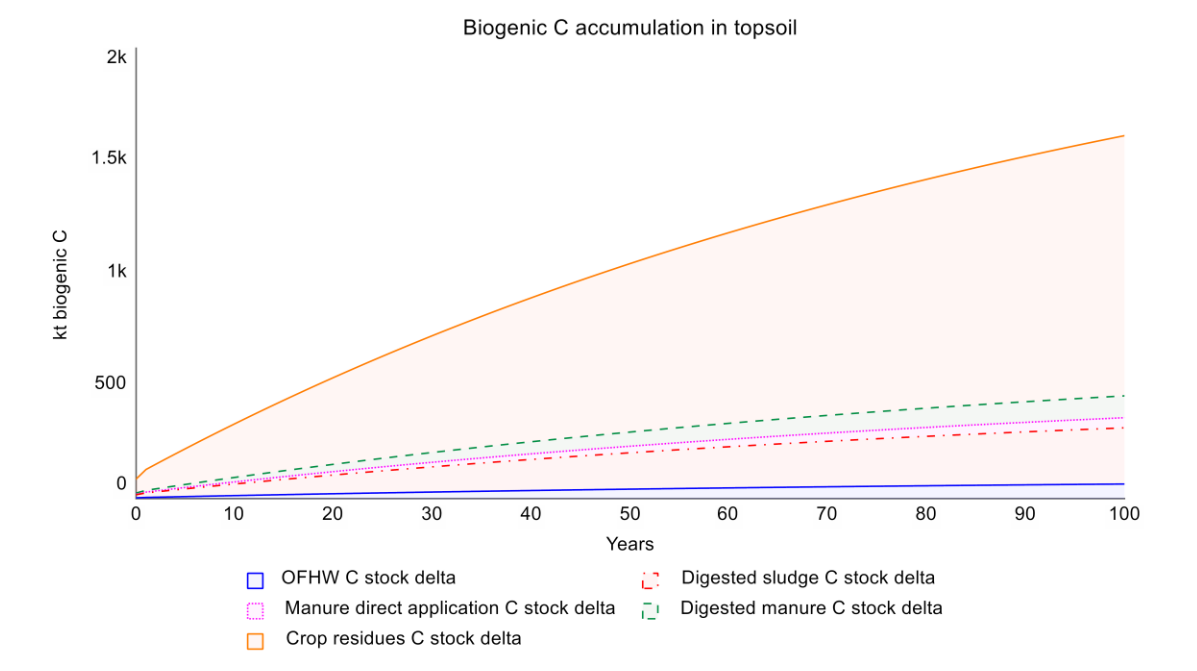

Figure 2. Net accumulation of biogenic carbon in soil in the study area over 100 years (in kilotons biogenic C), under constant annual application rates and management cycles. The figure is shown as a stacked chart showing the contribution of each input to the total soil biogenic carbon sequestered in the system. The contribution of a hypothetical 33% of OFHW anaerobically digested and applied to land, in the scenario studied, is shown in blue (solid line) adopting a constant annual management cycle over a period of 100 years.

As Table 1 highlights, OFHW is comparable to other organic materials applied to agricultural land (different raw or digested manures, digested sludge) regarding degradation rates. The recalcitrant fraction, i.e. the fraction of organic material remaining in soil for the long term, in digested OFHW is similar to digested pig slurry, much higher than cattle manure, and only insignificantly lower than that of straw left on or returned to fields. In the illustrating case study (see diagram in box above), the total amount of biogenic C in plant residues left in the soil (as opposed to recycled waste materials) is about twice the combined amount of C from the other organic-waste-derived inputs.

3.1.1. Biogas potentials and tradeoffs with biogas production

Table 2 shows the relatively high CH_4 yield to be obtained from digesting OFHW compared to other typical input feedstocks, coinciding with a higher potential for soil C sequestration due to the relatively high amount of recalcitrant organic matter in the digestate (see also Table 1).

Table 2. Typical CH_4 yields (in Nm^3 CH_4 and kg CH_4-C per kg DM of input feedstock), and potential C soil sequestration of digested feedstocks over a 100-year timeframe.

	CH_4 yield from anaerobic digestion		Volatile solids (VS)	C soil sequestration of digested feedstocks[2]
	[Nm^3 CH_4/kg DM][1]	[kg CH_4-C/kg DM]	[kg VS/kg DM][1]	[kg C/kg DM]
OFHW	0.50	0.27	0.87	0.241
Manure	0.18	0.10	0.78 (cattle), 0.75 (pigs)	0.128
Sludge	0.35	0.19	0.54	0.231

[1]Thomsen et al. (2017)
[1]single annual management cycle, after 100 years

Methane emissions from biogas plants are a significant trade-off of diverting OFHW away from incineration and to anaerobic digestion and subsequent fertiliser use, as the global warming potential of these methane emissions offset a part of the emission savings through soil C sequestration. When applied to the case study in this report, however, the model showed that these offsets still allowed significant GHG emission savings from biogenic carbon if anaerobic digestion was chosen over incineration of OFHW:

CASE STUDY: Trade-offs with biogas production

A single one-year management cycle with diversion of 33% of OFHW from incineration still results in a net saving of about 29% of greenhouse gas emissions (originating from the biogenic C in OFHW) in relation to incineration only (Table 6), or an emission of 90.74 kt CO_2-eq. (33% of OFHW applied to land as fertiliser) as compared to 128.4 kt CO2-eq. (all OFHW incinerated).

Potential net savings of GHG emissions (originating from the biogenic C content in OFHW only), single one-year management cycle. Emissions count CO_2 emissions from incineration, biogas combustion and fugitive losses of CH_4, as well as emissions from soil (degradation of organic material) over 100 years.

OFHW diverted from incineration	kt CO_2-eq. emitted from OFHW [kt CO_2-eq.]	CO_2-eq. net emission saving [%]
0%	128.34	0%
33% (23.4 kt DM)	90.74	29%
100% (70 kt DM)	14.43	89%

3.2. NITROGEN, PHOSPHORUS, AND CADMIUM LOADS

The biogenic C flows in the dynamic model entail different annual loads of plant nutrients (nitrogen, phosphorus) and contaminants (here exemplified by cadmium; cf. Pizzol et al. 2014) to soil, corresponding to the respective materials applied. While the fate of these substances in soil does not form part of the dynamic model, the annual loads of N, P, and Cd have potential implications for the regulatory compliance of the organic fertiliser materials. The biogenic C model thus needs to be accompanied by a quantification of nutrient and contaminant inputs. This assures a fertiliser quality compliant with the new fertiliser regulation (Regulation (EU) 2019/1009), makes it possible to design the ingestate feedstock composition so as to result in output characteristics that qualify for valorisation as an organic liquid or solid fertilizer product (Angouria-Tsorochidou and Thomsen, 2021).

Table 3. Nitrogen (total), phosphorus (total) and cadmium contents in selected organic fertiliser materials.

	N	P	N:P	Cd	Cd:P	Reference
	(kg/kg DM)	(kg/kg DM)		(mg/kg DM)	mg Cd/kgP	
Digested sludge	0.03	0.023	1.5	0.88	38	M. Thomsen et al. 2017; Poulsen et al. 2019
Manure	0.05	0.013	3.9	0.29	22	M. Thomsen et al. 2017; Poulsen et al. 2019
Digested manure	0.07	0.02	3.5	0.43	22	Frandsen et al. 2011; M. Thomsen et al. 2017; Poulsen et al. 2019
Digested OFHW	0.032	0.0039	8.3	0.037	10	(Riber et al. 2009; Larsen et al. 2016; M. Thomsen et al. 2017)

Regulations limiting nitrogen and phosphorus input (see text box below) are unlikely to be violated by the addition of digested OFHW, in the EU context. In the case study in this report, even an increase of 0% to 100% of OFHW used as fertiliser would only increase P input (via manure and sludge) from 8.4 to 9.1 kg P/ha and N input from 17.5 to 22.5 kg N/ha.

The separation of the digestates into liquid and solid fractions would increase the N:P ratio of the liquid digestate fraction (Poulsen et al. 2019), with only about 4% of digestate P and 35% of digestate N in the liquid fraction according to Thomsen et al. (2020). An N:P ratio of approximately 6.5 is desirable in many cases, since this would avoid reaching the regulatory ceiling for N input before the limit for P input is reached, or vice versa (Poulsen et al. 2019). Applying the liquid fraction locally, however, would necessitate transporting the P-rich solid fraction to, ideally, a P-deficient area, thus – since about 92% of carbon are in the solid digestate fraction (Thomsen et al. 2020) – offsetting a considerable share of the potential for soil C sequestration in the study area as well. Conversely, the transport and targeted application of separate N- and P-rich fractions where needed can well be an effective future strategy for digestate management, as suggested by Møller et al. (2000) and Poulsen et al. (2019).

CASE STUDY: Potential for nutrient self-supply, nutrient loads, and N:P ratio

The P demand of the crops produced in the case study area is approximately 1400 t, or 20.2 kg P/ha (Thomsen et al. 2017). The materials applied, without the addition of OFHW, meet approximately 42% of the annual P plant demand of 20.2 kg P/ha in the area, which would show a minor increase (to 45% of P demand) with 100% of OFHW digested and applied to land. Total plant N demand in the case study area is 9030 t (131 kg/ha; Thomsen et al. 2017). The materials applied in the model, without added application of digested OFHW, can meet approximately 13% of that amount. Digesting and applying 100% of OFHW to land would only increase this value to 17%. OFHW does therefore not hold a significant potential for increasing a region's nutrient self-supply.

The nitrogen and phosphorus demand of the crops in the case study area results in an ideal N:P ratio of at least 6.5 (Poulsen et al. 2019) to avoid that the legal limit for N input (170 kg N/ha) is reached before the limit on P input (30 kg P/ha; Landbrugsstyrelsen 2019), necessitating purchase of additional N fertiliser. The addition of OFHW, with an N:P ratio of 8.3 (Table 3), as an organic fertiliser, could be expected to have the potential of adjusting the N:P ratio upwards due to its comparatively low P content. The N:P ratio of the materials applied, however, cannot be greatly influenced by the amount of OFHW applied, changing from 2.1 (0% of OFHW used as fertiliser) to 2.5 (100% of OFHW as fertiliser).

3.2.1. Cadmium loads to soil

Global agricultural soil pollution by heavy metal represents one of the biggest challenges to sustainable development, with food crops as a main contributor to the daily intake of Cd, hence a risk indicator for future soil health and food safety (Marini et al., 2020; Misra and Thomsen, 2021).

With regard to heavy metals in sludge- or organic-waste-derived fertilisers, Danish and EU legislation sets a limit (Table 4) of 0.8 mg Cd/kg DM for sludge applied to conventional agricultural land (or 100 mg Cd/kg P). The limit is 0.7 mg Cd/kg DM for digested organic household waste, which may be applied to organically farmed agricultural land under certain preconditions (Miljø- og Fødevareministeriet 2018b). The EU Fertilizer Regulation (European Parliament and Council of the European Union 2019) sets a limit of 0.7 mg Cd/kg DM for organic fertilisers containing both organic carbon and nutrients (European Parliament and Council of the European Union 2019). Since the cadmium content of digested OFHW is relatively low (see Table 3), cadmium, as a micropollutant, does not appear as an obstacle to use as a fertiliser. As Poulsen et al. (2019) pointed out, only the micropollutant contamination in sludge that can impede its suitability for agricultural use. Still, the Cd content of mineral P-fertilizers is a factor 3-12 above the contamination levels in sewage sludge, manure, and food waste, albeit in lower concentrations; however in units of per mg/kg P (Pizzol et al. 2014; Angouria-Tsorochidou and Thomsen, 2021) with food waste being the organic fertilizer product of highest safety level (Table 3).

Table 4. Limits for heavy-metal content applicable to various organic fertiliser materials in the EU context.

	Cd	Hg	Pb	Ni	Cr	Zn	Cu
Sludge, conventional agriculture [mg/kg DM][1]	0.8	0.8	120	30	100	4 000	1 000
Sludge, conventional agriculture [mg/kg P][1]	100	200	10 000	2 500	-	-	-
Composted or anaerobically digested organic household waste, organic agriculture [mg/kg DM][2]	0.7	0.4	45	25	70	200	70
Organic fertiliser containing carbon and nutrients [mg/kg DM][3]	1.5	1	120	50	2 (Cr VI)	800	300

[1] Miljø- og Fødevareministeriet (2018a)
[2] Miljø- og Fødevareministeriet (2018b)
[3] European Parliament and Council of the European Union (2019)

4. Conclusions

This report presents a modelling framework for quantifying the regional net potential for climate change mitigation, via soil biogenic carbon sequestration, from applying a large portion of the organic fraction of household waste, or OFHW, on agricultural soil after anaerobic digestion. The model is illustrated, to aid practical application, by a case study from Denmark examining biogenic carbon flows resulting from anaerobic digestion and soil application of OFHW instead of incinerating this fraction with municipal solid waste. The case study illustrates the relative impact of a central element of the DECISIVE solution, i.e. the use of food-waste-derived fertiliser, on soil carbon restoration and nutrient recycling. For application to other DECISIVE case study region, e.g. in southern Europe, an adjustment of the turnover coefficients for organic C according to climatic conditions (or the use of appropriate values for different organic fertiliser materials) would be necessary. Likewise, the amounts of the various material inputs would have to be adjusted to reflect a different area. This can be done by changing the relevant values in the definitions of processes, parameters, and stocks used in the model (see Table A1-A3).

Due to the minor amounts of OFHW relative to other co-substrates for AD, a diversion of OFHW to biogas production and land application would increase soil organic C build-up, compared to the reference system with incineration of all OFHW, to a minor degree. The illustrative case study shows an additional soil build-up of biogenic C of approximately 4% for a one-third diversion of OFHW to AD. While methane emissions from biogas plants are a sizeable trade-off to soil C sequestration from digestate, these emissions do not outweigh the net process greenhouse gas savings from that practice, as the case study also shows.

In addition to modelling soil C sequestration, the nitrogen and phosphorus inputs corresponding to the biogenic C flows were examined, along with the associated cadmium loads to avoid the risk of adverse health effects. With regard to nutrients, the application of digested OFHW to soil does not have a significant impact on a region’s nutrient self-supply; digestion and land application of 100% of OFHW would meet the plant phosphorus demand of 3.5%, or 2377 ha, of the agricultural land in the case study area. The N:P ratio of OFHW does lift the N:P ratio of an input mix of OFHW, sludge, manure, and crop residues towards an ideal ratio of 6.5, albeit without reaching this value; liquid/solid separation and targeted application of the liquid (high N:P) or solid (low (N:P) fraction could be indicated as an additional management step. The cadmium loads associated with using digested OFHW on agricultural soil, meanwhile, are no obstacle to adding digested OFHW to soil as a fertiliser.

The impact of OFHW-derived fertiliser, relative to other fertiliser inputs, is of course strongly dependent on the amount of suitable food waste feedstock in a given area. A larger urban agglomeration than Greater Copenhagen (as in this study), surrounded by less cropland, would conceivably result in a larger relative impact of OFHW-derived fertiliser due to a larger amount of OFHW and smaller recipient area. This would also likely increase the ratio of nutrient self-supply. The application of OFHW-based fertiliser, however, cannot be regarded as a cure-all for the case study region examined here, although it does contribute to beneficial outcomes regarding carbon sequestration, nutrient recirculation, and nutrient composition, while avoiding negative impacts from cadmium contamination.

Finally, increasing the amount of food-waste derived fertilizers will contribute to a reduction of Cadmium in agricultural soils and improve soil health and food safety for future generations.

Appendix

Table A1. Definition of the processes used in the STELLA model.

Process	Definition	Unit	Description	Reference/remarks
Manure_production	24 700 000	t DM	Amount of manure (dry mass, DM) produced in the case study area	Thomsen et al. 2017
OFHW_production	70 000 000	t DM	Amount of manure (DM) produced in the case study area	Thomsen et al. 2017
Sludge_production	41 500 000	t DM	Amount of manure (DM) produced in the case study area	Thomsen et al. 2017
Crop_residues	26 550 000	kg C/yr	C content in crop residues (straw) returned to/left on fields	Thomsen et al. 2017
Manure_direct_application	Manure_production*0.42*0.17	kg C/yr	Fraction of manure applied directly to land	Thomsen et al. 2017
OFHW_manure_co-digestion	OFHW_to_AD_manure - Conversion_OFHW_manure_co-digestion	kg C/yr	Amount of digested sludge produced by manure-based AD	Thomsen et al. 2017
Losses	Leaching_&_erosion	kg C/yr	Organic C lost through leaching & erosion	
Mineralization	"Co-digested_(sludge)_OFHW"*(1-h_OFHW)*(1-EXP(-k_AD_OFHW*t)) + "Co-digested_(manure)_OFHW"*(1-h_OFHW)*(1-EXP(-k_AD_OFHW*t)) + Digested_sludge*(1-h_slu_dig)*(1-EXP(-k_AD_sludge*t)) + Digested_manure*0,77*(1-h_cattle_dig)*(1-EXP(-k_AD_manure*t)) + Digested_manure*0,23*(1-h_pig_dig)*(1-EXP(-k_AD_manure*t)) + Manure_direct_application*0,77*(1-h_cattle)*(1-EXP(-k_manure*t)) + Manure_direct_application*0,23*(1-h_pig)*(1-EXP(-k_manure*t)) + Crop_residues*(1-h_crop)*(1-EXP(-k_crop_residues*t))	kg C/yr	Mineralization of the degradable fraction biogenic C in 77% cattle, 23% pig manure (Thomsen et al. 2017)	See also Eq. 1 & 2; values for *k* see Table 1 *h_slu_dig*: recalcitrant C fraction *h* in sludge *h_cattle_dig*, *h_pig_dig*: recalcitrant C fraction *h* in digested cattle/pig manure *h_cattle*, *h_pig*: recalcitrant C fraction *h* in cattle/pig manure *h_crop*: recalcitrant C fraction *h* in crop resid. *h_OFHW*: recalcitrant C fraction *h* in OFHW
Manure_to_AD	Manure_production*0,8	kg C/yr	80% of manure sent to biogas plants	
OFHW_to_AD_manure	OFHW_production*(1/3)*0,22	kg C/yr	22% of the 33% of OFHW production diverted from WtE are routed to manure-based biogas plants	Thomsen et al. 2017
Digested_manure	Manure_to_AD - Conversion_manure	kg C/yr	Amount of digested manure produced by manure-based AD	Thomsen et al. 2017

Emissions_to_air_AD_manure	Conversion_OFHW_manure_co-digestion+Conversion_manure	kg C/yr	Air emissions of C (CH_4 losses and CO_2) of manure-based AD	Thomsen et al. 2017
OFHW_to_AD_sludge	OFHW_production*(1/3)*0,78	kg C/yr	78% of the 33% of OFHW production diverted from WtE are routed to sludge-based biogas plants	Thomsen et al. 2017
Sludge	Sludge_production	kg C/yr	C content in annual production of sewage sludge	Thomsen et al. 2017
Digested_sludge	Sludge - Conversion_sludge	kg C/yr	Amount of digested sludge produced by sludge-based AD	Thomsen et al. 2017
Emissions_to_air_AD_sludge	Conversion_sludge + Conversion_OFHW_sludge_co-digestion	kg C/yr	Air emissions of C (CH_4 losses and CO_2) of sludge-based AD	Thomsen et al. 2017
OFHW_sludge_co-digestion	OFHW_to_AD_sludge - Conversion_OFHW_sludge_co-digestion	kg C/yr	Amount of digested sludge produced by sludge-based AD	Thomsen et al. 2017
Emissions_to_air_WtE	Waste-to-Energy	kg C/yr	Emissions to air from WtE (incineration)	Thomsen et al. 2017
Harvest	45000000	kg C/yr	C content in harvested crops	Thomsen et al. 2017
OFHW_to_WtE	OFHW_production*(2/3)	kg C/yr	Fraction of OFHW directed to WtE (2/3)	Thomsen et al. 2017

Table A2. Definitions of the parameters used in the STELLA model.

Parameter	**Definition**	**Unit**	**Description**	**Reference/remarks**
Conversion_OFHW_sludge_co-digestion	(0.5*OFHW_production*(1/3)*0.78) *(0.71*12/16) + (35/65)* (0.5*OFHW_production*(1/3)*0.78) *(1.96*12/44)	kg C/yr	Biogas conversion of OFHW codigested with sludge	OFHW codigested with sludge; CH_4 yield: 0.5m^3/t DM (calculated from Thomsen et al. 2017) CH_4: 0.71 kg/m^3 CO_2: 1.96 kg/m^3 Biogas: 65% CH_4, 35% CO_2
Conversion_OFHW_manure_co-digestion	(0.5*OFHW_production*(1/3)*0.22) *(0.71*12/16) + (35/65)* (0.5*OFHW_production*(1/3)*0.22) *(1.96*12/44)	kg C/yr	Biogas conversion of OFHW codigested with manure	OFHW codigested with manure; CH4 yield 0.5m^3/t DM (calculated from Thomsen et al. 2017)
Conversion_sludge	0.35*Sludge_production *(0.71*12/16) + (35/65)* (0.35*Sludge_production) *(1.96*12/44)	kg C/yr	Biogas conversion of anaerobically digested sludge	CH_4 yield 0.35m^3/t DM
Conversion_manure	((0.77*0.175*Manure_production)+(0.23*0.205* Manure_production)) *(0.71*12/16) + (35/65)* ((0.77*0.175*Manure_production)+(0.23*0.205* Manure_production)) *(1.96*12/44)	kg C/yr	Biogas conversion of anaerobically digested manure	CH_4 yield, cattle manure: ca. 175 m^3/t DM; pig manure: ca. 205 m^3/ t DM (Thomsen et al. 2017)

CH4_emissions_AD_sludge	Emissions_to_air_AD_sludge*0.013*0.65*(16/12)	kg CH_4/yr	CH_4 emissions from sludge-based AD plants; 1,3% of produced methane	Emission factor fo 1.3% (vol/vol) based on Nielsen et al. 2019; assumed CH_4 content 65%
CH4_emissions_AD_manure	Emissions_to_air_AD_manure*0.042*0.65*16/12	kg CH_4/yr	CH4 emissions from manure-based AD plants; 4,2% of the produced methane	Emission factor of 4.2% (vol/vol) based on Nielsen et al. 2019; assumed CH_4 content 65%
k_AD_manure	0,77*((3/77*k1_cattle_dig)+(74/77*k2_cattle_dig)) + 0,23*((38/45*k1_pig_dig)+(7/45*k2_pig_dig))	1/yr	Degradation coefficient for digested manure	Fractions denote the relative amounts of fast- or slow-degrading C in the degradable C pool (see also Table 3): k1 - fast turnover fraction, k2 - slow turnover fraction). 77% cattle, 23% pig manure (Thomsen et al. 2017)
k_manure	0,77*((9/61*k1_cattle)+(52/61*k2_cattle)) + 0,23*((29/60*k1_pig)+(31/60*k2_pig))	1/yr	Degradation coefficient for manure applied directly on land	Fractions denote the relative amounts of fast- or slow-degrading C in the degradable C pool (see also Table 1): k1 - fast turnover fraction, k2 - slow turnover fraction). 77% cattle, 23% pig manure (Thomsen et al. 2017)
k_AD_sludge	(42/52*k1_slu_dig)+(10/52*k2_slu_dig)	1/yr	Degradation coefficient for digested sludge	Fractions denote the relative amounts of fast- or slow-degrading C in the degradable C pool (see also Table 1): k1 - fast turnover fraction, k2 - slow turnover fraction). 77% cattle, 23% pig manure (Thomsen et al. 2017)
k_crop_residues	(5/33*k1_crop)+(28/33*k2_crop)	1/yr	Degradation coefficient for crop residues (straw) left on or returned to fields	Fractions denote the relative amounts of fast- or slow-degrading C in the degradable C pool (see also Table 1): k1 - fast turnover fraction, k2 - slow turnover fraction). 77% cattle, 23% pig manure (Thomsen et al. 2017)
k_AD_OFHW	(42/52*k1_OFHW)+(10/52*k2_OFHW)	1/yr	Degradation coefficient for digested OFHW	Fractions denote the relative amounts of fast- or slow-degrading C in the degradable C pool (see also Table 1): k1 - fast turnover fraction, k2 - slow turnover fraction). 77% cattle, 23% pig manure (Thomsen et al. 2017)
Leaching_&_erosion	Agricultural_soil*0,01	kg C/yr		Assumption
Manure_production	24 700 000	t DM	Amount of manure (dry mass, DM) produced in the case study area	Thomsen et al. 2017

OFHW_production	70 000 000	t DM	Amount of manure (DM) produced in the case study area	Thomsen et al. 2017
Sludge_production	41 500 000	t DM	Amount of manure (DM) produced in the case study area	Thomsen et al. 2017

Table A3. Definition of stocks used in the STELLA model.

Stock	Definition	Unit	Decription
Agricultural_soil	Agricultural_soil(t - dt) + (Digested_sludge + Digested_manure + Crop_residues + Manure_direct_application + "Co-digested_(manure)_OFHW" + "Co-digested_(sludge)_OFHW" - Losses - Mineralization) * dt	kg C	C turnover/accumulation of agricultural soil
Anaerobic_digestion_manure_&_OFHW	Anaerobic_digestion_manure_&_OFHW(t - dt) + (Manure_to_AD + OFHW_to_AD_manure - Digested_manure - Emissions_to_air_AD_manure - "Co-digested_(manure)_OFHW") * dt	kg C	C turnover of manure-based AD plants
Anaerobic_digestion_sludge_&_OFHW	Anaerobic_digestion_sludge_&_OFHW(t - dt) + (OFHW_to_AD_sludge + Sludge - Digested_sludge - Emissions_to_air_AD_sludge - "Co-digested_(sludge)_OFHW") * dt	kg C	C turnover of sludge-based AD plants
Waste-to-Energy	"Waste-to-Energy"(t - dt) + (OFHW_to_WtE - Emissions_to_air_WtE) * dt	kg C	C turnover of WtE plant
Atmosphere	Atmosphere(t - dt) + (Emissions_to_air_WtE + Emissions_to_air_AD_manure + Emissions_to_air_AD_sludge + Mineralization - Harvest) * dt	kg C	C turnover/accumulation in the atmosphere caused by the processes in the case study

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