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Hoang, Dieu Linh; Wiersema, Brienne; Moll, Henri C.; Nonhebel, Sanderine

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RESEARCH AND ANALYSIS

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The impact of biogas production on the organic carbon input to the soil of Dutch dairy farms

A substance flow analysis

Dieu Linh Hoang | **Brienne Wiersema** | **Henri C. Moll** | **Sanderine Nonhebel**

Integrated Research on Energy, Environment and Society (IREES), University of Groningen, Groningen, The Netherlands

Correspondence
Dieu Linh Hoang; Integrated Research on Energy, Environment and Society (IREES), University of Groningen, Nijenborgh 6, 9747 AG Groningen, The Netherlands.
Email: d.l.hoang@rug.nl

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Abstract

The use of Dutch dairy manure for biogas production is expected to increase from 10% in 2020 to 60% in 2030. Traditionally, manure is returned to fields as a source of nutrients and organic carbon. Since a share of manure carbon is converted into biogas, this practice impacts the organic carbon input to soil (OCIS) of the dairy farms. The magnitude of the impact depends on the magnitude of the other sources of organic carbon. This impact is not considered by current advocates for large-scale use of dairy manure for biogas while understanding it is essential because of the risk of decreasing carbon soil input. Therefore, a study of carbon flows of dairy farms that eventually contribute to the OCIS is required. In this paper, we use substance flow analysis to quantify the carbon flows on different Dutch dairy farms and investigate the impact of using manure for biogas production to their OCIS (kgC/year/ha). The farms differ in farming practices such as whether cows are grazed outside or not. The results show that about 40% of OCIS of a Dutch dairy farm comes from manure and the rest comes from its crop production. The organic carbon from manure to the soil is also limited by the need to export manure due to the Dutch nutrient regulations. The overall reduction in OCIS caused by biogas production is 10%–20%. The impact is largest in farms with no grazing. These findings provide insights into the possible trade-offs of using manure for biogas production.

KEYWORDS
agricultural residue, bioenergy, carbon management, dairy production, industrial ecology, substance flow analysis

1 | INTRODUCTION

Biogas from dairy manure is proposed as a part of the Dutch renewable energy transition (Achinas et al., 2019; EZK, 2019; Gebrezgabher et al., 2012; Groen Gas Forum, 2014; NZO, 2018; Pierie et al., 2017). Biogas, via anaerobic digestion process, is a recycling product of manure carbon which originates from recently grown feeding crop in a short carbon cycle. With 55%–65% methane content, biogas can be a considerable source

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of energy (Islam, 2020). In the Netherlands, biogas from dairy manure is expected to be about 20 PJ[1] in 2030 with the assumption that the amount of manure used for biogas will increase to 60% from 10% in 2020 (Beckman & van den Beukel, 2019; Groen Gas Forum, 2014).

At dairy farms, where biogas production happens, the concerns are not only about energy but also the consequence of anaerobic digestion on its agricultural production. Dutch dairy farms raise cows and produce roughages as a part of the animal feed. Thus, the crop productivity is as important to the farmers as the milk productivity. Manure is often returned to the farm soil as a source of nutrient elements and organic carbon (Jie et al., 2017; Melse & Buisonjé, 2020). Organic carbon has an essential role in maintaining the soil structure and fertility. Biologically, organic carbon supplies substrates and energy for soil microbes. Via supporting soil microbial activities, soil organic carbon helps in regulating water movement through soil and cycling the nutrients for plant productivity, and enhances the cohesion of soil compartments to resist erosions (Milne et al., 2015). Biogas production removes a part of manure carbon and leaves the rest in the digested manure. Digested manure called digestate is also returned to the farm soil, but if the reduction in organic carbon input to the soil is large, biogas production could negatively influence the characteristics of the soil.

The impact of biogas production on organic carbon input to soil can be viewed from two perspectives. The first perspective looks at the quantity and quality of organic carbon in digestate compared to manure. The organic carbon, after soil application, is continuously decomposed. In undigested manure, a part of the organic carbons is broken easily and another part is more stable. The amount organic carbon in digestate is about 30%–50% less than that in the undigested manure (Holly et al., 2017). Previous studies show that digestate potentially changes the composition of soil microbial communities, because the decomposition of less stable carbon happens during biogas production (Möller, 2015). It is not clear how this affects soil fertility. Research has focused on the impact on soil organic carbon, which depends on the stable organic carbon. Studies using a 4-year experimental setup suggest that there is no long-term impact of replacing manure with digestate on soil organic carbon (Barłóg et al., 2020; Thomsen et al., 2013). Yet, some studies in commercial biogas production show that it is not always easy to obtain digestate with high stable organic compounds which may negatively impact the plant-soil system (Abdullahi et al., 2008; Alburquerque et al., 2012). In addition, literature recommends to further study this impact for a longer term than 4 year since the chemical properties of digestate may also influence the long-term accumulation and availability of soil nutrients (Nkoa, 2014). Furthermore, the impacts on other aspects of soil fertility are highly uncertain due to the currently limited knowledge of the ecology and food preferences of soil microbes (Harkes et al., 2019) The second perspective is to consider the broader system in which biogas production takes place. Möller (2015) suggests that assessments of the effect of digestate should consider the overall mass flows within the broader system affected by biogas production. Although manure is an important source of organic carbon, dairy farms include more and also substantial carbon flows, such as bedding materials and crop and harvest residues. To our knowledge, there are no previous studies that quantified the difference of *organic carbon input to soil* (OCIS) between dairy farms with and without biogas production.

The farm production options play an important role in determining the OCIS and the size of biogas production. Crop production of the dairy farm, via its residues, contributes to OCIS besides manure. Crop production and manure management of a dairy farm are materially connected by its animal production. Specifically, the number of cows and its milk productivity decides how much feed is needed, grown, and imported by the farm, and the amount of manure produced. In a Dutch farm, with the same level of milk production, there are farming options which relate to the extent that animals graze outside and extent of self-supplied feed (Schils et al., 2007; Van Vuuren & Van den Pol-van Dasselaar, 2007). Decisions on grazing determine the extent of manure directly going to the field and the extent of manure collectable for biogas production. Decisions on the extent of self-supplied feed first reflects different levels of animal density: A farm which self-supplies a large portion of feed holds a smaller number of animals per land unit compared to a farm which mainly imports feed. The size of the herd specifies the amount of manure for soil and for biogas production. Second, decisions on crop production include the type of crops grown on the farm which leads to varying amounts of organic carbon from the residue being added to the soil. Third, decisions on crop production also limit how much manure is allowed to be used on the land due to the Dutch regulations on nutrient management.

The Dutch government regulates the amount of phosphate and nitrogen from manure that can be used as organic fertilizer on the farm based on the area and type and agricultural land (RVO, 2020a). This is because these elements are desirable nutrient for crop but also can cause environmental impacts such as eutrophication. The surplus phosphate and nitrogen have to be transported out of the farm. In case of biogas production, digestate is considered as a type of manure. This export of manure or digestate also leads to export of carbon from the farm.

For these reasons, to understand the reduction of OCIS caused by biogas production from manure to a dairy farm, it is essential to account the carbon flows of the whole farm.

There is no study quantifying the carbon flows of a dairy farm in the context of biogas production. However, separate carbon flows that we are concerned with have been researched in specific studies such as studies conducting carbon footprints or life cycle assessments of dairy farms (Debruyn et al., 2020; Dieterich et al., 2014; Miranda et al., 2015; Rotz, 2018). Some carbon flows were also included in studies comparing the emissions of manure and digestate (Baral et al., 2018; Chianese et al., 2009; Czubaszek & Wysocka-Czubaszek, 2018; Holly et al., 2017).

Current advocates for large-scale use of dairy manure for biogas do not really consider its impact on the OCIS of a dairy farm. Understanding this impact is essential because of the risk of decreasing carbon soil input; therefore, a study of the carbon flows of a dairy farm which eventually

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[1] PJ: petajoule; 1 PJ = 10^{15} joule = 2.77 x 10^{8} kilowatt hours.

TABLE 1 Scenarios investigated by this study

Scenarios	Baseline-OR	Baseline-IR	Baseline-OG	Baseline-IG	Biogas-OR	Biogas-IR	Biogas-OG	Biogas-IG
Grazing options								
[O] *Outdoor*	×		×		×		×	
[I] *Indoor*		×		×		×		×
Crop production options								
[R] *All roughages*	×	×			×	×		
[G] *Only fresh grass*			×	×			×	×

contribute to the OCIS is required. In this paper, we integrate all available knowledge into an overall picture of the carbon flows on the dairy farm and address two research objectives:

1. To quantify the carbon flows which contribute to the OCIS of a dairy farm under the different grazing and crop production options in the cases without and with biogas production;
2. To compare the order of magnitude of the different changes in OCIS between the different grazing and crop production options caused by biogas production.

We believe this study provides a better understanding in the nexus of energy, agricultural, and environmental issues as well as studies on carbon flows and sustainable energy production.

2 | METHODS

2.1 | Static substance flow analysis

Substance flow analysis (SFA) is a methodology to study the state and changes of a single substance within a system defined in space and time (Brunner & Rechberger, 2016). SFA uses the law of conservation of matter to visualize all inputs and output of each process and to ensure their sources are traceable. This approach has been successfully applied to understand substance flows through a Dutch dairy farm such as phosphorus and nitrogen (Einarsson et al., 2018; Hoang et al., 2020; Schröder, 2009). This study accounts carbon as a single substance flow within a Dutch dairy farm; thus, SFA is a suitable methodology. Since the goal is to see the differences between the systems within the same time frame, we use static SFA. To build up the *carbon* (C)–SFA model, we take a systematic approach to combine secondary data from literature.

2.2 | System boundary, scope of C-SFA, and scenarios

2.2.1 | System boundary and scope of C-SFA

The system boundary of our C-SFA is a conventional Dutch dairy farm with specific choices to the extent that animals graze outside and the extent of self-supplied feed in each scenario. The unit of the carbon flows is kgC/ha/year.

The goal of the C-SFA is to quantify the OCIS of the dairy farm and its changes caused by anaerobic digestion of the manure. It should be noted that OCIS is not the same as soil organic carbon (SOC). SOC is a component of soil which originates from OCIS that has been decomposed by soil organisms (Stockmann et al., 2013). Since the difference in impact of organic carbon from manure and digestate on the soil is still uncertain as abovementioned, our model ends at OCIS and does not include soil processes and emissions. We also did not include carbon flows that do not impact OCIS such as emissions from fuel consumption.

2.2.2 | Scenarios

In this study, we first perform the C-SFA of the baseline without biogas production and then the C-SFA with biogas production. For different farming settings, we include two options regarding the extent of animal grazing (O, I) and two options regarding the extent of self-grown feed (R, G). To show the contrast, the options modeled in this study are extreme in each farming aspect. These options form eight scenarios in our study (see Table 1).

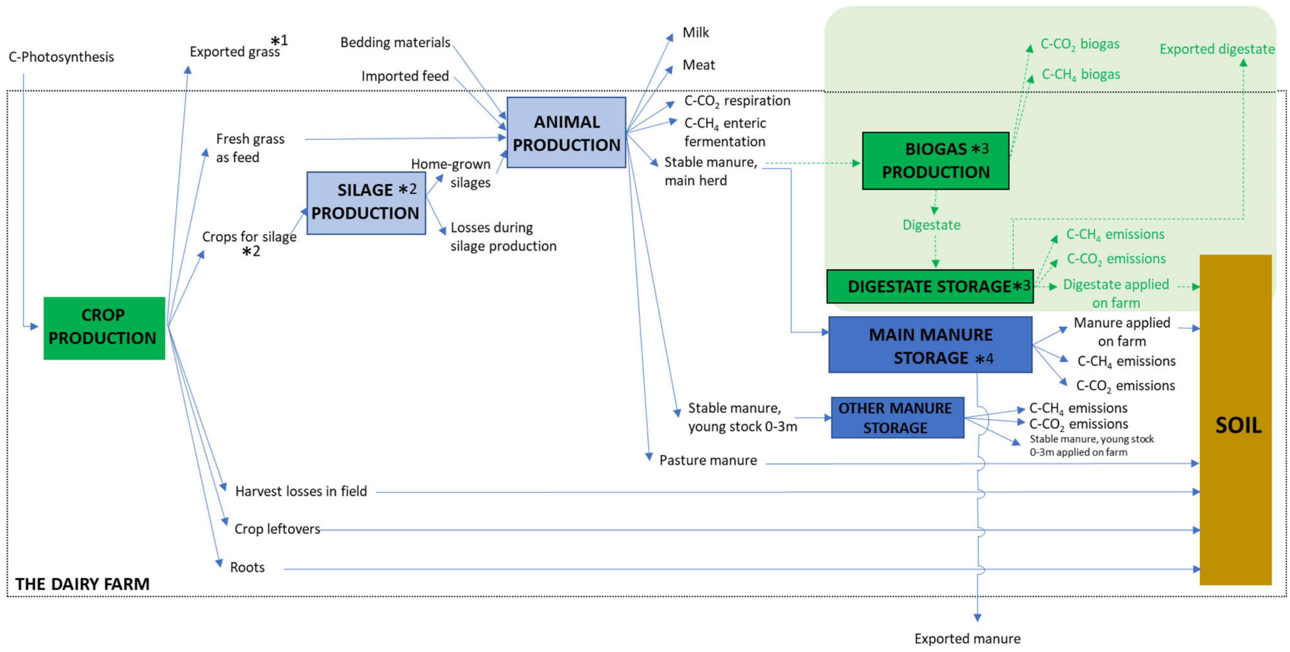

FIGURE 1 Farm activities and carbon flows included in this study. **1 is the flow absent in scenarios with "Outdoor" option. *2 are the flows and process absent in scenarios with "Only grass" option. *3 are the flows and process absent in Baseline scenarios. *4 are the flows and process absent in Biogas scenarios*

Options on grazing

[O] Outdoor: The herd are grazed outside for 182 days per year for 8 h per day; for the remaining 183 days, the herd is kept inside. Considering the temperate climate and the conventional Dutch dairy cow breeds, this is the largest possible extent of grazing (Klootwijk et al., 2016; Van Dutch Agro&Food Portal, 2020; Middelaar et al., 2013; Schroder et al., 2019a).

[I] Indoor: The herd is kept fully inside the stable throughout the year.

- Options on crop production:

  [R] All roughages: The farm produces all roughage of the feed ration which are fresh grass and silages.

  [G] Only grass: The farm only produces the fresh grass part of the feed ration.

- Options on biogas production:

  [Baseline] The farm has no biogas production

  [Biogas] The farm has manure anaerobically digested to make biogas (manure mono-digestion).

2.3 | C-SFA model and data

In this section, we describe the quantification of carbon flows for the following processes based on the system boundary identified in Section 2.2 and secondary data from literature. Farm activities and carbon flows included in this study are presented in Figure 1. This is based on descriptions of dairy farming and biogas production from existing literature (Chianese et al., 2009; Holly et al., 2017; Klootwijk et al., 2016; Mogensen et al., 2014). We first describe the model for scenarios Baseline-OR and Biogas-OR which have cows grazing outdoor and produce all roughages of the feed ration. Adaptions of the model for other farm settings are described in Section 2.3.6.

2.3.1 | The dairy farm: Land area, herd composition, and milk production

In this study, we started with a conventional Dutch dairy farm with grazing and producing its own roughage described by (Klootwijk et al., 2016). The data were produced via a dairy farm model developed by (Berentsen & Giesen, 1995; Van Middelaar et al., 2013, 2014) and data from the Dutch Agricultural Economics Research Institute (FADN, 2010).

TABLE 2 Yearly feed inputs for animal production & characteristics used in this study

Gross feed inputs	Annual farm consumption [*1.1] (tDM/farm/year)	DM content [*1.2] (gDM/kgFM)	C content [*1.3] (gC/kgDM)	VS content [*1.4] (gVS/kgDM)	P content [*1.5] (gP/kgDM)
Fresh grass	169	160	437.5	117	4.31
Grass silage	129	472	438.6	106	4.19
Maize silage	101	290	455.2	49	2.00
Concentrate	218	879	447.1	75	4.80
Powder milk	1.42	963	426.8		

*1.1 Data derived from Klootwijk et al. (2016), Van Middelaar et al. (2013), and Amado et al. (2019).
*1.2, 1.3, and 1.5 Taken from Feedprint (2020).
*1.4 Taken from Schroder et al. (2019a).

The farm is 50 ha with 80% as grassland and 20% as arable land for growing silage maize. The herd includes 87 dairy cows and 51 young stocks. We assume that half of these are *young stock less than 1 year* (YS1) and half are *young stock between 1–2 years* (YS2), so that the herd population and composition remain the same next year. The annual milk production of the farm is 707 ton with 4.4% fat and 3.5% protein.

In Sections 2.3.2–2.3.5, we describe how C value was calculated for each flow mentioned in Figure 2. To calculate the amount of C in each of the concerned flow, we need to know the mass of the material flow, the respective C content of the flow, area for crop production of the respective scenario, and use them in Formula 1.

$$\text{Formula 1}: \quad C_i = \frac{(M_i \times C\,\text{content}_i)}{A_s},$$

where *i* is the concerned flow; *s* is the concerned scenario; *A* is area for crop production; *M* is the mass value expressed in either *dry matter* (DM) or *fresh matter* (FM).

2.3.2 | Animal production

C in inputs of animal production

C in inputs of animal production is decided by the gross feed consumption of the farm. According to the farm's initial data from (Klootwijk et al., 2016), the animal feed consists of fresh grass, grass silage, maize silage, concentrate and powder milk. The first three are home-grown and the last two are imported. Yearly feed consumption of the farm is presented in Table 2: The yearly concentrate consumption of the farm is taken directly from (Klootwijk et al., 2016). Yearly home-grown feed consumption is derived from the dairy cow daily intake provided by (Klootwijk et al., 2016) and our assumption that the ratio of feed consumption of the dairy cow group to that of the whole farm is the same in all types of feed. Powder milk is only consumed by calves from birth till 9 weeks. The amount of powder milk is derived from the guidance of (Amado et al., 2019) on feeding young calves and the number of calves of the farm mentioned in Section 2.3.1.

Total C in outputs of animal production

The outputs of C from animal production are in milk, meat, CO_2-respiration, CH_4-enteric fermentation, feed losses in stable, and excretion of feces and urine.

C in milk output is determined by the amount of annual milk production; percentages of milk fat, milk protein, and lactose; and their C content. Percentages of milk fat and milk protein are mentioned in Section 2.3.1 and their C content are 70% and 46%, respectively (Byrne et al., 2007; Felber et al., 2016). Lactose accounts for 5% of cow milk in average and has the molecular formula $C_{12}H_{22}O_{11}$ (von Rymon Lipinski, 2006).

C in meat output: The amount of meat output of the farm is determined by the animal sold as new born calves, old cows, and dead cows. The weight increase of growing cows is included by the calculation of meat output via dead and sold animals. Throughout the year, each dairy cow produces one calf. To keep the number of the herd constant every year, the number of calves kept on the farm and the number of old cows is assumed to be equal to the number of YS1 mentioned in Section 2.3.1. Calves are sold at the weight of 52 kg/head and old cows are sold at the weight of 650 kg. For simplification, the numbers of sold calves and old cows also include the dead ones. The C content of animal liveweight is 136 gC/kgFM (Avila, 2006; Felber et al., 2016)

C in exhalations of the herd:

- CO_2 respiration of cows is calculated using the method of Chianese et al. (2009), which is based on the body weight and the daily feed intake. According to this, we have 3.1 and 3.5 kg C-CO_2/dairy cow/day in winter and summer, respectively. Since we do not have detailed feed diet for

TABLE 3 Dry matter partitioning and C content of different plant parts used in this study

	Dry matter partitioning (%)					C content (gC/kgDM)	
	Grass grazed outdoor	Grass fed indoor	Grass for silage	Maize for silage	Fresh grass	Grass for silage	Maize for silage
Net harvest	49	62	61	78	438	438	450
Harvest losses in field	0	5	5	6	438	438	450
Roots	18	18	19	11	450	450	450
Crop leftovers	33	16	16	6	438	450	450

young stock of the studied farm, we assume that the difference in daily C-CO_2 emissions between dairy cows and young stock is similar to the difference of manure volume excretion between these animals. Manure volume excretion between these animals is shown in Table 4.

- CH_4 enteric fermentation of each type of cows is taken from the Dutch national inventory report on greenhouse gas emission (Ruyssenaars et al., 2019), which are 134, 77, 35 gCH_4/animal/day for dairy cows, YS1, YS2, respectively.

C in total feed losses (C_{TFL}): A part of feed given to the herd was lost during the feeding process which ended up falling in the same area with the excretion. The ratio of feed losses is 2% for concentrate and 5% for silages. There is no available number for losses of the powder milk, but the powder milk is very small compared to the whole feed flow of the farm; therefore, we ignore it in this study.

C in excretion (C_{TE}): The excretion of the herd includes feces and urine. C in excretion is defined as the difference of C in the gross feed inputs and the sum of C in the feed losses, exhalations, and milk and meat production.

2.3.3 | Crop production and silage production

The data for C flows of crop production and silage production is taken from Mogensen et al. (2014). They calculated the carbon footprint of cattle feed and it is a complete inventory of carbon flows in crop production and silage production. Although the study was done for Danish dairy farms, the studied crop is similar to the one in the Netherlands in their harvest yields. We assume that the C allocations in crops, harvest losses, and silage production in Mogensen et al. (2014) are applicable to Dutch dairy farms.

Silage production

The C flows in silage production are determined by the amount of required silages for animal production in Table 2 and decide the C flows in the crop production in Section Crop production. According to Mogensen et al. (2014), from the harvested crops which are used for silage later, the loss of total dry weight is 7% during harvesting and 6% during silage production. Therefore, we use Formula 2 to calculate the amount of crop for silage. We define C losses during silage production as the difference of C in crop for silages and C in silages.

$$\text{Formula 2}: \quad DM_{CFS} = (DM_{GS} + DM_{MS}) \times \frac{1-(0.06+0.07)}{1-0.07},$$

where DM_{CFS} is the mass value expressed in dry matter for harvested crop for silages, DM_{GS} for grass silage, and DM_{MS} for maize silage.

Crop production

The C flows of crop production in our model are determined by the amount of crop for silage calculated in the section ";Silage production" and fresh grass in Table 2. C in residue flows of crop production are calculated based on the dry matter partitioning into different plant parts of the studied crops. The dry matter partitioning of the crops and C content of different plant parts are taken from Feedprint (2020) and Mogensen et al. (2014) and presented in Table 3.

2.3.4 | Manure handling and biogas production

In this study, we refer to manure as the combination of excretion, feed losses, and bedding material. The common Dutch dairy stable is a cubicle system with slatted floors and saw dust as the bedding material. Manure is regularly pumped into outside storage facilities, which are mandatory to be fully covered since 1987. The manure is in the form of slurry and thus can be applied directly to the soil without being composted (Ruyssenaars et al, 2019; Starmans & van der Hoek, 2007). In the case of biogas production, manure is collected from the stable regularly and immediately brought

TABLE 4 Age-based excretion of manure and nutrients by cows in the Netherlands (Centraal Bureau voor de Statistiek, 2012; RVO, 2019)

Type of animal	tFM slurry excretion /animal/year	kgN/animal/year	kgP_2O_5/animal/year
Dairy cow	26.9	125	41.3
YS1	11.9	69.5	22.3
YS2	5.2	34.1	9.7

to an anaerobic digester to maximize the biogas potential of manure (Ruyssenaars et al, 2019). Digestate is also stored in a covered storage system. Inside the stable and storage facilities, there are carbon emissions from manure and digestate since their organic carbon is decomposed. The details of carbon flows with manure and digestate and their emissions are discussed below.

C in manure as the input of manure handling process

Manure on dairy farm is handled differently, depending on the age and keeping location of the cows. In our model, there are three flows of manure as input for the manure handling processes: *pasture manure*, *stable manure of young stock between 0–3 months input (SMOI)*, and *stable manure of the main herd input (SMMI)*.

Pasture manure only includes excretion. Cows sleep around 4 h/day spread out over the day (The Cattle Site, 2015), which means that the rate of excretion of the herd is not different whether cows are inside or outside the stable. Thus, based on the grazing option mentioned in Section 2.3.1, we have the ratio of excretion in the pasture and inside stable as 20:80. Thus, C in manure pasture is 20% of the C in total herd excretion defined in Section Total C in outputs of animal production.

SMOI: Young stock between 0–3 months (YS0) are kept separately from the remaining herd. Its manure is collected and treated separately for health reasons (Gddiergezondheid, 2020; Schoemaker, 2006). No study was found on how exactly this manure is treated. We assumed that SMOI is stored separately but in the same method with SMMI and is applied on farm in all scenarios. SMOI includes excretion, feed losses, and bedding material which is often straw. Straw is ignored in our model due to the small amount of time and animals allocated for this manure flow. Excretion of YS0 is assumed to be 10% of that of YS1.

SMMI includes excretion, feed losses, and saw dust. The sawdust use of our modeled farm is 69 tDM/farm/year. This number is derived from the sawdust required for the farm with similar set up of Van Middelaar et al. (2013) and Thomassen et al. (2009) with the assumption that the sawdust required is proportional with the size of the herd. C content of saw dust is 509 gC/kgDM (ECN, 2020). Excretion of the main herd is from dairy cows, YS2, and 90% of YS1.

To calculate C in the two stable manure flow, we need to divide the C in total feed losses and C in total herd excretion calculated in Section Total C in outputs of animal production. The age of the cows determines their level of excretion. We did not find data on the difference in C content between the manure of cow groups, but the difference in nutrient content (nitrogen, potassium, and phosphorus) is small (Centraal Bureau voor de Statistiek, 2012; RVO, 2019) (see Table 4). Therefore, we assume (1) the difference in C content of excretion of different type of cows is ignorable; (2) the difference in C in excretion and C in feed losses of each cow group is proportional to the difference in their excretion volume. As the results, C in SMOI and C in SMMI are calculated as Formulas 3 and 4, respectively.

$$\text{Formula 3}: \; C_{\mathrm{SMOI}} = 0.1 \times (0.8 \times C_{\mathrm{TE}} + C_{\mathrm{TFL}}) \times \frac{N_{\mathrm{YS1}} \times \mathrm{FME}_{\mathrm{YS1}}}{\mathrm{FM}_{\mathrm{TE}}},$$

where C_{TE} is C in total herd excretion; C_{TFL} is C in total feed losses; N_{YS1} is the number of animals in the YS1 group; $\mathrm{FME}_{\mathrm{YS1}}$ is the yearly excretion mass per animal in the YS1 group expressed in fresh matter; $\mathrm{FM}_{\mathrm{TE}}$ is the yearly excretion mass of the whole herd expressed in fresh matter. $\mathrm{FM}_{\mathrm{TE}}$ can be calculated via the number of animals in each animal group mentioned in Section 2.3.2 and the excretion levels shown in Table 4.

$$\text{Formula 4}: \; C_{\mathrm{SMMI}} = C_{\mathrm{SD}} + C_{\mathrm{TFL}} + 0.8 \times C_{\mathrm{TE}} - C_{\mathrm{SMOI}},$$

where C_{SD} is C in saw dust; C_{TFL} is C in total feed losses; C_{TE} is C in total herd excretion.

C flows in biogas production

SMMI is the only manure source for biogas production.

CH_4 in biogas: CH_4 formation during anaerobic digestion is affected by many factors such as temperature, pH, retention time, and the chemical composition of the digested materials. In our model, we use the methodology of Vonk et al. (2018), which calculates CH_4 in biogas production from a Dutch agricultural perspective. The methodology focuses on the total volatile solid (VS) and the ratio between carbon and nitrogen (C:N) of the digested material while other factors are assumed similar among the Dutch dairy farms and given a default value. Besides this main literature, we also use the technical guidance (Schroder et al., 2019a, 2019b) derived from Vonk et al. (2018), which has formulas that fit our data.

According to Vonk et al. (2018) and Schroder et al., 2019a, 2019b), the higher VS content leads to a higher CH_4 yield in the common Dutch mono-manure digestion context. This conclusion is also confirmed in other literature (Hills, 1979; Lin et al., 2019) when the C:N ratio of the substrate is lower than the optimum which is between 20–30. The C:N ratio of the SMMI in our model is 9.7 calculated via annual N excretion per cow (Table 4) and C excretion in Section 2.3.2.

According to Schroder et al. (2019b), to account the total CH_4 biogas of the farm, we first calculate separately CH_4 biogas formed by each age-based group of animals. Calculation of CH_4-biogas produced by each group of animals is presented in Formula 5.1.

$$\text{Formula 5.1}: \ M_{\mathrm{CH4B}j} = (\mathrm{VS}_{Ej} + \mathrm{VS}_{\mathrm{FL}j} + \mathrm{VS}_{\mathrm{SD}j}) \times 0.95 \times \mathrm{Bo}_j,$$

where j is the age-based group of animals; M_{CH4B} is the mass of CH_4 in biogas expressed in kg; Bo is the CH_4 formation factor of the manure environment specific to a group of animals. Bo is 0.25 for dairy cows and 0.18 for the young stock; VS is the mass expressed in kg of yearly volatile solid excretion of each animal group; E, FL, SD, respectively, refer to the component of the manure: excretion, feed losses, and saw dust. Calculations for VS_{E}, $\mathrm{VS}_{\mathrm{FL}}$, and $\mathrm{VS}_{\mathrm{SD}}$ are presented in Formulas 5.2–5.4

$$\text{Formula 5.2}: \ \mathrm{VS}_{Ej} = \mathrm{KGN}_j \times N_j \times 0.8 \times 15.6,$$

where KGN is yearly N excretion per animal expressed in kg; N is the number of animals in each age-based group.

$$\text{Formula 5.3}: \ \mathrm{VS}_{\mathrm{FL}j} = \sum(\mathrm{DM}_{j,k} \times \mathrm{VSC}_k),$$

where k is the type of feed inputs; $\mathrm{DM}_{j,k}$ is the mass of the feed input k of animal group j and expressed in kg dry matter; VSC is the volatile solid content expressed in kgVS/kgDM

$$\text{Formula 5.4}: \ \mathrm{VS}_{\mathrm{SD}j} = 0.9 \times \mathrm{DM}_{\mathrm{SD}j},$$

where $\mathrm{DM}_{\mathrm{SD}j}$ is the mass of the amount of saw dust for animal group j and expressed in kg dry matter.

Be noted that the mass value division of feed losses and saw dust to each group of animals is assumed to be proportional with the division of the excretion mentioned in Table 4. VS content of each feed input is in Table 2.

CO_2 in biogas: Biogas from digesting only manure is assumed to be 63% CH_4 and 37% CO_2. This is the result of an experimental study on making mono biogas from dairy manure in the Netherlands (Kool et al., 2005). Calculation of CO_2 biogas is based on this ratio and the CH_4 biogas calculated above. CO_2 which was solubilized in the digestate is considered part of the C in the digestate flow.

Biogas leak: 4.3% of biogas produced leaks during the anaerobic digestion (Schroder et al., 2019b). In our study, this leak is just simply included in the biogas calculated above, since our main concerns is C left in manure after biogas production.

Digestate is the manure after the biogas production. It is stored at the same time period and condition with the undigested manure in baseline scenario. Similar and corresponding to manure flows, there are several flows with digestate in our model.

CH_4 emissions of manure/ digestate in stable and storage

CH_4 emissions of manure/digestate in stable and storage are combined in one flow and calculated by the method of Schroder et al., 2019a, 2019b). This method is based upon the "Tier 2" approach of the IPCC (IPCC, 2006) but more specific for group of animal and handling systems. Like CH_4 biogas, CH_4 emissions need to be calculated separately for each component of manure in each group of animals. Formula 6 explains the general calculation for these CH_4 emissions.

$$\text{Formula 6}: \ M_{\mathrm{CH4E}m,j} = \mathrm{VS}_{m,j} \times 0.67 \times \mathrm{Bo}_j \times \frac{\mathrm{MCF}}{100},$$

where j is the age-based group of animals; m is the manure component: excretion, feed losses, and saw dust; M_{CH4E} is the mass of CH_4 emissions expressed in kg; VS is the mass of yearly volatile solid excretion expressed in kg. VS of the manure components are calculated by Formulas 5.2–5.4; Bo is the CH_4 formation factor of the manure environment specific to a group of animals. Bo is 0.25 for dairy cows and 0.18 for the young stock; MCF is the CH_4 formation of the manure environment specific to the handling system. MCF is 17 for traditional manure storage and 3 for biogas production.

C-CO_2 emissions of manure/digestate and digestate in stable and storage

Manure emits CO_2 in stables and storages. This is not frequently addressed by studies on emissions and carbon footprints of manure since CO_2 emissions of manure is considered as a short cycle of CO_2 captured by feed production of the cows. However, these flows are essential in quantifying the capacity of manure on supplying carbon to the soil.

C-CO_2 emission of manure in stable used in this study is 70 kgC-CO_2/year/animal. This is derived from Chianese et al. (2009), since it the best data available on this parameter and has similar farm conditions as our model. We assumed the amount of CO_2 emissions during stables is proportional to the number of animals of the farm.

C-CO_2 emissions in storage are 0.32 kgC-CO_2/kgFM manure and 0.16 kgC-CO_2/kgFM digestate. These numbers are derived from three studies with different approaches: lab measurements, modeling, and reviewing literature (Chianese et al., 2009; Holly et al., 2017; Kupper et al. 2020). Although the approaches differ, these studies come up with similar CO_2 emissions. Covered storages like in the Netherlands reduce emissions five times compared to uncovered storages. To determine the fresh weight of manure, we calculated the fresh weight of each component of it. Manure in the form of slurry like in this model has a density of 1040 kg/m^3 and a DM content of 85% (Den Boer et al., 2012). Saw dust has a DM content of 92% (Lu et al., 2006). DM content of each type of feed inputs is in Table 1. As anaerobic digestion does not change the volume of the fresh manure (Penn State University, 2012), stable manure and digestate has the same value in FM.

C in exported manure/digestate

To calculate how much C in manure is exported, we first have to calculate how much manure is exported to conform to the regulations of nutrient management. The regulations in 2020 stated that a farm can apply maximum 240 kg N-manure/ha/year if grassland is 80% or above of the total agricultural land of the farm (RVO, 2020b). With regards to Phosphate Right, it is 75 kg P_2O_5/ha grassland/year and 40 kg P_2O_5/ha arable land/yr (RVO, 2020c). In this paper, to simplify, we convert these numbers in P_2O_5 into *phosphorus* (P) unit.

A quick calculation based on N and P excretion taken from Table 4 also shows that P is the deciding factor of how much manure should be exported. We assume the export happens only to stable manure handling of the main herd. Since anaerobic digestion does not change P availability of manure and the export happens at the end of the storage, the ratio between of C exported and C in SMMI is equal to the ratio between P exported to total P manure of the farm.

To calculate total P manure of the farm, we add up the P in total herd excretion, total feed losses, and saw dust. P excretion of the herd is in Table 4. P in feed losses is calculated via Total P in manure coming from the excretion. P content of different types of feed losses is in Table 2. P content of saw dust is 55 mg P/kgDM (ECN). Calculation of C in exported manure is presented in Formula 7.

$$\text{Formula 7}: \quad C_{\text{EXM}} = (C_{\text{SMMI}} - C_E - C_B) \times \frac{P_{\text{EXM}}}{P_{\text{TM}}},$$

where C_{EXM} is C in exported manure/digestate, C_{SMMI} is C in the stable manure of the main herd input, C_{E} is the total C in emissions from stable and storage, C_{B} is the total C in biogas, P_{TM} is the total P in manure of the farm, P_{EXM} is P in exported manure which is the difference between total P in manure and P quota calculated by the mentioned Phosphate Right and the land area of the farm mentioned in Section 2.3.1.

2.3.5 | Organic carbon input to the soil of the dairy farm

OCIS of the dairy farms consists of six following sources:

1. Roots of all roughages grown on the farm
2. Crop leftovers of all roughages grown on the farm
3. Harvest losses in field of all roughages grown on the farm
4. Pasture manure
5. Stable manure of young stock between 0–3 months applied on farm (SMOF)
6. Stable manure of the main herd applied on farm (SMMF)

The first four sources are calculated in Sections Total C in outputs of animal production and C in manure as the input of manure handling process. The last two sources are calculated by mass balance: subtracting the C in emissions, biogas, and manure export from the C in manure input.

2.3.6 | Adaptions of the model for options [I] and [G]

Adaptions for the [I]—Indoor option:

(i) The herd diet in indoor option is assumed to be the same with outdoor option. In fact, non-grazed cows need less energy. Our estimation of the energy difference of cows between being partly outside in our main model and when cows are fully outside is 1%, based on the guidance of protein and energy requirement for cows provided by Centraal Veevoederbureau (2016). Since this difference is small, we ignore it.
(ii) Fresh grass is harvested and brought to feed inside. Grass feeding inside has the same percentage of feed losses and losses during harvest with other silages. The amount of surplus of grass from the field after providing the diet is assumed to leave the farm as "sold grass."
(iii) 100% of the manure excretion by the main herd manure is available for biogas.

Adaptions for the [G]—Only grass option:

(i) The process of crop production and silage production of grass silage and maize silage are excluded from the calculation
(ii) The land for crop production is only to grow the part of grazed grass; therefore, the land area will be adjusted by Formula 8.
(iii) The phosphate right and exported manure are recalculated for the adjusted land.

$$\text{Formula 8}: \quad L_A = \left(50 \times 0.8 \times DM_{FG} \times \frac{P_{HGO}}{P_{HGI}}\right) / \left(DM_{FG} \times \frac{P_{HGO}}{P_{HGI}} + DM_{GS} \times \frac{93}{87}\right),$$

where L_A is the area of adjusted land in ha; DM_{FG} and DM_{GS} are the mass value expressed in kg dry matter of fresh grass and grass silage mentioned in Table 2; P_{HGO} and P_{HGI} are the dry matter partitioning (%) into net harvest of grass grazed outdoor and grass fed indoor mentioned in Table 3.

3 | RESULTS

The goal of this study is to obtain insights into the order of magnitude of the carbon flows on a whole farm. To do that, we created hypothetical dairy farm systems that represent the extremes available in Dutch dairy farming. The model outcomes should be interpreted in this way: They are not estimates for existing real farms but provide insights into how large the streams are and whether differences between systems can be expected.

3.1 | Overall C-SFA of the dairy farm

The overall carbon flows of the dairy farm and their magnitudes and the impact of biogas production on OCIS for all scenarios are illustrated in Figure 2. The graphs on the top represent farms self-producing all roughages and the ones on the bottom represent farms self-producing only grass. The graphs on the right show the farms keeping cows fully indoor and the ones on the left are the farms with grazing outdoor.

Though the size of carbon flows varies, all graphs show a similar structure:

- Animal production is the largest process of the farm that carbon goes through. Within its inputs, 10% is from bedding material and the rest is from feed. Carbon in animal production has 15% ending up in milk and meat, 45% in exhalations, and 40% in manure.
- Photosynthesis or crop production is the process that converts carbon entering the farm as CO_2 into a part of the animal feed. Only about half of C in photosynthesis ends up in harvested crop. The other half of C-photosynthesis, in the form of crop leftovers, harvest losses, and roots, directly contributes to the organic carbon pool of the soil. The OCIS of the farm comes to 60% from crop production and 40% from manure. The C flows of photosynthesis, harvested crop, and OCIS of all scenarios are also similar in absolute numbers.

The variations in the size of the carbon flows are the consequence of different farming options.

3.1.1 | Variations caused by crop production options

The total carbon flux through the farms producing only grass *(Baseline-OG and Baseline-IG)* is almost double the one in the farms producing all roughages *(Baseline-OR and Baseline-IR)*. This results from the fact that fresh grass provides half of the C in roughages part of the diet. This means for each cropping ha, the farms producing only grass can feed double amount of animal, resulting in double the productivity per ha in milk, meat,

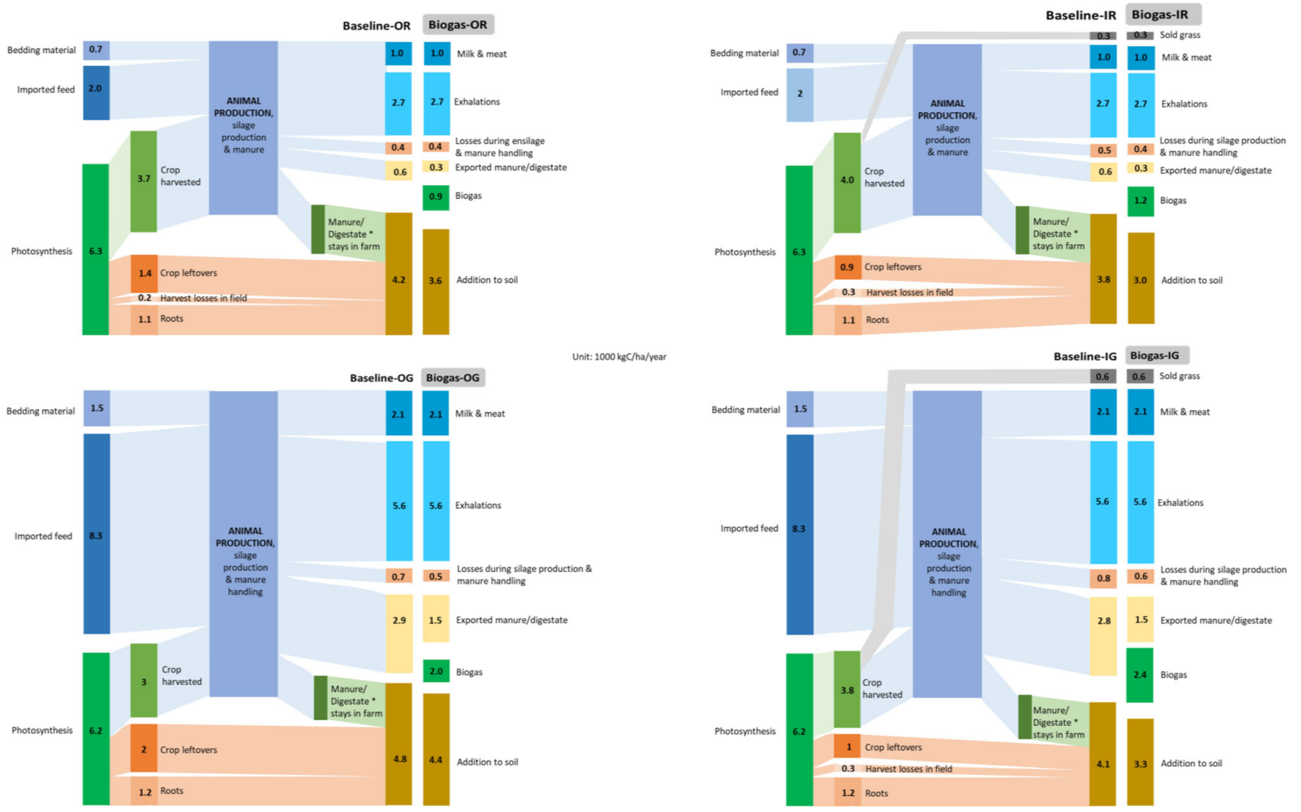

FIGURE 2 Aggregated carbon flows on the dairy farm in 8 scenarios; numbers are rounded (O, outdoor; I, indoor; R, all roughages; G, only grass)

manure, and thus biogas. Since the regulations standardize similar amounts of manure applicable per ha, farms producing only grass also have more manure exported.

3.1.2 | Variations caused by grazing options

Between scenarios with the same crop production option, the indoor scenario *(Baseline-IR/Baseline-IG)* has about 15% more carbon losses via emissions and 10% less OCIS in comparison with the grazing scenario *(Baseline-OR/Baseline-OG)*. Since our SFA only includes emission in stables but not emissions in pasture, indoor scenarios which have more stable manure end up with higher emissions. The higher emissions plus the amount of carbon leaving the farm as sold grass lead to a lower OCIS for the indoor option.

3.1.3 | Variations caused by biogas production

Carbon in biogas is about one-tenth of total outputs of the farm in all biogas scenarios. The difference in OCIS between a biogas production and its respective baseline is less than 20%.

Details of the flows for all scenarios are in Supporting Information S1 (Appendices A and B).

3.2 | Baseline scenarios: Carbon flows in handling stable manure of the main herd

The process handling SMMI in all scenarios shares the same type of carbon inputs and carbon outputs. However, the absolute and relative sizes of the flows vary. Although all scenarios used the same carbon emissions factors, the differences are caused by the variations in farming options and the composition of the manure input. Figure 3 shows the outputs of process handling SMMI in all scenarios. Detailed numbers on the figure are presented in Supporting Information S2 (Appendix D).

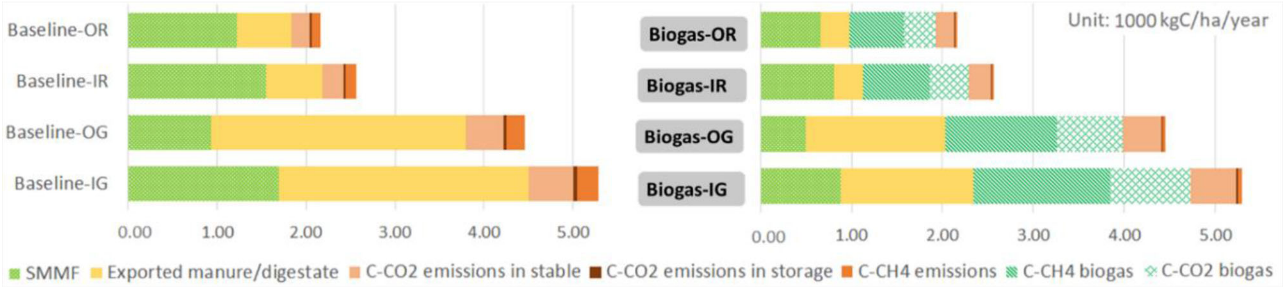

FIGURE 3 Outputs of SMMI handling process (O, outdoor; I, indoor; R, all roughages; G, only grass). The underlying data for this figure can be found in Supporting Information S2

3.2.1 | C in manure input

The input of the roughage scenarios *(Baseline-OR and Baseline-IR)* is almost half the input of the grass scenarios *(Baseline-OG and Baseline-IG)*. This is the result of the difference in animal density (see Section 3.1). In each crop production option, the non-grazing farm *(Baseline-IR/Baseline-IG)* has nearly 20% more C in the manure input to the main stable than the farm with grazing *(Baseline-OR/Baseline-OG)*. This difference is due to non-grazing scenarios having 20% more excretion in the stable, a small flow of extra feed losses as fresh grass, and the same amount of saw dust.

3.2.2 | C in manure export

The difference is mainly between the crop production options. The amount of manure export is decided by phosphate quota. The P quota is 18.5 kgP/ha in the roughage scenarios *(Baseline-OR and Baseline-IR)* and 20.5 kgP/ha for the grass scenarios *(Baseline-OG and Baseline-IG)*. The C:P ratio of manure is similar for all scenarios, so the P quota determines the C export.

- Manure export in a farm producing only grass is about four times higher than in a farm producing all roughage. This is because the P export in the roughage scenario is about one-third of its total P manure of the farm and because of the similarity in P quota per ha and double animal production in the grass scenarios.
- In contrast, manure export of scenarios with the same crop production option is almost the same because of same animal production and similar P quota.

3.2.3 | C in SMMF

Differences in C manure export lead to different amounts of C in SMMF.

- Indoor scenarios *(Baseline-IR and Baseline-IG)* have quite similar numbers of C in SMMF, though the grass scenario's (*Baseline-IG)* is a bit higher. This is because the main stable manure is almost all manure of the farm for indoor scenarios and thus it reflects the P quota of the farm.
- Having the same crop production, an outdoor scenario *(Baseline-OR/Baseline-OG)* has less C in SMMF than an indoor scenario *(Baseline-IR/Baseline-IG)*. This is the result of having similar manure export but different manure inputs.
- Having the same grazing option, the grass scenario *(Baseline OG)* has less SMMF than the roughage scenario *(Baseline OR)*. This is because of higher animal production in the grass scenario: pasture manure as another carbon source to soil increases, thus less manure in the main stable can be kept.

3.3 | Baseline scenarios: The total organic carbon input to soil

The amount of annual total carbon addition to soil in the baseline scenarios has a small range of 3.8–4.8 ton C/ha/year. The general similarity of OCIS can be explained as follow:

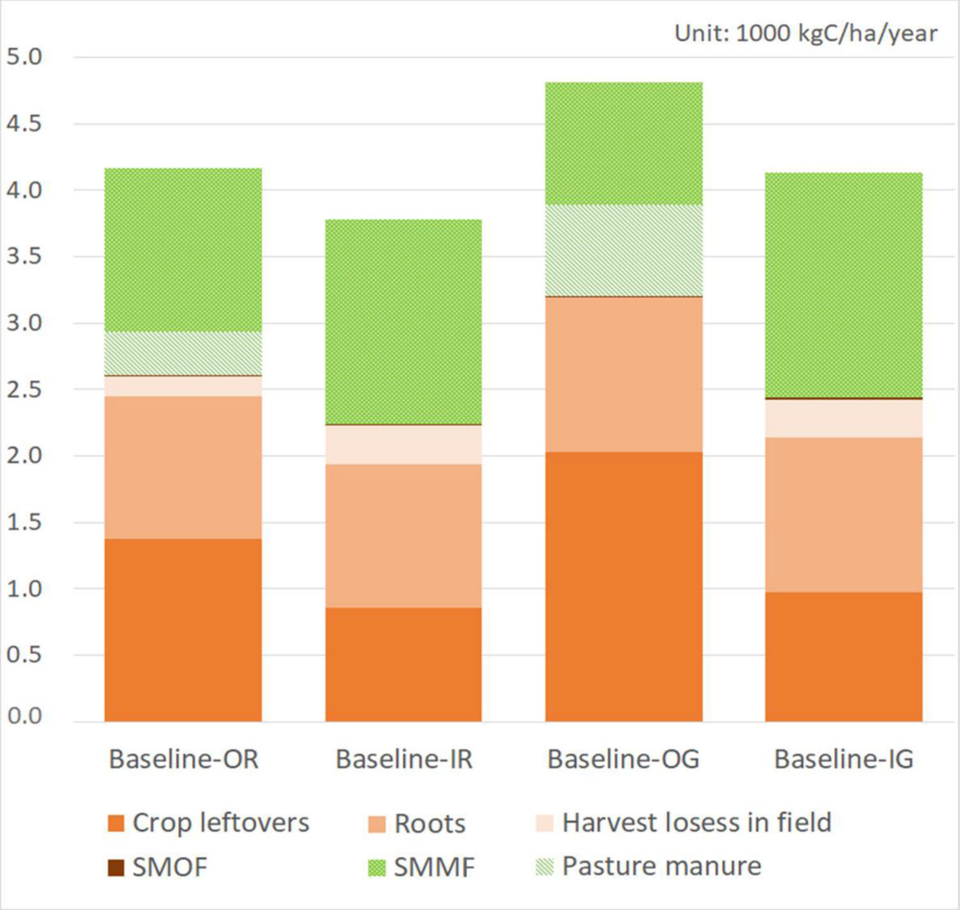

FIGURE 4 OCIS of the dairy farm and contributions of different sources in baseline scenarios (O, outdoor; I, indoor; R, all roughages; G, only grass). The underlying data for this figure can be found in Supporting Information S2

- The closeness in value of OCIS from crop production: First, the carbon in harvested crops of all scenarios are alike (see figure 2). This number in our model is a result of the assumption that the studied farm can produced just enough roughage feed for its animals. However, this can also be justified by the close values of annual carbon yield per ha of the studied crops in our methodological literature (Mogensen et al., 2014). Second, the carbon distribution from photosynthesis to the harvested part and the residues to soil of the studied crop are also comparable (see Table 2).
- The closeness in value of OCIS from manure is due to the similarity in manure phosphate quota per ha of the crop production options.

Yet, detailed differences of OCIS between these scenarios depend on the variations of individual carbon flows. The contribution of different sources to soil OCIS of the baseline scenarios is demonstrated in Figure 4. Detailed numbers on the figure are presented in Supporting Information S2 (Appendix E).

3.3.1 | Differences in the absolute amount of OCIS and in contributions of crop residue flows

- A farm producing all roughage *(Baseline-IR / Baseline-OR)* has 15% less OCIS compared to a farm producing only grass *(Baseline-IG / Baseline-OG)* which has the same grazing option. This is because maize for silage has less crop residue in comparison with other roughages, especially the amount of crop leftover (see Table 3). By not growing maize for silage, each ha of the land has more C from the residues of crop production.
- A farm without grazing *(Baseline-IR / Baseline-IG)* has less OCIS than a farm with grazing *(Baseline-IR / Baseline-IG)*. This results from the fact that grass leaves the double amount of crop leftover when it is grazed than when it is harvested (see Table 3). This is shown clearer between the two scenarios of farm producing only grass *(Baseline-OG & Baseline-IG)*. In case of roughage farms *(Baseline-OR & Baseline-IR)*, the difference becomes less since crop production also includes other harvested feed.

3.3.2 | Differences in contributions of manure flows

Manure from young stock 0–3 months is very small, less than 1% of total C manure. Stable manure is almost the only contributor to OCIS in indoor scenarios *(Baseline-IR/Baseline-IG)*. Pasture manure only exists in outdoor scenarios. Pasture manure of grass scenario *(Baseline-OG)* is double that of roughage scenario *(Baseline-OR)* according to their difference in animal production. Having pasture manure leads to less contribution of SMMF to OCIS. This number is about 30% in roughage scenarios *(Baseline-OR)* and about 20% in grass scenario *(Baseline-OG)*.

3.4 | Changing impact of biogas production on C in SMMF

Carbon flows related to biogas production as a way to handle the SMMI is shown in Figure 3. The impact of biogas production to this process is the same in all scenarios because of the similarity in manure composition and emission factors of biogas production: 45% of the C input ends up in biogas, C exports reduce by almost half, and SMMF also reduces by almost half. This can be explained by the fact that biogas leads to reduction of the C concentration in digestate. Since biogas production does interact with P in manure, a biogas scenario and its respective baseline have the same volume of manure export. This leads to the amount of C in exported manure export and C in SMMF both reducing by half.

3.5 | Changing impact of biogas production on OCIS of the dairy farm

Since biogas production only uses stable manure of the main herd, only the contribution of this flow is changed in biogas scenarios compared with their respective baselines (see Figure 4). The reduction of C by half in the digestate leads to 20% reduction of OCIS in indoor scenarios *(Biogas-IR and Biogas-IG)*, about 15% in outdoor scenario where the farm produces all roughages *(Biogas-OR)* and 10% in outdoor scenario where the farm produces only grass *(Biogas-OG)*.

4 | DISCUSSION

4.1 | Verification and flexibility of the C-SFA

As there are no studies analyzing carbon flows at farm level, it is not yet possible to compare our results with data from other studies. However, we can compare our intermediate results with the carbon flows in parts of the studied system in existing literature. The comparison shows that these values are in accordance with the existing knowledge (see Supporting Information S1, Appendix C), which suggests that the order of magnitude of the individual streams is in accordance with the actual situation.

Our model is also flexible although the current data is based on the specific diet and level of milk production. As the SFA approach clearly depicted the carbon inputs and outputs of the animal production and their connections with the rest of carbon flows of the farm, the model has room to improve the input data, although it is unlikely to change our conclusion within the order of magnitude. For example, the level of milk production is one parameter which likely varies in reality. Since roughage is almost a fixed part of the diet, the type and amount of concentrates might change to match the milk production (Centraal Veevoederbureau, 2017). This leads to little change in the studied crop production system but potentially a big change to the amount of manure being produced. Since the amount of manure carbon remaining on the farm is standardized as a consequence of the phosphate rights, the contribution of it to the OCIS of the farm in those scenarios should be similar to the values in our study. Besides, our model includes the extreme alternatives of the studied farming practice so that a wide range of changes in assumptions would be covered.

Thus, it is obvious that our model is not a representation of all farms in the Netherlands. However, since the large picture is consistent, general conclusions can be drawn on the impact of using dairy manure for biogas production on the OCIS at the farm level in the studied farming options.

4.2 | Impact of biogas production on OCIS at the dairy farm level

The existing crop production system of Dutch dairy farms, interestingly, is found to be a factor that buffers the impact of biogas production on OCIS to their farm soil. Our results show that a dairy farm receives a significant amount of organic carbon from crop production regardless of whether it produces all the roughages for the herd's diet or only fresh grass. Biogas production halves the organic carbon content of manure; however, the amount of crop-derived organic carbon scales down this impact to less than 20% of the total carbon input to soil.

The Dutch manure regulations are another factor reducing the impact of biogas production on the OCIS of the Dutch dairy farm. Our model shows that though manure regulations aim to limit the nutrient elements applicable on the dairy farm, they also limit the contribution of manure carbon to OCIS of the dairy farm. If all the manure could be applied to the farm soil, manure carbon would form a larger fraction of the OCIS, which also means that the organic carbon losses from biogas production would have a greater impact on the OCIS of the dairy farm.

4.3 | Impact of biogas production on OCIS under different farming options

Our results show how carbon flows to soil vary under different farming options and the extent that biogas production impacts them. The combination of grazing and growing only fresh grass leads to the least impact of biogas production on the OCIS of a dairy farm. Meanwhile, the option of non-grazing causes the highest impact on OCIS to the farm when having biogas. This impact is the same for farms regardless of the crop production options. As discussed earlier, farms growing only fresh grass indicate a high animal density. The above findings mean that for a dairy farm, more biogas can be produced with less impact on the total C in addition to its own soil if the farm has high animal production, and grazing even brings down the impact.

However, it is important to realize that the above conclusions only work in the Netherlands and countries with similar manure regulation approach. Without considering the manure regulation, the impact of biogas production on the total carbon in soil can be higher and its relative differences between the farming options would change.

4.4 | Limitations and recommendation for further research

To address the promotion of widely using dairy manure for biogas production, our study analyses the impact of this action to the OCIS at the farm dairy level. We conclude that the reduction impact is only about 10%–20% due to the large contribution to the OCIS from the roughage production system. However, our analysis also shows that other farms than the dairy farms might share the impact of biogas production on halving the organic carbon content of the manure stream itself. Our results also show that in high productivity cases, the manure export is larger than the amount that remains on the dairy farm. In the present situation, this exported manure is used in arable farming (NCM, 2019). For a proper evaluation on the impacts of large-scale biogas production from manure, it is essential that the impacts on OCIS for arable farms should also be analyzed, as the insights obtained in this paper indicate that large impacts are to be expected there.

Moreover, we also recommend further research of the impact of biogas production on soil considering more farming options and biogas production options. The studied farming option in our study is linked to the average type of milk production in the Netherlands. In practice, there are dairy farms with niche production options which are also interested in having biogas as a way to improve their overall environmental outcomes. For example, the grazing period can be increased if a different type of cows is used that can tolerate the Dutch winter, or an organic farm might either not use concentrate or make their own concentrate and have different types of feed crops. With these options, the links between animal production and crop production would change heavily, so that it is recommended to adjust these parameters before making use of our SFA strategy. With regards to biogas production options, we took the first step to model mono-digestion, the easiest and most common way of making biogas on dairy farm. Biogas with co-digestion which is known for its higher biogas yield will also be interesting to study. This pathway will add other C flows to the dairy farm and also increase the amount of manure which needs to be treated. To use our SFA strategy, besides information of the extra flows, the exact biogas yield of the co-digestion is required. This will require more technical knowledge, to ensure that the research is reliable.

Lastly, we recommend to use our results in combination with studies on soil's bio-physico-chemical activities to have a comprehensive judgment on the impact of biogas production on the soil of the dairy farm. This is because the SFA model in our study only discusses the quantity but not quality of the OCIS.

5 | CONCLUSION

Our paper is the first to study the impact of biogas production on dairy farms using SFA approach. We connected the two big existing literature fields, agriculture and carbon footprint, to provide insight into the change caused by biogas production on dairy farm to its total organic carbon input to soil.

The SFA model gives a transparent explanation of the carbon distribution on the dairy farms and how different farming options, with regards to grazing and crop production, lead to different levels of change in carbon input to soil caused by biogas production of manure. Our results conclude that within the common farming practice in the Netherlands, the reduction in annual amount of carbon addition to the farm soil due to using manure for biogas production is about 10%–20%. This small loss is because a large contribution to the carbon input to the farm soil comes from crop production residues and Dutch regulations on nutrient managements eventually limit the amount of manure carbon added to the dairy farm. With regards to different farming systems, dairy farms only producing grass, which might have higher animal production, can produce more biogas with less impact on reducing OCIS, and grazing can even further reduce this impact.

These findings contribute to a better understanding of the nexus of energy, agricultural, and environmental issues as well as studies on energy planning. Besides, this is also the basis for our recommendations on further researching the impact of biogas production on organic carbon input to soil including more biogas and agricultural configurations using the SFA framework.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ORCID

Dieu Linh Hoang https://orcid.org/0000-0002-5768-068X

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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