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Biogas production and changes in soil carbon input - A regional analysis
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Biogas production and changes in soil carbon input - a regional analysis

Running head: Biogas production and changes in soil carbon input

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Primary Research article

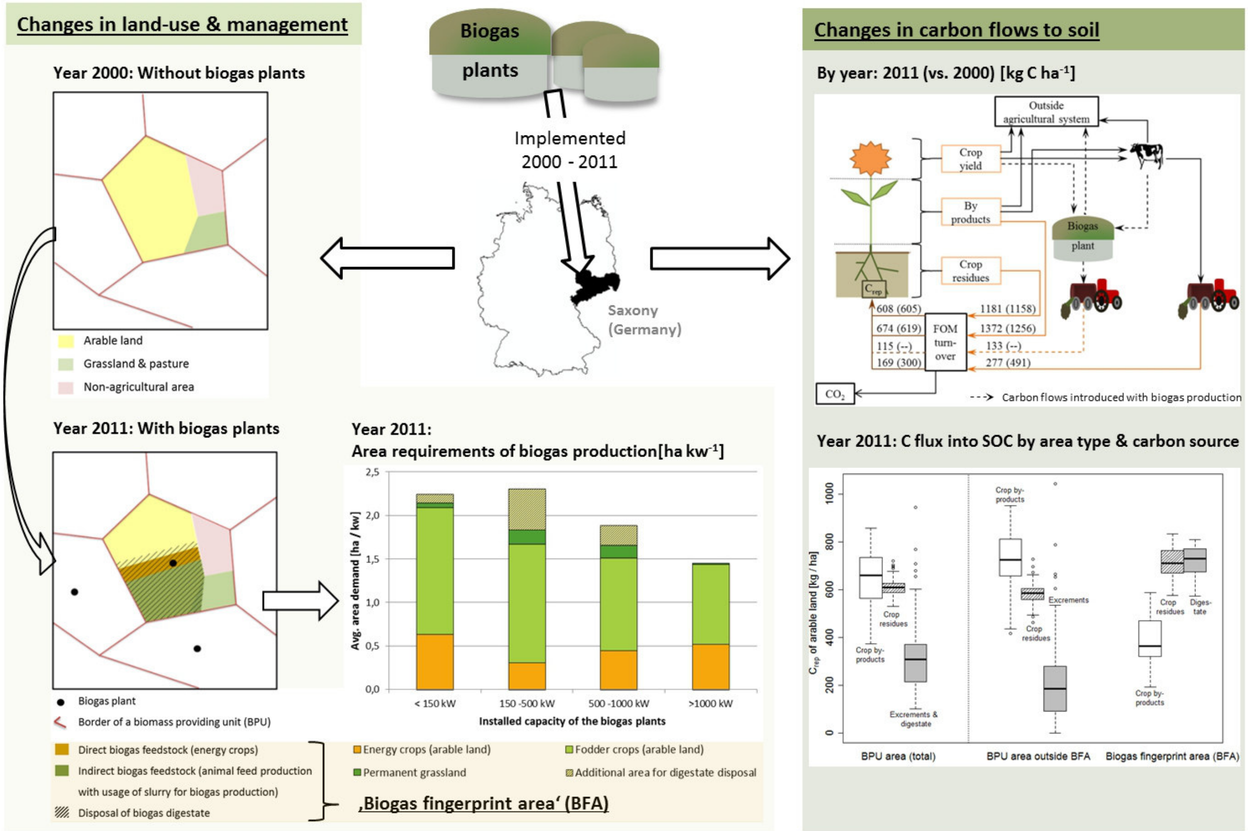
Abstract:

The inclusion of biogas production into the agricultural system has modified crop management and as a result the soil organic carbon (SOC) cycle of the agricultural landscape. To evaluate the effects for the German federal state of Saxony this study determines: (1) the share of agricultural land required for biogas production, (2) the change in regional carbon input fluxes to soil during the time of the establishment of the biogas production considering also the quality of sources of different fresh organic matter (FOM) for the formation of SOC and (3) the differences in carbon input to SOC between the area influenced by biogas production (here 'biogas fingerprint area' (BFA)) and the surrounding arable land.

Based on the location of biogas plants the region was subdivided into biomass providing units (BPUs) where a part of the arable land was considered as affected by biogas production (BFA). We hypothesized that each biogas plant uses a specific substrate mix according to its capacity. The carbon fluxes for each BPU were estimated for the years 2000 (without biogas plants) and 2011 (with biogas plants). For the year 2011, the analysis included the area demand for production of biogas feedstock and digestate recycling.

On average 17.6 % of the BPU agricultural land was required to supply the biogas plants and dispose of their digestate. Per kilowatt installed electrical capacity this equates to 2.0 ha, including inter alia 0.4 ha for energy crops. Highest area requirements have been observed for biogas plants with less than 500 kW installed capacity. Between 2000 and 2011 the total carbon flux into soil increased by 2.1 %. When considering the quality of different FOM sources the gain in carbon input was 2.8 %. The BFAs showed higher carbon input to soil than the surrounding agricultural land due to high contributions from digestate and crop

residues (esp. agricultural grass). This compensated the low carbon input from crop by-products (e.g. straw).



1 Introduction

Soil is one of the most important and most complex natural resources and is an essential contributor to the global ecosystem, providing a regulatory system that supports a multitude of ecosystem functions and services (Podmanicky *et al.*, 2011; Garrigues *et al.*, 2012; Adhikari & Hartemink, 2016). Soil organic matter (SOM) and its major component soil organic carbon (SOC) are fundamental to soil and its ecosystem functions in particular the sequestration of carbon (Podmanicky *et al.*, 2011; Campbell & Paustian, 2015; Yigini & Panagos, 2016).

Biogas production within conventional agricultural systems has been promoted as an integrated approach to support nutrient cycling, while mitigating greenhouse gases emissions from conventional fossil energy production. Germany is the largest biogas producer in the European Union, with almost 8,700 biogas plants installed in 2016 (Daniel-Gromke *et al.*, 2017a, 2017b). A previous study by Franko *et al.* (2015), for the region of Central Germany, identified a number of hot spots where the usage of carbon may raise a conflict between sustaining SOC and producing bioenergy. The expansion of the agricultural system to include bioenergy production has resulted in an adaption of the agricultural management (e.g. cultivated crops, digestate application instead of slurry), which in turn has changed the carbon input to soil within these agricultural landscapes. At the same time biogas production is heavily influenced by the regional availability and variability of feedstock.

To date, no general approach has been developed to understand the potential influence of bioenergy production on regional soil carbon cycling. It is a challenge to tackle the additional complexity which biogas production can introduce into agricultural systems (Arthurson, 2009; Möller & Müller, 2012; Barbosa *et al.*, 2014). Therefore, the aim of this study was an ex-post evaluation of the biogas production within the agricultural landscape of a case study region. For each biogas plant within the federal state of Saxony we estimated the agricultural area required for the provision of biogas feedstock and recycling of digestate, proposing the combination of this as “biogas fingerprint area” (BFA) of a biogas plant. The carbon input to arable soil has been estimated for two separate years 2000 (without biogas production) and 2011 (with biogas production). Here also the quality of different sources of fresh organic matter (FOM) regarding the formation of new SOC was considered. Furthermore, for the year 2011 we compared the carbon input on the BFAs and the arable land not affected by biogas production.

2 Material & Methods

2.1 Spatial units of investigation

The federal state of Saxony, in East Germany was used as the study region. During the last decade a rapid development of the biogas industry has been observed in this area (Grunewald, 2012). For regional subdivision of Saxony and main spatial element of the study we used ‘biomass providing units’ (BPU) which separate catchment areas (i.e. for agricultural substrates) from competing biogas plants as defined by Franko *et al.* (2015). The location and capacity of the biogas plants within Saxony were determined by Das *et al.* (2012). Relevant cropping and livestock data was aggregated to the BPU level.

We assumed that every BPU had a closed matter cycle regarding agricultural substrates in the context of biogas production. The feedstock demand of a biogas plant was supplied by the agricultural area within the associated BPU, with the biogas digestate being returned to the same area. The agricultural land required for the production of biogas feedstock and disposal of digestate was defined as “biogas fingerprint area” (BFA) of a BPU (section Estimation of the biogas fingerprint area). The soil related carbon flows within the BFAs are assumed to differ from the surrounding agricultural land (section Carbon flows into soil). It was hypothesized that depending on the installed electrical capacity and the feedstock mix of the biogas plant, as well as the regional agricultural parameters (e.g. crop mix and yields, livestock mix, management of the arable land), every biogas plant will have its own unique BFA.

For each BPU the associated land use considerations are shown in Figure 1. The crop mix of the BFA corresponds to the direct and indirect demands for biogas feedstock. Depending on the fertilization intensity, the agricultural area needed for the application of digestate may be smaller or larger than the area for production of biogas feedstock. If the area needed is larger, an additional area for the application of biogas digestate was considered to be necessary. Prior to the implementation of biogas production, livestock excrement were applied to all arable land (year 2000). However, with the installation of biogas plants (year 2011), it was assumed that excrement not used for biogas production were applied only to the BPU area outside of the BFA.

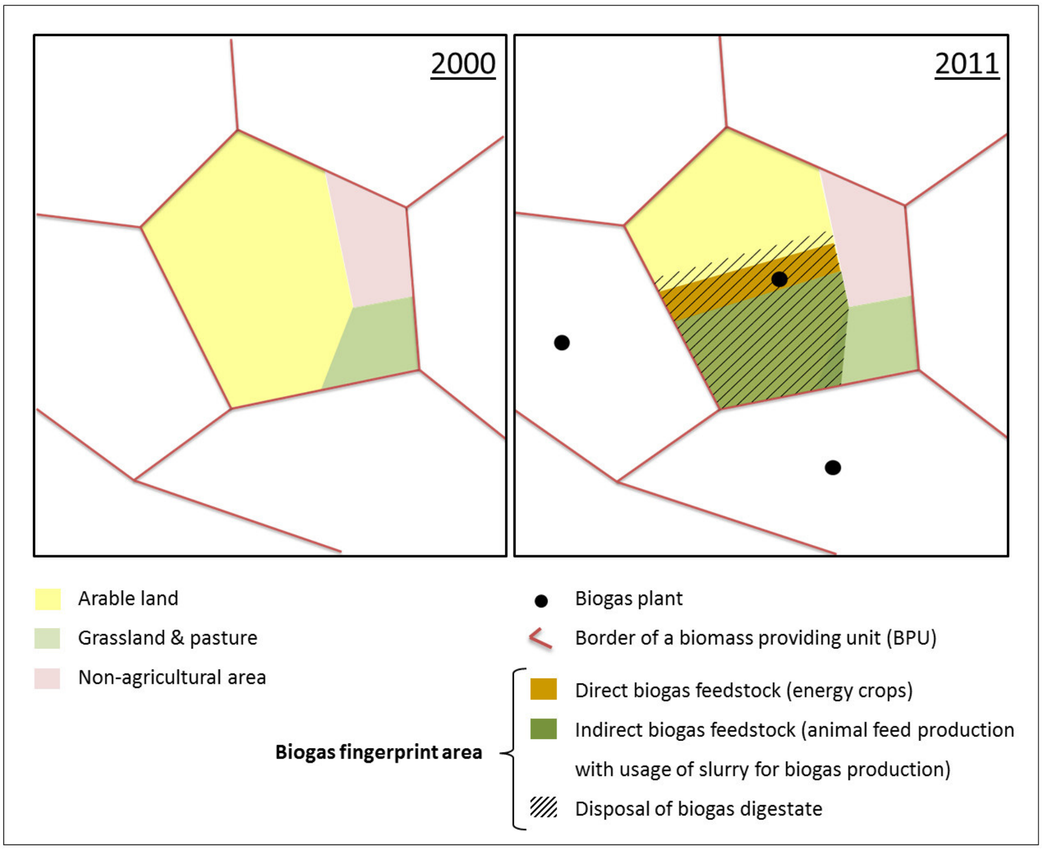


Figure 1: Graphical representation of a 'biomass providing unit' (BPU) and its associated land use categories for the base year of 2000 (without a biogas plant) and the year 2011 (with a biogas plant). For the 2011 time step a 'biogas fingerprint area' (BFA) is shown, to denote the area where the cycling of agricultural matter and the input of carbon to SOM is influenced by biogas production.

2.2 Regional agricultural parameters

2.2.1 Land use and agro-economic regions

The federal state of Saxony (approx. 18,400 km²) is dominated by arable land-use (Figure 2). Due to the very fertile loess soils, which cover a large part of the study area, 52 % of the region is used for agricultural purposes. Saxony can be subdivided into three main "agro-economic regions", based on characteristics of soil, landscape characteristics and their associated agricultural activities (LfL, 1999). These include: (1) Saxon heath and pond landscape, (2) Saxon loess region, (3) Saxon low mountain range and foreland. For more information see supplementary material (Table A1).

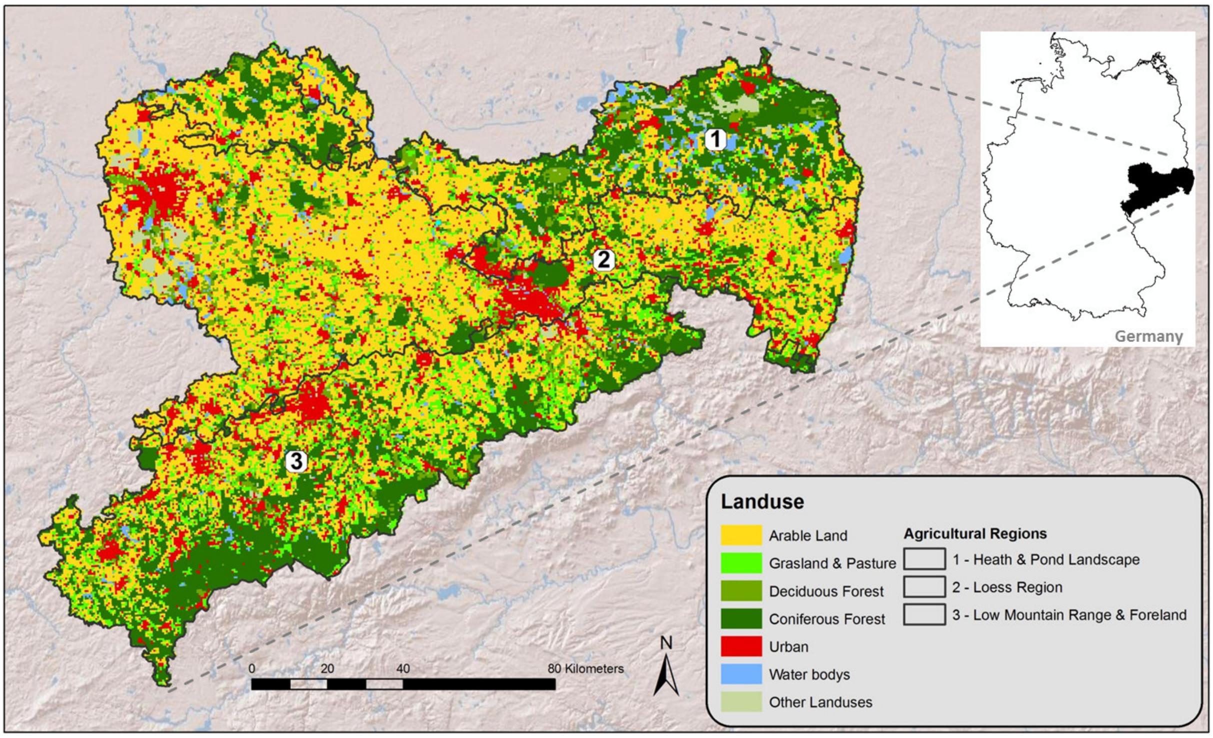


Figure 2: Location in Germany, land-use and the agro-economic regions of Saxony.

2.2.2 Crop harvest areas and yield

Data on crop harvest areas and crop yield for 20 different crops as well as catch crops have been provided by the 'State Agency for the Environment, Nature Conservation and Geology of Saxony' (LfULG). Crop harvest areas are derived from statistics on municipality level (year 2000) and InVeKoS data (Integriertes Verwaltungs- und Kontrollsystem) for the year 2011. Crop yield data was based on analysis of the software BEFU, a fertilization advisory system used by Saxon farmers (Förster, 2013). Essential crops included in the analysis, as well as their average areal share and yield for the period 2000-2011 are shown in Table 1. For these years cereals were found to be the dominant crops (58 %) in Saxony, followed by winter rape (15 %) and maize for silage (9 %).

Non-harvested biomass was characterized into two groups, crop residues and crop by-products, -based on the potential usage of the material (see also section Carbon flows into soil). While residues like crop roots and stubble were assumed to be left on the field, the fate of by-products depends on farmers decision: by-products (i.e. straw) can be left on the field or carried away to be used as litter for the livestock stable or sold on the market. Based on expert knowledge, at the state agency LfULG, it was assumed that by-products of relevant crops were removed from approx. 20% of the arable area.

Table 1: Average crop shares and crop yields within the agro-economic regions of Saxony for the period 2000-2011.

	Heath & Pond Landscape		**Loess Region**		**Low Mountain Range & Foreland**	
	Share [%]	**Yield** [t ha^{-1}]	**Share** [%]	**Yield** [t ha^{-1}]	**Share** [%]	**Yield** [t ha^{-1}]
Winter Wheat *(Triticum aestivum)*	13.7	6.4	31.9	7.2	15.5	6.5
Winter Barley *(Hordeum vulgare)*	13.0	5.9	14.5	6.9	11.8	60.0
Winter Rye & Triticale *(Secale cereal & Triticosecale)*	26.1	5.0	6.8	6.2	8.3	5.5
Spring Cereals *(Hordeum*	4.0	4.4	5.2	5.0	19.8	4.7

vulgare & Triticum aestivum)						
Winter Rape *(Brassica napus)*	12.2	3.4	16.9	3.9	14.3	3.8
Maize for Silage *(Zea mays)*	9.7	42.4	7.7	46.7	10.5	44.0
Field Grass *(Lolium multiflorum & Lolium perenne)*	2.5	30.9	1.6	38.5	5.4	39.0
Clover Grass *(Trifolium pretense & Lolium multiflorum)*	1.3	38.7	1.3	39.7	6.5	38.0
Other[1]	17.4		14.0		8.1	

[1]fallow, sugar beet *(Beta vulgaris)*, grain maize *(Zea mays)*, vegetables, legumes, sunflower *(Helianthus annuus)*, potatoes *(Solanum tuberosum)*

2.2.3 Excrement

We calculated the amount of excrement available for field application or biogas production ($excr_{av}$ in t a^{-1}) based on livestock statistics on district and municipality levels (StLa, 2016a, 2016b). Therefore the total amount of excrement produced from all livestock was corrected for the amount that is left on pasture during grazing (StLa, 2012a). For each animal group *i* the specific average annual amount of excrement (*$excr_i$ in* t a^{-1}; LfULG, 2015), the share of grazing time within one year (*grzt [-]*) and the number of individuals within this group (*n*) was used to calculate the amount of excrement which we assumed to be slurry:

(1)

The data was aggregated from municipality level to BPU level using the areal share of municipalities in the BPUs. Within the BPUs the excrement not used for the production of biogas was assumed to be equally distributed on arable land outside of the BFA.

2.3 Profile of regional biogas plants

2.3.1 Deriving representative feedstock mixes

The substrate mix used for the production of biogas can vary widely between individual biogas plants making it difficult to parameterize in large scale assessments. Therefore, the demand for biomass substrate was estimated using the approaches outlined in **O'Keeffe** *et al.* (2016) in collaboration with the DBFZ (Deutsches Biomasseforschungszentrum) (Ponitka *et al.*, 2015). Six biogas clusters with representative feedstock profiles for agricultural biogas plants were identified for the federal state of Saxony (Table 2). The biogas clusters were differentiated by installed capacity and for the capacity class 151-500 kW also by agro-economic region. For the other capacity classes, a regional differentiation was not possible due to data limitations. The representative feedstock profiles for each biogas cluster were used to generate the appropriate feedstock demand for each biogas plant based on their individual installed electrical capacities (kW_{el}). Manure and slurry have been merged to the feedstock class "animal excrement" using the differences in dry matter and carbon content of dry matter to be consistent with the calculation of available excrement (section Excrement).

Table 2: Profiles of representative feedstock demand (in tons of fresh matter) for 1 kW installed electrical capacity (tFM kW_{el}^{-1})

Power Category [kW_{el}]	**<150**	**150–500**			**500–1000**	**>1000**
Associated sub-region[1]		**HPL**	**LR**	**LMRF**		
Animal slurry	43.4	22.9	54.6	77.9	43.8	5.9
Animal manure	2.8	3.3	1.9	0.6	1.0	6.4
Maize silage	6.43	6.72	6.78	2.03	5.31	14.81
Cereals[2]	2.95	1.76	0.88	0.57	1.84	0.85
Grass silage	-	3.30	1.27	3.29	1.36	0.23

[1]HPL=Heath & Pond Landscape; LR=Loess region; LMRF= Low Mountain Range & Foreland

[2]Cereals is a grouping referring to the following crops: Rye, Barely, Triticale

2.3.2 Indirect feedstock requirements

Beside direct area requirements for the production of energy crops, the use of animal excrement for biogas production implicates an indirect land use, in relation to the fodder crops used for livestock production (i.e. the original carbon sources for the animal excrement). We determined the livestock associated with a biogas plant from the relation between the required amount of excrement of the biogas plant *($excr_{bg}$* in t a^{-1}) and the available excrement within a BPU, assuming that this relationship describes the proportion of animals associated with biogas production (N_i):

(2)

The total fodder amount of type *k* (tfd_k in t a^{-1}) necessary to feed the animals associated with a biogas plant was calculated, based on the typical daily fodder demand of type k (d$fd_{i,k}$ in t d^{-1}) and the total number of animals associated with biogas production:

(3)

The diet for dairy cows and cattle was assumed to be a silage mix from grass and maize of 25% and 75% respectively, with a cereals diet assumed for pigs (Table 3) (Gruber *et al.*, 2004, 2006). Additionally, it was assumed that only a basic diet is produced on the farm and concentrates were imported. Therefore, these were not considered for the calculation of the BFA (see section Estimation of the biogas fingerprint area).

Table 3: Daily fodder demand of cows, cattle (elder than one year), brood sows and other pigs used for the calculation of indirect feedstock requirements. Calves and piglets are not considered. DM = dry matter; FM = fresh matter

		Dairy cows	**Cattle**	**Brood sows**	**Other pigs**
Total forage intake	[kg DM d^{-1}]	18,4	10,7	6,5	2
Basic diet		70%	70%	80%	80%
Maize silage	[kg FM d^{-1}]	36	21	-	-
Cereals	[kg FM d^{-1}]	-	-	6	1,8
Grass silage	[kg FM d^{-1}]	14	8	-	-

2.3.3 Biogas digestate

The amount of biogas digestate (*BGD* in t a^{-1}) produced and available for field application was estimated using equation (4).

(4)

Where *FM* is the quantity of required substrate (t a^{-1}), *BG* is the amount of produced biogas (t a^{-1}), *L* is the amount of losses during the fermentation process (t a^{-1}) and *x* are the substrates listed in Table 4. According to Vogt (2008), the carbon flows in the biogas were assumed to consist of the sum of CH_4 and CO_2. The amount of biogas (t DM a^{-1}) was calculated with:

(5)

Where *DM* is the substrate specific matter content (% FM), *oDM* is organic dry matter content (% DM), α is a substrate specific conversion factor for biogas (l kg^{-1} oDM^{-1}) and ρ is the substrate specific biogas density. Additionally, the nitrogen (N) content of the biogas was assumed to be insignificant. The carbon content of the biogas was determined from the share of CH_4 and CO_2 according to the specific substrate mix of the cluster.

Table 4: Substrate parameters used for biogas production calculations. DM = dry matter, oDM = organic dry matter content, biogas yield = substrate specific conversion factor for biogas (α), biogas density = substrate specific biogas density (ρ), losses = ensiling losses for silages (L_s), CH_4 = methane share in produced biogas.

Substrate	DM[1] [%]	oDM[1] [%]	C cont. [%]	N cont.[1] [%]	losses[3] [%]	CH_4 [3] [%]	Biogas yield[3] [l kg^{-1} oDM^{-1}]	Biogas density [kg m^{-3}]
Animal slurry	10	80	35[1]	4.67	0	55	380	1.28
Maize silage	28	95	45[2]	0.38	12	52	650	1.32
Cereals	86	97	45[2]	1.96	0	52	730	1.32
Grass silage	20	90	45[2]	0.38	12	53	600	1.31

[1] from CANDY database (Franko, 1996), [2] from *Schilling* (2000), [3] from *KTBL* (2012)

Losses during the fermentation process (L) were estimated using equation (6) and based on the assumption of 10 % N losses during digestion (Vogt, 2008). N is the substrate specific N content (%).

(6)

Consequently the N content of the biogas digestate (N_{BGD}) is also based on the N content of the biogas substrate and was estimated using the following equation:

(7)

2.4 Estimation of the biogas fingerprint area

The BFA corresponds either to the area which is needed for the production of the biogas feedstock (A_{pr} in ha) or to the area needed for returning the digestate (A_{rc} in ha) when it exceeds the fertiliser demand of A_{pr}:

(8)

A_{pr} is calculated from the direct and indirect feedstock requirements of a biogas plant (see sections Deriving representative feedstock mixes and Indirect feedstock requirements), considering typical ensiling losses *Ls* (Table 4) and the BPU specific yield *Y* (t ha^{-1}) of the relevant crops (*x*):

(9)

FM_x (in t) represents the feedstock requirement of energy crops or fodder crops. Grass silage demand is primarily provided by temporal grass crops and later by permanent grassland, if more substrate is required.

The area needed to recycle the digestate of a biogas plant (A_{rc} in ha) depends on the total N content of the digestate (N_{BGD} in t N) and application rates of N on arable land. We assume that the total amount of digestate-N applicable on A_{pr} (N_{pr} in t N) (1) compensates N offtake with harvested crops while (2) taking into account an application limit of 0.17 t N per ha given by legislation (DüV, 2017). If N_{BGD} exceeds N_{pr} the application area has to be extended by an additional area (A_{ex} in ha) for the disposal of the excess N (N_{ex} in t N):

(10)

(11)

with:

(12)

where Nc_x is the N content in the fresh matter of the harvested yield of crop *x*.

If N_{BGD} is less than N_{pr} (N_{ex}<0), N_{BGD} will be evenly distributed on A_{pr}. If an additional area is required for digestate disposal (N_{ex} > 0), it is related to the average N removal by crop yield from the BPU area surrounding A_{pr} (N_{rem} in t N):

(13)

BPUs where the local cultivation characteristics could not completely cover the feedstock demand of the corresponding biogas plants with respect to every type of substrate were excluded from the analysis. For example, some biogas plants at the Saxony border would require additional substrate from outside of the study region. This reduced the number of biogas plants included in the study from 183 to 121.

2.5 Carbon flows into soil

To characterize the impact of different land management systems on SOC we consider: (1) the total carbon flux from FOM into the soil as well as (2) the quality of different sources of FOM regarding the formation of new SOC. To assess the quality of the carbon flux from FOM to SOC, we use the "carbon reproduction flux" (C_{rep}), an indicator that aggregates the effect of different carbon sources on SOC storage (Küstermann *et al.*, 2008; Kolbe, 2010; Franko *et al.*, 2011; Brock *et al.*, 2013).

The total carbon input from FOM, as well as the C_{rep} flux into soil were calculated in accordance with the approach of the carbon turnover models in CANDY (Franko *et al.*, 1995) and CCB (Franko *et al.*, 2011). In this approach the turnover of several FOM pools (C_{FOM}) results in a carbon flux to the atmosphere (mineralization) and a C_{rep} flux into the SOM pool. We calculated C_{FOM} and C_{rep} (in kg ha^{-1}) for different types of arable carbon sources: organic amendments (excrement, digestate), crop residues (roots and stubble) and crop by-products (straw and beat leaves) (Figure 3).

C_{FOM} flows were estimated using BPU specific yield data for each crop and application rates for organic amendments, as described in the previous sections. Parameterization of the different carbon sources and crops was taken from the CCB database. For the conventional agricultural carbon flows (residues, by-products, excrement) a more in-depth description is given by Franko *et al.* (2011). Regarding the matter flows from biogas digestate, equation (14) was used to calculate the carbon amount ().

(14)

Here C_{BG} is the carbon equivalent of the produced biogas and C_{FM} is the total carbon amount of the biogas feedstock according to the material properties:

(15)

The carbon equivalent of the biogas C_{BG} was calculated using the molar volume of an ideal gas at 1 atmosphere of pressure V_m=22.42 l mol^{-1}, amount of biogas (BG_x), molar mass of carbon (M_C) in V_m depending on the methane share, biogas density ρ_x (kg m^{-3}) as sum over all added substrates x:

(16)

For the calculations of C_{rep} every source of FOM has its specific substrate use efficiency parameter (η) characterizing the potential quality of the substrate for the formation of new SOC (Franko *et al.*, 2011). The substrate use efficiency of biogas digestate was determined according to Prays *et al.* (2017).

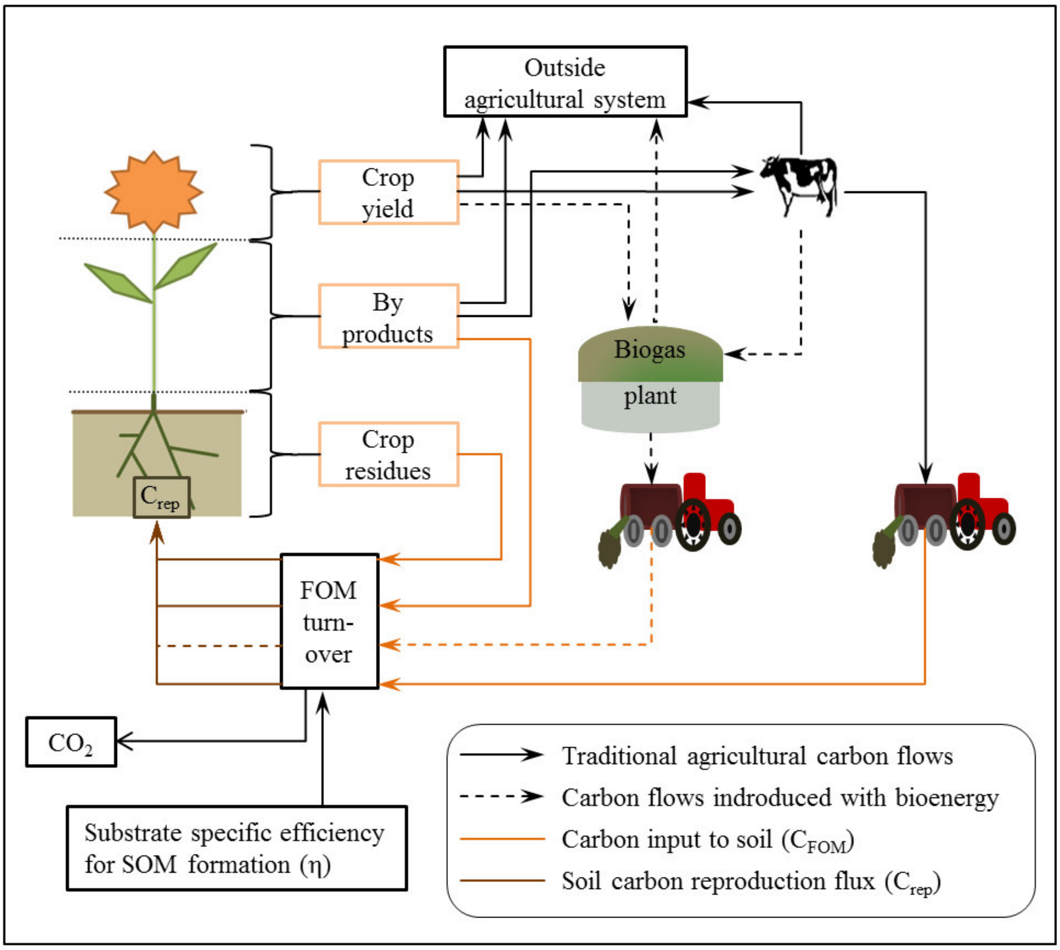


Figure 3: Carbon flows considered within the regional cycling of agricultural matter related to biogas production. Different pools of fresh organic matter (FOM) contribute to the total carbon flux to soil (C_{FOM}): crop residues, crop by-products, biogas digestate and livestock excrement. All sources of FOM have a different quality for the formation of new SOC. The C_{rep} flux is aggregating these differences and can be used as an indicator in a given environment to characterize the land use regarding SOC storage.

For the calculation of C_{FOM} and C_{rep} only arable land has been considered and permanent grassland has been left out. All carbon flows were calculated for two time steps, 2000 (without biogas) and 2011 (with biogas) for each BPU. For the year 2011, an additional analysis was performed for the BFA and for the area not affected by biogas production (see also section Spatial units of).

3 Results

3.1 Regional areal requirements of biogas production

3.1.1 BFAs and associated land use categories

The results of the model indicated that in 2011, the provision of biogas feedstock and distribution of digestate on average, affected 20.8 % of the arable land within the BPUs. When considering the total agricultural land in Saxony (including permanent grassland) the BFA of the biogas plants covered 17.6 % (Figure 4). Over 10 % of all BPUs, were found to have a fingerprint area exceeding 40 % of their BPU arable area.

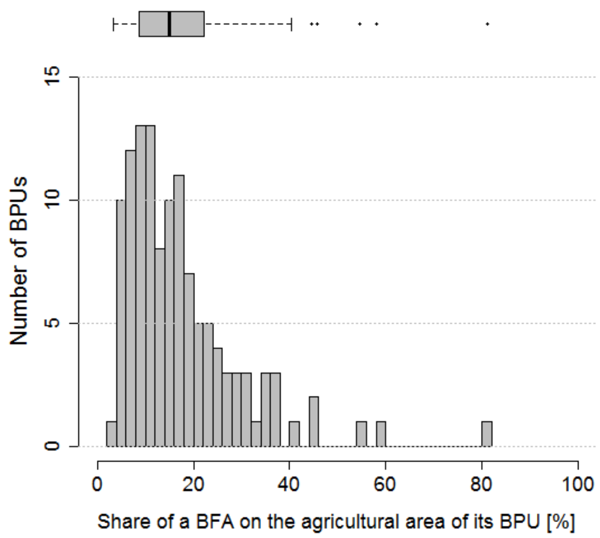


Figure 4: Share of the agricultural land of the BPUs in Saxony that is needed for the provision of biogas feedstock as well as for the distribution of digestate (BFA) in the year 2011.

The land use within BFAs was dominated by fodder crops on arable land (57.9 %). The primary use of these areas is the production of meat and milk. The use of the livestock excrement for the production of biogas is a secondary and indirect use of these areas. The cultivation of energy crops on arable land covered 19.8 % of the average BFA in Saxony and 7.1 % was covered by permanent grassland. For most of the BFAs an additional area for the application of digestate was necessary. Digestate application to additional land outside the feedstock catchment accounted for 15.2 % of an average BFA in Saxony.

3.1.2 Relationship between BFA and installed capacities

Relating the BFA to the installed electrical capacity of its biogas plant allows the different biogas systems to be compared with respect to the areal demand and hence areal efficiency per electrical energy output (ha kW_{el}^{-1}). On average for Saxony 2.0±0.4 ha kW_{el}^{-1} (± is the standard deviation) agricultural land was found to be influenced by biogas production. However, only 0.4±0.1 ha kW_{el}^{-1} from that was related to the cultivation of energy crops on arable land. The major part of the land demand consisted of fodder crops on arable land (1.2±0.3 ha kW_{el}^{-1}) for cattle supply, but also the additional area for digestate disposal was covering 0.3±0.3 ha kW_{el}^{-1}. To fulfill the demand for grass silage 0.1±0.1 ha kW_{el}^{-1} of permanent grassland was needed next to the use of field grass from arable land. Between individual BFAs the results differed due to regional differences in crop yields and livestock mix, as well as parameters of the specific biogas plant (e.g. installed capacity, feedstock mix).

The Saxon heath & pond landscape (1.8±0.3 ha kW_{el}^{-1}) as well as the loess region (1.9±0.2 ha kW_{el}^{-1}) showed significantly smaller area requirements than the low mountain range and foreland (2.6±0.4 ha kW_{el}^{-1}). Next to regional differences in crop yield this is a result of the greater number of smaller biogas plants in the low mountain range.

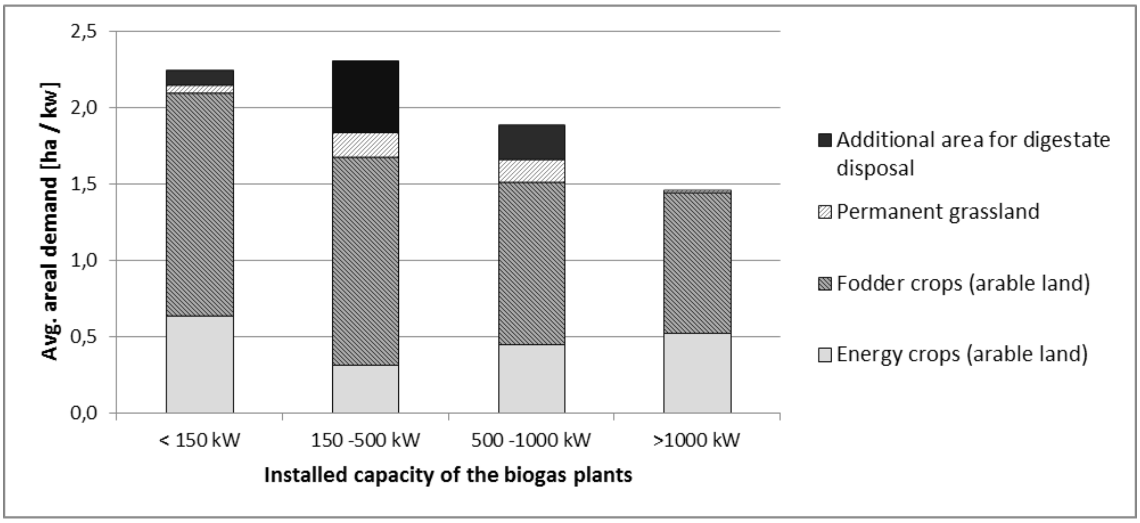


Figure 5: Average area demand (ha) per kilowatt installed electrical capacity of the biogas plants in Saxony. Biogas plants are differentiated by size classes. Area demand is separated by land use categories within a BFA.

Depending on the size classes of the biogas plants major differences in the total area demand and its composition have been observed (Figure 5). A constant decrease in the area requirements for the provision of biogas feedstock was found with increasing classes of plant size. While biogas plants with installed capacity < 150 kW_{el} typically needed 2.1±0.3 ha kW_{el}^{-1} for feedstock supply, plants > 1000 kW_{el} only needed 1.5±0.1 ha kW_{el}^{-1}. This pattern was primarily caused by lower indirect feedstock requirements in the feedstock mix of larger biogas plants. But also the location distribution of the biogas plants and the subsequent agricultural yields are important factors. The area demand for the cultivation of direct feedstock requirements (energy crops) was lowest (0.3±0.1 ha kW_{el}^{-1}) for biogas plants in the size class 150-500 kW_{el}. However, biogas plants in this capacity range showed the highest total areal demand per kW_{el} due to large requirements regarding additional area for digestate disposal (0.5±0.3 ha kW^{-1}). Input from energy crop cultivation was especially high within BPUs containing plants in the size classes <150 kW_{el} and >1000 kW_{el}. This was most of all due to a high share of energy crops (>1000 kW_{el}) and especially cereals (<150 kW_{el}) in the feedstock mix.

3.2 Regional carbon input to soil before and after implementation of biogas plants

The average carbon input into the arable soil of the Saxon BPUs was 2,905 kg C ha^{-1} in the year 2000 and increased slightly to 2,965 kg C ha^{-1} (+2.1 %) in the year 2011, after the implementation of biogas plants. When considering the quality of different sources of FOM for the formation of SOC by using the indicator C_{rep} we observed an even higher increase of 2.8 % (2000: 1,524 kg C_{rep} ha^{-1}; 2011: 1,567 kg C_{rep} ha^{-1}). Within the individual BPUs the changes between 2000 and 2011 are much more apparent, ranging from -388 kg C ha^{-1} to +576 Kg C ha^{-1} or -119 kg C_{rep} ha^{-1} to +297 kg C_{rep} ha^{-1} respectively.

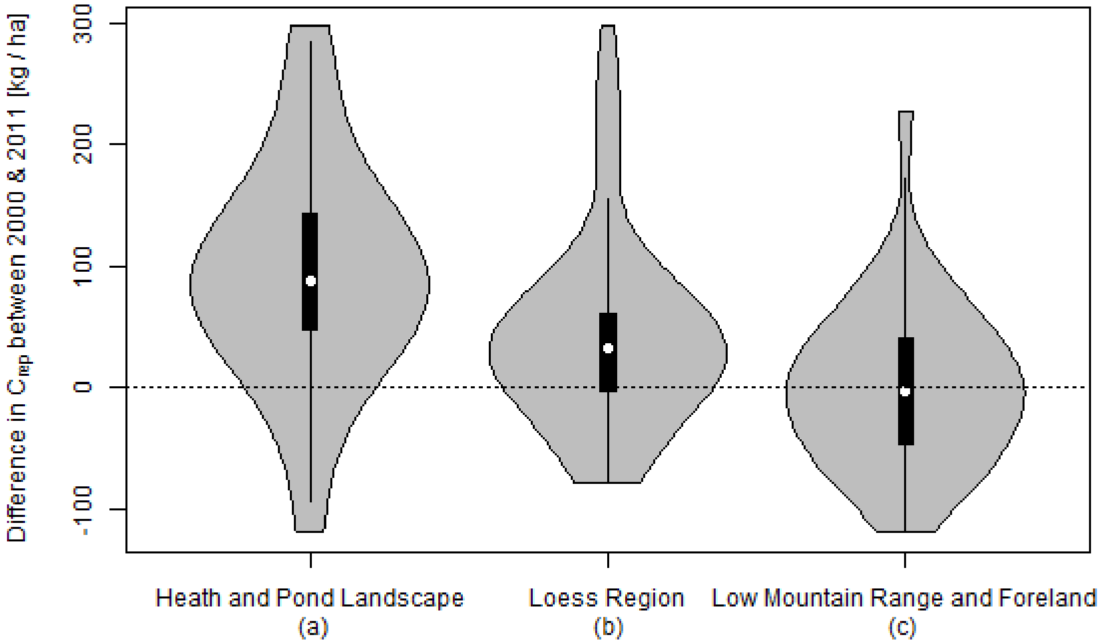


Figure 6: Violin plot showing the difference in C_{rep} between 2000 and 2011 on BPU-level, differentiated into the agro-economic regions within Saxony. The difference between the regions is significant (Welch t-test p-values: (a)-(b) 0.027, (a)-(c) <0.001, (b)-(c) 0.007). The Violin plot is combining a boxplot with a density plot.

The differences between individual BPUs were partly affected by their geographic location. On the level of agro-economic regions (Figure 6) significant differences in the temporal development of SOC input can be observed (ANOVA p-value: <0.001). Only limited statistical relationship between biogas plants capacity and SOC input have been found. BPUs having biogas plants in the power category 150-500 kW_{el} (+1.4 % C_{rep}) contributed significantly less to the increase C_{rep} fluxes than the BPUs having biogas plants in all the other power categories (+4.0 % C_{rep}) (Welch t-test p-value: 0.013).

3.3 Changes in carbon sources

3.3.1 SOC input from arable crops

The total crop based C flux into soil from all analyzed BPUs displayed a moderate increase (+5.8 %) between 2000 (1,453 × 10^3 t C) and 2011 (1,538 × 10^3 t C). At the same time the contribution of the different cultivated crops changed greatly. Table 5 summarizes the quality adjusted C input (C_{rep}) from individual arable crops for the two time steps, 2000 and 2011. Winter rape, maize, winter wheat and sugar beet showed a high total increase in C_{rep}. A decline in C_{rep} contribution was observed for all cereals other than winter wheat. The contribution from fallow land was also seen to drop remarkably, as these areas went back into cultivation. The shift in C input to SOM of different crops is primarily caused by changes in cultivated area and less by changes in yield.

Table 5: Total soil carbon reproduction flux (C_{rep}) from the cultivation of different arable crops for the two years 2000 and 2011. C_{rep} is aggregating the carbon input to soil considering also the quality of different sources of FOM for the formation of SOC. Altering C_{rep} flows are caused by changes in the crop specific cultivated area and crop specific yields between the two time steps 2000 and 2011.

	Total C_{rep}		**Differences between 2000 & 2011**	
	2000 [10^3 t C]	**2011** [10^3 t C]	**Cultivated area** [%]	**Yield per area unit** [%]
Winter Wheat	235.6	268.1 (+14 %)	+13.8	+0.1
Winter Barley	121.0	103.4 (-15 %)	-16.0	+2.4
Winter Rye & Triticale	98.1	62.4 (-36 %)	-32.3	-4.4
Spring Cereals	49.3	45.5 (-8 %)	-12.4	+7.0
Winter Rape	81.9	127.0 (+55 %)	+43.7	+9.1
Maize for Silage	26.8	43.2 (+61 %)	+61.4	-0.4
Grain Maize	12.2	21.7 (+78 %)	+63.9	+12.2
Field Grass	21.7	26.4 (+22 %)	+28.5	-9.9

Clover Grass	16.3	15.2 (-7 %)	-6.2	-4.2
Sugar Beet	22.1	32.3 (+46 %)	+23.4	+18.3
Other[1]	52.2	27.2 (-48 %)	-32.2	-

[1] Fallow, vegetables, legumes, sunflower, potatoes, catch crops

3.3.2 SOC input from organic amendments

Our results indicate that major shifts in C flows on arable soils between 2000 and 2011 were associated with the type and contribution of organic fertilizers (i.e. animal excrement and biogas digestate). The total amount of regionally available C from livestock excrement declined from 295.8 × 10^3 t in 2000 to 259.0 × 10^3 t in 2011 (12.4 %) due to a reduction of livestock numbers. In the year 2000 all excrement were assumed to be applied to arable land, whereas in 2011 only 65% (167.2 × 10^3 t) of the potential available C from livestock excrement could be used for this purpose. This was because the remaining part of livestock excrement (91.8 × 10^3 t C) was used for the production of biogas. However, due to the usage of plant material (additional to the excrement) for biogas production, the C input to soil from biogas digestate (80.3 × 10^3 t) compensates the livestock related C that was taken out of the traditional matter cycling. When considering the different quality of excrement and digestate for the formation of SOC the total contribution of organic amendments to C_{rep} fluxes decreased by only 5.1 % in the period under study (2000: 180.4 × 10^3 t C_{rep}; 2011: 171.1 × 10^3 t C_{rep}) despite the reduction in livestock (-12.4 %).

3.4 Carbon fluxes in- and outside of the BFA

Both C_{FOM} and C_{rep} were found to be lower on the arable land not needed for the provision of biogas feedstock and distribution of digestate (C_{FOM}: 2,956 kg ha^{-1}; C_{rep}: 1,518 kg ha^{-1}) than on the fingerprint areas of the biogas plants (C_{FOM}: 3,008 kg ha^{-1}; C_{rep}: 1,814 kg ha^{-1}). Indeed the C_{rep} fluxes were significant different (16.3%; Welch t-test p-value: <0.001).

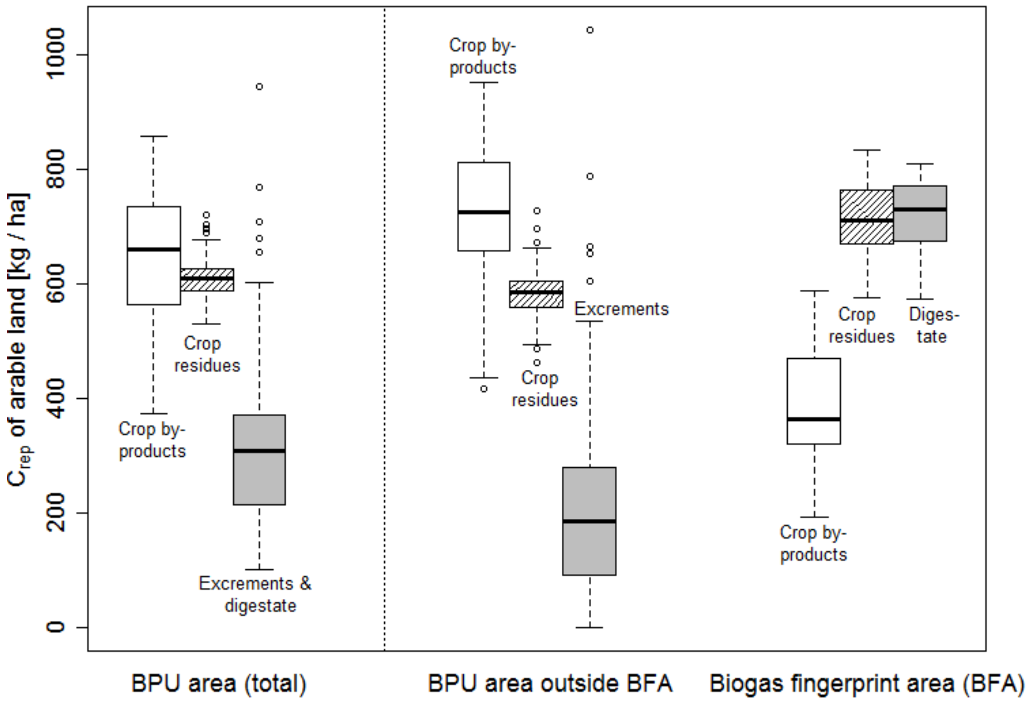


Figure 7: Soil-carbon reproduction fluxes (C_{rep}) of arable land for the year 2011 and with respect to different sources of carbon. C_{rep} aggregates the carbon input to soil considering also the quality of different sources of FOM for the formation of SOC. Regional basis are biomass providing units (BPU) as well as the two areal categories within a BPU: (1) biogas fingerprint area (BFA) and (2) BPU arable land outside of the BFA.

When analyzing the different carbon sources the BFAs showed a high carbon input to soil from crop residues and digestate application (Figure 7). The first is mainly due to a comparatively high share of agricultural grassland within the BFA which typically has higher amounts of residues (e.g. roots). The second is mainly due to the extensive application of digestate up to the limitation for organic N application. Furthermore, within the BFAs the amount of C from crop by-products (e.g. straw) is reduced, due to a lower share in cereal cultivation. In total the C_{rep} provision by arable crops (crop residues and crop by-products) is lower in the BFAs than in the surrounding BPU area.

4 Discussion

4.1 Influence of biogas production on land use

We developed a new approach of a 'biogas fingerprint area’ to determine and characterize the agricultural areas affected by biogas production, due to their feedstock requirements and digestate recycling. This is in contrast to the concept of the ‘ecological footprint’ (Wackernagel & Rees, 1997). We deal only with the direct land area requirement for the production of biogas and disposal of digestate and within this, only the associated direct soil carbon fluxes. The BFA aggregates effects of location (e.g. crop yields) and management (e.g. feedstock mix of the biogas plant, fertilization practices). Therefore, the relationships between (1) the BFA and the total agricultural land of its BPU, as well as between (2) the BFA and the installed electrical capacity of its biogas plant are two valuable indicators for the analysis and differentiation of bioenergy production systems on larger scales. In this study the application of our methodology was successfully demonstrated for Saxony.

The need to establish a greater understanding of the relationship between power supply and area requirements of different renewable energy sources has already been identified (Evans *et al.*, 2009; Lechon *et al.*, 2011; Scheidel & Sorman, 2012; Popp *et al.*, 2014; Wüstemann *et al.*, 2017). Therefore, the results of this study contribute to a better understanding of this in relation to biogas production on the regional scale. We found that biogas production consumed the harvested crop yield from 4.1% of the BPUs arable land due to their direct feedstock requirements. This corresponds to on average 0.4 ha of energy crops from arable land per 1 kW_{el} installed capacity of an average biogas plant in Saxony. A similar range has been discussed in other studies analyzing the area demand of biogas plants in German study regions (Hartmann, 2008; Delzeit *et al.*, 2011). But we also showed that the total area requirements of the biogas production systems in Saxony, including indirect feedstock requirements and the area needed for disposal of excess digestate, are many times larger than the area strictly dedicated to energy crop cultivation. Within the study period considered the harvest areas of the different cultivated crops changed considerably. While for the majority of crops, the increase in cultivated area may have been influenced by bioenergy production, the observed changes are also influenced by general changes in agricultural management (e.g. rotations).

Soil, climate and agricultural structure are important factors which distinguish the agro-economic regions in Saxony (StLa, 2004, 2012b) and effected the management (e.g. feedstock mix) and area requirements of the biogas plants. For example a large variability has been found with respect to the area needed for the disposal of digestate. But the regional properties (e.g. livestock numbers, yield potential) also affect the biogas plants themselves, e.g. with respect to the choice of power category that has been build. Other studies have shown, that there is an incentive to build larger biogas plants in areas having high yield expectations as this limits transportation distance and costs (Delzeit *et al.*, 2009, 2012). It is important to understand these relations to be able to give scientifically substantiated recommendations on how to improve the management of those complex agricultural systems. The indicators developed in this study can help to identify critical hot-spots, where an increased competition for agricultural area and harvested crop yield may occur on one side between neighboring biogas plants, but also between biogas production and food production.

4.2 Biogas driven modifications in SOC input

The approach presented in this study can show the differences in carbon fluxes into soil between conventional agricultural systems and those with integrated biogas production. This is important, as the effects of bioenergy feedstock cultivation on SOC storage is a key factor in determining the sustainability of bioenergy (Anderson-Teixeira *et al.*, 2009; Tiemann & Grandy, 2015; Schrama *et al.*, 2016). Our results indicate that biogas production can be a win-win strategy that substitutes fossil fuel and leads to a positive effect on regional SOC input in Saxony. This also applies when considering the quality of the different sources of FOM for the formation of SOC.

The observed temporal shifts in carbon fluxes cannot be used to predict changes in long term SOC stocks, as they also depend on regional turnover conditions and the historical SOC development of the site. Large scale detailed monitoring data of SOC stocks in agricultural soils would allow quantifying actual changes in SOC storage. However this kind of monitoring for the whole Saxon study region has yet to be conducted. For future studies it may be an option to initialize regional SOC levels based on interpolation of available site measurements (Schloeder *et al.*, 2001; Li, 2010; Mishra *et al.*, 2010).

We propose to use the difference between the carbon input fluxes inside and outside of the BFA as indicator to characterize the sustainability of biogas production in terms of SOC storage. In Saxony average C fluxes to soil have been higher in the BFAs than in the arable land outside the BFAs. However, BFAs had a very low carbon input to soil from crop by-products (e.g. straw), due to a low share in cereal cultivation. The BFAs benefited from the extensive application of digestate, as well as from a high area share of agricultural grassland which typically has higher amounts of residues (e.g. roots). The effect of feedstock mix on the sustainability of biogas production has already been recognized by policy measures (EEG, 2017). Policy measures addressing the feedstock mix can effectively control the use of substrates and would affect the area of crop cultivation (Britz & Delzeit, 2013).

The calculated amounts of organic fertilizers applied on arable land (excrement and digestate) are about 3% lower than reported in official statistics on the application of organic amendments in Saxony (StLa, 2011) but are within a reasonable range (9.6×10^6 t compared to 9.9×10^6 t). For all BPUs analyzed, the carbon input from organic fertilizers changed considerably within the observation time. While the application of livestock excrement on arable land was strongly reduced due to the use for biogas production and the reduction in livestock numbers, the application of digestate could almost completely compensate this. Here the higher quality of digestate for the formation of SOC is important. The digestate based carbon is essential to compensate the low crop based carbon fluxes within the BFAs. Most of the biogas plants needed more area for the application of digestate than for feedstock supply. More practical field research is required to determine the effects of applying digestate, as of yet this knowledge base is sadly lagging behind what is known about application of animal slurries.

It must be pointed out that the analysis focused only on the biogas catchments and does not consider any indirect effects on SOC outside of Saxony due to imported fodder. But for this study these possible drawbacks are quite low as the rate of internal fodder production in Germany kept at about 90 % between 2000 and 2011 (Deutscher Bundestag, 2012). Another uncertainty is the exact regional distribution of the livestock related organic fertilizers due to the spatial resolution of the initial data. However, the assumptions were consistent across the entire region and suitable for a relative comparison across the region.

4.3 Conclusions

The proposed modeling approach outlined in this paper has the benefit to provide better insight into agricultural carbon and matter fluxes, as well as regional area requirements related to biogas production. It is an attempt to understand the complexity of this system. It was shown that in the study region Saxony biogas plants can be operated sustainably with regard to SOC recycling. The total carbon flux into soil kept stable, with a slight tendency for an increase during the time period of the establishment of the biogas industry. On average, 17.6 % of the agricultural land in Saxony was determined to supply the biogas plants and dispose of their digestate in 2011. The comparison of carbon fluxes inside and outside of this biogas fingerprint areas is an easily applicable instrument to assess the influence of biogas production on the region’s SOC input.

Areas affected by biogas production showed a high carbon input to soil, but this was very reliant on the application of digestate. It could be beneficial if governments would develop “good farm practices” for agricultural systems operating biogas plants. Furthermore an adequate farm management planning has to be developed to deal with this different type of fertilizer.

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7 Supplementary material

Table A 1: Characterization of the agro-economic regions in Saxony. Average values for the specified periods.

	Heath & Pond Landscape	**Loess Region**	**Low Mountain Range & Foreland**
Temperature[1] [°C]	9,6	9,3	7,8
Precipitation[1] [mm]	736	770	961
Clay content[2] [%]	4,4	9,5	13,8
Silt content[2] [%]	22,8	65,3	58,2
Stone content[2] [%]	10,4	7,4	16,2
Arable land [%]	31,9	52,5	28,4
Grassland & pasture [%]	8,1	9,8	16,7
Catch crops[3] [%]	4,5	4,0	4,6

[1] Period 1990-2014, [2] of agricultural land (topsoil), [3] Period 2000-2012