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Long-Term Impact of Biogas Production on Soil Organic Carbon Storage

Nadia Prays[1] & Uwe Franko[2]

Abstract

Biogas residue (BGR) is a by-product of a biogas production, which is used as organic fertilizer in agriculture. We hypothesized that replacing undigested organic fertilizers with BGR leads to a decrease in soil organic carbon (SOC) due to (1) carbon off take during the anaerobic digestion process and (2) the change in cropping system after biogas production is implemented. Nine fields that were amended with BG Rs were selected to study carbon fluxes using the CANDY (CArbon and Nitrogen Dynamics) model. Two scenarios were analyzed. First, a simulation from 1973 to 2050 with a repeat of the cropping system and a crop rotation were used to evaluate the impact of BGR on soil. In the second scenario the BGR application was replaced with undigested cattle slurry using the same amount of N (kgNha^{-1}). Additionally, the cropping system from 1973 to 2016 was analyzed to highlight the most important drivers of SOC accumulation. The results demonstrated that BGRs did not affect SOC negatively over a period of ten years. The simulation predicted similar effect of BGRs and cattle slurry on SOC. The analysis of the cropping system showed that the changes in cropping system had greater impact on SOC than fertilization.

Keywords: bioenergy, carbon sequestration, modeling, farm scale, fertilization, biogas residues

1. Introduction

Biogas is an important renewable energy resource that decreases CO_2 emissions and can substitute fossil fuels. In 2016, most of the approximately 8,000 operating German biogas plants were part of agricultural farms. These farms use cattle slurry and energy crops to convert biomass into CH_4 and CO_2(DBFZ, 2015).During anaerobic digestion, approximately 60% of the carbon is transformed into CH_4 and CO_2. This observation supports the hypothesis that the application of biogas residue (BGR) decreases soil carbon and induces soil degradation when compared to the application of undigested organic material. Moreover, a shifting demand in agricultural products associated with biogas production may lead to changes, inter alia, in crop rotations that have a higher proportion of energy crops and management practices that reduce the recycling of byproducts (i.e., straw and beet leaves) into the soil. Under such conditions, the improvement and maintenance of soil quality in cropping systems may become critical to sustain agricultural productivity and environmental quality for future generations (Franko, Witing, Jäckel, & Volk, 2015).

The byproduct of biogas production is BGR. Biogas residues are usually applied as fertilizers to return nitrogen, carbon, and other nutrients to the soil. The effects of BGR application on crop yield, soil chemical, physical and microbial properties have been studied in small-scale experiments (Fouda, von Tucher, Lichti, & Schmidhalter, 2013; Sänger, Geisseler, & Ludwig, 2014) and short-term field experiments (Prays & Kaupenjohann, 2016; Terhoeven-Urselmans, Scheller, Raubuch, Ludwig, & Joergensen, 2009).Nevertheless, there is still little information available on the long-term effects of BGR on soil organic carbon(SOC) (Möller, 2015). Odlare et al. (2011)observed an increase in SOC after eight years of BGR application compared to a control treatment.

[1] Helmholtz Centre for Environmental Research – UFZ, Department of Soil Physics and Department of Bioenergy, Theodor-Lieser-Straße 4, 06120 Halle, Germany; nadia.prays@ufz.de; phone: +49-345-5585422, fax+49-341-235455422

[2] Helmholtz Centre for Environmental Research – UFZ, Department of Soil Physics, Theodor-Lieser-Straße 4, 06120 Halle, Germany; uwe.franko@ufz.de; phone: +49-345-5585 432

In contrast, Wentzel, Schmidt, Piepho, Semmler-Busch, and Joergensen (2015) showed that the application of biogas slurry over a 15- to 25-year period had no negative effect on SOC. Therefore, it is still an open question whether biogas can be used as a bioenergy source without depleting soil carbon stocks. BGR application adds carbon and nutrients to the soil, thus directly affecting soil organic matter (SOM) and long-term soil fertility. In contrast, biogas production could have an indirect effect via changes in the entire cropping system, e.g., in the crop rotation or the implementation of new energy crops. It is not entirely clear whether the largest impacton C_{org} results from direct application of BGRor indirect bioenergy-induced management changes (Möller, 2015). Wehypothesized that the replacement of undigested organic fertilizers with BGRs leads to a decrease in SOC due to carbon off take during the anaerobic digestion process together with the change in the cropping system after the implementation of biogas production. Therefore, we selected nine fields amended with BGR from a farm in Central Germany to study carbon fluxes using the CANDY (CArbon and Nitrogen Dynamics) model. This model processes site-specific information on soils, crops, weather, and land management to compute carbon stocks and fluxes in the topsoil of agricultural fields. To determine the sustainability of biogas production, the farmer's data records were used as input for the CANDY model. We evaluated the cropping system and focused on the changes in SOC stock during the following scenarios: a) the period before BGP installation, b) ten years after BGP installation and c)until 2050 with unchanged conditions.

2. Materials and Methods

2.1 Study area and farm environment

The farm is located south of Saxony-Anhalt, Germany. The long-term mean annual temperature is 9.6°C, and the long-term mean annual precipitation is 536mm. The soils are derived from loess and sand loess. The farm produces market and fodder crops as well as milk. A portion of the crops as well as the cattle slurry from dairy cows and cattle manure are used as substrates for the on-farm BGP. Five fields with typical cropping systems were selected. Three fields (62, 65, and 85) were less than 2kmfrom the biogas plant. Two fields (25 and 44) were the most distant (approximately 5 km) from the BGP. Between 1973 and 2003,four of the selected fields were split into subplots (e.g., field = 62, subplot = 620 and 621) if the chosen field was divided into two fields more often than 15% of the studied time-period. We evaluated nine fields, including 250, 251, 440, 441, 620, 621, 650, 651 and 850.

2.2 Biogas plant and BGR

The biogas plant was established in 2005and only uses substrates that are produced on the farm. The feeding mixtures consist of crops (27.6% maize silage, 2.1% lucerne, 1.1% grass silage, and 2.9% cereals) and animal excrement (52.9% cattle slurry and 13.4% cattle manure). The substrate is wet digested in two fermenters for 94 d at 40°C. The BGR is characterized by 5.4(±0.5)% of dry matter (DM), 7.9(±0.2)%total nitrogen, 4.5(±0.9)%NH_4-N, a C/N_{org} ratio of 13.9, a pH of 7.9,k of 0.408 d^{-1} and η of 0.887. Each chemical parameter of the BGR used in this study is a mean value from samplings in four different years. The decomposition rate coefficient k describes the rate of organic matter decay and the synthesis coefficient η describes SOM creation from BGR. These values were calculated from the pH and C/N ratio according to Prays, Sänger, Dominik, and Franko (2017).

2.3 Model calculations and input data

We used the simulation model CANDY (CArbon and Nitrogen Dynamics, http://www.ufz.de/ index.php?en=39725)as described in detail by (Franko, Oelschlägel, & Schenk, 1995).The model requires a site-specific description of the soil profile (texture, wilting point, water capacity, saturated conductivity, bulk and particle density), meteorological data (air temperature, precipitation, and global radiation or sunshine duration), and management information (tillage, fertilizer, organic amendments, and harvest).One important application of the CANDY model is the calculation of the long-term dynamics of organic matter turnover in arable soils and the short-term dynamics of nitrogen transformation (Franko et al., 1995).We used the CANDY model to calculate the SOC concentration (C_{org}) in the upper 30cm of soil as well as the yearly N uptake by the crops. Model initialization was performed by adjusting the initial value of C_{org}manually during the spin-up run to fit the SOC values to measured values.

2.4 Soil organic carbon measurements

Soil organic carbon measurements were required for model validation. Therefore, the C_{org} data from the farmer as well as our measurements were used. Data from the farmer included measurements from fields 250 and 251 from 2000 through 2002 and fields 620, 621, 650, 651, and 850 from 2000.

Our soil sample measurements were taken between 27.08.2013 and 05.11.2013. On each field, five to nine mixed samples were taken from 0-30cm, each with approximately 1kg of soil. For the organic carbon analysis, samples were milled and analyzed with a CN auto-analyzer (LECO Instruments, St. Joseph, USA). Mean values and standard deviations were calculated. RMSE was calculated between the modeled and measured C_{org} values and was used for validation.

Further input data is described in the following section.

2.5 Climatological time series

Daily means of air temperature (°C), daily sums of precipitation (mm), and daily sums of sunshine duration (hours) were collected from the meteorological station in Bad Kösenprior to 2007. This meteorological station is approximately five kilometers away from the farm (beeline) and therefore reflects the same climatic conditions of the farm. After 2007, data from the meteorological station in Bad Kösen were no longer available, and we used data from the station in Naumburg/Saale-Kreipitzsch (DeutscherWetterdienst, 2015). The farm and the meteorological station are approximately six kilometers apart. Nonetheless, the sunshine duration data from 1992-1993 and 2009-2014 as well as the air temperature between 1985 and 1993weremissing. For this period data, gaps were filled from the meteorological station in Osterfeld, which is approximately 30kmaway from the farm. For the predictions between 2016 and 2050,the weather data from a 30-year period (1987 to 2016)were repeated.

2.6 Soil data

Texture and bulk density [g cm-³] were extracted from the soil map VBK50 (scale 1:50,000)to determine soil type on the selected fields(LAGB, 2012). Particle density was set to 2.65 [g cm-³]. The soil type and bulk density were also used to derive the following parameters: field capacity [Vol.-%], wilting point [Vol.-%] and saturated conductivity [mm d-¹] according to the German mapping guideline KA5(Ad-hoc-AG Boden, 2005). The soil map provided information about silt dominated soil types, which are typical in the region (Table 1). As soil heterogeneity in this region is low, we selected the most representative soil types for modeling: soil 1 for fields 250, 251, 620, 621, 650, and 651; soil 2 for fields 440 and 441; and soil 3 for field 850. Table 1 Soil type properties of the investigated fields that were used for carbon flux modeling. BD=bulk density, PV=pore volume, FC=water content at field capacity, WP= water content at wilting point, Ks= saturated conductivity.

Soiltype	horizon	depth [dm]	BD [g/cm³]	PV [Vol-%]	FC [Vol-%]	WP [Vol-%]	Ks [mm/d]	clay [M-%]	Silt [M-%]
1	1	3	1.23	44	37	16	130	18	74
	2	5	1.42	43	37	12	120	16	79
	3	7	1.48	44	37	16	130	24	75
	4	20	1.52	43	37	12	120	14	79
2	1	3	1.23	44	37	16	130	18	74
	2	4	1.52	43	37	12	120	14	73
	3	8	1.53	43	37	20	90	25	70
	4	20	1.52	43	37	12	120	14	79
3	1	3	1.23	44	37	16	130	18	74
	2	5	1.34	44	37	16	130	21	72
	3	7	1.51	44	37	16	130	17	78
	4	20	1.52	43	37	12	120	14	79

2.7 Cropping system

To model the cropping system, information on sowing and harvest (date and yield), fertilization (date and amount) as well as date and depth of tillage were required. From 1973 to 1991, crop yields, application rates of mineral and organic fertilizers and information on tillage were available. Dates of sowing and organic fertilization missed completely. Seventy percent of the dates were available between 1973 and 1991 for mineral fertilization, tillage and harvest. All gaps were filled according to typical farm management from other years or according to good agricultural practices(Doleschel & Frahm, 2014). From 2003 to 2016, all required data were available. From 1992 to 2002, only crop rotation data were available. After consulting with the farmer, this data gap was filled by repeating the soil management from 2003 to 2016with respect to the cultivated crop.

During this period, cattle slurry was used instead of BGR, with an equivalent concentration of nitrogen. For data and trend analyses, we used the data from 1973-1991 and 2003-2016. We calculated the yields in $dtha^{-1}$, N application (mineral, organic and total) and N uptake by crops in $kgha^{-1}$ as well as the yearly means, standard deviations and linear trends. For every year, one mean value for all fields was calculated. The periods from 1973-1991 and 2003-2016 were compared. Trends were analyzed by a one-way ANOVA. Tukey's 'Honest Significant Difference' method (HSD) was used to compare mean values and to assess the significance of the differences between mean values. Trends were considered significant when $p< 0.05$. For silage maize and sugar beet yields, the trends were considered significant when $p< 0.1$.All statistical analyses were performed using R version 3.3.1 (The R Foundation for Statistical Computing, 2016).

2.8 Crop parameters

The model parameters of crops that were cultivated between 1973 and 2016 are listed in Table 2. Table 2 List of crops and their parameters for modeling. N = nitrogen concentration in aboveground biomass (yield+by-product); HI = harvest index, relation of by-product to main product; CEWR = N amount in harvest residues independent from yield; FEWR = factor between N in harvest residues, roots and yield, RP = raw protein content, sp. = spring, DM = reference dry matter during harvest.

English name	Latin name	DM [%]	N [%]	HI	CEWR [kg ha^{-1}]	FEWR [kg kg^{-1}]
alfalfa (perennial)	Medicago sativa	20	0.6	-	100	0.1111
carrot	Daucuscarota	15	0.22	-	23	1
clover-grass (perennial)	Trifoliumpratense	18	0.52	-	107	0
clover-grass (permanent)	Trifoliumpratense	18	0.52	-	105	0
durum wheat	Triticum durum	86	2.5	0	5.2	0.052
field bean	Viciafaba	86	5.6	-	37	0
mustard	Brassica juncea	17	3.4	0	20	0
oats 10%RP	Avena sativa	88	1.92	1.1	6.2	0.0812
oil radish	Raphanussativus	10	0.41	-	28	0
papaver	Papaver somniferum		2.42	0	26.04	0.0625
potato	Solanum tuberosum	22	0.35	-	3.2	0.264
summer rape	Brassica napus	88	4.47	1.6	6.6	0.0984
silage maize	Zea mays	33	0.38	-	23.1	0.0292
sp. barley brewing 11%RP	Hordeum vulgare	86	1.86	0.7	5.2	0.0699
sp. barley fodder 13%RP	Hordeum vulgare	86	2.19	0.8	5.2	0.05935
spring rye 11%RP	Secalecereale	86	1.96	0.9	8	0.0816
spring wheat 13%RP	Triticumaestivum	86	2.36	0.8	5.2	0.0551
sugar beet and fodder beet	Beta vulgaris	23	0.36	0.7	8	0.1111
winter barley 13%RP	Hordeum vulgare	86	2.19	0.8	8	0.073
winter rape-seed 23%RP	Brassica napus	88	4.47	1.6	6.6	0.0984
winter rye 11%RP	Secalecereale	86	1.96	0.9	8	0.0816
winter rye 14%RP	Secalecereale	86	2.38	0.9	8	0.0672
winter wheat 13%RP	Triticumaestivum	86	2.36	0.8	8	0.0678

2.9 Fertilizer parameters

The fraction (%) of NH_4-N from total N is desicive for mineral fertilizers. For ammonium phosphate, solution of urea and ammonium nitrate (UAN), urea and sulfur acid ammonia, this fraction was assumed to be 100%. For ammonia nitrate and calcium ammonia nitrate, this fraction was assumed to be 50%. In addition to BGR, cattle manure, cattle slurry, liquid manure and, in rare cases, pig slurry were applied as organic fertilizers (Table 3). Different parameters were taken from the CANDY database. Table 3 Organic fertilizers and their parameters used for modeling. DM = dry matter content, C in DM = carbon content in dry matter, C_{org} = organic carbon concentration, N_{org} = organic nitrogen concentration, N_{min} = mineral nitrogen concentration, k = decomposition coefficient, η = synthesis coefficient.

fertilizer	DM [M. %]	C in DM [M. %]	C_{org}/N_{org}	$C_{org}/(N_{org}+N_{min})$	N_{min}/N_{org}	k [d^{-1}]	η
cattle manure	0.25	0.31	18	14.07	0.28	0.1	0.6
liquid manure	0.02	0.24	16	2.18	6.33	0.05	0.65
cattle slurry	0.08	0.34	16	7.77	1.06	0.05	0.65
pig slurry	0.08	0.31	13	4.66	1.79	0.05	0.65

2.10 Scenarios

A simulation from 1973-2050 was performed to evaluate the long-term effects of BGR on soil. Therefore, the cropping system and crop rotation from 2005 to 2016 were repeated from 2017 onwards. To determine the effects of BGR on carbon storage in soil, a second scenario was simulated where the application of BGR was replaced with undigested cattle slurry with an equivalent concentration of N in $kgNha^{-1}$.

3. Results

3.1 Organic carbon

MeasuredC_{org} values in own soil samples confirmed the results from the farmer from the farmer. Thus, we combined both measurements into one subset and used it for model validation. Standard deviations were calculated for our samples only and ranged between 0.11% and 0.17%. The modeled trends of C_{org} were similar on all fields and soils (

Figure 1). Prior to 1991, C_{org} decreased up to 0.1 M%, whereas from1991 to 2005, a slight increase of approximately 0.1 M% was observed. After the installation of the biogas plant in 2005, C_{org} values in fields 250, 251, 620 and 621 were stable until 2016 and changed less than 0.05M%. In the other fields, an increasing trend is assumed and an increase in C_{org} of over 0.1M% is predicted by the model. The difference between the measured and simulated value (RMSE) was smaller than the errors from the C_{org} measurements in the soil samples.

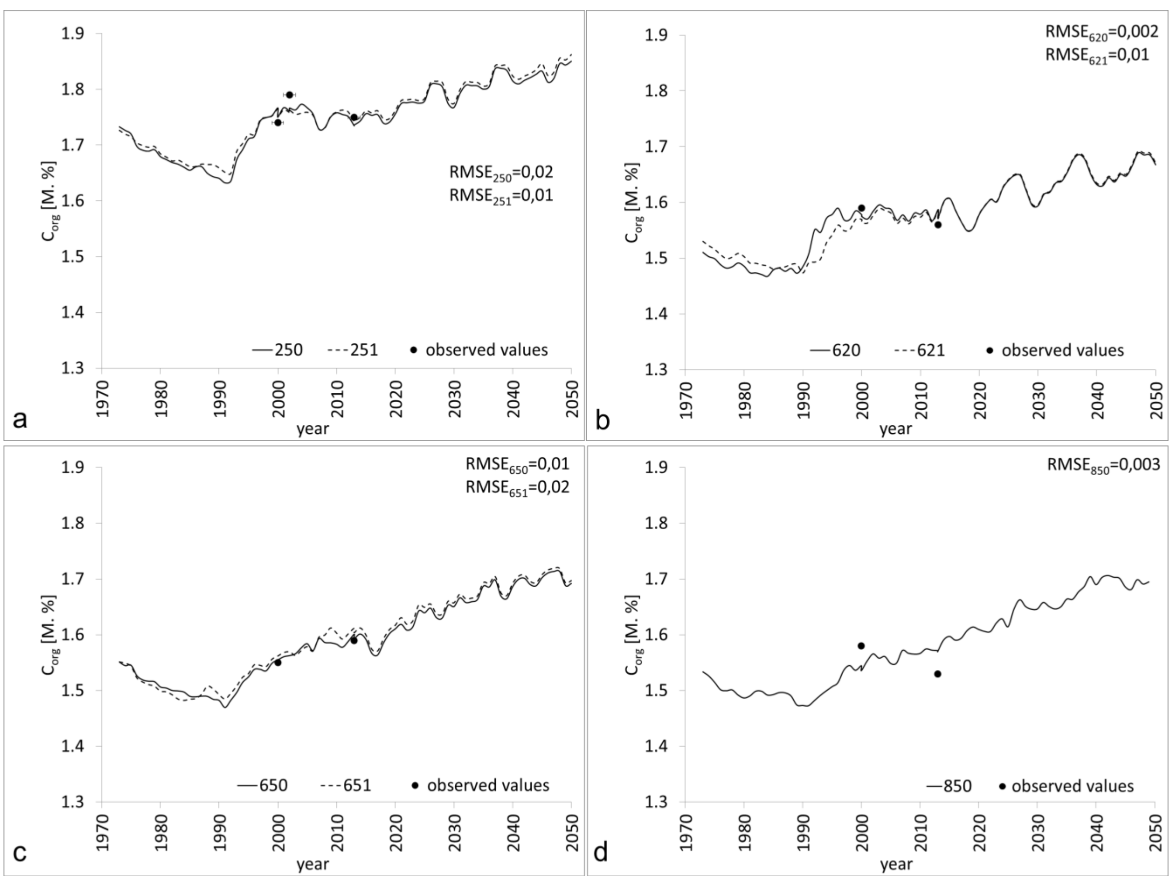


Figure 1 Soil C_{org} change over time in different fields

The modeled scenario with cattle slurry instead of BGR provided similar results. The C_{org} differences between both scenarios ranged from 0.001% and 0.02% in 2050. Biogas residue and cattle slurry appear to have the same impact on carbon storage, even though approximately 33% less C_{org} is applied to the soil when BGR is used (with equivalent N concentrations).

3.2 Cropping system

The cropping system changed over the 40 years of farming. From 1973 to 1991, 17 different crops were cultivated within the crop rotation. After 1991, the crop rotation was oriented for market development and consisted of sugar beets, winter rape or silage maize, winter wheat planted twice, followed by summer barley. During the experimental period, the area share of root crops (sugar beet and potato) decreased in selected fields from approximately30% in1973-1991 to approximately10% after the establishment of the biogas plant. The area share of silage maize increased from7% to 28% during the same period.

Prior to 1991, byproducts such as straw and sugar beet leaves were removed after harvest. From 1991 onwards, byproducts were incorporated into the soil, and in 1995,the tillage system was changed to no-till. From 1973 to 2016, crop yields improved continuously (

Figure 2). The grain yield of winter wheat increased from approximately 50dtha^{-1} to approximately 90dtha^{-1}, spring barley increased from 40dtha^{-1} to 50dtha^{-1}, silage maize increased from 330 dt ha^{-1} to 450 dt ha^{-1} and sugar beets doubled from 1973 to 2016 from 330 dt ha^{-1}to over 660 dt ha^{-1}.The only change that was not statistically significant was the increase of winter barley from less than 50 dt ha^{-1} to approximately 60dtha^{-1}. Winter rape was not included in the trend analysis because it was only cultivated in 1991 and after 2004.

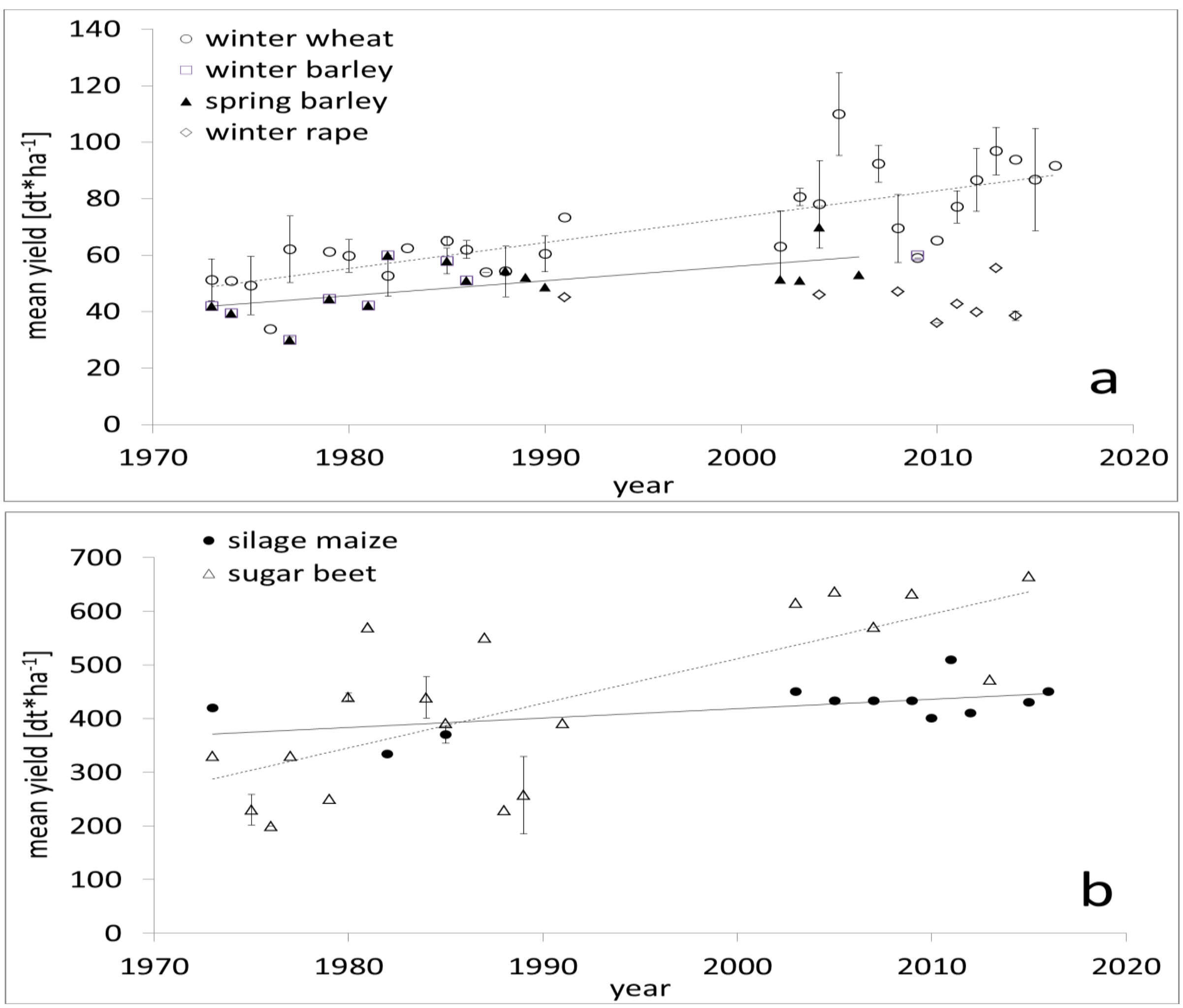
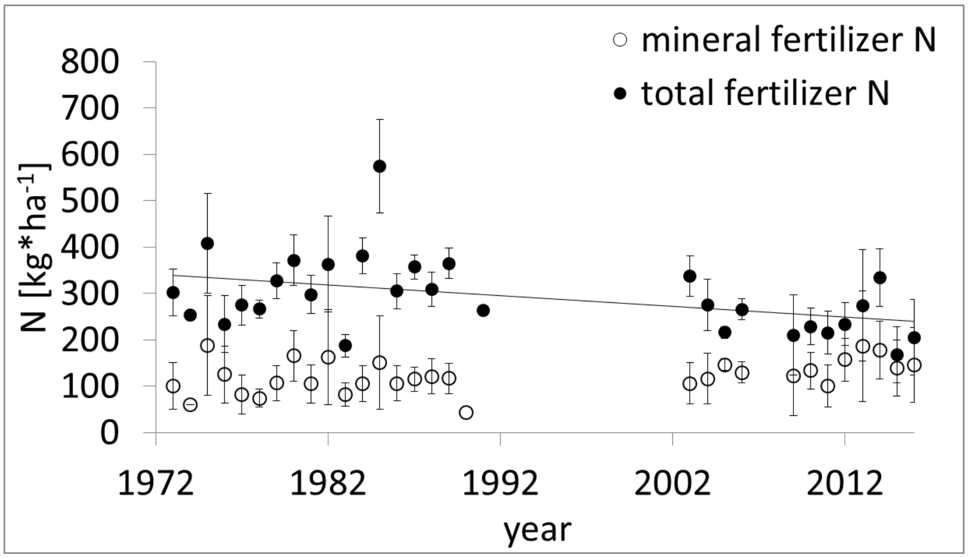


Figure 2Mean annual yields and standard deviations of a) wheat, barley and rape, b) maize and sugar beets. Trend lines are shown for winter wheat and sugar beets (dashed line) and spring barley and silage maize (continuous line).

The cropping system as well as the fertilization regime changed over the 40 years of farming. Prior to 1991, during the vegetation period, cattle slurry was used as an organic fertilizer. Calcium ammonium nitrate and urea were applied as mineral fertilizers. After harvest in autumn, cattle manure was applied before plowing. After 2003, calcium ammonium nitrate, urea and ammonium nitrate (UAN) were primarily used as mineral fertilizers. Cattle slurry was replaced after 2005 with BGR, although cattle manure is still applied as organic fertilizer. The frequency of the BGR application on fields which are closer to the biogas plant and which are furthest away was in the same range of 4 to 6 times from 2005-2016.



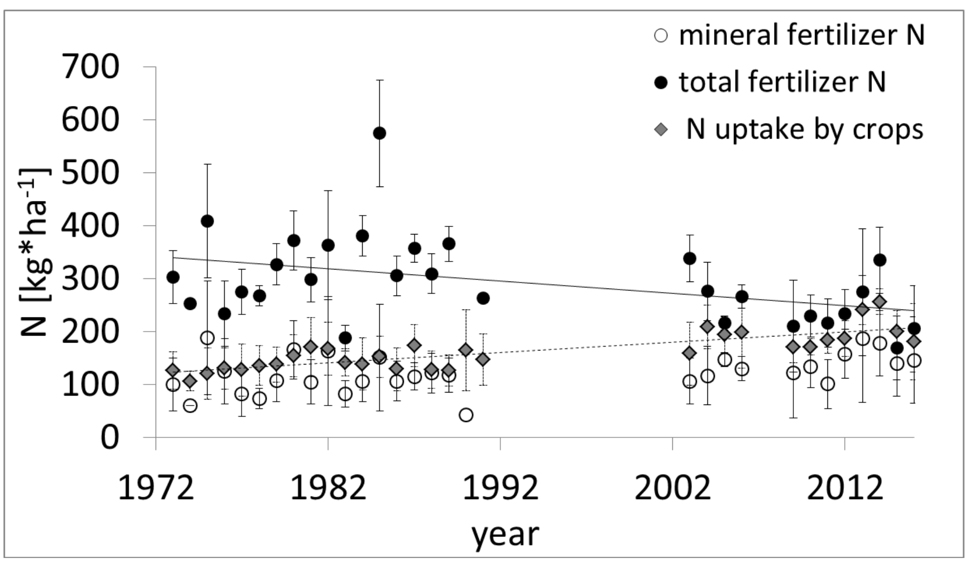


Figure 3Mean yearly sum of mineral and total (mineral and organic) fertilizer N application and total yearly N uptake by crops. The trend line for total fertilizer N ($p<0.05$) is represented by a continuous line and the trend line for N uptake by crops ($p<0.05$) is represented by a dashed line.

Mineral fertilizer usage increased from approximately 105kgNha^{-1} in the 1970s toapproximately150kgNha^{-1}after 2010. In contrast, the usage of cattle slurry and cattle manure as organic fertilizer decreased significantly ($p<0.05$) from 190kgNha^{-1} in the 1970s to approximately 90kgNha^{-1} after 2010. Prior to 1991, applied N was primarily derived from organic fertilizer (Figure 3). In 2015, the largest fraction of total applied N was derived from mineral fertilizers. Overall, the trend of total applied N decreased from the 1970s to 2015. At the same time, the N uptake by the crops increased from approximately 126kgNha^{-1} in the 1970s to 195kgNha^{-1} from 2005 to 2015.

4. Discussion

4.1 Prior to biogas plant implementation

According to our model, C_{org} decreased in all fields from 1973 to 1991, despite high N application rates with organic fertilizer, likely as a result of the intensive use of root crops and the removal of byproducts (Figure 3). The amount of applied organic fertilizer in the field was more than two times the N uptake by crops. An increase in SOC is expected following the application of animal manure, as reported by many studies. For example, (Gami, Lauren, & Duxbury, 2009)observed an increase in SOC(0-30cm) of approximately 19,100kgCha^{-1}after cattle manure was applied for 25years,compared to plots with mineral fertilizer. After pig manure was applied for 22 years in China, the surface soil layer (0-15cm) increased by 3,800kgCha^{-1}compared to when mineral fertilizer was applied (Huang, Peng, Huang, & Zhang, 2010). However, and in agreement with our results, some studies reported no significant change or a negative change in SOC stocks following manure application (Angers, Chantigny, MacDonald, Rochette, & Côté, 2010; Franzluebbers, Stuedemann, & Wilkinson, 2001). Clearly, there is significant variability in the change in SOC after manure application.

Soil organic matter storage capacity in agro ecosystems varies with soil type, climate and agricultural management practices (Angers et al., 1997). After 1991,C_{org} increased in all fields. This increase is a result of the change in byproduct management (increased carbon input)and the introduction of no-till (reduced carbon turnover) practices. In our study, the farmers incorporated byproducts such as straw and sugar beet leaves into the soil after 1991. Schlesinger (2000) showed that approximately twice as much carbon can be retained from crop residues than from manure, as indicated by our results. Liao, Wu, Meng, Smith, and Lal (2015)showed that incorporation of crop residue can significantly contribute to the maintenance of SOM in agricultural systems. Smith et al. (2005) reported that the input of crop residue could attain the highest rate of C sequestration in comparison with that of mineral N fertilizer.

In addition to residue management, it is likely that soil tillage has a substantial impact on SOM turnover. Long-term experiments have shown that plowing can lead to decreases in soil carbon (Franko & Spiegel, 2016).Frequent soil disturbances (i.e., tillage) expose protected organic matter and increase the rate of decomposition, resulting in lower steady-state SOC(Grandy & Robertson, 2007). In our study, no-till practices were instituted after 1995. A comparison of conventional cropping systems to those converted to no-till indicate higher median concentrations of carbon in the no-till cropping systems (Kopittke, Dalal, Finn, & Menzies, 2017). Additionally, other studies have shown that conventional tillage is associated with decreased SOC compared to no-till(Alvarez, 2005). Abreu, Godsey, Edwards, and Warren (2011) stated that intensive tillage has greatly reduced the organic carbon content of cropland in Oklahoma. They observed a greater C_{org} in no-till fields compared to tilled fields across all locations and depths. In contrast, no significant differences were found between tillage treatments in the total organic carbon storage to a depth of 60 cm in a range of soils in eastern Canada under continuous corn and small grain cereal production (Angers et al., 1997).

4.2 After biogas plant implementation

During the cycling of organic matter, we expect a carbon deficit because CH_4 and $CO_2$are extracted during anaerobic digestion. Furthermore, organic farmers argue that fertilizing with BGR may impair the micro biota and soil fertility because it contains more mineral N and less organic carbon than undigested manure (Insam, Gómez-Brandón, & Ascher, 2015).

Nonetheless, C_{org} measurements together with the modeling results showed that the SOC did not decrease during the ten years of biogas production on the farm. Furthermore, the CANDY simulation predicted an increase in C_{org} until 2050, even though BGR supplies less carbon and biomass than cattle slurry for equivalent amounts of N. Thus, at the farm scale, and when applied correctly, anaerobic digestion is not averse to other manure treatment options. This result is possibly due to the higher residence time of the carbon from BGR compared to undigested material. Presumably, SOC pools do not suffer from reduced carbon input (Insam et al., 2015). Thomsen, Olesen, Møller, Sørensen, and Christensen (2013) confirmed these findings and suggested that the retention of plant-derived carbon in soil is only slightly affected by anaerobic digestion over a greater time scale. Möller (2015) concluded that carbon losses during the anaerobic digestion process are compensated by lower C degradation after field application.

Furthermore, De Neve, Sleutel, and Hofman (2003) reported that the organic carbon in BGR is more stable compared to other organic wastes. In these reports, stability is used synonymously with residence time.

In our model, the higher residence time is a consequence of the improved transfer of carbon from fresh organic matter to the SOM pools. The SOM synthesis coefficient η of BGR is higher than that of cattle slurry or manure, and thus its contribution to SOM is higher (Prays et al., 2017). Numerous studies have compared BGRs with other organic amendments (Abubaker, Cederlund, Arthurson, & Pell, 2013; Abubaker, Odlare, & Pell, 2013; Möller & Stinner, 2009; Stumpe et al., 2012) and concluded that there is no long-term negative effect on the SOC if manures are an aerobically digested.

The analysis of the cropping system revealed that the fraction of silage maize increased substantially after the biogas plant was established. This result corresponds with other observations in Germany(FNR, 2010). Important cropping system improvements allow for yield increases and a decrease in applied organic fertilizer over time. From 1973 to 2016, the yields of most crops increased significantly. After 1991, significantly less organic fertilizers and N were applied to soils compared to 1973-1991. These developments are assumed to be independent from the establishment of the biogas plant. Nevertheless, increased yields lead to improved carbon input due to additional roots and byproducts (Franko, Kolbe, Thiel, & Ließ, 2011; Merbach & Schulz, 2013; Wiesmeier et al., 2014).

4.3 Limits and outlook

To the best of our knowledge, this study is the first analysis of the impact of biogas production at the farm scale. The farm in this study is a typical farm in Central Germany and the biogas plant is representative of other plants in the area with respect to the electrical capacity and substrate mix (FNR, 2010). In addition, the studied region is characterized by loess soils, which have beneficial agricultural properties, such as good air and water regimes. These conditions could mask the effects of BGR fertilization and the cropping system, which may be more apparent on sandy soils. Our analysis is restricted by the low number of C_{org}observations per field used for the validation. More validation points would improve the results. The application of this approach in areas with different soils or at larger scales such as in landscapes and catchment areas requires future studies, which will improve our understanding of the impact of biogas production on C_{org}. However, we consider our results as a representative example for highly productive soil in Central Germany.

5. Conclusions

In summary, our findings suggest that at the farm scale, the replacement of undigested organic fertilizers with BGR does not lead to a decrease in SOC with in ten years of biogas plant operation. Furthermore, our model indicated that, despite carbon removal during anaerobic digestion, the C_{org} did not decrease under the tested cropping conditions (until 2050). The incorporation of crop residues, no-till practices and successive yield growth were the most important drivers that influenced soil carbon. The direct effect of fertilization with BGR appears to be of minor relevance at the farm scale.

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