Greenhouse gas fluxes from soils fertilised with anaerobically digested biomass from wetlands

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SUMMARY

Riverine wetlands play important roles at local and global scales by contributing to climate regulation, biodiversity maintenance, flood attenuation and water purification. They also supply large amounts of biomass that can be used as a substrate for the production of biogas, while post-fermentation material can be used as an organic fertiliser, although the latter may constitute a source of greenhouse gases (GHG). The aim of the study was to determine the intensity of GHG fluxes from soils enriched with anaerobically digested plant biomass sourced from the wetlands of the Narew River Valley. The study has shown that anaerobically digested wetland biomass is a source of easily biodegradable organic compounds and its mineralisation in the soil results in the release of GHG to the atmosphere. Fluxes of carbon dioxide (CO_2) and methane (CH_4) were short-term, while nitrous oxide (N_2O) fluxes remained at elevated levels for a period of two weeks after fertilisation. During the course of the experiment, carbon (C) losses were much higher than nitrogen (N) losses and amounted to 8–50 % of the amount supplied by digestate. The analysed digestates clearly differed in terms of the intensity of changes that occurred after application to the soil. The lowest GHG fluxes and the lowest amount of C mineralised (8 % of the amount supplied) were observed with the digestate of common reed (*Phragmites australis*), which would indicate that it should be primarily considered as a substrate for biogas production. The relatively small amounts of C and N in particular, released in gaseous form from the digestates indicate that GHG fluxes from agricultural soils may be mitigated if digestates are used in place of inorganic fertilisers. However, it should be noted that the obtained results should be treated as approximates, as due to analytical limitations, they were carried out without replications. However, these results indicate that common reed could be used as a substrate for biogas production, its digestate applied on arable land as a fertiliser and should be examined in more detail.

KEY WORDS: digestate, greenhouse gases fluxes, wetland biomass

INTRODUCTION

Wetlands play important roles at both local and global scales, contributing to climate regulation, biodiversity maintenance, flood attenuation, water purification, and providing areas for recreation (Millennium Ecosystem Assessment 2005). Sustainable production of biomass on rewetted peatlands is part of the concept of paludiculture related to the productive utilisation of these areas (Wichtmann & Joosten 2007). European treeless wetlands, endangered by secondary succession and subject to active protection, are a sustainable source of biomass that can be used for many purposes, such as bedding for cattle, as a raw material for roof thatching, for the production of insulation products or plant-based lightweight concrete (Pude *et al*. 2005). However, in the majority of cases, the collected biomass is regarded as a waste material that needs to be utilised (Banaszuk & Kamocki 2008).

In recent times, the use of wetland biomass for energy generation, including biogas production, has been proposed. Although biogas yield from common and highly productive species, such as *Phragmites australis*, *Phalaris arundinacea* and *Carex spp.*, is significantly lower when compared to typical biogas substrates, such as maize and sorghum (Gizińska-Górna *et al*. 2016), wetland plants could be an interesting co-substrate (Roj-Rojewski *et al*. 2018). Their co-digestion with manure is one possible method to increase volumetric methane (CH_4) production, in comparison to manure fermentation alone (Lehtomäki 2006).

A by-product of biogas production is the post-fermentation material that can be used as an organic fertiliser, reducing the demand for synthetic fertilisers (Hansson & Fredriksson 2004). Its application to soils has been found to improve soil properties and production capabilities, due to the fact that the use of anaerobic digestates reduces bulk

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density, improves hydraulic conductivity and enhances the soil moisture retention capacity (Nkoa 2014). Chemically, it has a higher pH and mineral nitrogen (N) content, and lower organic N and total organic carbon (TOC) content compared to untreated manure (Anderson-Glenna & Morken 2013). Furthermore, the application of digestate obtained from wetland plants onto adjacent arable upland soils may be an essential link to close the flow of elements and energy in the landscape. The nutrients and energy gained from wetlands, which can be considered as a sink for such constituents lost from arable land, may be partly returned to these soils.

However, there are certain environmental concerns, such as odours, regarding the agricultural use of digestate (de la Fuente *et al*. 2013). The adverse effect of soil amendment with digestate may also result from the high concentration of readily available inorganic forms of nutrients (Crolla *et al*. 2013), which can cause an excessive increase in soil microbial activity (Alburquerque *et al*. 2012a) resulting in oxygen depletion and N-immobilisation (Bernal & Kirchmann 1992). There is also the threat of soil and groundwater eutrophication (Alburquerque *et al*. 2012b).

It is highly likely that microbial mineralisation of organic matter, along with the transformation of N contained in the various organic amendments (including the digestate) can lead to the release of greenhouse gases (GHG) after its application. However, the intensity of this process depends on the properties of the substrates used for biogas production. These properties, especially the content of the indigestible fractions, determine their susceptibility to anaerobic degradation (Triolo *et al*. 2012), thus affecting the quality of the residue remaining after this process. The biomass obtained from wetlands is characterised by a large diversity of species; hence, it is also diversified in terms of its chemical and physical properties. For this reason, biomass use for energy purposes should include a determination of the potential for biogas production and an analysis of the processes that occur in the soil after the application of digestate. This paper presents preliminary results of the determination of carbon dioxide (CO_2), nitrous oxide (N_2O) and CH_4 fluxes from soils treated with anaerobically digested biomass sourced from five different plants in the fluviogenous wetlands of the Narew River Valley (NE Poland). The aim of this study was to identify plant species that should be subject to further detailed research in regard to their use for biogas production and possible agricultural use of the residue that remains after this process.

METHODS

Analysis of digestates

Digestates from five different organic materials were used in this study. The digestates were obtained in a laboratory experiment related to the bio-methane potential (BMP) of five plant species: reed sweet-grass (*Glyceria maxima*; R-S), common reed *(Phragmites australis*; C-R), tufted sedge (*Carex elata*; T-S), reed canary grass (*Phalaris arundinacea*; R-C) and woollyfruit sedge (*Carex lasiocarpa*; W-S). The purpose of the experiment was to determine the suitability of these plants for biogas production. The plants were harvested in mid-summer 2015 in the wetlands of the Narew National Park, NE Poland (52° 57' 3" to 53° 8' 56" N, 22° 51' 36" to 22° 58' 7" E). After the BMP test, the digestates were transferred to a water bath and stored under anaerobic conditions for three months at 38±1 °C. In the case of all the analysed materials, the total solids content (TS) was determined with the use of the weight method by oven-drying at 105 °C, while the volatile solids content (VS) was determined with the use of the weight method by ignition at 550 °C in a muffle furnace.

Electrical conductivity (EC) and pH were measured with a HQ40D meter (Hach, USA); TOC was measured with a TOC-L analyser equipped with a SSM-5000A Solid Sample Combustion Unit (Shimadzu, Japan); while total Kjeldahl N content (TKN) was measured with a VAP50s analyser (Gerhardt, Germany). Total contents of phosphorus (P), sodium (Na) and potassium (K) were determined after sample mineralisation in an ETHOS One (Milestone, Sorisole, Italy) microwave oven. Phosphorus was determined spectrophotometrically with the use of the vanadate-molybdate method (with UV-1800, Shimadzu, Japan); while Na and K were determined with a flame photometer (BWB Technologies, Newbury, England). The analyses of organic materials were run in triplicate.

Soil analysis

The soil for incubation was sampled in an arable field (upper 20 cm) located 19 km north of Białystok, Poland (53° 18' 1" N, 23° 11' 49" E; 147 m a.s.l.). The soil was classified as a Luvisol (WRB 2015), and was chosen for the experiment as it is the most representative soil of the region in regard to agronomics. The soil was air-dried, sieved to 2 mm size and analysed for texture (on the basis of the hydrometer method), pH (in H_2O and 0.1M KCl 1:2.5 w/v solution), TOC, total N, total P, Na and K contents, by means of the methods and equipment used in the digestate analysis. Plant-available phosphorus (P_2O_5) and potassium (K_2O) were determined after their extraction with calcium lactate solution. The soil analyses were run in triplicate. The basic properties of the soil used in this study are shown in Table 1.

Incubation experiment

Before the experiment, soil moisture was maintained at a 60 % of water field pore space with deionised water, and the soils were pre-incubated for a week under aerobic conditions at 25±1 °C. Afterwards, the fresh digested materials were thoroughly mixed with soil in an amount corresponding to a fertiliser application of 170 kg N ha^{-1}, which is the recommended annual rate of N applied in organic fertilisers (Journal of Laws of 2007 No. 147 item 1033). The soil-amendment mixtures were placed in 3 L plastic boxes and compacted to a bulk density of 1.5 g cm^{-3}. The mixtures were incubated in darkness under aerobic conditions at 25±1 °C for 28 days. In order to maintain a constant temperature throughout the experiment, the chambers were held in a thermostatic cabinet. To prevent water evaporation, plastic sheets with pin holes were placed above each sample. The soil without amendments (S) was incubated under the same conditions and constituted a control sample. This part of the study was conducted without replications. This was due to the analytical capabilities of our gas chromatograph (GC), equipped with a manual sampling valve. On one hand, this system allows the analysis of samples with a large volume, while on the other; it prevents the automation of the process. In practice, only one soil treated with digestate could be examined in a 24-hour period with the parameters of the analytical program of the GC. The purpose of the study was to compare soil GHG fluxes after introduction of five different digestates into the soil and achieving this goal required maintaining the conditions of all incubation experiments as similar as possible. This was mainly addressed in the period of digestate storage, which should have been the same for all digestates. As the BMP tests for all the plants finished on the same day, we also had to start the incubation tests for all digestates on the same day. Taking into account the assumed high frequency of sampling, the replications made for each of the studied materials would have resulted in a several-week shift between the flux measurements of the individual digestates.

GHG fluxes

Fluxes of CO_2, CH_4 and N_2O were measured with the use of the chamber method (Pumpanen *et al*. 2009). The chambers were made from 18 dm^3 plastic containers placed on a plastic plate and sealed with porous rubber. On the top of the container, a 3-way valve was mounted for gas sampling. On the day of the incorporation of digestate (day “0”), the fluxes were determined immediately after the amendments were mixed with the soil. Further measurements were made on days 1, 2, 4, 7, 10, 14, 21 and 28. Gas samples were taken with 10 ml air-tight syringes. In total, five samples were taken; at 0, 15, 30, 45 and 60 minutes after chamber closure. The temperature inside the chamber was measured with the use of a digital thermometer. Gas concentrations were analysed with a Shimadzu GC-2010A gas chromatograph equipped with a barrier ionisation discharge detector (BID; Tracera System). A 2-m Micropacked ShinCarbon ST 100/120 column with helium as a carrier gas was used for sample preparation. For every 5 samples, a standard mixture with a known concentration of CO_2, CH_4 and N_2O was run for quality control. The values (in ppm) for individual gases were corrected using the ideal gas law, then converted to gas flux rates (mg m^{-2} h^{-1}). The fluxes were calculated after Villa & Mitsch (2014).

Table 1. Basic properties of the soil used in the incubation experiment (mean value ± standard deviation (*n*=3)). Soil texture = content of soil fraction (%); pH = reaction; TOC = total organic carbon (g kg^{-1}); N = total nitrogen content (g kg^{-1}); P = total phosphorus content (g kg^{-1}); K = total potassium content (g kg^{-1}); Na = total sodium content (g kg^{-1}); P_{av} = plant-available phosphorus (g kg^{-1}); K_{av} = plant-available potassium (g kg^{-1}).

Soil texture Soil fraction (mm)			pH		TOC	N	C/N	P	K	Na	P_{av}	K_{av}
0.05–2	0.002–0.05	<0.002	H_2O	KCl								
83 ± 1	16 ± 1	1 ± 1	5.92 ± 0.02	4.7 ± 0.02	15.3 ± 0.27	1.05 ± 0.04	14.5 ± 0.4	0.90 ± 0.01	0.80 ± 0.15	0.14 ± 0.02	0.09 ± 0.01	0.09 ± 0.01

Statistical analyses

Basic statistical analyses of the data were performed with the use of Statistica 13.1 (StatSoft) software. Significant differences among the studied digestates were determined by one-way analysis of variance (ANOVA). Normal distribution of data was checked using the Shapiro Wilk test. Mineralisation of the organic-C from the digestates (C_m) was calculated as the difference between the CO_2–C evolved in the amended soils and that produced in the control (unamended) soil, and was expressed as a percentage of the TOC added with the digestates. C-mineralisation in the soils was analysed by means of a single exponential model with the following equation:

$$C_m = C_0 (1 - e^{-kt}) \quad [1]$$

where C_m represents the percentage of C mineralised at time t, C_0 is the potentially mineralisable C, k is mineralisation rate (d^{-1}), t is time. The data was fitted to the function using the non-linear least-squares technique (Levenberg-Marquardt algorithm) with Statistica 13.1 (StatSoft) software.

RESULTS

Properties of digestates

The digestates obtained from the wetland plants differed in their physical and chemical properties (Table 2). The greatest differences were found in VS, pH and Na content. The differences in TS, TOC and EC were less pronounced, while the smallest differences were observed in TKN. The two parameters that did not differ significantly were K and P contents ($p>0.05$). The C-R digestate differed from the other amendments the most ($p<0.05$) and was characterised by the lowest pH, EC values and Na content and the highest TS, VS, TOC and C:N ratio.

Carbon dioxide and methane fluxes

The addition of organic materials to the soils caused an immediate release of CO_2-C and CH_4-C (Figure 1). In regard to the initial amounts of gases produced; the differences between the digestates were clear and ordered as followed: R-C > T-S > R-S > W-S > C-R and R-C > R-S > T-S > W-S > C-R for CO_2-C and CH_4-C, respectively. The control soil

Table 2. Physical and chemical properties of the digestates and statistical significance between properties (mean value ± standard deviation (*n=3*), data expressed on a fresh weight basis). TS = total solids (%); VS = volatile solids (% of TS); pH = reaction; EC = electrical conductivity (mS cm^{-1}); TOC = total organic carbon (g kg^{-1}); TKN = total Kjeldahl nitrogen content (g kg^{-1}); P = total phosphorus content (g kg^{-1}); K = total potassium content (g kg^{-1}); Na = total sodium content (g kg^{-1}).

	Wetland plants from which the digestate was obtained						
	Reed sweet-grass (R-S)	Common reed (C-R)	Tufted sedge (T-S)	Reed canary grass (R-C)	Woollyfruit sedge (W-S)	*F* value	P
TS	4.29 ± 0.07	5.32 ± 0.19	4.93± 0.16	4.89 ± 0.03	4.75 ± 0.19	20.2	<0.0001
VS	73.48 ± 0.45	76.29 ± 0.27	67.73 ± 0.60	71.18 ± 0.17	74.64 ± 0.22	233.4	<0.0001
pH	8.51 ± 0.02	8.45 ± 0.01	8.64 ± 0.01	8.56 ± 0.01	8.56 ± 0.01	92.0	<0.0001
EC	17.1 ± 0.48	16.42 ± 0.43	20.38 ± 0.60	18.92 ± 0.30	17.05 ± 0.25	43.1	<0.0001
TOC	15.4 ± 0.3	20.31 ± 0.78	16.86 ± 0.85	17.84 ± 0.64	18.75 ± 0.84	20.7	<0.0001
TKN	3.42 ± 0.13	3.60 ± 0.20	3.00 ± 0.15	4.00 ± 0.30	3.38 ± 0.10	10.9	<0.05
C/N	4.50 ± 0.13	5.66 ± 0.45	5.62 ± 0.07	4.47 ± 0.24	5.55 ± 0.37	13.1	<0.05
P	0.52 ± 0.02	0.46 ± 0.05	0.48 ± 0.05	0.58 ± 0.07	0.48 ± 0.02	3.0	0.07
K	2.95 ± 0.34	2.48 ± 0.26	2.65 ± 0.18	2.80 ± 0.01	3.35 ± 0.47	3.3	0.06
Na	0.14 ± 0.02	0.10 ± 0.02	1.17 ± 0.01	0.15 ± 0.01	0.12 ± 0.01	3631.2	<0.0001

(S) showed initial mineralisation, which was the result of degradation of soil organic matter. The dynamics of the process was very similar for all the tested substrates. Production of all gases decreased rapidly during the first days of incubation. However, the reduction was more pronounced in the case of CH_4 (Figure 1a); observable fluxes declined sharply after several hours, and remained very low (<1 μg kg^{-1} d^{-1}) until the end of the incubation period. Negative CH_4-C fluxes values were observed, indicating CH_4 consumption by methanotrophs (Hanson & Hanson 1996). After 28 days, the amount of CH_4-C evolved from soils treated with C-R and W-S was lower than at the beginning of the experiment (Figure 2). In the case of the control soil, negative values occurred throughout the whole experiment. CO_2 fluxes lasted longer than CH_4 fluxes and decreased to a constant value (<5 mg kg^{-1} d^{-1}) after 10 days (Figure 1b). Therefore, in the following section of this article, attention will be focused on CO_2-C

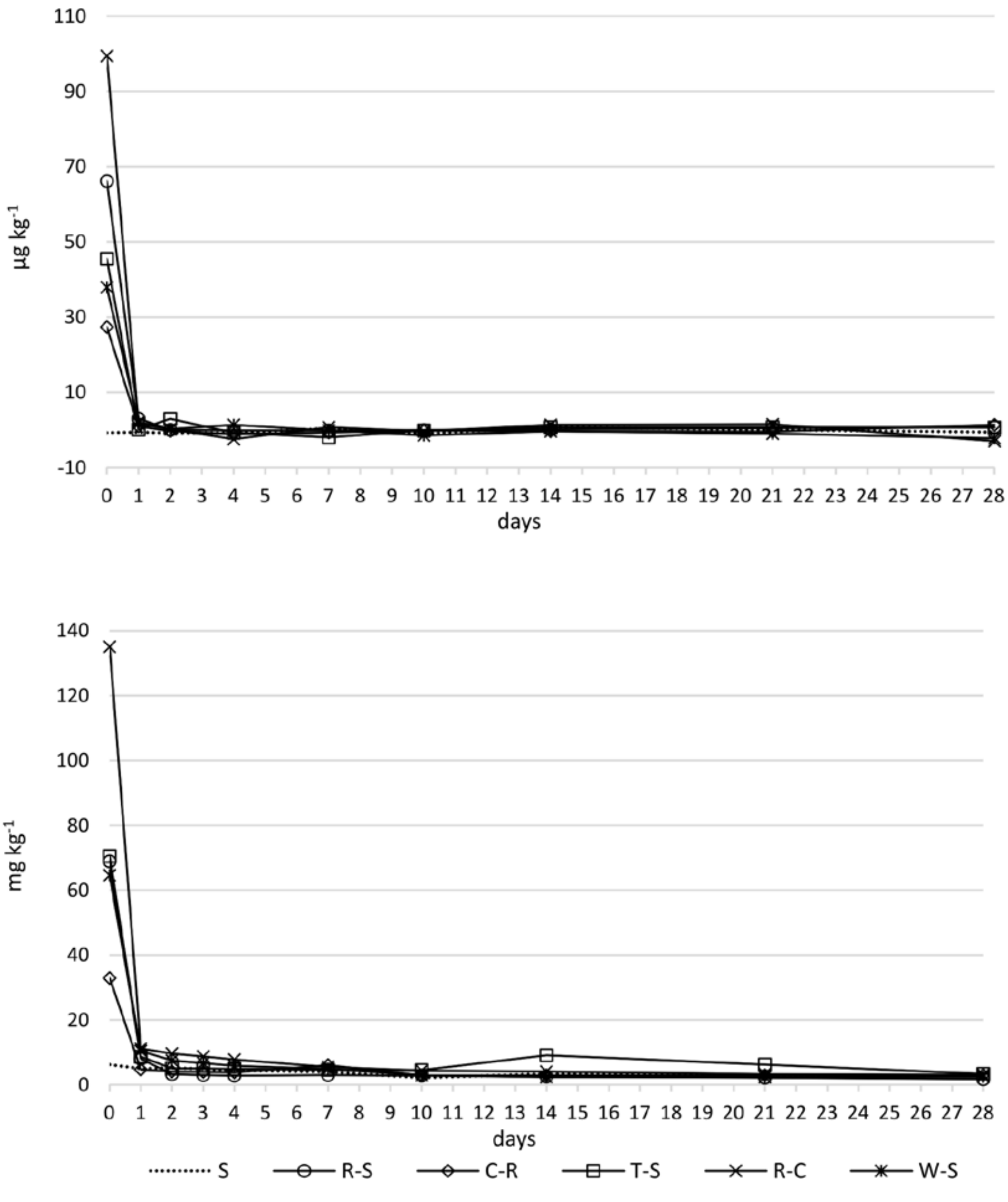

Figure 1. Daily production of (a) methane (expressed as CH_4-C) and (b) carbon dioxide (expressed as CO_2-C) from soils amended with digestates. Amendments: R-S = Reed sweet-grass digestate, C-R = Common reed digestate, T-S = Tufted sedge digestate, R-C = Reed canary grass digestate, W-S = Woollyfruit sedge digestate, S = unamended soil. Negative CH_4 values indicates consumption (uptake) by methanotrophs.

fluxes caused by the transformation of organic substances added to the soil with the digestates.

The cumulative amount of CO_2-C (mg kg^{-1}) evolved from digestate-treated soils after 28 days of incubation (Figure 3) varied considerably among the digestates: R-C (269) > T-S (235) > W-S (164) > R-S (143) > C-R (130) and this pattern was a function of the initial fluxes at day zero. Fluxes from the control soils (approximately 99 mg kg^{-1}), were much lower compared to the fertilised soils.

The share of TOC mineralised from the digestate reflected the differences in the biodegradability of organic matter (Figure 4). At the end of the incubation period, the lowest percentage of

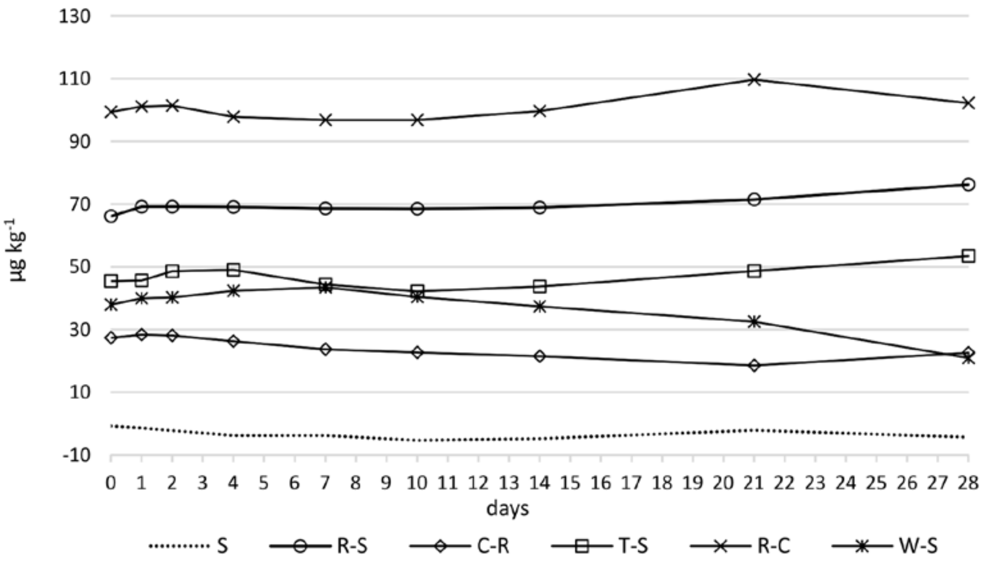

Figure 2. Cumulative methane (expressed as CH_4-C) evolved from the amended soils during incubation. Amendments: R-S = Reed sweet-grass digestate, C-R = Common reed digestate, T-S = Tufted sedge digestate, R-C = Reed canary grass digestate, W-S = Woollyfruit sedge digestate, S = unamended soil.

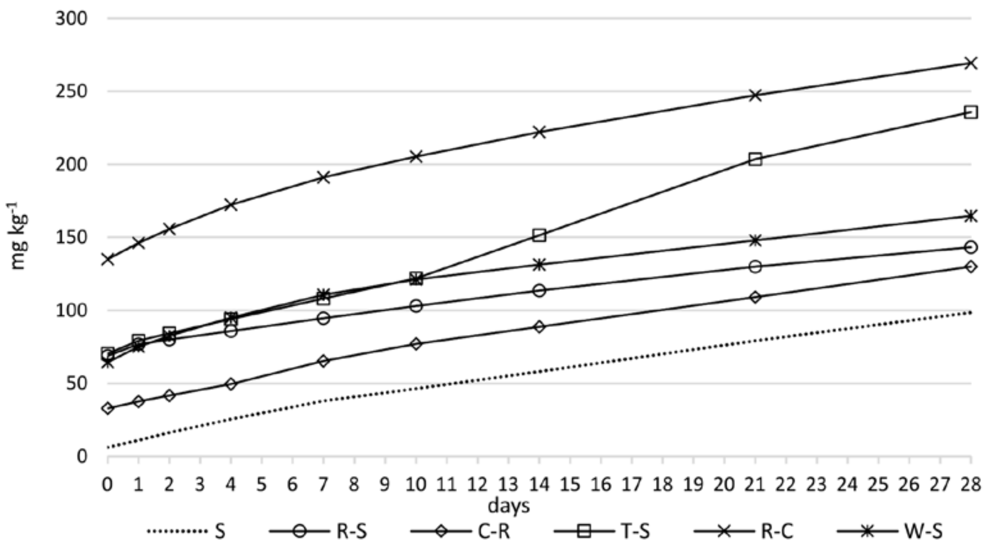

Figure 3. Cumulative carbon dioxide (expressed as CO_2-C) evolved from the amended soils during incubation. Amendments: R-S = Reed sweet-grass digestate, C-R = Common reed digestate, T-S = Tufted sedge digestate, R-C = Reed canary grass digestate, W-S = Woollyfruit sedge digestate, S = unamended soil.

mineralised-C was found in C-R (8 % of added TOC), followed by R-S (15 %), W-S (19 %), T-S (43 %) and R-C (50 %). The C-mineralisation data fitted to a first-order kinetic model showed the amount of potentially mineralisable-C, thereby allowing the differences in the tested treatments to be distinguished in terms of their biodegradability (Table 3). The R-S digestate was characterised by the highest rate of decomposition (the highest value of the rate constant), while the lowest rate was found for T-S (Table 3). Data on capacity for mineralisation of organic matter applied to soils with digestates allowed us to estimate the amount of C that could remain in the soil after CO_2-C release. The greatest potential was demonstrated by C-R digestate, which increased TOC content by 0.362 g kg^{-1} soil. The other digestates also enriched the soil C pool and increased TOC content by 0.283 (W-S), 0.233 (R-S), 0.198 (T-S) and 0.181 g kg^{-1} soil (R-C).

Nitrous oxide fluxes

The evolution of N_2O-N from soils amended with digestates progressed in a different way compared to the fluxes of CO_2 and CH_4 (Figure 5). Fluxes started to increase on the first day after application but the rate of this process was different for each digestate. The most intense N_2O-N increase was observed for the soil treated with W-S followed by soils treated with R-S, C-R, R-C and T-S. The N_2O-N fluxes from the soil amended with T-S reached a maximum value of 12μg kg^{-1} d^{-1} after 10 days of incubation and then started to decrease systematically. Fluxes from the soils containing the other digestates were more intense but in some cases (e.g. C-R), lasted only slightly longer than T-S. The differences in flux patterns and rates influenced the amount of N_2O-N evolved from the treated soils during incubation. The digestates emitted 4.5 (R-S), 4.2 (W-S), 2.8 (R-C), 2.5 (C-R) and 0.7 mg kg^{-1} for T-S (Data not shown).

The proportion of N supplied to the soils with the digestates and transformed into gaseous form was small when compared to the values observed for C. When expressed as a percentage of TKN added to the soil, the following values were obtained: 6.7, 6.2, 2.9, 2.9 and 0.4 % for R-S, W-S, C-R, R-C and T-S, respectively. Conversion of these results to weight values revealed that the individual amendments supplied 1 kg of soil with the following amounts of TKN (g): 0.073 (R-C), 0.071 (C-R), 0.060 (R-S), 0.060 (W-S) and 0.056 (T-S).

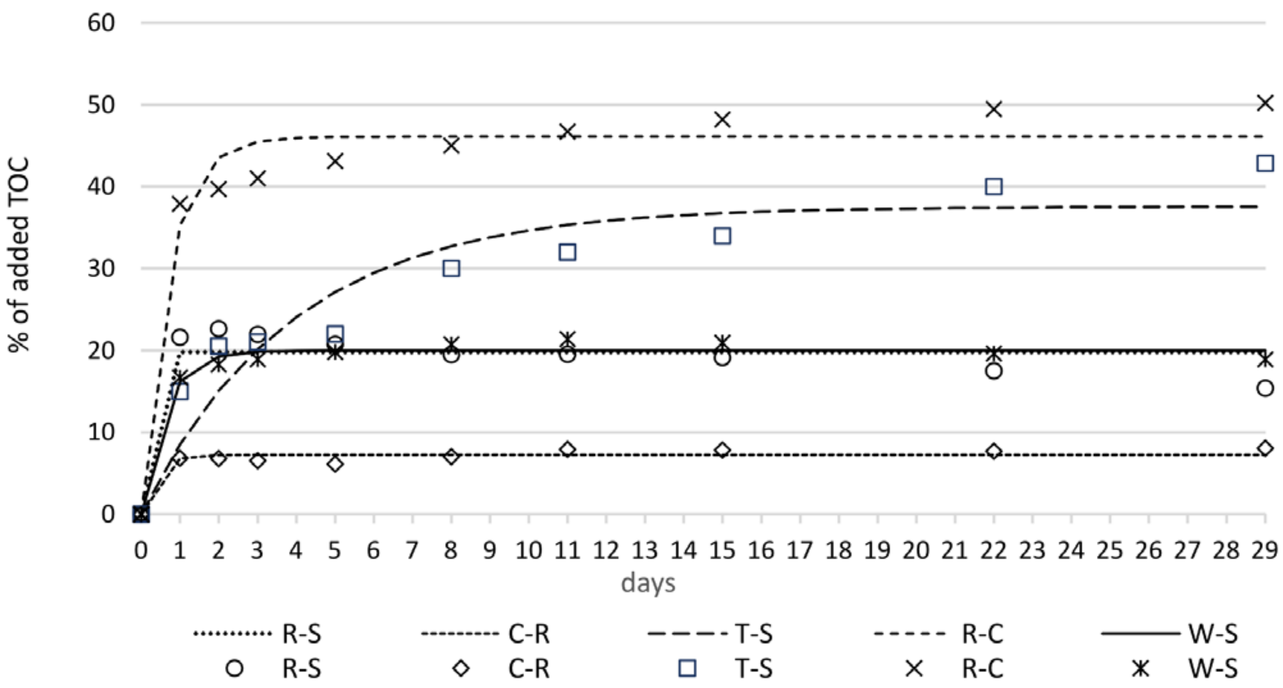

Figure 4. Cumulative mineralised-C from the amended soils (dots are experimental data and lines represent the curve-fitting). Amendments: R-S = Reed sweet-grass digestate, C-R = Common reed digestate, T-S = Tufted sedge digestate, R-C = Reed canary grass digestate, W-S = Woollyfruit sedge digestate.

Table 3. Parameters of the first-order kinetic model [$C_m=C_0(1-e^{-kt})$] used to describe C-mineralisation of the organic materials. C_m = mineralised-C (% of TOC added), C_0 = potentially mineralisable-C (% of TOC added), k = rate constant (day^{-1}). Treatment: R-S = Reed sweet-grass digestate, C-R = Common reed digestate, T-S = Tufted sedge digestate, R-C = Reed canary grass digestate, W-S = Woollyfruit sedge digestate.

Treatment	C_m	C_0	k
R-S	15.39	19.78	23.72
C-R	8.03	7.25	2.73
T-S	42.83	37.58	0.26
R-C	50.22	46.12	1.45
W-S	18.91	19.98	1.66

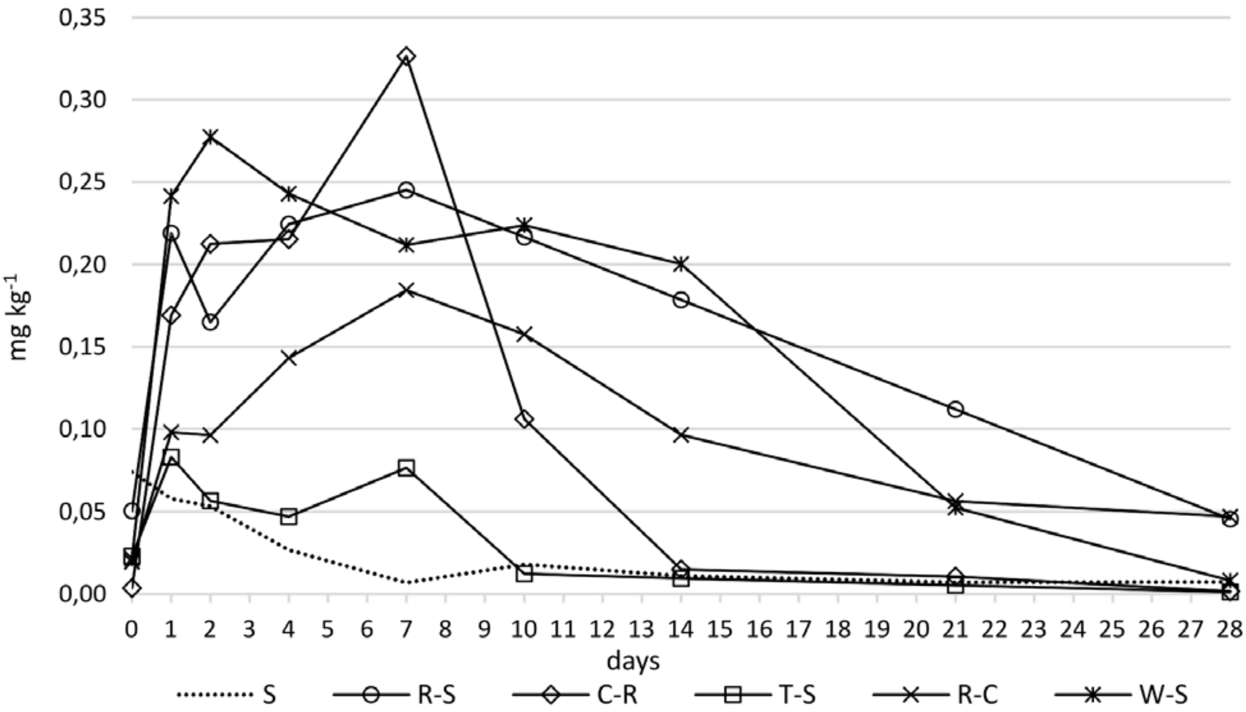

Figure 5. Daily production of nitrous oxide (expressed as N_2O-N) from the amended soils. Amendments: R-S = Reed sweet-grass digestate, C-R = Common reed digestate, T-S = Tufted sedge digestate, R-C = Reed canary grass digestate, W-S = Woollyfruit sedge digestate, S = unamended soil.

DISCUSSION

The rapid increase in CO_2-C fluxes from soils fertilised with digestates obtained from wetland plants is a response to changes in the microbial activity caused by altered amounts of utilisable C and N in the soil (Perelo & Munch 2005). Alburquerque *et al*. (2012b) stated that rapid development of microbial activity is related to the presence of an easily degradable organic fraction in the digestate, detected in the biochemical oxygen demand (BOD) test. The decrease in CO_2-C fluxes that was observed in this study several days after the addition of digestate is consistent with the results presented by de la Fuente *et al*. (2013). According to those authors, a constant flux value, similar to that observed from the control soil (S) in our study, relates to the total consumption of readily mineralisable organic matter sources that were supplied with the digestate.

Differences in CO_2 fluxes from soils fertilised with the examined digestates resulted from the susceptibility of organic matter supplied with these amendments to mineralisation. All plants were harvested in summer, when the quality of the material is particularly favourable for biogas production (Hansson & Fredriksson 2004). Despite the fact that most of the readily degradable organic matter derived from these plants was consumed during the fermentation process, and only a small part could have been incorporated into the soil with the digestate, the wide range in C fluxes indicates a high variability in the substrates that they were derived from. In this study, fertilisation was based on a constant N application. For this reason, the individual digestates differed in the amount of C added, which could be an additional reason for the variation in CO_2 fluxes. Research by Risberg *et al*. (2017) has shown that C mineralisation could be more dependent on the amount of C added than on the biodegradability of the C source.

In the case of digestates from wetland plants, the degree of C-mineralisation varied between 7 % (C-R) and 46 % (R-C) of the added TOC. Of particular note is C-R, which showed a very low rate of mineralisation and emitted the lowest amounts of CO_2-C of all the digestates obtained from wetland plants. The results obtained in this study show that the amount of individual components contained in plant tissues, especially lignin (which is the most recalcitrant component of the plant cell wall and makes lignocellulose resistant to chemical and biological degradation (Taherzadeh & Karimi 2008)) can affect both the susceptibility of organic matter to degradation in anaerobic fermentation and its subsequent transformation after its introduction into the soil as a residue from biogas production. This is especially true for the two “extreme” plants, i.e. common reed (C-R) and reed canary grass (R-C). Common reed (C-R) contains 15 % DM lignin, 27 % DM hemicellulose and 42 % DM cellulose (Lizasoain *et al*. 2016). In reed canary grass (R-C), the contents of these components are 8 % DM, 26 % DM and 30 % DM, respectively (Oleszek *et al*. 2014). Cellulose and hemicellulose (other than the lignin components of lignocellulose) can be anaerobically converted to CO_2 and CH_4, but the rate of conversion strongly depends on their ratio to lignin concentration in feedstock (Klimiuk *et al*. 2010). In the case of R-C, an additional factor favouring its high C-mineralisation rate is the low C:N value (Table 2), which promotes organic matter decomposition (Riffaldi *et al*. 1996). The positive impact of C-R digestate on soil properties, as identified in this study, is significant due to the fact that common reed occupies the largest area in the Narew National Park (Wołkowycki *et al*. 2016). Measures to control or mitigate its population can provide local communities with significant amounts of biomass for sustainable biogas production (Lizasoain *et al*. 2016), which will not only provide them with an energy source but will also be a source of valuable fertiliser.

Despite the fact that N_2O fluxes persisted longer than CO_2 fluxes, they were less intense. Therefore, the significance of N (delivered mainly in mineral forms to the soil with the digestates) was small or negligible. This can be explained by microbial immobilisation of inorganic-N by soil microorganisms (Alburquerque *et al*. 2012a), as evidenced by the strong C-mineralisation found in all the treated soils. In this situation, only a minor part of N was released as N_2O (Johansen *et al*. 2013). The intense N_2O fluxes observed for several days after soil amendments was the result of denitrification induced by the reduction of oxygen concentrations in the soil system caused by intense microbial respiration (Clemens & Huschka 2001).

The characteristics of digestates originating from wetland plants are similar to other solid remnants produced by anaerobic decomposition and so would permit their use in agriculture. They are a source of organic substances and thus they improve soil quality by enhancing soil aggregate stability, water holding capacity, soil porosity and water infiltration (Leroy *et al*. 2008). Moreover, the increased supply of organic components is beneficial for such soil characteristics as pH, EC, and cation exchange capacity. Additionally, the studied digestates were characterised by an alkaline reaction, which may be particularly important for their agricultural use as it raises soil pH and thus affects the availability of plant nutrients, especially N, P and K (Bulluck III *et al*. 2002). The bbeneficial effect on agricultural soils from digestate addition can also result in mitigation of GHG fluxes. Substitution of mineral fertilisers by digestate will contribute to the reduction of N_2O fluxes, whose main source are N fertilisers with an impact 265 times greater than CO_2 in term of climate warming (IPCC 2013).

It is emphasised that the results presented here should be treated as approximate values as they were carried out without replications due to analytical limitations. However, these results do indicate that common reed could be used as a substrate for biogas production with the digestate applied on arable land as a fertiliser. Therefore further studies on this digestate should be carried out.

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