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Research article

The greenhouse gas emission effects of rewetting drained peatlands and growing wetland plants for biogas fuel production

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ABSTRACT

Efforts to mitigate greenhouse gas (GHG) emissions are receiving increased attention among governmental and commercial actors. In recent years, the interest in paludiculture, i.e. the use of rewetted peatlands, has grown because of its potential to reduce GHG emissions by stopping soil decomposition. Moreover, cultivating wetland plants on rewetted peatlands for bioenergy production that replaces fossil fuels in the transport sector, can contribute to additional GHG emission reductions. In this study, an analysis of literature data was conducted to obtain data on GHG emissions (CO_2 and CH_4) and biomass production from rewetted peatlands cultivated with two different wetland plant species: *Phragmites australis* (Pa) and *Typha latifolia* (Tl). In addition, a biogas experiment was carried out to investigate the biomethane yield of Pa and Tl biomass, and the reduction of global warming potential (GWP) by using biomethane as vehicle fuel. The results show that peatland rewetting can be an important measure to mitigate the GWP as it reduces GHG emissions from the soil, particularly on a 100-year timescale but also to some extent on a 20-year timescale. More specifically, rewetting of 1 km^2 of peatland can result in a GWP reduction corresponding to the emissions from ±2600 average sized petrol cars annually. Growing Pa on rewetted peatlands reduces soil GHG emissions more than growing Tl, but Pa and Tl produced similar amounts of biomass and biomethane per land area. Our study concludes that Pa, because of a more pronounced GWP reduction, is the most suitable wetland plant to cultivate after peatland rewetting.

1. Introduction

In the COP 21 meeting in Paris (2015), the EU and its member states agreed to decrease their greenhouse gas (GHG) emissions with 40% by 2030 compared to levels of 1990 (Liobikiene and Butkus, 2017). An important step towards this goal is to reduce the large quantities of GHG emitted from peatlands that have been drained to enable agriculture and forestry (Kekkonen et al., 2019). Tubiello et al. (2016) estimated that emissions from drained organic soils, i.e. most commonly drained peatlands (Craft, 2016), represent more than one-fourth of net carbon dioxide (CO_2) emissions from agriculture, forestry, and other land use. The land management concept of "paludiculture", which induces a transition from agriculture on drained peatlands to cultivation of moisture tolerant plant species on rewetted peatlands (Wichtmann et al., 2016), is a possible measure for mitigating these GHG emissions (Geurts et al., 2019; Joosten et al., 2012; Kasimir et al., 2018). The immediate benefits of increasing the water table (rewetting) on drained peat soils are the reduction of soil subsidence and the decrease in carbon dioxide (CO_2) emissions caused by peat mineralization (Kløve et al., 2017). According to the IPCC (2014), rewetting cropland and grassland on drained peat soils in temperate climates has a high GHG reduction potential. Although methane (CH_4) emissions from rewetted peat soils most probably will increase, the overall GHG emissions can be reduced (Wilson et al., 2016). A GHG reduction potential can also be expected in a longer time perspective due to belowground peat accumulation by wetland plants (Joosten et al., 2012). Rewetting can result in the restoration of degraded peatlands, and over time reestablish ecosystem services and functions, e.g. carbon sequestration and storage, increase biodiversity, and regulate nutrient balance and hydrology (Wichmann, 2017).

To avoid losing productive land in paludiculture, Wichtman et al. (2010) found that tall, highly productive, wetland plants such as reeds and cattails are appropriate to cultivate on rewetted peatland. The continuous biomass production and low decomposition rate of wetland

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plants result in peat accumulation as only the aboveground biomass is harvested (Joosten et al., 2012). Wetland plants can also minimize peat degradation and maximize the yield of economic valuable biomass that could be used for renewable energy production (Wichtmann and Schäfer, 2007). Apart from agriculture, the transport sector is another large contributor to GHG emissions. In 2017, 25% of the GHG emissions in the EU were attributed to transport (Eurostat, 2019). In addition to improved energy efficiency of vehicles, the production and use of environmentally friendly fuels needs to be promoted to reduce GHG emissions from the transport sector. An alternative for paludiculture is therefore using the harvested plant biomass as substrate for biogas production (Eller et al., 2020; Weiland, 2010). Biogas, which is produced through anaerobic digestion, is a versatile carrier of renewable energy that, when upgraded to biomethane, constitutes an environmentally friendly energy supply that can be used as vehicle fuel to replace petrol and diesel in the transport sector (Ohlrogge et al., 2009; Olsson and Fallde, 2015). The by-product of biogas production, the digestate, is a valuable biofertilizer with high nutrient availability that enables the fertilization of agricultural land during the growing season, which potentially reduces run-off and the eutrophication of streams (Bougnom et al., 2012; Scarlat et al., 2018). Moreover, biogas production can provide farmers with an income from rewetted land (Wichtmann and Wichmann, 2011), and cost savings by reducing the purchase of chemical fertilizers and herbicides (Massé et al., 2011).

Overall, paludiculture can combine several interests such as GHG reduction (Croon, 2014), renewable energy production, and the creation of new business opportunities (Jäveoja et al., 2016). Additionally, paludiculture can contribute to societal benefits such as open cultural landscapes and groundwater retention (Wichtmann and Schäfer, 2007), nutrient retention (Weisner et al., 2016), regional cooling effects (Wichtmann and Wichmann, 2011), and the prevention of regional floods without harming crops (Kløve et al., 2017). The aim of this study was to investigate the GHG reduction potential of rewetting temperate peatlands and cultivating them with two productive wetland plant species for producing biogas used as substitute for fossil vehicle fuel. The two plant species were common reed (*Phragmites australis*; Pa) and broad-leaved cattail (*Typha latifolia*; Tl). The rest of the paper is structured as follows. Section 2 describes the research method and data analysis. Section 3 presents the results based on the literature analysis and the biogas experiment. Section 4 discusses the implications of the study, offers suggestions for future research, and presents the main conclusions.

2. Method

2.1. GHG emissions of rewetted peat soils

2.1.1. Article selection for literature analysis

An analysis of literature data was conducted to compare net GHG emissions from rewetted peatlands in temperate climates where either Pa or Tl was the dominant plant species. Scientific articles were selected based on the presence of quantitative data on net CO_2 and CH_4 emissions from rewetted peatlands covered with Pa or Tl (Table 1). Since the articles needed to be field studies (i.e. not experimental laboratory studies) in temperate climate conditions, the number were limited to six. To verify that the six articles were representative of temperate climate, precipitation and temperature were checked as both parameters have a large impact on water level and consequently on peatland soil GHG emissions. Nitrous oxide (N_2O) emissions in the selected articles were either negligible or not measured. Prior to rewetting, the drained peat soils were used for agriculture, peat excavation or as grassland. To exclude large flux fluctuations from early stage rewetting, the selected articles reported data on GHG emissions from not harvested peatlands after a minimum of nine years of rewetting. The studies in the selected articles were performed in northern Europe, except for one article that investigated an area in New York, USA. Measuring techniques used were either closed chamber measurements on the ground or eddy covariance flux measurements above the canopy.

Hendriks et al. (2007) measured GHG emissions with eddy covariance flux technique and closed chambers, on an abandoned agricultural peat meadow in the Netherlands that was converted into a wetland ten years earlier with a vegetation dominated by Pa. Günther et al. (2015) used closed chambers to analyze the impact of winter harvesting of Pa and Tl on GHG emissions of a rewetted peatland in a two-year study in Germany. Minke et al. (2016) also conducted a two-year field study with closed chambers to investigate the impact of water level and vegetation type on GHG emission from a rewetted peatland in Belarus that had Pa and Tl as dominating species. Franz et al. (2016) presented data on emissions from a rewetted peatland in Northern Germany. Eddy covariance studies were conducted for the whole ecosystem (including open water) but only the flux data from the zone with emergent vegetation dominated by Tl were used here. Van den Berg et al. (2016) also measured GHG emissions with eddy covariance flux measurements in Northern Germany on a rewetted fen that had been drained for agricultural purposes 200 years ago, but then gradually has developed to a natural fen with Pa as the dominating vegetation. Yavitt (1997) used closed chambers to collect GHG emission data from a rewetted peatland in New York (USA) that was overgrown with Tl.

2.1.2. Processing emission data

The GHG emission data of the six articles focus on CH_4 and CO_2. Three of the articles (Günther et al., 2015; Hendriks et al., 2007; Minke et al., 2016) are two-year studies and thus two measurements could be used from each of them. Altogether, seven measurements for Pa and six measurements for Tl were used for studying the relations between CO_2, CH_4, total GHG emissions and water level. Water levels varied between −19 and + 14 cm in the rewetted soils, where 0 cm is ground level. To calculate the climate impact of these GHG emissions, CH_4 emissions were transformed into CO_2-equivalents with a 100-years perspective using a Global Warming Potential (GWP) factor of 34 (Wilson et al.,

Table 1
Overview of the articles used to calculate GHG emissions from rewetted peatland in temperate areas. NL: The Netherlands; GE: Germany; BL: Belarus; USA: United States of America; EC: Eddy covariance; CC: Closed chambers.

	Article	Country	GHG measuring technique	Drained period (years)	Rewetted period (years)	Land use before rewetting	Vegetation after rewetting	Biomass reported (g/m^2)
1	Hendriks et al. (2007).	NL	EC→CO2 CC→CH4	100	10	Agriculture & grassland	Pa	Yes
2	Günther et al. (2015)	GE	CC→ CO2, CH4	37	15	Grassland	Pa and Tl	Yes
3	Minke et al. (2016)	BL	CC→ CO2, CH4	10	12	Peat extraction & grassland	Pa and Tl	No
4	Franz et al. (2016)	GE	EC→ CO2, CH4	100	9	Agriculture	Tl	No
5	Van den Berg et al. (2016)	GE	EC→ CO2, CH4	200	Gradually	Peat extraction & agriculture	Pa	No
6	Yavitt (1997)	USA	CC→ CO2, CH4	50	50	Grassland	Tl	Yes

2016). Additionally, since global warming and climate change need urgent attention and drastic actions to limit the warming to a maximum of 1.5 °C (Tollefson, 2018), the CH_4 emissions were also transformed to CO_2-equivalents with a 20-year perspective using a GWP factor of 86 (IPCC, 2013). The impact of N_2O emissions on GWP were not included as, for temperate peatlands that are rewetted for 9 years or more, this impact is negligible compared to impact of CO_2 and CH_4 emissions (Wilson et al., 2016).

2.2. Methane yield from plant biomass

2.2.1. Biogas experiment set-up

The biogas experiment investigated and compared the CH_4 yields in biogas produced from biomass of Pa and Tl. Aboveground biomass of Pa and Tl was harvested in an experimental wetland area in southern Sweden on the June 2, 2016 by cutting shoots above the water surface (approximately 5 cm). The area was constructed in 2002 and consists of 18 wetlands receiving agricultural groundwater (Weisner and Thiere, 2010). Biomass samples of each species were taken from different wetlands and dried to constant weight in ventilated ovens at 50–60 °C. Samples were cut and grounded corresponding to a mesh size of 1 mm.

The biogas experiment was performed in the laboratory using 1-liter glass bottles as anaerobic batch digesters (Fig. 1). The experiment was conducted with 14 digesters (5 digesters with biomass of each species and 4 controls). Inoculum (250 g wet weight) was added to all digesters. Between 2 and 11 g dry weight (DW) biomass sample was added to the digesters. The different amounts of biomass were added to establish relationships between the biomass amounts and methane yield. Controls contained only inoculum. Digestate from a mesophilic industrial biogas plant, where pig manure, plant residues, and various types of industrial waste are digested, was used as inoculum. The inoculum was stored at 37 °C for 4 days before the experiment to reduce remaining CH_4 production. The digesters were placed randomly in an incubator with a constant temperature (37 °C, i.e. mesophilic conditions) and were manually stirred daily for 1 min. The digesters were sealed with gas-tight rubber stoppers with septum equipped outlets where gas samples were taken. Each digester was connected, through a plastic tube, to a glass U-tube which was partly filled with water. Due to the increased pressure from produced biogas, the water surface will elevate in the second part of the U-tube. A Styrofoam ball was placed on the water surface and when the water reaches an IR-photo sensor, the sensor detects the ball after which an "event" is registered by a counter that was connected to a computer. Simultaneously, water levels in the two parts of U-tube are reset through the interconnecting pipe. The U-tubes were calibrated so each event corresponded to 45 ml gas production.

Biogas composition (CH_4 and CO_2) in each digester was determined at 5 occasions (day 7, 9, 10, 15, and 21) during the experiment by taking 20 μl gas samples using a Hamilton 50 μl syringe (Fig. 1). The samples were analyzed in a Varian CP-3800 gas chromatograph using a TCD detector and CP-Porabond Q capillary column. The experiment lasted 21 days; it was terminated when average daily gas production in the digesters had decreased to 0.5 events, corresponding to less than 10% of the maximum daily production.

2.2.2. Processing methane yield data

For each digester, the daily (24-h) production of CH_4 was calculated by multiplying the produced gas volume with daily concentrations. Daily CH_4 concentrations were obtained by interpolating between measurements. Sampling occasions were adjusted to capture concentration changes. Total CH_4 production for each digester was calculated as the sum of the daily values and the amount of CH_4 remaining in the gas space at the end of the experiment. The latter was calculated by multiplying final CH_4 concentration with the volume of the gas space in the digester (0.75 L). Finally, the CH_4 yield from plant biomass was calculated for each digester with added plant biomass by subtracting the mean CH_4 production of the 4 control digesters from the total CH_4 production of the digesters with plant biomass. The CH_4 yield is expressed per plant biomass unit (l/g DW) using equation (1).

$$CH_4\ yield\ per\ biomass\ unit = \frac{Total\ CH_4\ production - Mean\ total\ inoculum\ CH_4\ production}{Amount\ plant\ biomass\ added} \quad \text{(Equation 1)}$$

The density of CH_4 (0.657 g L^{-1}) at the conditions in the U-tubes (25 °C and 1 atm) was used for converting CH_4 yield from produced volume per biomass to produced weight per biomass.

2.3. Emission scenario calculations

A comparison was made between two different emission scenarios that connect the GHG emissions from peatlands and the transport sector:

1) Paludiculture management scenario. This scenario expresses the GWP of 1 m^2 of rewetted peatland covered with Pa or Tl. Furthermore, the distance a vehicle can be driven on biogas (biomethane) produced from plant biomass harvested in this area was calculated.
2) The business as usual scenario. This scenario expresses the GWP of 1 m^2 of drained peatland and CO_2 emissions from petrol-fueled cars travelling the same distance as in the paludiculture management scenario.

Annual plant biomass production in DW per peatland area in temperate rewetted peatlands dominated by either Pa or Tl was obtained from literature (Günther et al., 2015; Hendriks et al., 2007; Schulz et al., 2011; Yavitt, 1997; Zerbe et al., 2013). CH_4 yield per peatland area and year (g/m^2) was calculated using equation (2):

$$CH_4\ yield\ per\ land\ area = CH_4\ yield\ per\ biomass * Annual\ biomass\ production\ per\ area \quad \text{(Equation 2)}$$

Equation (3) expresses how CH_4 yield per land area was transferred into the range vehicle can be driven on biogas produced from biomass on 1 m^2 of rewetted peatland. The mean biomethane consumption (3.7 kg/

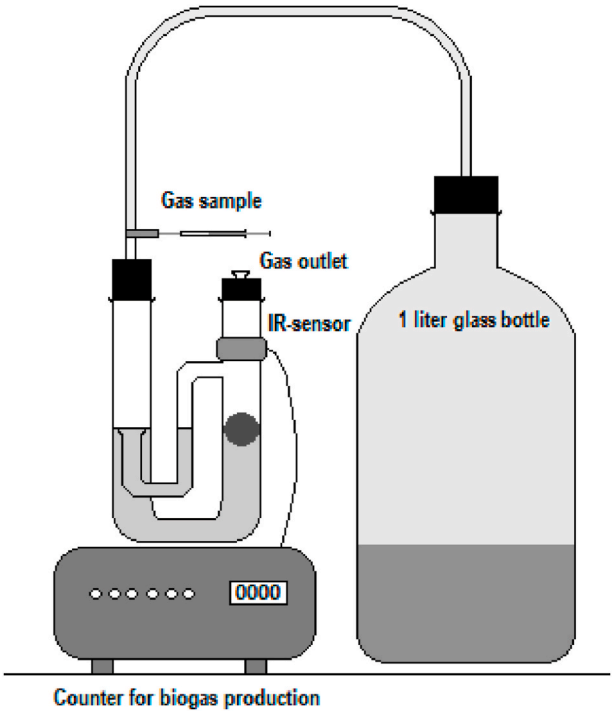


Fig. 1. Principal set-up of one unit for measuring biogas production. The experimental set-up consisted of 5 bottles for each plant species and 4 bottles with only inoculum, placed in a randomized design in an incubator at 37 °C.

100 km) of three average sized gas-fueled cars (Skoda Octavia G-Tec, Volvo V90 Bi-Fuel, and Volkswagen Polo 1.0 TGI) was used (Gröna bilister, 2016a; 2016b; 2018). As the fuel consumption of these cars is based on biomethane that consists of 97% CH_4 (Swedegas, 2019), the consumption of CH_4 is slightly less which is accounted for in equation (3).

$$Range(km) = \frac{CH_4 yield\ per\ land\ area}{Biomethane\ consumption\ (3.7\ kg/100\ km)*0.97}$$

(Equation 3)

For the business as usual scenario, the GWP data of Wilson et al. (2016) on drained peatlands in temperate climates was used, focusing on cropland and grassland categories. However, we also added a 20-years perspective to these data by using GWP-factors of 86 and 268, respectively, for transforming emissions of CH_4 and N_2O to CO_2-equivalents. CO_2 emissions caused by petrol fueled cars in a 20-years and 100-years perspective were calculated using the mean CO_2 emissions per km (123 g) for petrol cars registered within the EU (European Environment Agency, 2019).

2.4. Statistical analyses

Regression models for GHG emissions (CO_2, CH_4, and GWP) with water level as independent variable (covariate) were examined for statistically significant differences between peatlands with Pa and Tl, with analysis of covariance (General Linear Model, ANCOVA). The relations between water level and gas fluxes were further tested for Pa and Tl with Spearman rank correlations (rank correlations are reported only when $p < 0.05$). The difference between peatlands with Pa or Tl in overall GHG emissions, not including water depth as a factor, was statistically tested with a Mann-Whitney *U* test.

Differences in CH_4 yield between Tl and Pa in the biogas experiment was tested with ANCOVA with added plant biomass as covariate. Further, the mean CH_4 yields per biomass were calculated and the difference between Pa and Tl was tested with a Mann-Whitney *U* test. The

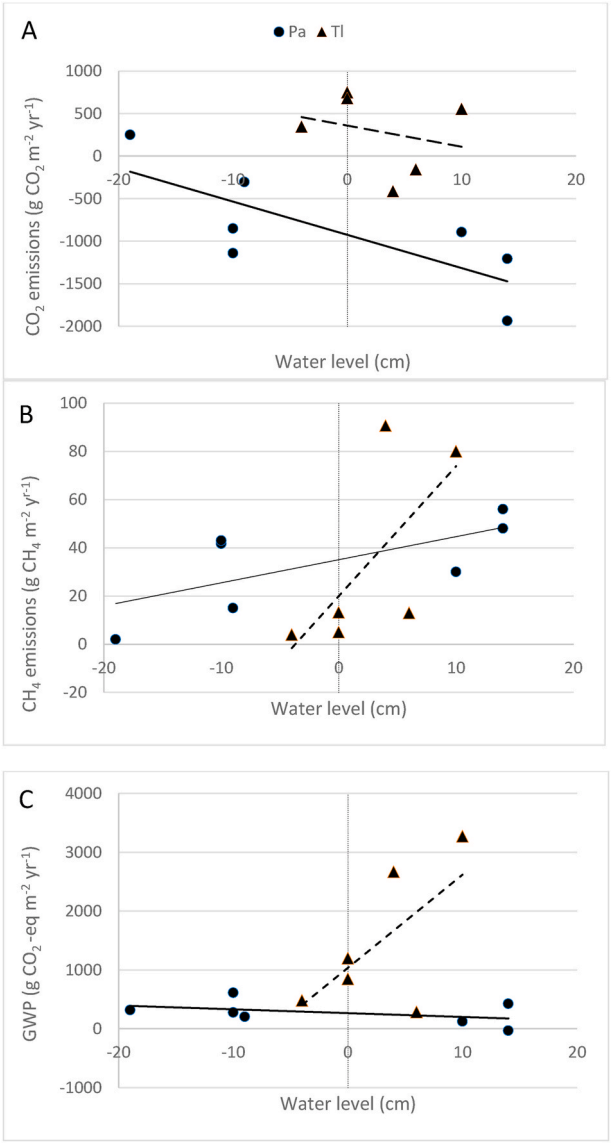


Fig. 2. Relation between water level and emissions of CO_2 (A) and CH_4 (B), and GWP on a 100-year timescale (C). In all graphs, Pa is represented with dots and Tl with triangles. The trend line of Pa is a full line and the trend line of Tl is a dashed line. The dotted line perpendicular to the x-axes indicates the soil surface level (0 cm).

difference in annual biomass production between Pa and Tl, according to the biomass values from different locations ($n = 6$ for Pa and $n = 6$ for Tl) obtained in the literature analysis, was also analyzed with a Mann-Whitney *U* test. All statistical tests were performed in SPSS (version 24) based on two-tailed hypotheses. Effects were considered statistically significant at $p < 0.05$.

3. Results

3.1. Impact of plant species and water level on GHG emissions

Fig. 2 illustrates emissions of CO_2 and CH_4, and GWP from rewetted peatlands in relation to water level, in a 100-years perspective. CO_2 emissions were significantly higher from peatlands covered with Tl compared to peatlands covered with Pa (ANCOVA; $p = 0.002$). There was no statistically significant overall relation of CO_2 emissions to water level and no significant interaction between effects of water level and species on CO_2 emissions (i.e. no difference between species in the slope

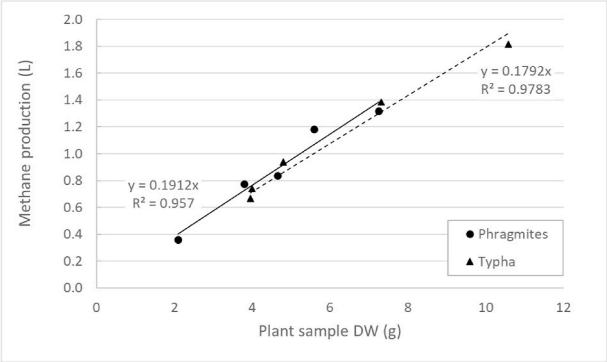


Fig. 3. CH_4 yield of Pa and Tl in relation to the added amount of biomass in the biogas experiment. Pa is represented with dots and Tl with triangles. The trend line of Pa is a full line and the trend line of Tl is a dashed line.

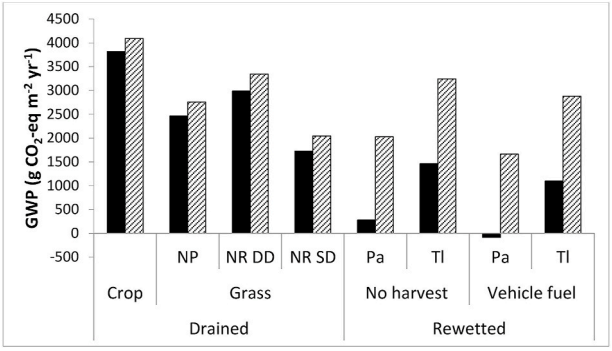


Fig. 4. Global warming potential for drained agricultural peatlands in the temperate zone, and for rewetted peatlands covered with either *Phragmites australis* (Pa) or *Typha latifolia* (Tl) according to this study. Crop = drained peatland used for crop production, NP = nutrient poor grassland, NR = nutrient rich grassland, DD = deeply drained, SD = shallowly drained (Wilson et al., 2016). No harvest = plant biomass not harvested or not used for any purpose affecting global warming, Vehicle fuel = plant biomass harvested and used for biogas production substituting fossil vehicle fuel. Black columns represent GWP on a 100-year timescale and dashed columns represent GWP on a 20-year timescale.

of the regressions between water level and CO_2 emissions) according to the ANCOVA. However, CO_2 emissions from peatlands with Pa did have a negative correlation with water level according to Spearman rank correlation ($p = 0.038$), resulting in lower CO_2 emissions in deeper water. CO_2 emissions for rewetted peatlands with Pa tended to be negative, which means that these peatlands generally sequestered more atmospheric CO_2 than was released (Fig. 2A).

CH_4 emissions from rewetted peatlands were positively related to water level (ANCOVA; $p = 0.024$), resulting in higher CH_4 emissions in deeper water (Fig. 2B). There was no statistically significant difference between peatlands with Pa and Tl in CH_4 emissions and no significant interaction between effects of water level and species on CH_4 emissions. According to ANCOVA, there was no statistically significant overall effect of water level on GWP. However, there was a significant interaction between effects of water level and species on GWP (ANCOVA; $p = 0.037$). Fig. 2C illustrates that this difference results in a higher GWP from rewetted peatlands covered with Tl compared to those covered with Pa. The GWP, in total CO_2-equivalent GHG emissions, not including water depth as a factor, differed significantly between rewetted peatlands covered with Tl and Pa (Mann-Whitney *U* test; $p = 0.014$). The mean GWP for rewetted peatlands covered with Pa or Tl was 276 and 1460 g CO_2-eq m^{-2} yr^{-1}, respectively.

3.2. Methane yield from plant biomass

CH_4 yield in the biogas experiment was closely related to the added amount of biomass, both for Pa and Tl (Fig. 3). The relationship between biomass and CH_4 yield was statistically significant ($p < 0.001$) and did not differ between the species according to ANCOVA. The mean CH_4 yield per biomass unit was 190 L per kg DW for Pa and 182 L per kg DW for Tl, although this difference was not statistically significant. Therefore, the mean value between the plant species (186 L per kg DW, corresponding to 122 g CH_4 per kg DW) was used in further calculations.

3.3. Emission scenarios

The mean annual biomass production per peatland area, based on the reported values from the reviewed literature, was higher for Pa (973 g DW m^{-2}) than for Tl (724 g DW m^{-2}), although not statistically significant. Since there were no significant differences between Pa and Tl both regarding CH_4 yield per biomass in biogas production and annual biomass production per peatland area, the mean values of the two plant species were used when calculating the biogas production per rewetted peatland area and year, the distance a gas-fueled vehicle could run on CH_4 after being upgraded to biomethane, and the emissions caused by petrol-fueled vehicles when the same distance was travelled. Values used and obtained in these calculations are given in Table 2.

Wilson et al. (2016) reported drained peatland emission data in temperate climates for cropland, nutrient poor grassland, and deeply or shallow drained nutrient rich grassland. Fig. 4 presents these data for scenario comparisons with rewetted peatland areas cultivated with Pa or Tl, and the GWP effect if plant biomass from these areas is harvested and used for production of biogas substituting petrol as vehicle fuel. As

Table 3
Emission reductions expressed as GWP reduction for rewetted peatlands covered with either *Phragmites australis* or *Typha latifolia* whose biomass is used for producing biogas as vehicle fuel. Crop = drained peatland used for crop production, NP = nutrient poor grassland, NR = nutrient rich grassland, DD = deeply drained, SD = shallow drained (Wilson et al., 2016).

GWP reduction (g CO_2 eq m^{-2} yr^{-1})				
	***Phragmites australis* (Pa)**		***Typha latifolia* (Tl)**	
	100 years	**20 years**	**100 years**	**20 years**
Crop	3906	2428	2722	1211
Grass NP	2550	1093	1366	**−124**
Grass NR DD	3073	1678	1889	461
Grass NR SD	1813	377	629	**−840**

Table 2
Calculation of mitigated GHG emissions by vehicles when petrol is substituted by biogas produced from Pa and Tl biomass harvested on 1 m^2 of rewetted peatland and the mean values of the two species.

	Methane yield per biomass unit (g/kg DW)	Biomass per peatland area (g/m^2)	Methane yield per peatland area (g/m^2)	Range of a biogas vehicle (km/m^2)	Mitigated emissions per peatland area by substituting petrol (g CO_2/m^2)
Pa	125	973	121	3.40	418
Tl	120	724	87	2.42	298
Pa & Tl	122	848	103	2.80	364

shown in Fig. 4, the GWP is very high for drained peatlands used for crop production. However, the GWP can be reduced if the peatland is used as grassland. A shallowly drained grassland shows a more than two times lower GWP than a crop production peatland both on a 100- and a 20-year timescale. Rewetting the peatland reduces the GWP even more, particularly on a 100-year timescale if Pa is planted and harvested for biogas production (vehicle fuel). Tl showed a higher GWP than Pa when planted and harvested on rewetted peatlands and did not improve GWP compared to shallowly drained grasslands on a 20-year timescale. This was mainly due to higher CO_2 emissions from rewetted areas when Tl was the dominant plant species compared to the situation when Pa was dominant (Fig. 2).

Calculations of emission reductions when comparing peatland use for crop production or as grassland (nutrient poor or nutrient rich either deeply or shallowly drained) with rewetting the peatland with cultivated Pa or Tl for vehicle biogas production, clearly show the difference between the 100- and 20-years GWPs (Table 3). Rewetting with Pa shows emission reductions, particularly in a 100-year perspective, while the effect is lower on a 20-year perspective. By rewetting the peatland with Tl, the 20-year perspective was negative compared to nutrient poor as well as shallowly drained nutrient rich grasslands, but the 100-year perspective was positive in all cases.

4. Discussion and conclusions

4.1. Factors influencing GHG emissions in rewetted peatlands

Paludiculture, i.e. rewetting and cultivating biomass on previously drained peatlands provides multiple ecosystem services, the reduction of GHG emissions being a major one (IPCC, 2014; Kasimir et al., 2018; Wilson et al., 2016). This study confirms what was shown before (Wilson et al., 2016; Dragoni et al., 2017; Taft et al., 2018): shallow flooding of drained peatlands represents a GHG mitigation option. More specifically, we found that the water level and the type of plants cultivated on a peatland are two main factors that influence the magnitude of GHG emission reduction on rewetted peatlands.

4.1.1. Water level

Although this study did not find a statistically significant overall relation between GWP and water level, the water level of rewetted peatlands is still an important factor for determining their GHG emissions. The water level regulates in which form carbon is released when organic material is decomposed through aerobic or anaerobic respiration, which leads to CO_2 or CH_4 emissions, respectively (Hendriks et al., 2007; Kasimir et al., 2018). In line with this, our results showed that CO_2 emissions from peatlands covered with Pa were negatively related to water level and emitted less CO_2 as a result of anaerobic conditions in flooded soils. Regarding CH_4 emissions, we found a positive correlation with water level in rewetted peatlands covered with either Pa or Tl, resulting in higher CH_4 emissions in flooded conditions. The final result of these effects of water level on CO_2 and CH_4 emissions is that Tl, compared to Pa, exhibits a significantly steeper relationship between water level and GWP (Fig. 2C). This indicates that water level has a larger effect on GWP of rewetted peatlands vegetated with Tl compared to Pa. As Tl was generally growing in deeper water, this resulted in markedly higher GWP for Tl than for Pa.

4.1.2. Plant species

In this study, CO_2 emissions from rewetted peatlands with Pa vegetation were significantly lower than CO_2 emissions from those with Tl vegetation. Pa was in general capable of sequestering more CO_2 than was emitted from soil and plant respiration, resulting in a negative CO_2 emission. Thus, rewetted peatlands with Pa vegetation may function as carbon sinks (Poyda et al., 2016; Van den Berg et al., 2016). However, rewetted peatlands with Tl vegetation had a positive CO_2 emission, i.e. functioning as a carbon source. Peatlands with Pa and Tl had, although differently affected by water depth, similar average CH_4 emissions that were comparable to the CH_4 emissions in wet peatlands in general (Couwenberg and Fritz, 2012). Vroom et al. (2018) report that Tl efficiently mitigates CH_4 emissions of rewetted peatlands in contrast to unvegetated rewetted peatlands. Dominant processes causing this emission reduction are attributed to the oxidation of CH_4 in rhizomes (Agethen et al., 2018). Moreover, in temperate climates, wetland plants like Pa and Tl tend to have higher rhizome/shoot ratios compared to similar plants in subtropical climates (Brix et al., 2001). High rhizome/shoot ratios can lead to less CO_2 and CH_4 emissions and large peat accumulation (Brix et al., 2001). Overall, GHG emissions showed statistically significant differences between rewetted peatlands with Pa and Tl, resulting in a higher GWP on rewetted peatlands with Tl vegetation compared to Pa vegetation. This finding supports previous studies that show that Pa is a good option for cultivation of flooded temperate fens (Günther et al., 2015; Minke et al., 2016).

4.2. Biomass yield and biogas production in paludiculture

An important aspect for the success of paludiculture is the choice to cultivate crops that meet different needs related to productivity, longevity and the potential of producing bioenergy (Liu et al., 2012; Dragoni et al., 2017). The results of the biogas experiment showed no statistical differences regarding CH_4 yield between the two species. The average yield of 186 L CH_4 per kg DW corresponds to 198 ml CH_4 per g volatile solids (VS), based on an ash content of 6% (Hernández-Crespo et al., 2016). The CH_4 yield is similar to the reported yield of 188 ml CH_4 g^{-1} VS for Pa (Lizasoain et al., 2016), but lower than the yield of 220 ml CH_4 g^{-1} VS (Risén et al., 2013) and 260 ml CH_4 g^{-1} VS reported by Jagadabhi et al. (2011). Regarding the CH_4 yield of Tl, Nkemka et al. (2015) reported a yield of 151 ml CH_4 g^{-1} VS, which is slightly lower than the CH_4 yield in this study. However, Alvinge (2010) reported a yield of 300 ml CH_4 g^{-1} VS which is markedly higher than in this study.

Because Pa and Tl are lignocellulosic substrates, the CH_4 yield can be substantially improved with mechanical, alkaline, and acid pretreatment methods that break the cell structure of the substrate and facilitate the microbial breakdown (Lizasoain et al., 2016; Tsapekos et al., 2018). For instance, Alvinge (2010) reports that mechanical pretreatment of Tl (as in this study) increased the biogas yield with 16% compared to untreated biomass, and alkaline pretreatment with lime increased the biogas yield with 27% at room temperature and 22% at 55 °C. Consequently, pretreatment is an important aspect for efficient biogas production from wetland plants. The extent to which different pretreatment methods has been applied can thus explain why CH_4 yield results from Pa, Tl, and similar lignocellulosic substrates vary widely between different studies. Overall, calculations of pretreatment costs in relation to the value of the increased biogas production are needed in order to make a decision if it is economically feasible to pretreat lignocellulosic substrates (Passos et al., 2017).

According to Dragoni et al. (2017), Pa and Tl have substantially lower biomass yields compared to conventional crops used for biogas production, which makes both species uncompetitive choices for the sole purpose of bioenergy production. From a paludiculture perspective, however, Pa constitutes an interesting cultivation option taking into account the additional value of peatland rewetting by promotion of ecosystem services, such as peatland restoration, reduced GHG emissions, and improved biodiversity. The choice of Pa as suitable crop for paludiculture is further supported by Roj-Roweski et al., (2019) who found that Pa, under wet conditions, can be an important source of biomass to be used as substrate for biogas production for improving the economic viability of paludiculture. Also, Tl has been suggested as a suitable paludiculture crop (Vroom et al., 2018; Pijlman et al., 2019), and biomass production of other lignocellulosic plant species (e.g. *Arundo donax*) has been suggested for biofuel in constructed wetlands, which also have a GHG emission reduction potential (Liu et al., 2012).

4.3. Reduction of GWP in rewetted peatlands

Drained peatlands used for conventional crop production are important sources of GHG emissions, peat degradation and soil subsidence (Pijlman et al., 2019). Increasing the water level can mitigate these effects but on the other hand enhance CH_4 emissions produced under anaerobic conditions in the water saturated zone (Kasimir et al., 2017). In line with Dragoni et al. (2017), our study shows that paludiculture provides several ways for reducing the GWP, both on a 20-year and 100-year timescale. More specifically, this study addresses the possibilities of changing agricultural land use on drained peat soils to paludiculture with Pa or Tl as crops and using the harvested plant biomass to produce biogas that can be utilized as vehicle fuel to reduce the use of and dependency on fossil fuels. Harvested Pa or Tl from 1 m^2 of rewetted peatland could, according to our results, drive a vehicle for 2.8 km on biomethane. The absolute GWP values of different land use practices after rewetting indicate that the actual rewetting of peat soils realizes the largest GWP reduction. If the biomass from 1 m^2 of rewetted peatland, covered with Pa, would be used for biogas vehicles (paludiculture scenario), the GHG reduction potential would be 3906 g CO_2-eq m^{-2} yr^{-1} (100-year timescale; Table 3) in comparison to the business as usual scenario (emissions of drained peatlands used for crop production together with petrol emissions from vehicles). On a 20-year timescale the GWP reduction is lower, but still substantial for Pa. If the GWP reduction of Pa is converted to the emission of petrol cars (using the mean value of 123 g CO_2 per km), with an average annual mileage of 12 000 km (Transport Analysis, 2019), rewetting 1 km^2 of peatland would annually reduce GHG emissions corresponding to 2600 cars on a 100-year timescale and 1600 cars on 20-year timescale.

In the long-term perspective, paludiculture would ideally result in the accumulation of peat again through carbon sequestration (Shultz et al., 2011). Even though the aboveground biomass would be harvested, peat accumulation will continue through belowground roots and rhizomes (Joosten et al., 2012). This study was not able to show belowground biomass production of Pa and Tl, but several other studies have stated that Pa accumulates more biomass than Tl after peatland restoration (Schulz et al., 2011; Zerbe et al., 2013).

4.4. Practical implications and future research

Paludiculture requires a radical change of agricultural activities but can induce innovative farming practices and give access to new markets by providing new products and services from paludiculture (Wichtmann et al., 2010). In this way, paludiculture could become part of the agricultural core activities by creating new business models and providing climate regulating services at the same time (Wichtmann and Wichmann, 2011). Using wetland plants for bioenergy production, as investigated in this study, is one such example. The use of perennial plant species as biogas substrates that replace fossil energy sources presents an alternative income for farmers, while increasing the sustainability of the energy sector (Dragoni et al., 2017). Both biogas and biofertilizer (digestate produced as a by-product of biogas production) can be sold as sustainable products after proper processing (Hagman and Eklund, 2016), although further studies are needed to explore the cost-effectiveness of harvesting wetland plants in a paludiculture system (Wichmann, 2017) and the subsequent biomass use. Moreover, since the transition to paludiculture might lead to an initial loss of income for farmers and landowners, upcoming research needs to investigate the economic feasibility of paludiculture as a form of sustainable land use. For instance, it is important to evaluate and develop incentives and subsidies from the public sector that can financially support long term, environmentally friendly business decisions amongst farmers and landowners (Karlsson et al., 2017) on rewetted peat soils. It is also relevant to further investigate the perceived drivers and barriers for sustainability-oriented business decisions (Björklund, 2018; Karlsson, 2019; Rauter et al., 2017), such as replacing conventional agricultural practices with innovative production systems such as paludiculture.

Additionally, since it is difficult to make general and predictive statements on GHG emissions, because their spatial variability depends on geographical location and weather conditions (Minke et al., 2016), further research is needed to confirm the results from this study. Upcoming studies in a temperate climate setting with larger sample sizes are thus needed in order to validate our results and expand the gained insights from our study. Furthermore, there is also a need of quantifying the GHG emission reduction that can be reached by paludiculture in different situations. For instance, Pa contributes to peat accumulation and negative CO^2 emissions, but its GHG reduction potential in a long-term perspective needs to be calculated and evaluated. A recent study by Pijlman et al. (2019) has indicated that yields of Tl peak between the middle and end of the growing season and that increased harvesting frequency (comparable with grazing) drastically reduced productivity. The effects of yearly harvests and optimal harvest times for biomass used in biogas production are parameters that need to be investigated. More studies are also needed to cover data on GHG emissions and water tables in a larger geographical area, including different climate zones, in order to identify suitable areas for paludiculture (Schlattmann and Rode, 2019).

4.5. Concluding remarks

This research focused on rewetted peatlands vegetated with Pa or Tl that were harvested for biogas production and their impact on GWP. This land management approach (paludiculture) was able to successfully reduce the GWP particularly on a 100-year timescale and, to a lesser extent, on a 20-year timescale. Pa, with a significantly lower mean GWP than Tl, was considered to be the most suitable plant to grow on rewetted peatlands. Moreover, wetland plants such as Pa are suitable substrates for the production of biogas that can be used in the transport sector as a substitute for fossil fuels. We conclude that rewetting peatlands and harvesting Pa biomass to be used as a substrate for biogas production could be an important measure for reducing the substantial climate impact of agriculture.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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