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Mitigation of methane emissions from constructed farm wetlands

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Abstract

Constructed wetlands are increasingly used for water pollution treatment but may also be sources of the greenhouse gas CH₄. The effect of addition of two potential inhibitors of methanogenesis - iron ochre and gypsum - on net CH₄ emissions was investigated in a constructed wetland treating farm runoff in Scotland, UK. CH₄ fluxes from three 15-m² wetland plots were measured between January and July 2008 in large static chambers incorporating a tunable diode laser, with application of 5 t ha⁻¹ ochre and gypsum in May. CH₄ fluxes were also measured from control and ochre- and gypsum-treated wetland sediment cores incubated at constant and varying temperature in the laboratory. Ochre addition suppressed CH₄ emissions by 64±13% in the field plot and > 90% in laboratory incubations compared to controls. Gypsum application of 5 t ha⁻¹ in the field and laboratory experiments had no effect on CH₄ emissions, but application of 10 t ha⁻¹ to a sediment core reduced CH₄ emissions by 28%. Suppression of CH₄ emissions by ochre application to sediment cores also increased with temperature; the reduction relative to the control increased from 50% at 17.5 °C to > 90% at 27.5 °C. No significant changes in N removal or pH and potentially-toxic metal content of sediments as the result of inhibitor application were detected in the wetland during the study.

Keywords: constructed wetland; farm; gypsum; methane; ochre; pollution swapping

1. Introduction

CH₄ is the largest contributor after CO₂ to direct anthropogenic radiative forcing of the atmosphere, currently comprising 20% of direct forcing (IPCC, 2007), and is expected to contribute significantly to global warming and changes in atmospheric chemistry in the future. Natural wetlands are the single largest source of CH₄ globally, emitting 100-231 Tg CH₄ y⁻¹, with substantial emissions also occurring from rice agriculture (IPCC, 2007). Constructed

wetlands which mimic natural wetlands have been demonstrated to remove suspended solids, organic matter, N, P, potentially toxic metals, and pathogenic microorganisms from point and non-point source water pollution (e.g., Scholes et al., 1998; IWA, 2000; Hunt and Poach, 2001; Vymazal, 2007) and represent a promising technology for sustainable treatment of polluted water, including farmyard runoff (Carty et al., 2008). Such use of constructed wetlands for wastewater treatment may therefore result in ‘pollution swapping’ by increasing CH₄ emissions (Reay, 2004). Consequently, there is considerable interest in managing constructed wetlands, and also flooded rice fields, to minimise CH₄ emissions.

CH₄ emission from wetlands is the net outcome of CH₄ oxidation and production processes, the latter occurring as anaerobic microbial decomposition of organic material by methanogens, in particular de-carboxylation of acetate and reduction of CO₂ (Conrad, 1989). Decreases in CH₄ emissions measured after addition of SO₄²⁻ and Fe³⁺ to wetland soils (mainly in rice fields - e.g., van der Gon and Neue, 1994; Jäkel and Schnell, 2000; Ali et al., 2008, but also peatlands - e.g., Dise and Verry, 2001; Gauci et al., 2002) have been attributed to inhibition of methanogenesis, predominantly through stimulation of SO₄²⁻ and Fe³⁺ reducing bacteria which outcompete methanogens for acetate and hydrogen. Stimulation of CH₄ oxidation by SO₄²⁻ (under anaerobic and aerobic conditions) and Fe³⁺ addition (under anaerobic conditions) may also contribute to these observed decreases in CH₄ emissions (Kumaraswamy et al., 2001).

Gypsum is a SO₄²⁻ source that is already widely used for improvement of agricultural soils and is the most common amendment for reclaiming sodic soils. A sustainable and cheap source of Fe is increasingly available in countries with a history of mining, such as the UK, in the form

of 'ochre' (i.e., $\text{Fe}(\text{OH})_3$ and $\text{FeO}(\text{OH})$), generated in large quantities by the precipitation of Fe in schemes to remediate drainage from abandoned mines. Although several possible uses of ochre have been identified, there is no large-scale outlet and it is often disposed of to landfill in the UK (Dobbie et al., 2009). However, ochre could be used in a more sustainable manner, by applying it to managed wetlands to stimulate Fe^{3+} reducers and thereby reduce CH_4 production. Although CH_4 suppression arising from SO_4^{2-} and Fe^{3+} addition to wet soils has been widely demonstrated, the effect of ochre on CH_4 emissions has not been investigated. One concern with the use of ochre is the release of potentially toxic metals, which may also have been removed with Fe during mine water treatment. Furthermore, few studies with CH_4 inhibitors have been conducted in a temperate wetland environment and none in a constructed farm wetland. The aims of this study were to measure the effect of gypsum and ochre additions on CH_4 emissions from a constructed farm wetland and to evaluate the interaction between inhibitor application and temperature on CH_4 emissions.

2. Materials and methods

2.1 Study site and field experiment

The wetland studied was constructed in May 2004 to treat lightly contaminated water from a mixed beef and arable farm in south east Scotland ($55^\circ 48'$ N, $2^\circ 13'$ E). The 0.9 ha wetland comprises five ponds separated by vegetated overland flow areas and receives field drainage, farmyard runoff and septic tank overflow via two inlets. In 2006-2007 N removal and CH_4 and N_2O fluxes were monitored for the overland flow area between the first and second ponds (Reay and Paul, 2008; van de Weg et al., 2008). The same area was used for this study, in which, in

January 2008, three parallel plots (10 m x 1.5 m and 0.5 m apart) that exhibited uniform vegetation (dominated by *Holcus lanatus* grass), topography and hydrology were delineated by curved tunnels of 3-m long fibreglass canes.

The experimental design for both field plot and laboratory incubation studies was based on the before-after-control-impact-pairs method widely used in ecological studies (e.g., Carpenter, 1990). CH₄ fluxes were determined using ‘mega-chambers’ created on each measurement occasion by covering the fibreglass canes at each plot with a gas-impermeable highly reflective sheet, to minimise super-ambient heating, which was sealed around its bottom edge with lengths of heavy chain. The effectiveness of this closure technique had been demonstrated previously in identical mega-chambers at the site by measuring the linearity of CH₄ accumulation and dilution of SF₆ (Reay and Paul, 2008). CH₄ concentration in each mega-chamber was measured as a 5-s average using a tunable diode laser (Gas Finder 2.0, Boreal Laser Inc., Canada, lower detection limit 0.1 ppm at 10 m path length) connected to a laptop. A chamber closure period of 15 min was used and CH₄ flux rates were calculated from linear regression of accumulation curves. CH₄ fluxes were measured at around midday on six occasions between January and July 2008, three before and three after application of the inhibitors. Triplicate CH₄ flux measurements were normally made at each plot, with 5-min manual flushing between enclosures, apart from on 31 January 2008 when single measurements were made. CH₄ production and oxidation rates were not measured as net CH₄ flux was the key variable of interest in this study. Water pH and temperature was measured using hand-held probes in surface water overlying each field plot on every measurement occasion. From mid March 2008 water temperature was also measured every 5 s using a HOBO Pendant Temperature Logger installed below the water surface in between the

plots. The central plot was designated the control (no treatment). On 8 May 2008, after CH₄ flux measurement, 5 t ha⁻¹ of either ochre or gypsum was applied to the other plots following the methods of previous field studies using gypsum. Gypsum granules (diameter 2-5 mm, moisture content < 1.5%, Rootwise Ltd., North Yorkshire, UK) and ochre pellets (diameter 6.4-9.5 mm), made from a mixture of dried ochre, organic and inorganic binders, pelletizing aids and 5% by weight of water, were used. Laboratory solubility tests found that gypsum granules dissolved completely after 62 d but ochre pellets were still intact after 6 months submerged in deionised water.

2.2 Water and sediment sampling and analysis

Measurements of N removal by the wetland were not designed specifically to assess the effect of treatment, but formed part of the long-term monitoring of the wetland since 2006. NO₃ and NH₄ concentrations were determined by automated colorimetry using standard methods (Autoanalyser II, Bran+Luebbe, Norderstedt, Germany) in water samples collected every 2 wk at the wetland inlets and outlet. Potentially toxic metals and pH were measured in three separate sediment samples collected from each plot on 2 March 2008 before treatment and on 3 July 2008, approximately two months after treatment. The samples were collected using a stainless steel hand corer with a plastic liner (diameter 48 mm, length 0.51 m, Wildco, Buffalo, NY, USA), transported to the laboratory at 4 °C and homogenised by hand before analysis. pH was determined with a calibrated hand-held probe in a slurry of 25 g fresh sediment mixed with 50 mL deionised water that had been stirred, left for 30 min and then re-stirred. Available potentially toxic metals (Al, As, Cd, Cu, Fe, Mn, Ni, Pb, Zn) were determined by ICP-OES (Perkin Elmer 5300DV Optima, Waltham, Massachusetts, USA) in filtered extracts prepared

within 24 h of sampling by shaking 5 g fresh sediment with 100 mL 2.5% acetic acid for 2 h. Total potentially toxic metals were determined by ICP-OES in digests of milled and ashed sediment prepared using HCl and HNO₃ (Allen et al., 1974). All sediment analyses were performed in duplicate and blanks were prepared.

2.3 Laboratory sediment core incubation experiments

Incubation experiments were conducted in a temperature-controlled water bath on pairs of sediment cores collected adjacent to the field plots in steel cylinders (diameter 0.18 m, height 0.12 m). The cores were sealed in plastic bags to minimise moisture loss and transported to the laboratory at 4 °C where they were transferred to Perspex containers (diameter 0.19 m, height 0.40 m), each sealed with a lid equipped with gas sampling ports. Both containers were incubated for 4-7 d for acclimatisation (until measurable CH₄ emissions were detected from both cores) at the water temperature measured with the hand-held probe at the coring location immediately before the cores were taken. Gypsum or ochre was then applied to the surface of one of the cores, with the other serving as an untreated control. Because the cores were collected on five occasions between March and July 2008 the acclimatisation water temperature varied between experiments. Three experiments were conducted as follows. First, to identify the effect of inhibitor application on CH₄ emissions, pairs of cores were incubated at constant field water temperature for 6 d after treatment of one of the cores with ochre or gypsum at the same application dosage as the field plots (5 t ha⁻¹). In the second experiment a pair of cores was incubated at constant field water temperature as in the first experiment but a higher gypsum application dosage of 10 t ha⁻¹ was used for the treatment core. The third experiment, to examine the interaction between temperature and inhibitor application, was exactly the same as the first

experiment, apart from that after treatment the water temperature was increased in 5 °C -steps, normally every 48 h. In all experiments the CH₄ flux from each core was determined three times a day from the change in headspace CH₄ concentration (3-h accumulation period on average), before and after flushing, measured using a Hewlett Packard 5890 series II gas chromatograph (Palo Alto, CA, USA) equipped with a flame ionisation detector (lower detection limit 0.01 ppm).

2.4 Data Analysis

All statistical analysis was conducted with Minitab v.15 using a significance level of $P < 0.05$. 1- and 2-way ANOVA followed by Tukey tests was used to compare CH₄ emissions before and after inhibitor application, and N removal (calculated as the % change on each sampling occasion in NO₃ and NH₄ concentrations between the wetland inlet and outlet water samples) between years and pH in surface water between field plots. Paired t-tests were used to assess whether any differences in pH and available and total potentially toxic metal concentrations in sediment between the field plots were affected by inhibitor application. The responses of CH₄ emission rates from the field plots and incubated sediment cores to temperature were determined by calculating Q₁₀ values. These indicate the increase in emission rate with a temperature increase of 10 °C and were calculated from the slopes of the CH₄ emission rates at different temperatures.

3. Results

3.1 Field experiment

CH₄ emissions from the field plots were positively related to water temperature, but were suppressed in the ochre plot after inhibitor application (Fig. 1). In the period before the application of inhibitors, there was no significant difference between the mean CH₄ emissions from the gypsum, control and ochre plots, these being 6.8, 5.2 and 5.3 mg CH₄ m⁻² h⁻¹, respectively. In the period after inhibitor application mean CH₄ emissions from the plots were significantly different (P = 0.021); the mean emission rate from the ochre plot of 9.0 mg m⁻² h⁻¹ was significantly lower than that from the control and gypsum plots of 27 and 28 mg m⁻² h⁻¹, respectively. This corresponded to a 64±13% reduction in CH₄ emitted from the ochre-treated plot compared to the control. There was no significant change in % removal of NO₃ (P = 0.968) and NH₄ (P = 0.806) in 2008 compared to 2006 and 2007 (Table 1), indicating that the ochre/gypsum applications did not appear to influence the N removal capacity of the wetland as a whole. Mean surface water pH was 6.9-7.1 in the plots before inhibitor application and 7.0-7.1 afterwards; it did not differ significantly between plots (P = 0.906) nor before and after treatment (P = 0.773). In addition there was no significant effect of inhibitor application on pH (6.9-7.2 before and 6.8-7.3 after) or concentrations of available and total potentially toxic metals in the field plot sediments. Although total Mn (P = 0.033) and available Ni (P = 0.030) sediment concentrations were significantly different after inhibitor application the increase occurred in all the plots.

FIG. 1 AND TABLE 1 HERE

3.2 Laboratory sediment core incubation experiments

In the experiments conducted under constant temperature conditions using the same 5 t ha⁻¹ inhibitor application dosage as in the field plots, ochre application resulted in a 90% reduction in CH₄ emissions compared to the control core only 5 d after application (Fig. 2a). There was no difference in CH₄ emissions between control and treatment cores after gypsum application (Fig. 2b) but, when a higher gypsum application dosage of 10 t ha⁻¹ was used (Fig. 2c), emissions from the gypsum-treated core were on average 28% lower than emissions from the control core. The large differences in CH₄ emission rates between control cores and the experiments probably result from the different core collection dates giving rise to different experimental incubation water temperatures and perhaps differences in activity of methanogenic organisms in the sediment cores (although microbial counts and activity measurements were not conducted). Figure 3 shows the CH₄ fluxes measured from the control and treatment (5 t ha⁻¹ inhibitor applications) sediment cores incubated at different temperatures. In the ochre experiment, CH₄ emissions from the two cores were similar in the acclimatisation period but, after treatment, CH₄ emissions from the control core increased more rapidly with temperature than emissions from the ochre core, before levelling off at 27.5 °C (Fig. 3a). The extent of suppression of CH₄ emissions resulting from ochre addition increased with temperature, rising from about 50% at 17.5 °C to > 90% at 27.5 °C compared to the control core. In contrast, in the gypsum experiment, there was no apparent difference in CH₄ fluxes from the gypsum-treated and control cores at any of the incubation temperatures over the entire experiment (Fig. 3b).

FIGS. 2 AND 3 HERE

3.3 CH₄ emission-water temperature relationships

In the field experiment, CH₄ emissions from all three plots increased exponentially and significantly with water temperature between 3.5 °C and 16.5 °C (Table 2). However, the response of CH₄ emissions to temperature was less marked in the ochre plot compared to the control and gypsum plots. This effect was also apparent in the lower Q₁₀ value calculated for the ochre plot of 2.2 compared to 6.5 and 7.6 and for the gypsum and control plots, respectively. In the variable temperature sediment incubation experiments, CH₄ emissions increased either exponentially or linearly in all the incubated sediment cores for all the temperature ranges investigated, apart from the higher temperatures reached towards the end of the experiments. The diminished response of CH₄ emissions to temperature after ochre addition was also evident in these experiments as the Q₁₀ values for the ochre core were < 50% and < 20% those for the control core in the 12.5-22.5 °C and 17.5-27.5 °C temperature ranges, respectively. In contrast, in the gypsum treatment experiment Q₁₀ values for the treated and control cores were similar for the three temperature ranges tested.

TABLE 2 HERE

4. Discussion

The CH₄ fluxes measured in the field experiment were within the range of those determined from a constructed wetland in Finland receiving agricultural runoff and other constructed wetlands in northern Europe treating municipal wastewater (Søvik et al., 2006). CH₄ fluxes from the control and gypsum plots showed the same seasonal pattern, with low emissions in winter and higher emissions in summer as water temperatures increased. There was no significant

difference in CH₄ emissions between the field plots before treatment, but, after addition of inhibitors, CH₄ emissions from the ochre-treated plot were suppressed by 64% compared to the control plot during the 56-d post-treatment monitoring period. In sediment incubation experiments, CH₄ emission from the ochre-treated core was reduced by > 90% compared to the control core on the last day of the experiment. Similar reductions of 50-90% in CH₄ emissions have been reported after the addition of amorphous Fe(III) oxyhydroxide to tidal and freshwater river sediments (Lovley and Phillips, 1986). The expected mechanisms for decreased CH₄ emissions after ochre application are promotion of the activity of Fe³⁺ reducing bacteria, resulting in a switch in electron flow from methanogenesis to Fe³⁺ reduction (Frenzel et al., 1999) and/or increased CH₄ oxidation (Kumaraswamy et al., 2001). The incomplete suppression of CH₄ emissions after the addition of ochre to the field plot may have a number of causes, which need further investigation, including: the low solubility of ochre; application of ochre to the vegetated surface of the wetland without mixing to incorporate it throughout the sediment depth; the continued presence of oxic zones due to the flow of oxygenated water through the wetland; and the high organic matter content of the wetland sediment (25% loss on ignition after heating overnight at 500 °C in a muffle furnace).

There was no change in CH₄ emissions compared to controls in either the field and laboratory experiments when gypsum was applied at 5 t ha⁻¹. However, at a higher gypsum application dosage of 10 t ha⁻¹ in the laboratory, there was evidence of some suppression of CH₄ emissions, indicating that SO₄²⁻ additives may have the potential to limit CH₄ emissions in constructed wetlands. Further investigation is required to understand the apparent absence of CH₄ suppression after gypsum application to the study wetland, but the following explanation

may be suggested at this stage. The ratio of SO_4^{2-} to organic matter in the wetland sediment may have been too low for the gypsum application to have any effect as SO_4^{2-} reducers can only out-compete methanogens for organic carbon if SO_4^{2-} is in excess (van Bodegom and Stams, 1999). Reductions in CH_4 emissions reported after gypsum application at lower dosages than used in this study (for example, 1-2 t ha⁻¹ to rice fields reduced CH_4 emissions by 29-46% (Lindau et al., 1994)) could have occurred because these agricultural soils have a sufficiently high ratio of SO_4^{2-} to organic matter for methanogens to be suppressed. This explanation is supported by studies which showed that organic matter addition to rice fields resulted in increased CH_4 emissions (Schütz et al., 1989; Wassmann et al., 2000).

The Q_{10} values for the field experiment indicate a strong response of CH_4 emissions to water temperature and are of similar magnitude to values of 2.7-7.9 derived from reported CH_4 emissions from peatlands in Minnesota, USA (Dise et al., 1993). The lower Q_{10} for the ochre-treated plot could be indicative of the greater activity of Fe^{3+} reducers after ochre application since a lower Q_{10} value for Fe reduction than CH_4 production has been reported for rice field soils (Roden, 2003). Whilst the variable temperature sediment incubation experiment was conducted at higher water temperatures than at the field site it does indicate how suppression of CH_4 emissions from wetlands by inhibitors may respond to changing temperatures.

5. Conclusions

Application of the ochre pellets used in this study at 5 t ha⁻¹ would be anticipated to suppress CH_4 emissions from temperate constructed farm wetlands for at least 6 months, since the pellet

dissolution rate is > 6 months. There was no apparent increase in potentially toxic metals or pH change in sediment or change of N removal capacity of the wetland arising from application of ochre. Hence ochre pellets appear to be a suitable material for mitigating CH₄ emissions from constructed farm wetlands, thereby reducing the risk of pollution swapping and providing an additional benefit through use of a waste material which would otherwise have been landfilled. The results indicate that gypsum addition may also reduce CH₄ emissions from temperate constructed farm wetlands, but probably at higher application dosages. Further laboratory and field experiments are required to optimise the gypsum application dosage and examine its environmental acceptability before widespread application of gypsum to constructed wetlands can proceed. These studies should also seek to elucidate the mechanisms responsible for the reduction of CH₄ emissions from constructed wetlands by including killed control laboratory experiments and measurements of SO₄²⁻ and Fe species and the activities of different bacterial communities in wetland sediment and water before and after inhibitor application.

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Fig. 1. Mean CH_4 flux ($\pm$ standard error, where $n = 3$) and water temperature for the field plots on each measurement occasion. The January water temperature was the mean of measurements made at each plot using the hand-held probe. Thereafter, the water temperature is the mean of the values measured by the logger for the period of CH_4 measurements (3-4 h). The vertical arrow represents the application of inhibitors after 8 May measurements.

Fig. 2. Mean daily CH_4 fluxes ($\pm$ standard error, $n = 3$ measurements per day) from pairs of sediment cores incubated at constant temperature with different treatments (a) ochre (cores collected 8 April 2008, water temperature 7.5°C , application rate 5 t ha^{-1}), (b) gypsum (cores collected 14 June 2008, water temperature 11.5°C , application rate 5 t ha^{-1}), (c) 'high' gypsum (cores collected 3 July 2008, water temperature 13.5°C , application rate 10 t ha^{-1}). Negligible CH_4 fluxes were measured at the start of the acclimatisation period which is represented by negative days. Inhibitor application to one of the cores occurred on Day 0 approximately 3 h before the first headspace CH_4 sampling.

Fig. 3. Mean daily CH₄ fluxes ($\pm$ standard error, $n = 3$ measurements per day) from pairs of sediment cores incubated at varying water temperature for (a) ochre and (b) gypsum treatment experiments. Negative days represent the acclimatisation period. Inhibitor application at 5 t ha⁻¹ to one of the cores occurred on Day 0 approximately 3 h before the first headspace CH₄ sampling. The different temperature ranges in the experiments were due to different field water temperatures when the cores were collected. After treatment the water temperature was normally increased by 5 °C-steps every 48 h. In (a) CH₄ fluxes from Day -7 and Day -7 to -5 in the control

Table 1. Mean (n = 2-4) monthly % removal of NO₃ and NH₄ by the wetland calculated from the differences in concentration between water samples at the wetland inlets and outlet. Data for 2006 and 2007 are from van de Weg et al. (2008) and Reay and Paul (2008), respectively.

	NO ₃			NH ₄		
	2006	2007	2008	2006	2007	2008
January	-	-	-3	-	-	35
February	9	25	75	90	-29	31
March	22	84	32	99	84	67
April	39	31	63	70	68	97
May	75	77	21	12	59	96
June	99	54	70	64	88	76
July	-	-	99	-	-	62

Table 2. Q_{10} coefficients and best-fit CH_4 emission-water temperature relationships for the field experiment and the ochre and gypsum treatment sediment core experiments incubated at varying temperature in the laboratory.

Temperature range °C	Control plot/core		Treatment plot/core	
	Q_{10}	Temperature relationship	Q_{10}	Temperature relationship
Field experiment				
3.5-16.5	7.58	Exponential ($R^2 = 0.953$, $P=0.001$)	2.24	Ochre: Exponential ($R^2 = 0.831$, $P=0.011$)
			6.50	Gypsum: Exponential ($R^2 = 0.997$, $P<0.001$)
Ochre laboratory experiment				
7.5-17.5	57.5	Exponential ($R^2 = 0.800$, $P=0.007$)	34.3	Exponential ($R^2 = 0.909$, $P=0.001$)
12.5-22.5	34.4	Exponential ($R^2 = 0.938$, $P=0.002$)	17.1	Exponential ($R^2 = 0.902$, $P=0.001$)
17.5-27.5	5.98	Linear ($R^2 = 0.951$, $P=0.001$)	0.948	None ($R^2 = 0.001$, $P=0.952$)
Gypsum laboratory experiment				
10-20	2.82	Linear ($R^2 = 0.599$, $P=0.071$)	5.70	Linear ($R^2 = 0.817$, $P=0.013$)
15-25	9.55	Exponential ($R^2 = 0.764$, $P=0.053$)	11.3	Exponential ($R^2 = 0.865$, $P=0.022$)
20-30	5.36	Exponential ($R^2 = 0.581$, $P=0.134$)	3.94	Exponential ($R^2 = 0.404$, $P=0.250$)