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Nitrous oxide emissions from a gully mire in mid-Wales, UK, under simulated summer drought

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Abstract. Certain general circulation models predict that a doubling of atmospheric carbon dioxide concentrations will increase the frequency of summer drought in northern wetlands due to hotter, drier summers. There is currently much uncertainty as to how drought will affect emissions of the greenhouse gas, nitrous oxide, from wetlands. We have demonstrated that an eight centimetre drawdown of the water table in a gully mire does not significantly affect nitrous oxide emissions from this site. However, under a more extreme drought scenario carried out on peat monoliths, nitrous oxide emissions increased exponentially with a linear decrease in water table height. Drought caused a significant increase in nitrous oxide production *below* the water table but most of the total increase could be attributed to increased emissions *above* the water table. Results from an acetylene block experiment suggested that increased emissions were caused by increased nitrous oxide production from denitrification, rather than by increased production from nitrification. In the laboratory study, drought severity had no effect on peatwater nitrate concentrations below the water table, however, increasing drought severity decreased ammonium concentrations.

Introduction

The global mean surface-air temperature of the earth has increased by between 0.3 and 0.6 °C since the late nineteenth century. Climate is expected to change further in the future, with many climate models predicting a mean surface-air increase of about 2 °C over the next 100 years (Houghton et al. 1996). This may lead to a decrease in soil wetness during the summer in Western Europe and North America (Manabe & Wetherald 1986). Water is an important factor regulating the biogeochemistry of soils, particularly wet-

land soils (Ponnamperuma 1972). Therefore, an increase in the frequency or severity of summer drought may have a profound impact on wetland biogeochemistry.

One aspect of wetland biogeochemistry which has received little study is the effect of drought on nitrous oxide emissions. Soils are probably the largest source of this potent greenhouse gas, with atmospheric concentrations currently increasing at the rate of 0.2–0.3% per year (Houghton et al. 1996). Most studies to date have concentrated on either the effect of extreme drought (Freeman et al. 1993a) or drainage (Augustin et al. 1996; Martikainen et al. 1993, 1995; Nykänen et al. 1995; Regina et al. 1996). These studies have demonstrated either an increase or little effect of drought on nitrous oxide emissions. However, we have recently demonstrated a decrease in nitrous oxide emissions from a gully mire in mid-Wales during a simulated low-intensity drought (Freeman et al. 1997). We considered that these conflicting results may be explained by differences in the severity of drought addressed by each study.

Here, we present results from a field study examining the effects of simulated more intensive summer drought on nitrous oxide emissions from a gully mire in mid-Wales, UK. We hypothesized that a further lowering of water table levels at this site may increase nitrous oxide emissions, due to release of nitrate in the aerobic zone above the water table, as demonstrated by Freeman et al. (1993b). In a parallel laboratory experiment on intact peat monoliths taken from the site, water table levels were manipulated to varying extremes and nitrous oxide emissions and soil water nitrate and ammonium concentrations measured. Specifically, we evaluated changes in nitrous oxide emissions down through peat profiles in order to examine the role of position above or below the water table. We also examined whether increases in the rate of nitrous oxide production were caused by a change in nitrification or denitrification.

Methods

The field study

The field drought simulation was carried out on a flushed gully mire at Cerrig-yr-Wyn, Plynlimon, Wales, UK (52°28′N; 3°45′W). The site is dominated by *Sphagnum* and *Juncus* species. Part of the mire downstream of a control site was isolated by installing a dam at the bottom of the control site and installing pipes at the dam which carry water around the experimental site, thereby causing the site to dry (Freeman et al. 1993c). The drought severity was manipulated by varying the number of pipes which carry water

around the experimental site. Water table levels in the experimental site were manipulated between the beginning of May and the beginning of September, 1994.

Nitrous oxide emissions from the control and experimental site were determined every two weeks between the end of April and the beginning of October, 1994. Five, 4.5 litre polyethylene bottles with the bases removed were inserted into the peat at the beginning of the experiment every two metres down a transect from the top to the bottom of the control and experimental sites. The background air was sampled before each bottle was capped. Following two hours of incubation, a 10 ml gas sample was removed through a piece of tubing 3 mm in diameter inserted into the cap. Rates of nitrous oxide emission were determined as the increase in headspace concentration above background nitrous oxide concentration over the two hour incubation period. The bottles were left *in situ* over the course of the experiment with the caps removed to minimise disturbance to the peat.

The laboratory study

Thirty-two intact peat cores were collected from nearby the Cerrig-yr-Wyn control site. At the time of collection, peatwater 5 cm below the surface had a pH of 4.7, with concentrations of the major ions of: 0.4 mg l^{-1} for NH_4-N; 0.1 mg l^{-1} for NO_3-N; 0.1 mg l^{-1} for PO_4-P; 0.9 mg l^{-1} for potassium and 0.7 mg l^{-1} for SO_4-S.

Cores 11 cm in diameter were cut into the peat to a depth of 20 cm with a knife, and a piece of OSMA$^{(TM)}$ PVC plastic piping 11 cm diameter by 20 cm long eased around each core. The peat around each core was excavated, to allow access to the bottom of each core, each core carefully removed, and placed into a plastic bag to minimise water-loss. This method ensured that each peat core was disturbed as little as possible.

Peat cores were incubated in a modification of the perfusion system of Freeman et al. (1993d). In this experiment, the central chamber was shortened to 20 cm. A leaching port five centimetres up from the bottom of the central chamber enabled removal of peatwater samples. The cores were incubated in a constant temperature room at 12 °C with a 12 hour light: 12 hour dark cycle. The water table of each core was maintained at the correct level by addition of a sufficient quantity of water from the sample site. Initially, the water table of each core was maintained at the peat surface and nitrous oxide emissions determined after one and two weeks to verify that there was no significant difference between nitrous oxide fluxes prior to treatment.

Following the second week of gas sampling, the perfusion system side arms were shortened to decrease the water table level in eight cores to 7 cm below the surface, eight cores to 14 cm below the surface, and eight cores to

20 cm below the surface. Eight cores were maintained with the water table at the surface of the peat as a control. Nitrous oxide emissions were determined every week for a further ten weeks.

Once a week between weeks four and ten, five millilitres of water was removed from each core through the leaching port and analysed for ammonium and nitrate using ion chromatography. Each sample was filtered through a Nalgene 0.2 μm CA pre-filter and a DIONEX On-Guard P sample pre-treatment cartridge prior to analysis using a DIONEX 2000i/sp system fitted with conductivity detection and auto self-regenerating suppression. Nitrate was determined with an AS4A column, ammonium with a CS12 column.

Nitrous oxide analysis

Nitrous oxide emissions were determined by capping each of the 32 perfusion system central chambers with an ABS cap for two hours, followed by removal of one 5 ml gas sample through a septum in the lid of each chamber.

Linearity of nitrous oxide emission rates were determined on the control cores and cores with a water table drawdown of 20 cm on the fifth week of drought by determining emissions after 0 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours and 4 hours. Nitrous oxide emissions from both treatments were linear over a two hour period ($r^2 = 0.999$, $p < 0.001$ for the control cores; $r^2 = 0.989$, $p < 0.05$ for the cores with a water table drawdown of 20 cm).

Gas samples from the field and laboratory study were analysed using an Ai Cambridge model 92 gas chromatograph fitted with a Porapak QS column operating at 70 °C and an electron capture detector operating at 350 °C. Nitrogen was used as the carrier gas at a flow rate of 70 $cm^3\ min^{-1}$.

Nitrous oxide emissions through depth profiles

After ten weeks of simulated drought in the laboratory, five peat cores from each treatment were removed from the perfusion systems and peat samples between depths of 2–4 cm, 9–11 cm and 16–18 cm homogenised. 30 g samples of peat from each depth were placed in 100 ml glass bottles, incubated for 24 hours at 12 °C, and nitrous oxide emissions determined by capping each bottle for one hour, followed by removal of a gas sample through a silicone septum in the lid. Linearity of nitrous oxide emission rates was determined once on slurries taken from a depth of 2–4 cm from the cores with a water table drawdown of 20 cm. Gas sampled following 0 minutes, 15 minutes, 30 minutes, 1 hour and 2 hours of incubation demonstrated that nitrous oxide emissions were linear over a two hour period ($r^2 = 0.995$; $p < 0.001$).

Fluxes of nitrous oxide produced by nitrification and by denitrification

Nitrous oxide produced by nitrification was determined using 10 Pa of acetylene, which blocks nitrification, but has no significant effect on denitrification (Davidson et al. 1986). Soil slurries from five replicate cores at a depth of 2–4 cm from cores with a water table drawdown of 20 cm were prepared as above. Capped 100 ml bottles were injected with 0.01 ml of acetylene through a septum in the lid. Every hour for four hours, bottles were flushed with air, capped, 0.01 ml of acetylene reinjected into each bottle and the headspace sampled after 30 minutes. Acetylene was generated by the action of water on calcium carbide.

Rates of denitrification were determined on peat slurries at a depth of 2–4 cm from the control cores and cores with a water table drawdown of 20 cm using the 'acetylene block' technique (Yoshinari et al. 1977). Rates were determined in the same way as nitrification, however, to block the conversion of N_2O to N_2, 15 ml of air was replaced with 15 ml of acetylene in each capped bottle, using a syringe. Every hour for four hours, bottles were flushed with air, capped, 15 ml of air removed from each bottle with a syringe, 15 ml of acetylene reinjected into each bottle and the headspace sampled after 30 minutes.

Statistical analysis

Trends over time were analysed using repeated measures ANOVA on SPSS version 6.1 (SPSS, Inc.). Nitrous oxide production rates down through peat core depth profiles were analysed using ANOVA on Minitab, version 9.2 (Minitab, Inc.). Error bars on graphs are ± 1 standard error.

Results

A water table drawdown of up to 8 cm had no net effect on nitrous oxide emissions from the field site (Figure 1) or from the laboratory manipulation (Figure 2). However, more severe simulated drought in the laboratory caused an increase in nitrous oxide emissions with a water table drawdown of 14 cm ($p < 0.05$) and 20 cm ($p < 0.001$). Emissions increased within the first week, no significant increases in emission rates were observed after three weeks of simulated drought. A linear decrease in water table height caused a logarithmic increase in nitrous oxide emissions from the intact cores (Figure 3; $p < 0.01$).

Depth profiles of nitrous oxide emissions demonstrated that almost all of the increase in emissions following simulated drought could be accounted

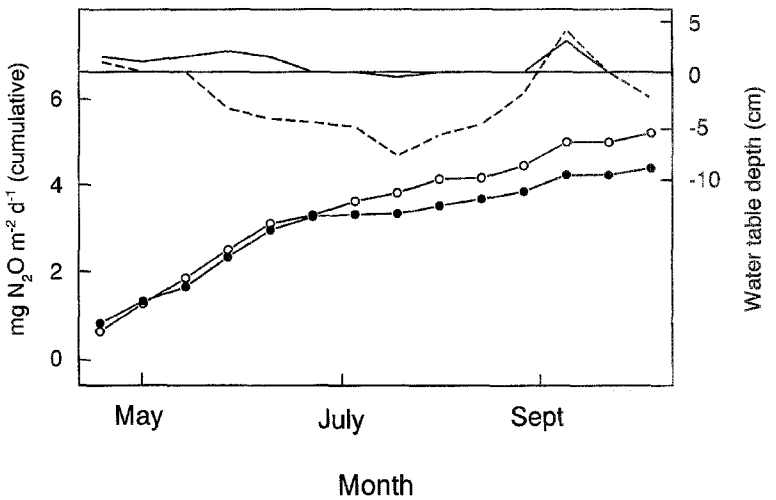

Figure 1. Cumulative nitrous oxide emissions during the summer of 1994 from the control site (closed circles) and experimental site (open circles). Water table depth in the control wetland is represented by a solid line; water table depth in the experimental wetland by a dashed line.

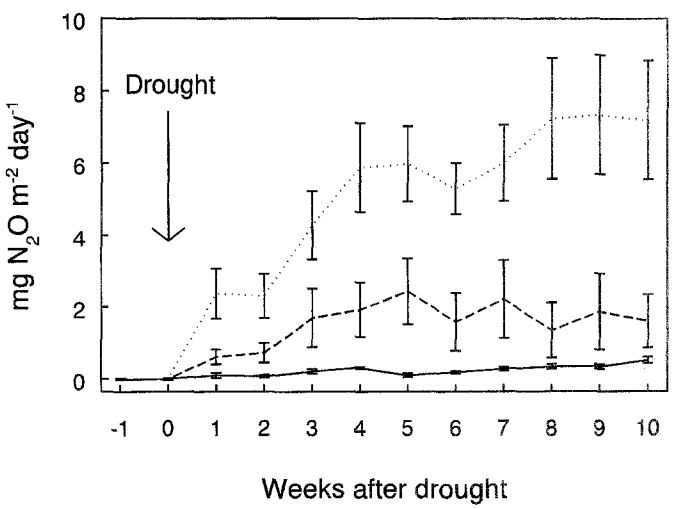

Figure 2. Nitrous oxide emissions from peat cores over a ten week period with the water table held 7 cm below the peat surface (solid line), 14 cm below the peat surface (dashed line), and emissions from drained cores (dotted line). For clarity, emissions from the control cores are not shown. Mean rate of nitrous oxide emission from the control cores over the 10 week sampling period was 0.05 mg m^{-2} day^{-1}.

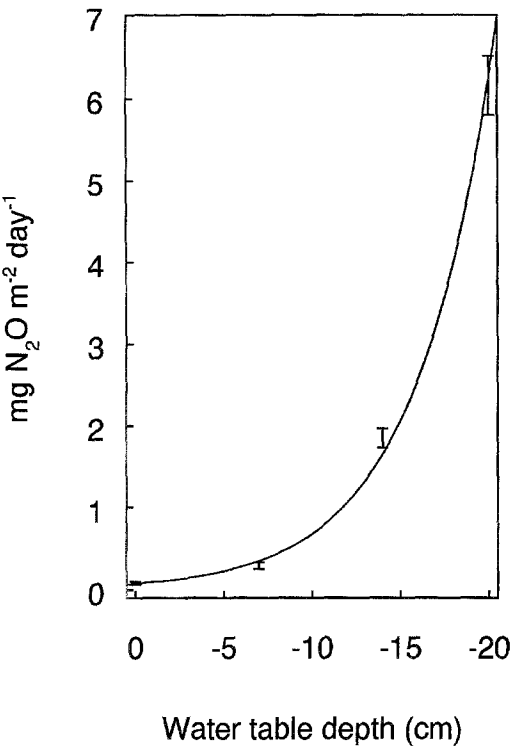

Figure 3. Mean rate of nitrous oxide emission from the control cores and three drought treatments between weeks three and ten.

for by increases in nitrous oxide production *above* the water table (Figure 4). However, drought also significantly increased nitrous oxide emissions *below* the water table with a drawdown of 7 and 14 cm compared with the control (ANOVA; $p < 0.05$), with the exception of a drawdown of 7 cm at a depth of 10 cm.

The acetylene block technique did not significantly increase nitrous oxide emissions from the control core peat slurries. Emissions of 0.01 μg g^{-1} peat $hour^{-1}$ ± 0.01 before the addition of acetylene were not significantly greater than zero. However, nitrous oxide emissions from peat taken at the same depth from the treatment with a water table drawdown of 20 cm were 0.87 μg g^{-1} peat $hour^{-1}$ before the addition of acetylene. Acetylene addition increased emissions to 1.31 μg g^{-1} peat $hour^{-1}$, suggesting that nitrous oxide accounted for 67% ($\pm 3\%$) of denitrification products. Emissions increased significantly during the first 30 minutes following addition of acetylene to the slurries. No significant increase in emissions was observed following one hour of incubation. Furthermore, 10 Pa of acetylene had no effect on nitrous oxide emissions from the treatment with a water table drawdown

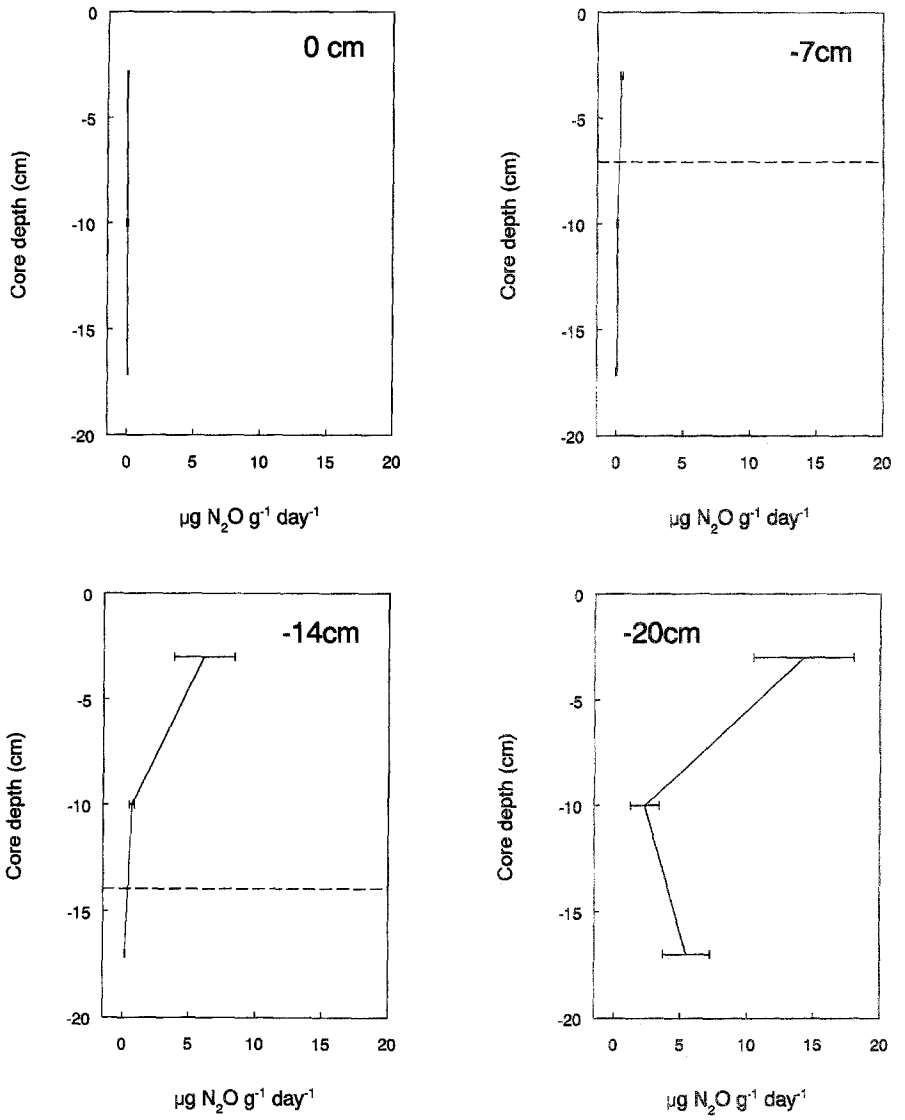

Figure 4. Depth profiles of nitrous oxide emissions from the control cores and three drought treatments. Dashed lines represent the water table position.

of 20 cm, suggesting that the observed increases in nitrous oxide emission during drought were not caused by nitrification. Mean nitrous oxide emissions were 0.66 μg g^{-1} peat $hour^{-1}$ $\pm$0.06 before the addition of 10 Pa of acetylene and 0.68 μg g^{-1} peat $hour^{-1}$ $\pm$0.04 following acetylene addition.

Drought did not significantly affect nitrate concentrations in the peatwater below the water table from the laboratory simulation (Figure 5). However,

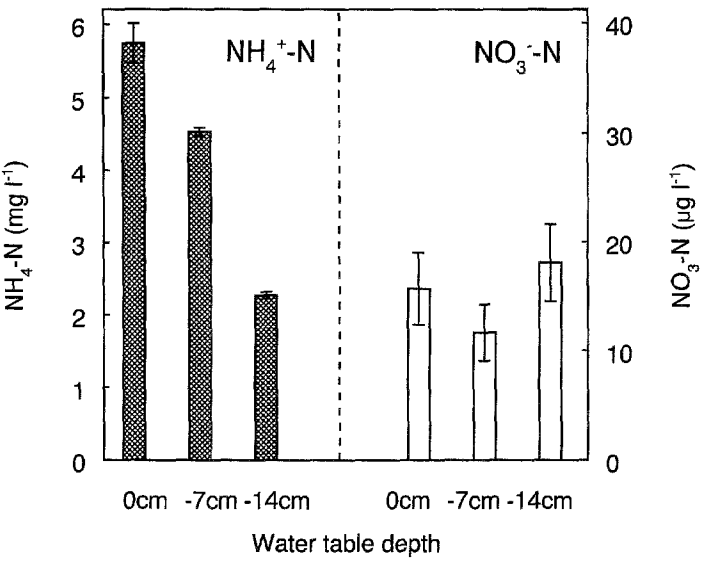

Figure 5. Mean peatwater nitrate and ammonium concentrations between weeks three and ten at a depth of 15 cm from peat cores with the water table at the surface, 7 cm below the surface, and 14 cm below the surface.

peatwater ammonium concentrations were significantly reduced in the cores with a lowered water table, compared with the control cores (Figure 5; ANOVA; $p < 0.001$).

Discussion

Though our site gains most of its water from ground and surface sources, it is relatively nutrient poor. Drainage can increase nitrous oxide emissions from minerotrophic peatlands, but not from peatlands low in nitrate (Martikainen et al. 1993, 1995). Nitrous oxide emissions from nutrient poor sites are considered to be affected little by drought because they lack nitrate (Martikainen et al. 1993, 1995), which is a precursor and a major control on denitrification rates (Seitzinger 1994) and nitrous oxide emissions (Bowden et al. 1992) from organic soils. The results of this laboratory study indicate that nitrous oxide emissions from a nutrient poor site increase under simulated drought. Freeman et al. (1993b) reported that drainage of intact peat cores from this site released significant quantities of nitrate. Because denitrification is an anaerobic process, and nitrate production is an aerobic process, it is often suggested that nitrate is produced in the upper profile, diffuses down into the anaerobic zone below the water table, and is denitrified (Patrick & Reddy 1976; Regina et al. 1996). However, depth profiles of nitrous oxide

production demonstrate that, in this site, increases in denitrification during drought are primarily occurring above the water table.

Our acetylene inhibition experiments suggest that the dominant source of nitrous oxide above the water table is denitrification, and that nitrous oxide is unlikely to be released as a by-product of nitrification there (e.g. Regina et al. 1996). Nitrous oxide production from denitrification is favoured by partially anoxic conditions, with the highest rates of production occurring under saturated, but not waterlogged, conditions (Bandibas et al. 1994). After 10 weeks of simulated drought in the laboratory, the peat above the water table still contained approximately 90% water by weight, with a decrease in water content of less than 5% compared with the control cores with the water table held at the surface.

There are, however, a number of potential problems associated with the use of acetylene as an inhibitor of both nitrification (Davidson et al. 1986) and the reduction of nitrous oxide to dinitrogen (Knowles 1982; Tiedje 1988; Tiedje et al. 1989). Incomplete diffusion of low levels of acetylene into slurries or soil cores may lead to inaccurate estimation of the importance of nitrification. Likewise sectioning cores and homogenising samples disrupts the peat, which can cause changes in oxygen and carbon availability (Tiedje 1988). Therefore, conclusions about processes responsible for nitrous oxide fluxes derived from slurries must be viewed with care.

The results from this laboratory study confirm laboratory studies of Freeman et al. (1993a), but apparently contradict field studies of Freeman et al. (1997) which demonstrated that drought can decrease nitrous oxide emissions from this site. We believe that these conflicting results can be attributed to differences in drought severity. In the field study reported here, simulated drought decreased the depth of the water table to a minimum of eight centimetres, whereas the minimum depth of the water table during our earlier study was 3.5 cm. Modest drought may decrease the amount of nitrate entering the site via ground and surface water sources (Freeman et al. 1997), but not change the peat water content or aeration status sufficiently to induce nitrate production. With a further decrease in water table depth, decreases in nitrate input may be offset by increases in nitrate production above the water table. This situation was demonstrated by our laboratory study under the severe drought conditions.

To date, the potential effect of climatic change induced drought on peatland nitrous oxide emissions have been inferred from studies on drained peatlands (Martikainen et al. 1993). However, our studies suggest that drought severity strongly regulates the pattern of nitrous oxide release. While modest summer drought scenarios may have little effect on nitrous oxide emissions, more extreme drought may increase nitrous oxide emissions. Controlled

drought studies in a variety of systems are needed to accurately predict the responses of wetland nitrous oxide emissions to summer drought.

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