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Fluxes of CO_2, CH_4 and N_2O from a Welsh peatland following simulation of water table draw-down: Potential feedback to climatic change

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Abstract. A potential effect of climatic change was simulated by manipulating the water table height within intact peat monoliths. The treatment decreased methane flux (maximum −80%) and increased both carbon dioxide flux (maximum 146%) and nitrous oxide flux (maximum 936%). Returning the water table height to its original level caused both nitrous oxide and carbon dioxide flux to rapidly return to control levels. However, methane flux remained at its experimentally induced low levels.

Introduction

Atmospheric concentrations of carbon dioxide, methane and nitrous oxide are increasing at rapid rates (IPCC 1990). While much attention has been devoted to quantifying and predicting the likely impact of these emissions on global warming (Rodhe 1990; Cannel & Hooper 1990), there have been few attempts to experimentally predict how climatic changes might influence the biogeochemistry of terrestrial systems, including the rates of production of greenhouse gases (Gorham 1991; Pulliam & Meyer 1992).

Wetlands are significant natural sources of greenhouse gases, contributing one fifth of global methane emissions (Cicerone & Ormeland 1988). The wetlands' anaerobic conditions are highly favourable for the production of methane (Clymo 1983) and nitrous oxide (Hemond 1983). These gases have 25 and 200 times, respectively, greater impact upon the greenhouse effect than carbon dioxide, on a molar basis (Rodhe 1990).

Of the many predictions of global climate change, those suggesting an increased frequency of summer drought and/or increased evapo-transpiration over western Europe and north America (Manabe & Wetherald 1986; Mitchell & Warrilow 1987) are of particular relevance to wetlands.

The reduction in water availability implicit in these scenarios threatens to compromise the very factor (abundant water) that gives wetlands their unique properties.

The few investigations of the potential effects of global warming on wetland greenhouse gas production to date have generally only considered direct temperature effects (Hameed & Cess 1983; Lashof 1989; Harriss & Frolking 1992). However, Gorham (1991) recently suggested that the indirect effects of global warming (namely those affecting wetland hydrology) were likely to have a far greater impact upon wetland methane and carbon dioxide production than more direct effects such as increased temperatures. A number of studies have indicated that hydrological changes can have a pronounced effect upon methane and carbon dioxide production. These include field studies (e.g. Silvola 1986; Harriss et al. 1982) and in particular a laboratory study by Moore & Knowles (1989) which found that reduced water table levels resulted in reduced methane fluxes but increased carbon dioxide fluxes.

The laboratory-based study of Moore & Knowles (1989) was performed on columns of peat from 3 Canadian wetlands which were prepared by repacking the columns to a depth of 75 cm with material from the 0—30 cm depth of the wetland soil profiles. However, such disturbed columns would lose the original hydrological and structural properties of the peat profile (sensu Gafni & Brooks 1990; Mathur & Lavesque 1985). This would also disrupt any spatial interaction (at a micro-site level) between the microbial communities which have a dominant role in production of greenhouse gases. In the light of these observations, the following study was undertaken using relatively undisturbed intact monoliths from a Welsh peatland. We simulated climatic change induced water table draw-down using a newly designed perfusion system (Freeman et al. in press). The study investigated the effect of draw-down and rewetting on the production of methane, carbon dioxide and nitrous oxide.

Materials and methods

Peat core collection

Intact cores were collected from a small gully mire wetland characterised by *Sphagnum* and *Juncus* species. The organic-rich flushed peat (pH 5—5.5) was underlain by a layer of mineral deposits in the base of the gully. The site is located close to Cerrig-yr-Wyn, Plynlimon, mid-Wales (UK Nat Grid Ref SN 820 866) and was sampled using the central core chamber described below (essentially, a length of PVC pipe). This ensures minimal disturbance to the sample, by avoiding the need to transfer material from a separate coring device into the perfusion system. To avoid compaction of the cores, a three stage extraction procedure was adopted, involving first cutting through the initial 15 cm depth using a sharp knife (using the external face of the core chamber as a template). The chamber was then eased into the pre-cut peat to the full 15 cm depth. A 10 cm wide trench was excavated around the outside of the chamber, which then allowed access with the knife so that the next 15 cm of the core could be — 'cut, encased and excavated', — as above. This was repeated until the desired core depth (0.5 m) was achieved. The final stage involved sliding a Durapipe ABS$^{\text{TM}}$ plastic cup under the core, followed by careful withdrawal of the intact monolith from the excavated pit and immediate transportation back to the laboratory.

Perfusion system

The apparatus (Fig. 1) was based around a central chamber containing a monolith of peat and consisted of a 60 cm length of 110 mm diameter OSMA$^{\text{(TM)}}$ PVC plastic piping. The top of the core was maintained in an open condition, allowing the input of deionised water (via a peristaltic pump delivery system), a free exchange of gases between the core and the atmosphere, and the access of light for the approximately 1 cm depth upper layer of living material (predominantly *Sphagnum*). The base of the chamber was plugged with an interference-fit Durapipe ABS$^{\text{(TM)}}$ cap, drained by 12.5 mm diameter Durapipe$^{\text{(TM)}}$ tubing which rises via two consecutive 90° Durapipe$^{\text{(TM)}}$ connectors to rise parallel to the core chamber in a 'J' shaped fitting. The key feature to note is that the height of the outlet from the 'J' tube can be raised or lowered to manipulate the

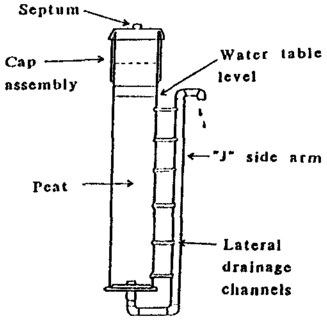

Fig. 1. The core perfusion system.

height of the water table inside the column, thereby simulating the water table reductions imposed by climatic change.

At 10 cm intervals, 2.5 ml Plastipak$^{(TM)}$ syringes cut to 20 mm length and packed with glass wool were inserted through drilled holes into the sides of the chamber with the Luer tip outermost. These ports served two functions. Firstly, they could be used to sample fluids from within the core with minimal disturbance, thus providing supporting hydro-chemical data, and secondly, when not in use for sampling, the outlet from the luer tip was connected via (auto-analyser) transmission tubing to the 'J' drainage pipe. This simulated natural conditions where precipitation entering a wetland not only travels downwards but also laterally (particularly in wetlands lying on a gradient) to an extent dependent upon the hydraulic conductivity of the medium.

Climate change simulation

Ten replicate perfusion systems were set up in a constant temperature laboratory (11 °C) with a 12 h light:dark cycle (light intensity 9.4 μmol m^2 s^{-1}). Half of these were maintained with the water table at the surface (controls) while the water table in the remaining systems was gradually reduced by lowering the water outlet on the 'J' side arm over a 10 week period to a maximum 20 cm depth. This is within the range normally experienced during field observations of severe drought, (R. Smit & H. A. P. Ingram, pers. comm.). This water table depth was maintained for a further 6 weeks, until week 16, when the end of the drought was simulated by returning the water table to its original position. Fluxes of carbon dioxide, methane and nitrous oxide were monitored every 2 weeks of the simulation until the final measurement on week 18. The condition of the *Sphagnum* in the 'drought' treated cores deteriorated rapidly as the simulation progressed, until by week 11 almost all of it had died.

Measurement of CO_2, CH_4 and N_2O production

The rate of gaseous efflux from the peat cores was determined by capping and noting the increase in concentration over a collection period of 2 hours. This period was chosen because previous experiments indicated that gas accumulation was not linear over longer collection periods (Freeman et al. in press). Measurement of the accumulated gases at 45 minute intervals over 3 hours on week 10 confirmed that accumulation remained linear even with water tables at their lowest levels (R^2 = 0.98 (N_2O); 0.89 (CH_4); 0.99 (CO_2)). Samples were routinely collected at the beginning and end of the incubation through a Subaseal^{TM} septum using 10 ml Plastipak^{TM}

syringes, and the gases analysed by gas chromatography using an Ai Cambridge model 92 gas chromatograph (GC). This was a two column GC fitted with a flame ionisation detector with a $CO_2 \rightarrow CH_4$ catalytic converter (to detect carbon dioxide in addition to methane) on one column and an electron capture detector operating at 350 °C (to determine nitrous oxide) on the other. Porapak QS columns were used at 35 °C with N_2 carrier gas at 30 cm^{-3} min^{-1}.

Results

Statistical analysis using a repeated-measures-design ANOVA, showed that the simulated drought produced significant effects upon peatland greenhouse gas flux. Carbon dioxide flux (Fig. 2) increased (F-ratio 33.4, $p < 0.001$) from a mean control level of 646 mg CO_2 m^{-2} d^{-1} to a maximum of 1590 mg CO_2 m^{-2} d^{-1} at the peak of the simulated drought. Linear regression analysis revealed a highly significant inverse correlation between production and water table height ($R^2 = 0.921, p < 0.001$).

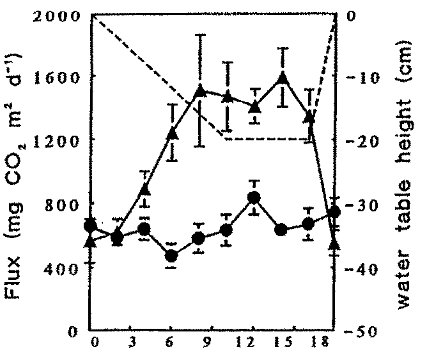

Fig. 2. Wetland carbon dioxide flux from control (—●—) and simulated drought (—▲—) treated systems. (Error bars indicate ± standard error, broken line indicates water table height).

In contrast to the relatively stable carbon dioxide flux from the control cores, the methane fluxes (Fig. 3) were highly variable. There was nevertheless a significant reduction (F-ratio 6.2, $p < 0.05$) from the mean control flux of 230 mg CH_4 m^{-2} d^{-1} to a minimum of 45 mg CH_4 m^{-2} d^{-1} during the drought. Linear regression of methane flux (or log methane flux) against water table height failed to indicate significant correlations

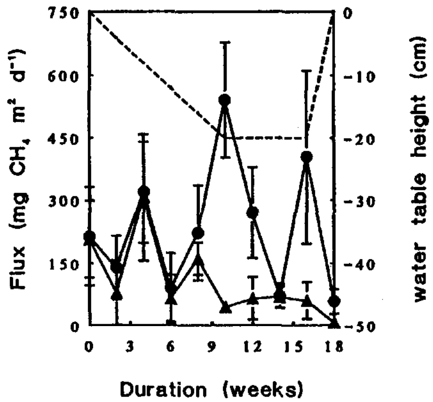

Fig. 3. Wetland methane flux from control (—●—) and simulated drought (—▲—) treated systems. (Error bars indicate ± standard error, broken line indicates water table height).

although non-parametric analysis showed a weak but significant Spearman-Rank correlation of 0.445 ($p < 0.05$).

The simulated drought had a pronounced effect (F-ratio 31.4, $p < 0.001$) on nitrous oxide production (Fig. 4), rising from a mean control level of 0.11 mg N_2O m^{-2} d^{-1} to a maximum of 1.14 mg N_2O m^{-2} d^{-1} at the height of the drought. A highly significant inverse correlation between nitrous oxide flux and water table height was also observed ($R^2 = 0.636$, $p < 0.001$).

Simulation of the end of the drought (raising the water table) caused both nitrous oxide and carbon dioxide fluxes to fall rapidly towards those of the controls. However, methane production did not respond in this manner and remained at its experimentally induced lower levels.

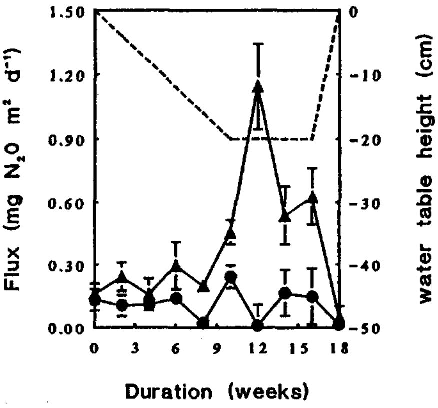

Fig. 4. Wetland nitrous oxide flux from control (—●—) and simulated drought (—▲—) treated systems. (Error bars indicate ± standard error, broken line indicates water table height).

Discussion

The results of this study were largely in agreement with those of Moore & Knowles (1989), in that a simulated drought produced significant increases in the carbon dioxide flux but decreases in the methane flux. Unlike the Moore & Knowles study (in which only fluxes from the *peat* were measured), our carbon dioxide fluxes included the release of CO_2 due to respiratory processes in both peat and *Sphagnum*. However, mean fluxes from the control cores at 0.65 g CO_2 m^2 d^{-1}, were very similar to their findings (0.3—0.5 g CO_2 m^2 d^{-1}). Moreover, we found a very strong inverse correlation between carbon dioxide flux and water table height. This may be related to the lower rates of metabolism that occur under anaerobic than aerobic, conditions. In addition, the end-products of anaerobic metabolism include a greater proportion of organic solutes such as organic acids, alcohols, aldehydes and ketones (Ponnamperuma 1972). This contrasts with aerobic metabolism which is more efficient, and tends to favour the rapid production of carbon dioxide and thus gaseous inorganic rather than dissolved organic, carbon end products.

Our CO_2 findings can only be considered as night time fluxes due to the dark conditions while the cores were closed for gas collection. The maximum increase (246% of the control flux) may therefore underestimate the true magnitude of the impact. In daylight, CO_2 would be taken up for photosynthesis in the control cores, while in the drought-treated cores, uptake would be prevented by the death of the *Sphagnum*.

Our findings concerning methane were far less in agreement with those of Moore & Knowles. For cores with the water table maintained at the surface, the 230 mg CH_4 m^2 d^{-1} flux observed in our study was far higher than theirs (<2—28 mg CH_4 m^2 d^{-1}). This could simply be due to a difference between the Welsh and Canadian wetlands, although two other factors could be involved; (1) The stricter conditions required for methanogenesis may have meant that the less disruptive approach adopted in our study resulted in a better maintenance of conditions necessary for this process. (2) Our earlier studies (Freeman et al. in press) had indicated that in closed laboratory columns, the production of methane only approximated towards linearity for approximately 2 hours, while carbon dioxide accumulation rates remained linear for at least 12 hours. Thus the 24 hour gas accumulation period adopted by Moore & Knowles would give CO_2 results which were comparable to our own, but may have resulted in a substantial underestimation of the methane flux. We were also unable to confirm the strong correlation that they observed between methane flux and water table height.

At the end of the simulated drought, both nitrous oxide and carbon dioxide fluxes rapidly fell towards control levels, confirming the close relationship between the production of these two gases and water table height. However, methane, which had stabilised at a flux of 45—70 mg CH_4 m^2 d^{-1} towards the end of the drought, in fact showed its lowest value of the study (7.4 mg CH_4 m^2 d^{-1}) upon re-wetting. It may be significant that re-wetting following a period of dry conditions has been noted to cause a dramatic mobilisation of sulphate (oxidised from sulphide during the drier, more aerobic conditions) (Braekke 1981). Sulphate can suppress methanogenesis (Ormeland 1988), and thus its presence may have prevented the re-establishment of higher methane fluxes.

Comparison of the relative contribution of carbon dioxide and methane to the total gaseous carbon flux from the wetland can be made from the molar ratio of CO_2:CH_4. Moore & Knowles found carbon dioxide to be the dominantly produced gas even under inundated conditions (ratios 4—173). Our own finding of molar ratio 0.9 under these conditions was far closer to the observations of Yavitt et al. (1987) who found equimolar production of the two gases at 19 °C. A maximum molar ratio of 10.4 was observed during the simulated drought, far lower than the >2500 observed by Moore & Knowles.

The mean nitrous oxide flux from our control cores (0.11 mg N_2O m^2 d^{-1}) lies between values observed by Hemond (1983) of <0.72 mg N_2O m^2 d^{-1} and Urban et al. (1988) of 0.023 mg N_2O m^2 d^{-1}. The increased nitrous oxide flux observed upon water table drawdown confirmed similar observations upon drainage of a flooded organic soil in Florida (Terry et al. 1981). The environmental conditions within an undisturbed peatland are considered highly favourable for nitrous oxide production through denitrification (i.e. anaerobic and relatively acidic, Hemond 1983), although low nitrate concentations severely limit the extent to which the process can proceed. Thus, since no exogenous nitrate was added to our systems, it seems likely that the increased aeration brought about by the simulated drought caused mineralisation (and nitrification) of some of the organic-N within the peat matrix (Williams & Wheatley 1988), thus providing the substrates for denitrification either in the lower anaerobic zone or else within anaerobic microsites (Sexton et al. 1985) within the upper, predominantly aerobic layer. In addition, the aerobic processes of nitrification are a potential nitrous oxide source (Bremmer & Blackmer 1978).

Estimation of the annual flux of nitroux oxide based upon a daily flux of 0.11 mg N_2O m^2 d^{-1} (control cores) assumed to be constant year round, and an area of intact sub-arctic/boreal peatland of 3.3×10^{12} m^2 (Gorham 1991), yields an annual flux of 0.133 Tg yr^{-1}. This represents a relatively small contribution to global N_2O emissions of 12.4 Tg N_2O yr^{-1} (Davidson 1991). However, estimates including the increased rates of

N_2O flux observed in our drought simulation yield an annual flux of 0.442 Tg yr^{-1} and result in a 2.5% increase in global N_2O emissions. Thus, drying wetlands may become one more in the increasing list of contributors to the imbalance in the global nitrous oxide budget (IPCC 1992).

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