IMPACT OF GLOBAL WARMING AND RISING CO_2 ON METHANE EMISSIONS FROM NATURAL VEGETATION

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What impact do global warming, the ongoing rise in the air's carbon dioxide (CO_2) content and a number of other contemporary environmental trends have on the atmosphere's methane (CH_4) concentration? The implications of this question are substantial, in light of the fact that methane is a more powerful greenhouse gas, molecule for molecule, than is carbon dioxide. We here consider this question as it applies to methane emissions associated with natural vegetation.

Beginning with a model-based study, Frolking and Roulet (2007)[1] introduced their work by stating that "throughout the Holocene, northern peatlands have both accumulated carbon and emitted methane," so that "their impact on climate radiative forcing has been the net of cooling (persistent CO_2 uptake) and warming (persistent CH_4 emission)." Against this backdrop they then developed Holocene peatland carbon flux trajectories based on estimates of contemporary CH_4 flux, total accumulated peat C, and peatland initiation dates, which they used as inputs to a simple atmospheric perturbation model to calculate the net radiative impetus for surface air temperature change. In doing so, Frolking and Roulet note that early in the Holocene the capture of CO_2 and emission of CH_4 by Earth's northern peatlands is likely to have produced a net warming impetus of up to +0.1 W m^{-2}. Over the following eight to eleven thousand years, however, they say Earth's peatlands have been doing just the opposite, and that the current radiative forcing due to these atmospheric CO_2 and CH_4 perturbations represents a net *cooling* force on the order of -0.22 to -0.56 W m^{-2}. It can thus be appreciated that the impetus for global cooling due to carbon sequestration by Earth's peatlands historically has been - and currently is - significantly greater than the global warming potential produced by their emissions of methane.

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Writing as background for their work, Toet *et al*. (2001)[2] state that "only three previous published studies have assessed the impacts of O_3 on CH_4 and CO_2 fluxes in peatlands." Niemi *et al*. (2002), as they describe it, "reported that CH_4 emissions more than doubled when

1 http://www.co2science.org/articles/V10/N33/C1.php.
2 http://www.co2science.org/articles/V14/N9/C2.php.

peatland microcosms were exposed to 100 ppb O_3 over 4-7 weeks during summer in controlled-environment chambers." In contrast, they state that "Rinnan *et al*. (2003) reported no significant effect on CH_4 emissions of a 7-week exposure of peat microcosms to 100 or 200 ppb O_3." Last of all, they indicate that "Morsky *et al*. (2008) reported that open-field exposure of boreal peatland microcosms in central Finland to a doubling of ambient O_3 concentrations caused a decrease in CH_4 emission at the end of the first growing season," but they note that the decrease "was lost in the three subsequent growing seasons." Thus, it is clear that prior work on the subject has not provided a definitive answer to the core question of whether rising O_3 concentrations have a significant impact, one way or the other, on methane emissions from peatlands.

In a study that was more reflective of reality in terms of *scale*, Toet *et al*. moved up in size from *micro*cosms to *meso*cosms, which they collected from a lowland raised bog on the northern shore of Morecambe Bay, Cumbria, UK (54°13'N, 3°1'W) and subsequently placed into open-top chambers situated on a level gravel base at Newcastle University's field station (54°59'N, 1°48'W). And there, for the next two years, they observed what happened in four ambient and four O_3-enriched chambers, the latter of which had their atmospheric O_3 concentrations raised by 50 ppb for eight hours of each day during the summer period (April-early October) and by 10 ppb for eight hours of each day throughout the winter.

Results indicated that "methane emissions were significantly reduced, by about 25%, by elevated ozone during midsummer periods of both years," but that "no significant effect of ozone was found during the winter periods." And after lengthy discussion of their findings, as well as those of other researchers they cite, Toet *et al*. concluded in the final sentence of their paper that "increased O_3 could be a significant brake on the increased flux of CH_4 that is expected as these northern peatlands warm."

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In another paper, Davidson *et al*. (2004)[3] reported that the climate of the Amazon Basin may become gradually drier due to the intensification of a number of different phenomena, including (1) less recirculation of water between the increasingly-deforested region and the atmosphere, (2) more rainfall inhibition by smoke caused by increased biomass burning, and (3) a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to

[3] http://www.co2science.org/articles/V7/N31/C3.php.

the eastern Amazon Basin (Nepstad *et al*., 1999; but see Timmermann *et al*., 1999 as well). Driven by concern about these potential problems, they devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of two important greenhouse gases: nitrous oxide (N_2O) and methane (CH_4).

In the Tapajos National Forest near Santarem, Brazil, the researchers modified a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the amount of rain that reached the forest floor (throughfall) while maintaining an otherwise similar one-hectare plot of land as a control for comparison. Prior to making this modification, they measured the gas exchange characteristics of the two plots for a period of 18 months; then, after initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This protocol revealed, in their words, that the "drier soil conditions caused by throughfall exclusion inhibited N_2O and CH_4 production and promoted CH_4 consumption." In fact, they say that "the exclusion manipulation lowered annual N_2O emissions by >40% and increased rates of consumption of atmospheric CH_4 by a factor of >4," which results they attributed to the "direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy."

As for the implications of their work, if global warming did indeed increase the frequency and/or intensity of El Niño events - which real-world data suggest is highly debatable (see El Niño - Relationship to Global Warming[4] in our Subject Index) - the results of this study suggest that the anticipated drying of the Amazon Basin would initiate a strong negative feedback to warming via (1) large drying-induced reductions in the evolution of N_2O and CH_4 from its soils and (2) a huge drying-induced increase in the consumption of CH_4 by its soils. Although Davidson *et al*. envisaged a more extreme second phase response, "in which drought-induced plant mortality is followed by increased mineralization of C and N substrates from dead fine roots and by increased foraging of termites on dead coarse roots" (a response that would be expected to *increase* N_2O and CH_4 emissions), it should be noted that the projected rise in the air's CO_2 content would likely prohibit such extreme events from ever occurring, in light of the tendency for elevated levels of atmospheric CO_2 to greatly increase the water use efficiency of essentially all plants (see Water Use Efficiency[5] in our Subject Index, including the subsection Trees), which would enable the Amazon Basin's vegetation to continue to flourish under significantly drier conditions than those of the present.

In another paper, Strack *et al*. (2004)[6] also reported that climate models predict increases in evapotranspiration that could lead to drying in a warming world and a subsequent lowering of water tables in high northern latitudes. This prediction stresses the importance of determining how lowered water tables will impact peatland emissions of CH_4; and in a *theoretical* study of the subject, Roulet *et al*. (1992) calculated that for a decline of 14 cm in the water tables of northern Canadian peatlands, due to climate-model-derived increases in temperature (3°C) and precipitation (1mm/day) predicted for a doubling of the air's CO_2 content, CH_4 emissions would decline by 74-81%. Hence, in an attempt to obtain some *experimental* data on the subject, at

4 http://www.co2science.org/subject/e/ensogw.php.
5 http://www.co2science.org/subject/w/subject_w.php.
6 http://www.co2science.org/articles/V7/N52/B3.php.

various times over the period 2001-2003 Strack *et al*. measured CH_4 fluxes to the atmosphere at different locations that varied in depth-to-water table within natural portions of a poor fen in central Quebec, Canada, as well as within control portions of the fen that had been drained eight years earlier. And what did they find?

At the conclusion of their study, the Canadian scientists reported that "methane emissions and storage were lower in the drained fen." The greatest reductions (up to 97%) were measured at the higher locations, while at the lower locations there was little change in CH_4 flux. Averaged over all locations, they determined that the "growing season CH_4 emissions at the drained site were 55% lower than the control site," indicative of the fact that the biosphere appears to be organized to resist warming influences that could push it into a thermal regime that might otherwise prove detrimental to its health.

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In one final anaerobic-based study, Garnet *et al*. (2005)[7] grew seedlings of three emergent aquatic macrophytes (*Orontium aquaticum* L., *Peltandra virginica* L. and *Juncus effusus* L.) plus one coniferous tree (*Taxodium distichum* L.), all of which are native to eastern North America, in a five-to-one mixture of well-fertilized mineral soil and peat moss in pots submerged in water in tubs located within controlled environment chambers for a period of eight weeks. Concomitantly, they measured the amount of CH_4 emitted by the plant foliage, along with net CO_2 assimilation rate and stomatal conductance, which were made to vary by changing the CO_2 concentration of the air surrounding the plants and the density of the photosynthetic photon flux impinging on them.

In doing so, it was found that methane emissions from the four wetland species increased linearly with increases in both stomatal conductance and net CO_2 assimilation rate; but the researchers report that changes in stomatal conductance affected foliage methane flux "three times more than equivalent changes in net CO_2 assimilation," making stomatal conductance the more significant of the two CH_4 emission-controllers. In addition, they note that evidence of stomatal control of CH_4 emission has also been reported for *Typha latifolia* (Knapp and Yavitt, 1995) and *Carex* (Morrissey *et al*., 1993), two other important wetland plants. And, since atmospheric CO_2 enrichment leads to approximately equivalent - but oppositely directed - changes in foliar net CO_2 assimilation (which is increased) and stomatal conductance (which is reduced) in most herbaceous plants (which are the type that comprise most wetlands), it can be appreciated that the ongoing rise in the air's CO_2 content should be acting to *reduce*

[7] http://www.co2science.org/articles/V8/N36/B2.php.

methane emissions from Earth's wetland vegetation, because of the three-times-greater negative CH_4 emission impact of the decrease in stomatal conductance compared to the positive CH_4 emission impact of the equivalent increase in net CO_2 assimilation.

Shifting to studies examining *aerobic* conditions, Dueck *et al*. (2007)[8] introduced their work by stating that recent findings suggest that terrestrial plants may "emit methane under aerobic conditions by an as yet unknown physiological process (Keppler *et al*., 2006), and in this way may substantially contribute to the annual global methane budget (Bousquet *et al*., 2006)," resulting in "estimated values for methane emission by terrestrial plants varying between 10 and 260 Tg yr^{-1} (Houweling *et al*., 2006; Keppler *et al*., 2006; Kirschbaum *et al*., 2006)." To test the validity of this claim the fifteen Dutch researchers conducted two separate experiments involving six plant species - *Ocimum basilicum* L. (basil), *Triticum aestivum* L. (wheat), *Zea mays* L. (maize), *Salvia officinalis* L. (sage), *Lycopersicon esculentum* Miller (tomato), and *Oenothera biennis* L. (common evening primrose) - the first three of which were also used by Keppler *et al*. (2006) in their study.

The experiments were performed in "a unique hermetically sealed plant growth chamber with a volume of 3500 liters, specifically designed for atmospheric isotope labeling," where "plants were grown hydroponically to exclude any methane production derived from anaerobic soil pockets." When all was said and done, Dueck *et al*. report there was no evidence for substantial aerobic methane emission by the terrestrial plants they studied, stating that "maximally," it was only "0.3% of the previously published studies." Indeed, they say that methane concentrations in continuous-flow gas cuvettes with plants "were not significantly higher than those of control cuvettes without plants," stating that under both the short- and long-term, they "did not find any evidence of a substantial emission of methane."

Keppler *et al*.'s findings have been further debunked by other researchers. Beerling *et al*. (2008)[9], for example, raised the C_4 plant *Zea mays* and the C_3 plant *Nicotiana tabacum* from seed for six weeks at an ambient CO_2 concentration of 400 ppm and an ambient methane concentration of 1800 ppb, after which their leaves were studied in "a custom-built flowthrough cuvette with a sufficiently large area to allow the detection of methane emissions" via "a process gas chromatograph linked to a high-precision, high-accuracy flame ionization detector," all of which was done in a controlled-environment room. In describing their findings, the team of five UK researchers report that "well-illuminated actively photosynthesizing *Z. mays* leaves did not, in our experimental system, emit substantial quantities of methane during repeated three-hour high irradiance episodes," while adding that "neither did we detect methane emissions from actively respiring leaves during repeated three-hour dark periods." They additionally state that "measurements with leaves of the C_3 species *N. tabacum* also failed to detect substantial aerobic methane emissions in the light when photosynthesizing with regular stomatal conductances, and in the dark when respiring."

8 http://www.co2science.org/articles/V10/N47/B2.php.

9 http://www.co2science.org/articles/V11/N38/B2.php.

For their part, Nisbet *et al*. (2009)[10] "conducted further experiments on plants grown in controlled conditions" and "re-analyzed the previously published data" on the topic. Accordingly, the fourteen researchers (thirteen from the UK and one from Sweden) were able to demonstrate that "plants do not contain a biochemical mechanism for methanogenesis," and that they "cannot produce methane as an end-product or by-product of their metabolism." However, they determined that "when plants transpire, any methane that is already dissolved in the water derived from the soil will be released into the atmosphere," and that "under high stress conditions, such as high UV radiation, methane is released as part of the cellular breakdown process." In light of such findings, plus "a new analysis of global methane levels from satellite retrievals," Nisbet *et al*. concluded that "plants are not a major source of the global methane production." On the other hand, they acknowledge "the role of plants in moving methane about," and indicate their importance in the global *cycling* of methane, but not its production.

The role of stress in plant CH_4 production in the global CH_4 cycle could be important in a changing world …

Thus, it can be appreciated that the historical rise in the air's CO_2 content should have gradually been alleviating the level of stress experienced by Earth's plants; and this phenomenon should have been gradually reducing the rate at which the planet's vegetation releases CH_4 to the atmosphere.

In one final study, Wang *et al*. (2009)[11] concluded after their review of the scientific literature that "aerobic CH_4 [methane] emissions from plants may be affected by O_2 stress or any other stress leading to ROS [reactive oxygen species] production," leading the team of researchers to examine whether or not physical injury would also affect CH_4 emissions from plants. In doing so their work revealed that "physical injury (cutting) stimulated CH_4 emissions from fresh twigs of *Artemisia* species under aerobic conditions," and that "more cutting resulted in more CH_4 emissions," as did hypoxia in both cut and uncut *Artemisia frigida* twigs.

In discussing their findings, and those of previous studies that suggest, in their words, "that a variety of environmental stresses stimulate CH_4 emission from a wide variety of plant species," Wang *et al*. concluded that "global change processes, including climate change, depletion of stratospheric ozone, increasing ground-level ozone, spread of plant pests, and land-use changes, could cause more stress in plants on a global scale, potentially stimulating more CH_4 emission globally," while further concluding that

[10] http://www.co2science.org/articles/V12/N29/B2.php.
[11] http://www.co2science.org/articles/V12/N36/EDIT.php.

"the role of stress in plant CH_4 production in the global CH_4 cycle could be important in a changing world."

It is significant to note, however, that although *lots* of things "could" be important in this regard, the ongoing rise in the air's CO_2 content is hard at work *countering* stress-induced CH_4 emissions from plants. In the Antioxidants[12] heading of our Subject Index, for example, it is seen that environmental stresses of all types do indeed generate highly-reactive oxygenated compounds that damage plants, but that atmospheric CO_2 enrichment typically boosts the production of antioxidant enzymes that *scavenge* and *detoxify* those highly-reactive oxygenated compounds. Thus, it can be appreciated that the historical rise in the air's CO_2 content should have gradually been *alleviating* the level of stress experienced by Earth's plants; and this phenomenon should have been gradually *reducing* the rate at which the planet's vegetation releases CH_4 to the atmosphere. In addition, it should have been doing it at *an accelerating rate* commensurate with the accelerating rate of the upward trend in the air's CO_2 content.

In closing, it would appear that current environmental trends that may impact methane emissions from natural vegetation, including the ongoing rise in the air's CO_2 content, primarily tend to *reduce* this flux; and perhaps that is why the rate-of-rise of the atmosphere's methane concentration has changed little over the past couple of decades (see Methane (Atmospheric Concentrations)[13] in our Subject Index).

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[12] http://www.co2science.org/subject/a/summaries/antioxidants.php.
[13] http://www.co2science.org/subject/m/methaneatmos.php.

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