



HAL
open science

Risk analysis of global warming-induced greenhouse gas emissions from natural sources

Ülo Mander, K. Sohar, Julien Tournebize, J. Parn

► **To cite this version:**

Ülo Mander, K. Sohar, Julien Tournebize, J. Parn. Risk analysis of global warming-induced greenhouse gas emissions from natural sources. *International Journal of Safety and Security Engineering*, 2016, 6 (2), pp.181-192. 10.2495/SAFE-V6-N2-181-192 . hal-01548828

HAL Id: hal-01548828

<https://hal.science/hal-01548828>

Submitted on 28 Jun 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

RISK ANALYSIS OF GLOBAL WARMING-INDUCED GREENHOUSE GAS EMISSIONS FROM NATURAL SOURCES

Ü. MANDER^{1,2}, K. SOHAR^{1,3}, J. TOURNEBIZE² & J. PÄRN^{1,4}

¹University of Tartu, 46 Vanemuise St, Tartu, Estonia.

²Irstea, HBAN, Antony Cedex, France.

³Czech Academy of Sciences, Zámek 1, Průhonice, Czech Republic.

⁴Keele University, Staffordshire, UK.

ABSTRACT

The increase in the emissions of greenhouse gases (GHG) CO₂, CH₄, and N₂O is the most important factor causing global warming. Natural sources make up about 96%, 46%, and 64% of total emissions of the three gases, respectively. Relatively small man-made CO₂ fluxes, together with CH₄ and N₂O (with a radiative force 34 and 298 times higher than that of CO₂, respectively) upset the natural balance of the carbon (C) cycle and create an artificial forcing of global temperatures which is warming the planet. However, even after stopping all anthropogenic CO₂ emissions, the warming-induced GHG from natural sources will cause an on-going temperature increase and many resulting environmental problems. Based on literature, we analyse the potential change in GHG emissions from the main natural sources, which are influenced by the effects of global warming. Since there are various uncertainties in the estimations of terrestrial-atmosphere and ocean-atmosphere CO₂ exchange, this most important factor remains un-predicted and needs significantly more investigation of the ability of oceans and terrestrial ecosystems to absorb CO₂. Both CH₄ and N₂O emissions may continue to increase. The thawing of CH₄ hydrates in the ocean shelf and in permafrost regions is the largest long-term threat for global warming, but even now rising temperature will enhance emissions from wetlands, lakes, vegetation and even upland soils, due to an increasing threat of wildfires. Changes in hydrological regime are the main driving force for N₂O emissions.

Keywords: carbon dioxide, climate extremes, floods, methane, methane hydrates, nitrous oxide, wetlands, wildfire.

1 INTRODUCTION

Changes in the atmospheric concentrations of greenhouse gases (GHG) and aerosols, land cover, and solar radiation alter the energy balance of the climate. Global GHG emissions have grown since the early days of the industrial revolution (1,750), with an average increase of 80% between 1970 and 2011. The atmospheric concentrations of GHG carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) have all increased since 1750 due to human activity. In 2011 the concentrations of these GHGs were 391 ppm, 1,803 ppb, and 324 ppb, and exceeded pre-industrial levels by about 40%, 150%, and 20%, respectively [1]. Concentrations of CO₂, CH₄, and N₂O now substantially exceed the highest concentrations recorded from ice cores during the past 800,000 years. The rates of increase in atmospheric concentrations over the past century are unprecedented in the last 22,000 years [1]. All of the GHG significantly increase the total anthropogenic radiative forcing (RF), which has led to an uptake of energy by the climate system. According to the 2013 IPCC report [1], the RF from

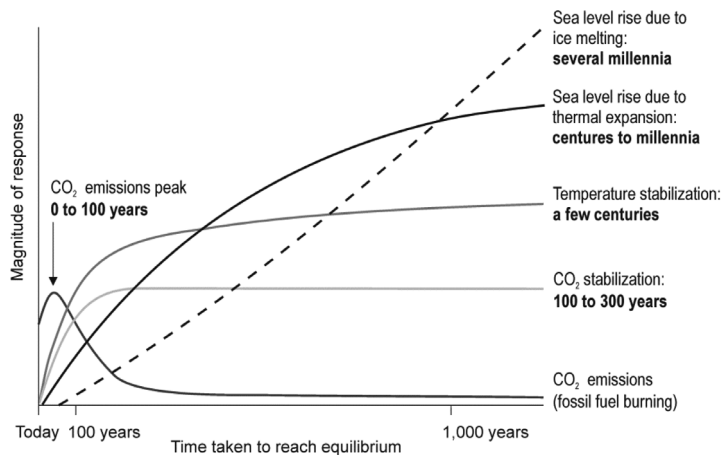


Figure 1: Continuing rise of CO₂ concentration, temperature, and sea level long after emissions have been reduced. Adapted from: IPCC 2001 Climate Change Report [2].

the emissions of the well-mixed GHG (CO₂, CH₄, N₂O, and Halocarbons) for 2011 relative to 1,750 is 3.00 (2.22 to 3.78) W m⁻². The largest contribution to total RF is caused by the increase in the atmospheric concentration of CO₂. These emissions alone have caused an RF of 1.68 (1.33 to 2.03) W m⁻². Emissions of CH₄ and N₂O have caused an RF of 0.97 (0.74 to 1.20) and 0.17 (0.13 to 0.21) W m⁻², respectively [1].

This all supports the idea of the predominantly anthropogenic origin of the global warming. This knowledge led most of the world's countries to consolidate and agree to decrease anthropogenic GHG emissions and to set a goal of limiting global warming to less than 2°C compared to pre-industrial levels [3]. However, even after stopping all anthropogenic CO₂ emissions, due to the inertia in the biosphere, the atmospheric air temperature will stabilize in a few centuries whereas the sea level will still continue to rise, due to thermal expansion and ice thawing (Fig. 1). Warming-induced GHG from natural sources may be one of the reasons behind this trend.

The main objective of this study is to analyse the potential change in GHG emissions from natural sources, which are influenced by the effects of global warming. Possible trends in GHG emissions will also be discussed.

2 MATERIAL AND METHODS

We analysed the literature sources on global perspectives for CO₂, CH₄, and N₂O emissions from natural sources, particularly their relationship to prevailing environmental factors. We also focused on the main environmental processes that are known to be most sensitive to global warming. For instance, the frequency of climate extremes (both droughts and floods) and related wildfires have increased in connection with global warming. The shift in vegetation and land cover types due to changing temperature and water regime patterns is a climate-change-induced phenomenon belonging to the general issue of land use changes. Finally, global temperature increases causes melting of permafrost in the Arctic and related methane hydrates thawing in the continental slopes of oceans.

Based on these data and widely used modelling results we analysed the risk of the increasing emissions of three most important GHG – CO₂, CH₄, and N₂O.

3 RESULTS AND DISCUSSION

3.1 Current emissions of GHG from natural sources

3.1.1 Carbon dioxide

CO₂ emission from natural sources makes up about 95.8% of the total annual average emissions of 219,545 Tg CO₂-C yr⁻¹. Terrestrial plant, animal, and soil respiration makes up about 57%, ocean-atmosphere exchange about 43%, and volcanic eruptions only 0.03% of emissions [4]. Annual CO₂ emissions from fossil fuel combustion and cement production were 8,183 and annual net CO₂ emissions from anthropogenic land-use change about 1,090 Tg CO₂-C yr⁻¹ averaged over the period 2002–2011 (Fig. 2) [1]. The estimated average CO₂ exchange between the continents and atmosphere is about 33% greater than the ocean-atmosphere exchange but in both cases sequestration is greater than emission (Fig. 2). However, all estimations have a wide fluctuation and up to 20% of the terrestrial C sink is still unidentified [4].

Human CO₂ emissions, which are much lower than natural emissions, upset the natural balance of the carbon (C) cycle. While fossil-fuel derived CO₂ is a small component of the global carbon cycle, the extra CO₂ is cumulative because the natural carbon exchange cannot absorb all of the additional CO₂. Thus, CO₂ in the atmosphere has increased by a third since the year 1750, creating an artificial forcing of global temperatures which is warming the planet.

3.1.2 Methane

Similarly to CO₂, methane fluxes from natural sources have not been accurately estimated. According to the US EPA report [5], for several natural sources (terrestrial and marine geological sources, gas hydrates, and wildfires) no clear estimates but only a range are available (Table 1). On the other hand, the still unknown role of vegetation has resulted in contradictory estimates ranging from 0 to 20–60 Tg CH₄-C yr⁻¹. In our study, we calculated emission estimates based on these range values, and also included the average possible emission from vegetation (Table 1). Thus, the total average annual methane emissions from continents and oceans constitute about 666 Tg CH₄-C yr⁻¹, 37% of which comes from natural sources [5].

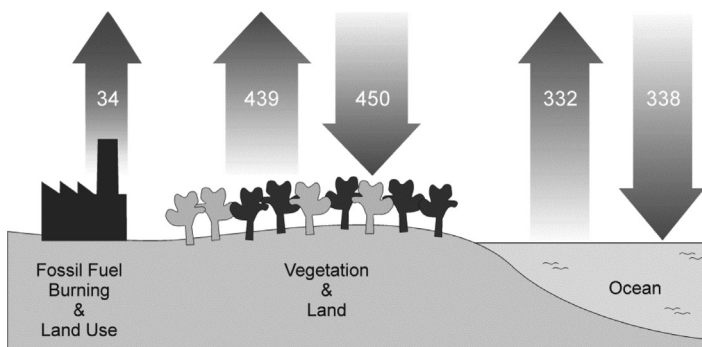


Figure 2: Average annual fluxes of man-made (fossil-fuel and land-use) and natural (vegetation + land and ocean) CO₂ (Tg CO₂-C yr⁻¹). Based on the *IPCC 2007 Climate Change Report* [4] updated on the basis of the *IPCC 2013* [1].

The greatest natural methane sources are wetlands emitting 170.3 Tg CH₄-C yr⁻¹, whereas tropical swamps emit about 75% and northern bogs 25% of the total amount. This is followed by terrestrial geological sources, lakes, terrestrial arthropods (insects, arachnids, crustaceans, and others), marine geological sources, wild animals, and oceans (35, 30, 20, 17, 8, 7.5 and 5 Tg CH₄-C yr⁻¹, respectively; Table 1). The thawing of gas hydrates as a methane source as well as aerobic CH₄ production by forests have not been sufficiently studied. Therefore, future investigations may cause significant changes to the estimates.

Table 1: Current methane and nitrous oxide emissions from natural sources. The global warming-induced sources are shadowed. Modified from: *U.S. EPA 2010. Methane and nitrous oxide emissions from natural sources, EPA 430-R-10-001* [5]

Source	Methane (Tg CH ₄ -C yr ⁻¹)			Nitrous Oxide (Tg N ₂ O-N yr ⁻¹)		
	Emissions estimate	Range	% of total	Emissions estimate	Range	% of total
Wetlands	170.3		55.3			
Northern/bogs	42.7	24–72	13.9		^a 0.09–0.15	
Tropical/swamps	127.6	81–266	41.4			
Upland; riparian areas	–30	n.a.	–9.7	6.6	3.3–90	53.7
Oceans	7.6		2.5	3.8		30.9
Estuaries & rivers	0.5	2.3–15.6	0.2	0.9	1.5–9.1	7.3
Coasts	1.1		0.4	0.8		6.5
Permafrost	0.5	0–1	0.2			
Lakes	30	10–50	9.7	^b 0.1	0.004–0.4	^b 0.8
Gas hydrates	^b 5	2–9	^b 1.6			
Terrestrial geological sources	^b 35	28–43	^b 11.4		Not relevant	
Marine geological sources	^b 17	14–21	^b 5.5			
Wildfires	^b 3	2–5	^b 1.0	0.1	n.a.	0.8
Vegetation	^{b,c} 40	20–60 (0)	^b 13.0			
Terrestrial arthropods	20	2–22	6.5		Not relevant	
Wild animals	8	2–15	2.6			
All natural sources	308		100	12.3		100
All sources	666	503–710		18.8	8.5–27.7	
% natural sources	46%			64%		

^aEstimation based on recent publications [6, 7]. According to rough estimations, drainage of wetlands may increase emissions up to 2 Tg N₂O-N yr⁻¹.

^bEstimated on the basis of range values.

^cIncluded: recently, there is more evidence of the importance of this flux.

Thanks to predominating aerobic soil conditions, uplands and to a large extent also riparian zones are the main areas of CH₄ consumption (−30 Tg CH₄-C yr⁻¹; Table 1).

The comparison of the main methane fluxes and transformation paths in wetlands and uplands (Fig. 3) shows large ranges of emissions from global wetlands (80 to 237 Tg CH₄-C yr⁻¹). On the one hand, there are not enough continuous measurements from the world's wetlands, especially in tropical areas and the vast Siberian permafrost regions [8]. On the other hand, gaps in our knowledge of the role of methane oxidation by methanotrophs in peatlands [9] and uptake by vegetation [10] make the global estimations insufficient. Moreover, Keppler *et al.* [11] first showed that plants themselves may emit a large amount of CH₄ through an as-yet-unidentified aerobic process. Recent studies connect it with exposure to ultraviolet light [12], which may trigger chemical reactions that produce CH₄ from antioxidants commonly found in the mitochondria of living cells [13, 14]. For this reason we consider forest vegetation to be a significant CH₄ source. Similarly, consumption in upland soils shows substantial variability (Fig. 3).

Wetlands are the largest terrestrial deposits of organic carbon, as 455,000 Tg is accumulated in peatlands alone, which cover an area of 4 million km² [15, 16] and about 600,000 Tg in all wetlands considering the global estimate of 7 million km² [15]. Their actual C sequestration is about 830 Tg yr⁻¹ [17]. Thus, the role of wetlands as a significant methane source must be analysed in the context of their ability to sequester carbon. Whiting & Chanton [18] and Mitsch *et al.* [17] demonstrate that within 300 years CH₄ emissions will be compensated

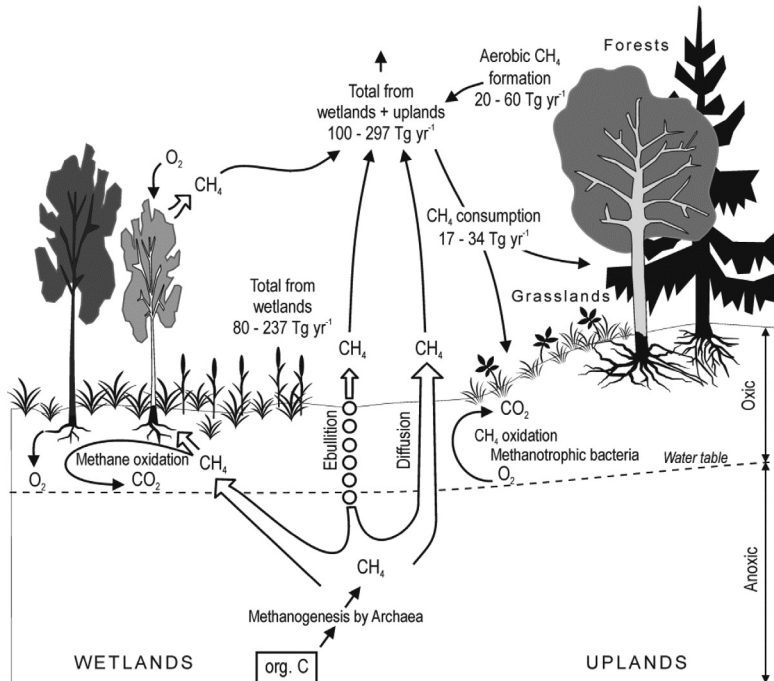


Figure 3: The range of methane emission and oxidation in wetland and upland ecosystems. Based on data from: *U.S. EPA 2010. Methane and nitrous oxide emissions from natural sources, EPA 430-R-10-001* [5].

by C sequestration in wetlands. In the short-term, however, wetlands will be increasingly important sources of global warming.

3.1.3 Nitrous oxide

N_2O is mainly emitted from upland ecosystems and riparian areas ($6.6 \text{ Tg } N_2O-N \text{ yr}^{-1}$; Table 1; Fig. 4). Depending on the adjacent land use type, riparian zones can be significant hotspots of N_2O emission [19]. Oceans, estuaries, rivers, and coasts follow ($3.8, 0.9$ and $0.8 \text{ Tg } N_2O-N \text{ yr}^{-1}$, respectively). Both wildfires and lakes make a contribution by $0.1 \text{ Tg } N_2O-N \text{ yr}^{-1}$. Wetlands have been neglected as a source of N_2O , however, and recent investigations have shown that the drainage of wetlands and especially peatlands may increase emission up to $2 \text{ Tg } N_2O-N \text{ yr}^{-1}$ [6, 7].

3.2 Possible changes in GHG emissions from natural sources

Considering the continuing temperature increase in our biosphere, the increasing frequency of climate extremes (droughts and floods), and consequent phenomena (wildfires, vegetation shift, permafrost and gas hydrates thawing), we can infer some basic trends in further GHG emissions and gas exchange between the atmosphere and terrestrial/marine surfaces.

Carbon dioxide emissions will increase due to more wildfires, greater soil respiration and possibly also changing albedo (Fig. 5). Wildfires will cause an enormous flux of carbon into the atmosphere but will also reduce soil fertility for a long time [20], and will disturb carbon stocks, especially in peatlands [21]. Page *et al.* [22] estimated that during the huge wildfires and related CO_2 pulse of 1997–98 from Southeast Asia, emissions have been $0.8\text{--}2.6 \times 10^{15}$ grams – petagrams (Pg) or gigatonnes – of carbon. This is equivalent to 13%–40% of the annual emissions from anthropogenic fossil-fuel combustion. Changing albedo due to the changes in forest type from deciduous to coniferous may increase CO_2 fluxes from forests [23].

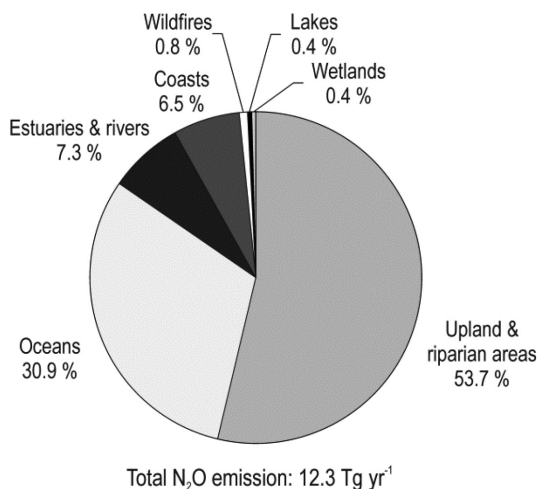


Figure 4: Nitrous oxide emission from natural sources. Based on data from: *U.S. EPA 2010. Methane and nitrous oxide emissions from natural sources, EPA 430-R-10-001* [5].

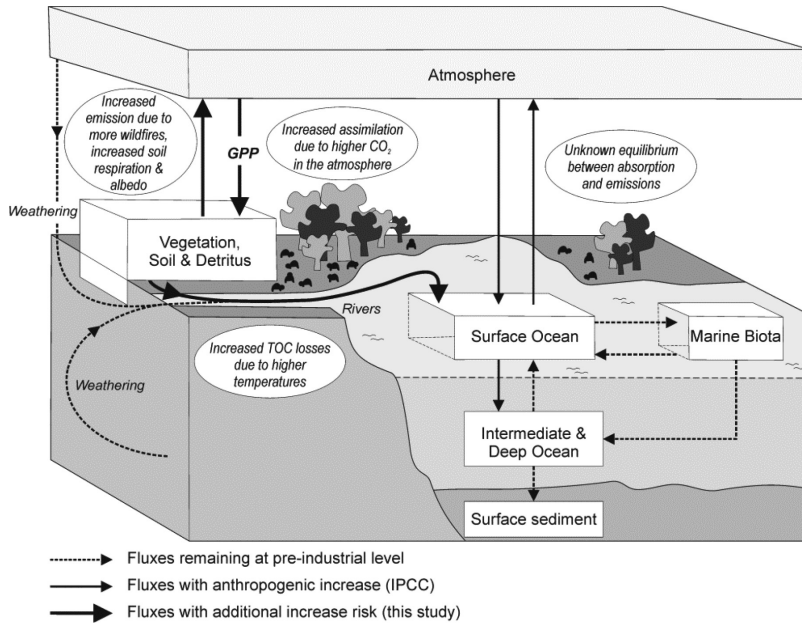


Figure 5: Possible change in the CO₂ balance of natural sources due to global warming. Based on the *IPCC 2007 Climate Change Report* [4].

On the other hand, due to the elevated CO₂ concentrations in the atmosphere, some ecosystems may show increased assimilation of CO₂ in photosynthesis, i.e. increasing gross primary production (GPP) of vegetation (Fig. 5) [24]. Thus the land/vegetation–atmosphere exchange may stabilize, although it will fluctuate over space and time. The same can be assumed regarding the ocean–atmosphere CO₂ exchange, because until now, no evidence has been found regarding the increasing absorption ability of more acid ocean waters [1].

More intensive losses of organic carbon (both the dissolved and total form; DOC and TOC) from northern catchments due to higher temperatures will be a trend that will play out in the 21st century [25], although its impact will be significant at the local and regional levels but possibly not at the global level (see Fig. 5).

Methane emissions are assumed to increase as well but in this case, we can distinguish between short-term and the long-term phenomena.

First, short-term and already ongoing processes are related to wildfires, disturbances in vegetation and temperature increase. Wildfires and temperature increases will enhance methane emissions in wetlands and lakes, and possibly, due to the increasing stress, also the consequent emissions of biogenic volatile organic compounds (BVOC) from vegetation (Fig. 6). The increasing frequency of wildfires in peatlands [21] will not only create a pulse of carbon emission but also destroy the methanotrophs in the top layer, thus opening the way for CH₄ fluxes from deeper peat layers [26]. Likewise, in the uplands wildfires will disturb soils CH₄ sinks [27], which may also decrease the activity of methane-producing arthropods. The share of emissions from wild animals will possibly decrease, due to the destruction of the grassland biome worldwide (Fig. 6). Regarding the coastal and estuarine fluxes, the continued rise in the sea level will bring more saline water to these ecosystems, which will probably reduce CH₄ emissions (Fig. 6) [28].

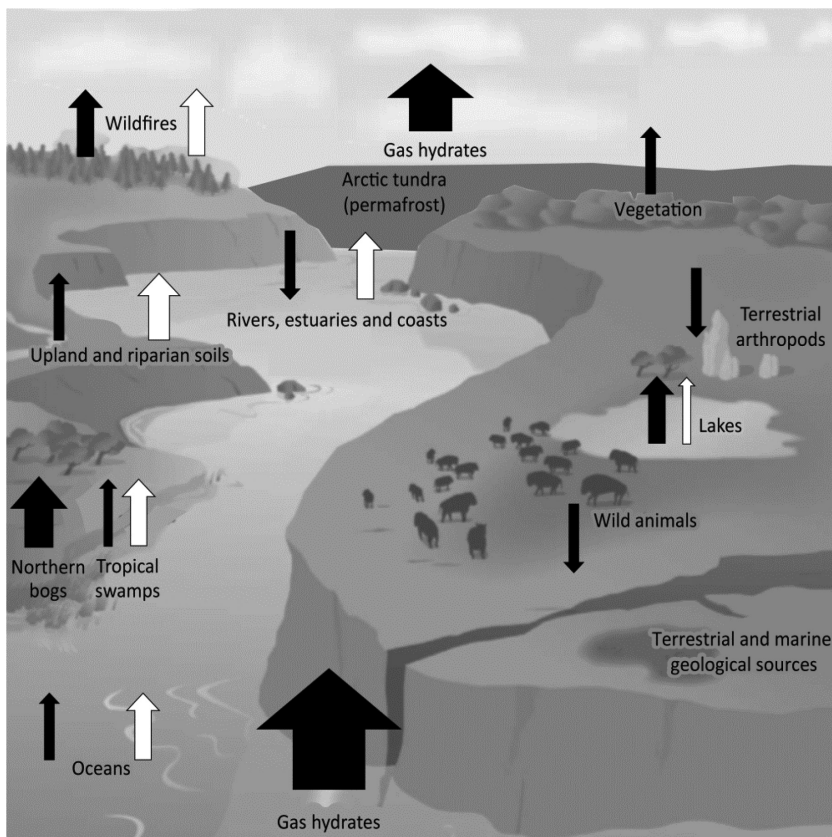


Figure 6: Potential trends in methane (black arrows) and nitrous oxide (white arrows) emissions from natural sources. The size of arrows is proportional to the potential trend; the arrow's direction signifies an increase (upwards) or decrease (downwards) in fluxes. Adapted from: *U.S. EPA 2010. Methane and nitrous oxide emissions from natural sources, EPA 430-R-10-001* [6].

The long-term effects are related to marine hydrates and permafrost thawing. According to the IPCC 2013 report [1], the release of CO_2 or CH_4 from thawing permafrost carbon stocks to the atmosphere will be within the range of 50,000 to 250,000 Tg C even in the 21st century (Fig. 7). Significantly more, up to several millions teragrams of CH_4 will be emitted from the potential thawing of marine hydrates but this will take place within the next thousand years (Fig. 7) [29].

Nitrous oxide emissions will increase from both oceans and upland areas, which together constitute the largest recent source (Fig. 4). In both cases, wildfires will be a factor for both wetland and upland emissions (Fig. 6). Likewise, floods in uplands soils will enhance N_2O emissions. Soosaar *et al.* [30] showed that the long-term fertilization load from adjacent uplands will significantly increase N_2O fluxes from riparian forests. However, there is already evidence that drainage [31] and possibly also more frequent droughts will significantly increase N_2O emissions from wetlands (Fig. 7) [19].

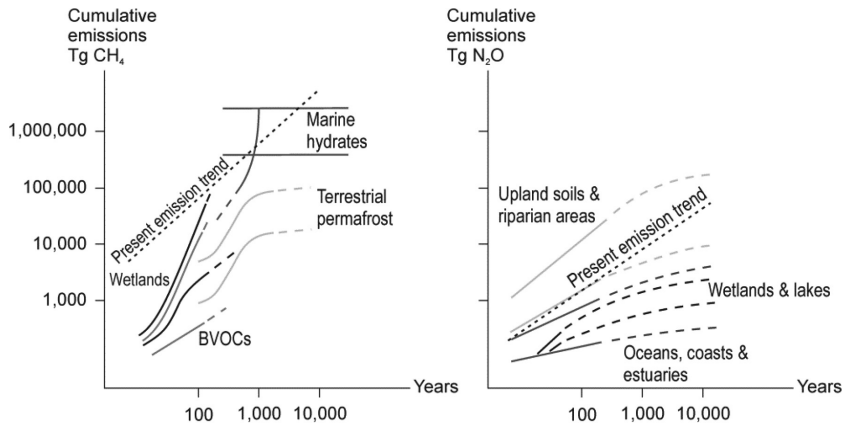


Figure 7: Summary diagram of the relative sizes and timescales associated with methane (a) and nitrous oxide (b) feedbacks. The methane figure is adapted from O'Connor *et al.* [29].

3.3 Further research perspectives

There are many additional areas in which research would help improve CO₂, CH₄, and N₂O flux estimates [5]. The following aspects can be pointed out.

(1) Additional data are required in order to estimate trends in terrestrial and marine C sinks and sources. (2) Data on CH₄ and N₂O fluxes in tropical and southern oceans, estuaries, and rivers, as well as estimates of upwelling sources are needed. (3) Better quantification of CH₄ reserves stored as gas hydrates, as well as better estimation of CH₄ absorption into oceans and CH₄ oxidation in the water column is recommended. (4) More evidence for vegetation as a source of CH₄ is necessary. (5) Permafrost models must be upgraded to give better estimations of their CH₄ fluxes. (6) Data on fluxes from wetlands, wildfires and lakes, particularly in the Arctic and boreal regions, and the tropics must be collected. (7) Research that better quantifies the oxidation of CH₄ through termite mounds, confirms CH₄ from non-termite terrestrial arthropods, and quantifies the activity of arthropods and wild animals, must be continued.

4 CONCLUSIONS

Owing to large amounts of land–atmosphere and ocean–atmosphere CO₂ exchange and the great variability in its estimations, the possible trend of global CO₂ emissions from natural sources will remain uncertain. Most probably, increasing frequency of droughts and related wildfires will result in increasing emissions from terrestrial ecosystems. On the other hand, increasing air humidity in the northern regions would enhance productivity and inhibit soil respiration, counterbalancing the effects of drought. In addition, the long-term impact of rising ocean acidity on CO₂ absorption requires further investigation.

For CH₄ and N₂O the estimations show an increasing trend. In a short-term, rising temperature will increase CH₄ emissions from wetlands and decrease consumption by upland soils. Likewise, vegetation in combination with VOC release will enhance CH₄ emissions. The long-term forecast foresees manifold increases CH₄ emissions from gas hydrates in both the oceans and the permafrost regions. Nitrous oxide emissions will increase from changing

hydrological conditions in both wetlands (drought effect) and uplands (temporary floods). Oceans and coastal areas will show an increasing N₂O trend.

ACKNOWLEDGEMENTS

This study was supported by the Estonian Research Council (the IUT2-16 and PUT JD618 grants); and the EU through the European Regional Development Fund (the ENVIRON and EcolChange Centers of Excellence).

REFERENCES

- [1] Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds), Climate change 2013: the physical science basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535, 2013.
- [2] Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. & Johnson, C.A. (eds), Climate change 2001: the scientific basis. *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 881, 2001.
- [3] Davenport, C., Nations approve landmark climate record in Paris, *New York Times*. 12 December 2015, retrieved 14 December 2015, available at <http://www.cop21.gouv.fr/en/>
- [4] Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds), Climate change 2007: the physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press: Cambridge, UK, and New York, NY, p. 996, 2007.
- [5] U.S. EPA, Methane and nitrous oxide emissions from natural sources EPA 430-R-10-001, 2010.
- [6] Leppelt, T., Dechow, R., Gebbert, S., Freibauer, A., Lohila, A., Augustin, J., Drösler, M., Fiedler, S., Glatzel, S., Höper, H., Järveoja, J., Lærke, P.E., Maljanen, M., Mander, Ü., Mäkiranta, P., Minkinen, K., Ojanen, P., Regina, K. & Strömrgren, M., Nitrous oxide emission hotspots from organic soils in Europe. *Biogeosciences*, **11**, pp. 6595–6612, 2014. <http://dx.doi.org/10.5194/bg-11-6595-2014>
- [7] Pärn, J., Aasa, A., Egorov, S., Filippov, I., Gabiri, G., Gheorghe, I., Järveoja, J., Kasak, K., Laggoun-Défarge, F., Luswata, C., Maddison, M., Mitsch, W., Óskarsson, H., Pellerin, S., Salm, J.-O., Sohar, K., Soosaar, K., Teemusk, A., Tenywa, M., Villa, J., Vohla, C. & Mander, Ü., Global boundary lines of N₂O and CH₄ emission in peatlands. In *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape*, ed. J. Vymazal, Springer International Publishing, Třeboň, pp. 87–102, 2015. http://dx.doi.org/10.1007/978-3-319-08177-9_7
- [8] Bridgham, S., Cadillo-Quiroz, H., Keller, J. & Zhuang, Q., Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. *Global Change Biology*, **19**(5), pp. 1325–1346, 2013. <http://dx.doi.org/10.1111/gcb.12131>
- [9] Choudhury, T.R. & Dick, R.P., Ecology of aerobic methanotrophs in controlling methane fluxes from wetlands. *Applied Soil Ecology*, **65**, pp. 8–22, 2013. <http://dx.doi.org/10.1016/j.apsoil.2012.12.014>

- [10] Sundqvist, E., Crill, P., Mölder, M., Vestin, P. & Lindroth, A., Atmospheric methane removal by boreal plants. *Geophysical Research Letters*, **39**, L21806, 2012.
- [11] Keppler, F., Hamilton, J.T.G., Brass, M. & Rockmann, T., Methane emissions from terrestrial plants under aerobic conditions. *Nature*, **449**, pp. 187–191, 2006.
<http://dx.doi.org/10.1038/nature04420>
- [12] Vigano, I., van Weelden, H., Holzinger, R., Keppler, F., McLeod, A. & Rockmann, T., Effect of UV radiation and temperature on the emission of methane from plant biomass and structural components. *Biogeosciences*, **5**, pp. 937–947, 2008.
<http://dx.doi.org/10.5194/bg-5-937-2008>
- [13] Ghyczy, M., Torday, C., Kaszaki, J., Szabo, A., Czobel, M. & Boros, M., Hypoxia-induced generation of methane in mitochondria and eukaryotic cells - an alternative approach to methanogenesis. *Cellular Physiology and Biochemistry*, **21**, pp. 251–258, 2008.
<http://dx.doi.org/10.1159/000113766>
- [14] Messenger, D.J., McLeod, A.R. & Fry, S.C., The role of ultraviolet radiation, photosensitizers, reactive oxygen species and ester groups in mechanisms of methane formation from pectin. *Plant Cell and Environment*, **32**, pp. 1–9, 2009.
<http://dx.doi.org/10.1111/j.1365-3040.2008.01892.x>
- [15] Yavitt, J.B., Williams, C.J. & Wieder, R.K., Soil chemistry versus environmental controls on production of CH₄ and CO₂ in northern peatlands. *European Journal of Soil Science*, **56**, pp. 169–178, 2005.
<http://dx.doi.org/10.1111/j.1365-2389.2004.00657.x>
- [16] Joosten, H., *The Global Peatlands CO₂ Picture*. Peatland status and emissions in all countries of the world. Wetlands International, Ede, Draft, pp. 1–35, 2009, available at https://unfccc.int/files/kyoto_protocol/application/pdf/draftpeatlandco2report.pdf
- [17] Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, L., Jørgensen, S.E. & Brix, H., Wetlands, carbon, and climate change. *Landscape Ecology*, **28**(4), pp. 583–597, 2013.
<http://dx.doi.org/10.1007/s10980-012-9758-8>
- [18] Whiting, G.J. & Chanton, J.P., Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. *Tellus*, **53B**, pp. 521–528, 2001.
<http://dx.doi.org/10.1034/j.1600-0889.2001.530501.x>
- [19] Hefting, M.M., Bobbink, R. & deCaluwe, H., Nitrous oxide emission and denitrification in chronically nitrate -loaded riparian buffer zones. *Journal of Environmental Quality*, **32**(4), pp. 1194–1203, 2003.
<http://dx.doi.org/10.2134/jeq2003.1194>
- [20] Schimel, D. & Baker, D., The wildfire factor. *Nature*, **420**, p. 29, 2002.
<http://dx.doi.org/10.1038/420029a>
- [21] Turetsky, M.R., Benschoter, B., Page, S., Rein, G., van der Werf, G. & Watts, A., Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience*, **8**, pp. 11–14, 2015.
<http://dx.doi.org/10.1038/ngeo2325>
- [22] Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.-D.V., Jaya, A. & Limin, S.H., The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**, pp. 61–65, 2002.
<http://dx.doi.org/10.1038/nature01131>
- [23] Naudts, K., Chen, Y.Y., McGrath, M.J., Ryder, J., Valade, A., Otto, J. & Luysaert, S., Europe's forest management did not mitigate climate warming. *Science*, **351**(6273), pp. 597–600, 2016.
<http://dx.doi.org/10.1126/science.aad7270>

- [24] Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore, B., Vorosmarty, C.J. & Schloss, A.L., Global climate-change and terrestrial net primary production. *Nature*, 363, pp. 234–240, 1993.
<http://dx.doi.org/10.1038/363234a0>
- [25] Monteith, D.T., Stoddard, J.L., Evans, C.D., de Wit, H.A., Forsius, M., Hogasen, T., Wilander, A., Skjelkvåle, B.L., Jeffries, D.S., Vuorenmaa, J., Keller, B., Kopacel, J. & Vesely, J., Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature*, 450, pp. 537–539, 2007.
<http://dx.doi.org/10.1038/nature06316>
- [26] Danilova, O.V., Belova, S.E., Kulichevskaya, I.S. & Dedysh, S.N., Decline of activity and shifts in the methanotrophic community structure of an ombrotrophic peat bog after wildfire. *Microbiology*, 84(5), pp. 624–629, 2015.
<http://dx.doi.org/10.1134/S0026261715050045>
- [27] McNamara, N.P., Gregg, R., Oakley, S., Stott, A., Rahman, M.T., Murrell, J.C., Wardle, D.A., Bardgett, R.D. & Ostle, N.J., Soil methane sink capacity response to a long-term wildfire chronosequence in Northern Sweden. *PLoS ONE*, 10(9), e0129892, 2015.
<http://dx.doi.org/10.1371/journal.pone.0129892>
- [28] Middelburg, J.J., Nieuwenhuize, J., Iversen, N., Hogh, N., De Wilde, H., Helder, W., Seifert, R. & Christof, O., Methane distribution in European tidal estuaries. *Biogeochemistry*, 59(1–2), pp. 95–119, 2002.
<http://dx.doi.org/10.1023/A:1015515130419>
- [29] O'Connor, F.M., Boucher, O., Gedney, N., Jones, C.D., Folberth, G.A., Coppel, R., Friedlingstein, P., Collins, W.J., Chapellaz, J., Ridley, J. & Johnson, C.E., Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. *Reviews of Geophysics*, 48(RG4005), pp. 1–33, 2010.
<http://dx.doi.org/10.1029/2010rg000326>
- [30] Soosaar, K., Mander, Ü., Maddison, M., Kanal, A., Kull, A., Lõhmus, K., Truu, J. & Augustin, J., Dynamics of gaseous nitrogen and carbon fluxes in riparian alder forests. *Ecological Engineering*, 37(1), pp. 40–53, 2011.
<http://dx.doi.org/10.1016/j.ecoleng.2010.07.025>
- [31] Martikainen, P.J., Nykänen, H., Crill, P. & Silvola, J., Effect of a lowered water-table on nitrous-oxide fluxes from northern peatlands. *Nature*, 366, pp. 51–53, 1993.
<http://dx.doi.org/10.1038/366051a0>