Effect of the 2018 European drought on methane and carbon dioxide exchange of northern mire ecosystems

J. Rinne1, J.-P. Tuovinen2, L. Klemedtsson3, M. Aurela2, J. Holst1, A. Lohila2,4, P. Weslien3, P. Vestin1, P. Łakomiec1, M. Peichl5, E.-S. Tuittila6,7, L. Heiskanen2, T. Laurila2, X. Li8, P. Alekseychik4,7, I. Mammarella4, L. Ström1, P. Crill8 and M. B. Nilsson3

1Department of Physical Geography and Ecosystem Science, Lund University, Sweden
2Climate System Research, Finnish Meteorological Institute, Helsinki, Finland
3Department of Earth Sciences, University of Gothenburg, Sweden
4Tanem Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, University of Helsinki, Finland
5Department of Forest Ecology and Management, Swedish Agricultural University, Umeå, Sweden
6School of Forest Sciences, University of Eastern Finland, Joensuu, Finland
7Bioeconomy and Environment, Natural Resources Institute Finland, Helsinki, Finland
8Department of Geological Sciences and Bolin Centre for Climate Research, Stockholm University, Sweden

We analysed the effect of the 2018 European drought on greenhouse gas (GHG) exchange of five North European mire ecosystems. The low precipitation and high summer temperatures in Fennoscandia led to a lowered water table in the majority of these mires. This lowered both carbon dioxide (CO2) uptake and methane (CH4) emission during 2018, turning three out of the five mires from CO2 sinks to sources. The calculated radiative forcing showed that the drought-induced changes in GHG fluxes first resulted in a cooling effect lasting 15–50 years, due to the lowered CH4 emission, which was followed by warming due to the lower CO2 uptake.

This article is part of the theme issue ‘Impacts of the 2018 severe drought and heatwave in Europe: from site to continental scale’.

1. Introduction

During the summer of 2018, Northwestern Europe experienced an exceptional drought and heatwave, also affecting Fennoscandian mire ecosystems [1–3]. The drought and associated warm temperatures can alter the short-term hydrological status of mire ecosystems, leading to alterations in biogeochemical processes within these ecosystems. These changes can have a drastic effect on greenhouse gas (GHG) exchange between the mires and the atmosphere [4].

Northern mire ecosystems are characterized by two considerable GHG fluxes, viz. carbon dioxide (CO2) uptake and methane (CH4) emission, that generate opposite radiative forcing (RF) [5]. On longer timescales, e.g. over millennia, carbon uptake and storage as peat, i.e. sequestration of CO2 from the atmosphere, results in a climate cooling effect. Methane emission, on the other hand, has an intense short-term warming effect on the atmospheric radiative balance [6].

The seasonal variation in the CO2 and CH4 fluxes between the atmosphere and mires has generally been observed to be related to temperature and water
Dry conditions and lowered water tables hinder CO₂ uptake [7,12], but they also lead to a reduction in CH₄ emission [4,13,14]. Thus, the same environmental forcing of GHG exchange of mires can lead to counteracting climatic effects.

To assess the climatic impact of weather events through ecosystem GHG exchange, the differing radiative properties and atmospheric lifetimes of GHGs need to be accounted for. Global warming potential (GWP) is a commonly used metric that integrates the radiative forcing due to a GHG pulse emission over a prescribed time (typically 20 or 100 years) and is expressed as CO₂ equivalents, i.e. the cumulative RF relative to that of CO₂ [15]. A more dynamic approach to compare the effects of different GHG fluxes is to examine the development of instantaneous RF due to these fluxes [16,17].

In addition to effective metrics, reliable data on ecosystem GHG exchange are needed to assess the climatic impact of weather events. In Sweden and Finland, GHG fluxes are measured at several mire ecosystems using eddy covariance (EC), mostly within national networks of the Integrated Carbon Observation System (ICOS-Sweden and ICOS-Finland). Appropriate environmental parameters are also measured at each site. In this paper, we will use EC and auxiliary data from five sites to analyse the effect of the 2018 European drought on the CO₂ and CH₄ fluxes of mire ecosystems in relation to changes in key environmental drivers. Furthermore, we will analyse the climatic effect of the drought-induced changes in GHG fluxes by using both the GWP and dynamic RF approaches.

2. Material and methods

We selected natural mire ecosystems that have EC measurements of both CO₂ and CH₄ fluxes during 2018 and at least one additional reference year of data. The sites are listed in table 1 and their locations are shown in figure 1. Many of these sites are either ICOS stations or in the process of becoming such and thus the measurements follow the ICOS protocols of CO₂ and CH₄ fluxes, and those of auxiliary parameters [24–27]. The average temperature at the sites ranges from −1.4°C to +6.8°C. None of these sites contain permafrost. The vegetation at the mires is listed in table 2, with associations to different mire types.

The effect of drought on GHG fluxes was estimated as differences in the cumulative annual CO₂ and CH₄ fluxes between 2018 and a reference period (ΔF_{CO₂} and ΔF_{CH₄}). The reference period was selected as a single year or several years with rainfall and temperature close to the 30-year average (tables 3 and 4). However, flux data availability places a strong constraint on this. For some sites, only a few years of data exist on both CO₂ and CH₄ fluxes, and the maximum length of time series for any of the sites was 15 years. As a result of flux data availability, these reference years vary among different mire sites and the environmental conditions during these years may slightly deviate from the long-term average climatological conditions. We related the changes in annual cumulative fluxes to average changes in temperature and water table in summertime, as the drought and heatwave were most conspicuous during this period. The significances of these relations were estimated by non-parametric Spearman’s rank correlation test (Matlab R2015b, corr function). We also compared the apparent temperature dependence of methane emission during the drought and reference years using bin-averaged daily mean methane fluxes. For this, we used daily mean peat temperatures and 2°C bins starting at 0°C.

For the long-term climate reference, we used the 1981–2010 monthly precipitation and monthly average air temperature
Table 2. Dominating vascular plant vegetation on the five mire sites (1 = presence of the species). Mire type indicates the species main distribution range according to the Northern vegetation classification by Påhlsson [28]; nutrient poor ombrotrophic bog (B) and minerotrophic fens in order of increasing nutrient availability: poor fen (PF), intermediate fen (IF) and moderate fen (MF). G indicates that the species can be found in all four mire types, and if present in several types the preferred mire type is indicated by *.

| species                      | mire type | Mycklemossen | Degerö | Siikaneva | Kaamanen | Lompolojänkkä |
|------------------------------|-----------|---------------|--------|-----------|----------|---------------|
| Calluna vulgaris             | B         | 1             |        |           |          |               |
| Erica tetralix               | B         |               |        |           |          |               |
| Empetrum nigrum              | B         |               |        |           |          |               |
| Ledum palustre               | B         |               |        |           |          |               |
| Vaccinium uliginosum         | B         |               |        |           |          |               |
| Vaccinium vitis-idaea        | B         |               |        |           |          |               |
| Rubus chamaemorus            | B, PF     | 1             | 1      | 1         | 1        |               |
| Eriophorum vaginatum         | B*, PF    | 1             | 1      | 1         | 1        |               |
| Rhynchospora alba            | B*, PF    | 1             |        |           |          |               |
| Carex lasiocarpa             | PF, IF, MF| 1             |        |           |          |               |
| Carex rostrata               | PF, IF, MF| 1             | 1      | 1         | 1        |               |
| Eriophorum angustifolium     | PF, IF, MF| 1             |        |           |          |               |
| Carex chordorrhiza           | PF, IF*, MF| 1            |        | 1         |          |               |
| Carex aquatilis              | IF, MF    |               |        |           |          |               |
| Carex livida                 | IF, MF    |               |        |           |          |               |
| Carex magellanicus           | IF, MF    |               |        |           |          |               |
| Carex buxbaumii              | MF        |               |        |           |          |               |
| Andromeda polifolia          | G         | 1             | 1      | 1         |          |               |
| Vaccinium oxycoccus          | G         |               |        |           |          |               |
| Carex limosa                 | G         | 1             | 1      | 1         |          |               |
| Trichophorum cespitosum      | G         |               |        |           |          |               |

Plant community composition taken from Ström unpubl. results [18,19] [8] [21] [23]

Table 3. Overview of climate datasets from weather stations. For Utsjoki Kevo and Muonio, the reference year is 2017. For Vindeln Svarterget, the reference year is the average of 2015–2016. For Juupajoki Hyytiälä, the reference year is the average of 2010–2013. For Vänersborg and Uddevalla, the reference year is 2016.

| station (mire)       | location | source | mean annual precipitation [mm] | mean annual temperature [°C] |
|----------------------|----------|--------|--------------------------------|-----------------------------|
|                      |          |        | 1981–2010 ref. 2018            | 1981–2010 ref. 2018         |
| Utsjoki Kevo (Kaamanen) | 69°43’ N 27°01’ E | FMI | 433 | 519 | 410 | −1.3 | −1.1 | −0.3 |
| Muonio Alamuonio & kk (Lompolojänkkä) | 67°58’ N 23°41’ E | FMI | 528 | 443 | 472 | −0.4 | 0.3 | 1.4 |
| Vindeln Svarterget (Degerö) | 64°14’ N 19°36’ E | SLU | 613 | 648 | 546 | 1.9 | 3.1 | 2.8 |
| Juupajoki Hyytiälä (Siikaneva) | 61°51’ N 24°17’ E | FMI | 703 | 731 | 540 | 3.5 | 4.3 | 4.8 |
| Vänersborg (Mycklemossen) | 58°21’ N 12°22’ E | SMHI | 803 | 655 | 599 | 6.8 | 7.7 | 8.2 |
| Uddevalla (Mycklemossen) | 58°22’ N, 11°56’ E | SMHI | 990 | 886 | 820 | n.a. | n.a. | n.a. |

data from nearby weather stations of the Swedish Meteorological and Hydrological Institute (SMHI) and the Finnish Meteorological Institute (FMI). For Siikaneva and Lompolojänkkä, we selected the nearby stations of Juupajoki Hyytiälä and Muonio (Alamuonio and kk), respectively. For Degerö, we used climate data collected by the Swedish Agricultural University (SLU) at Vindeln Svarterget. For Mycklemossen, we used precipitation from Uddevalla and temperature from Vänersborg, and for Kaamanen we used Utsjoki Kevo. An overview of these data sets is given in table 3.

Annual CO₂ and CH₄ flux time series were derived from the half-hourly EC flux data. Missing observations
due to atmospheric conditions not fulfilling micrometeorological flux quality criteria or due to instrument malfunctions were filled in the time series. The CO₂ fluxes were gap filled as in Wutzler et al. [29]. For CH₄ fluxes, daily averages were calculated [10] and gap filling was conducted by linear interpolation. The uncertainty caused by linear interpolation was assessed by creating artificial gaps in data, representing the number and distribution of gaps in original data, and interpolating the resulting time series. Repeating this 100 times indicated uncertainty generally below 10%. As the automatic water table measurement at the Kaamanen site was not operational in 2017–2018, we used averages of manual measurements to calculate the monthly water table depths at this site.

The statistical significance of difference in the daily CO₂ and CH₄ fluxes between 2018 and the reference years was tested using the non-parametric Mann–Whitney–Wilcoxon test (Matlab R2015b, ranksum function, 5% significance level). The test was conducted for July–August, which was the peak flux period and had a large 2018-to-reference difference in water table at most sites.

To compare the climatic effects of the drought-induced changes in CO₂ and CH₄ fluxes, we used the GWP of CH₄ with two different time horizons, 20 and 100 years, referred to as GWP₂₀ (=84) and GWP₁₀₀ (=28). Multiplying the change in the annual CH₄ mass flux by these GWP values results in fluxes in which CO₂ and CH₄ are expressed in common units, i.e. CO₂ equivalents [15]. To characterize the dynamics of the radiative effect of the GHG flux changes in more detail, we calculated the radiative forcing due to these changes, i.e. again adopting a ‘normal’ year as a reference. We used the impulse-response model described by Lohila et al [16] and subsequently updated to include the indirect RF due to atmospheric CH₄-to-CO₂ oxidation [30], revised radiative efficiencies [31] and

![Figure 2. Annual cycle of monthly average air temperatures: long-term mean (crosses); reference period (diamonds); 2018 (dots) from weather stations listed in table 3.](image)

| Location         | CO₂ reference g C m⁻² | CO₂ 2018 g C m⁻² | CH₄ reference g C m⁻² | CH₄ 2018 g C m⁻² | ΔCO₂-eq 20 yr | ΔCO₂-eq 100 yr |
|------------------|-----------------------|------------------|----------------------|------------------|---------------|----------------|
| Degerö           | −31.4 (2015–2016)     | 15.2             | 11.4 (2015–2016)     | 9.5              | −36           | 100            |
| Kaamanen         | −8.5 (2017)           | −5.6             | 7.6 (2017)           | 6.8              | −80           | −20            |
| Lompolojänkkä   | −29.1 (2017)          | −56.0            | 15.0 (2017)          | 22.0             | 680           | 160            |
| Mycklemossen     | −1.4 (2016)           | 54.7             | 9.7 (2016)           | 5.6              | −260          | 51             |
| Siikaneva        | −78.8 (2010–2013)     | 18.4             | 11.5 (2010–2013)     | 7.6              | −74           | 220            |
future GHG concentration scenarios [32]. The use of this method allowed us to estimate the decline of an atmospheric GHG perturbation and the related instantaneous RF over time. We also positioned the mires to the instantaneous RF switchover time diagram based on the ratio of changes in annual CH₄ and CO₂ fluxes [6].
3. Results

The summer of 2018 was warmer than on average during the 30-year period of 1981–2010 at all weather stations near the flux measurement sites, with May and July being especially warm (table 3 and figure 2). Temperatures in the selected reference years were close to the 30-year averages during the summer periods at the three northernmost sites, while at the two southernmost sites, the reference summertime temperatures were somewhat higher than the 30-year mean. In 2018, annual precipitation was considerably lower than the 30-year mean, especially at Mycklemossen/Uddevalla and Lompolojänkkä/Muonio, where the drought conditions prevailed during the whole year (figure 3). It is noteworthy that at Mycklemossen/Uddevalla the years 2016, 2017 and 2018 all had below-normal annual precipitation. At Siikaneva/Juupajoki and Degerö/Svartberget, the precipitation in the first half of 2018 was close to the 1981–2010 average, but the end of the year was much drier. At Utsjoki Kevo, the annual precipitation in 2018 was close to the long-term average but the first half of the year had below-average precipitation. The water table at all mires, except for Lompolojänkkä, was lower in summer 2018 than during the reference years (figure 4).

Thus, all mire sites except for Lompolojänkkä experienced a dry year in 2018, as judged from the variations of the water
The differences in precipitation between 2018 and reference years at different mires did not correlate with the corresponding differences in water table position. All the sites showed a typical annual cycle of both daily CO₂ and CH₄ fluxes, with CO₂ uptake in summer and release outside the growing season, and CH₄ emission peaking during summer months (figures 5 and 6). The effects of drought and heatwave on CO₂ exchange is conspicuous, with reduced summertime CO₂ uptake at Degerö, Mycklemossen and Siikaneva, and increased uptake at Lompolojänkkä. Summertime CH₄ emission is reduced at all sites except Lompolojänkkä. The difference in daily CH₄ fluxes during July–August between 2018 and the reference period was significant for all sites. For CO₂ fluxes, the difference was significant for all sites except Lompolojänkkä.

The cumulative CO₂ fluxes at Degerö, Lompolojänkkä and Siikaneva showed annual CO₂ uptake in the reference years, whereas at Mycklemossen and Kaamanen the cumulative net CO₂ uptake was close to zero (figure 5). In 2018, annual CO₂ uptake was reduced at all sites except for Lompolojänkkä and three sites acted as CO₂ sources at an annual timescale. The annual cumulative ecosystem CH₄ emission was reduced during 2018 as compared to the reference years, except at Lompolojänkkä (figure 6). Not accounting for this site, the change in the annual CO₂ flux (ΔF_CO₂) ranged from 3 g C m⁻² to 100 g C m⁻², while the change in annual CH₄ flux (ΔF_CH₄)
ranged from −0.8 g C m\(^{-2}\) to −4 g CH\(_4\) m\(^{-2}\). Lompolojänkkä had opposite changes compared to the other sites, with increased CO\(_2\) uptake (ΔF\(_{CO2}\) = −27 g C m\(^{-2}\)) and CH\(_4\) emission (ΔF\(_{CH4}\) = 7.0 g C m\(^{-2}\)).

The relations of ΔF\(_{CH4}\) and ΔF\(_{CO2}\) to the 2018-to-reference difference in summertime water table position (ΔWT) or the difference in air temperature were not significant (ΔT) (figure 7). However, at all sites with a lowered water table, the CH\(_4\) emissions at a given temperature bin were generally lower during the drought year than in the reference years (figure 8).

For all mires with a substantial water table lowering in 2018, the drought-induced changes in the annual CO\(_2\) and CH\(_4\) balances, estimated above, correspond to a cooling effect when the fluxes are expressed as GWP\(_{20}\)-based CO\(_2\) equivalents (negative CO\(_2\) equivalents, table 4). This indicates the short-term dominance of reduced CH\(_4\) emissions. However, the corresponding GWP\(_{100}\)-based values were positive, indicating warming, at all sites except for Kaamanen.

The instantaneous RF due to GHG flux changes, caused by dry conditions, show an initial cooling effect resulting from the reduced CH\(_4\) emission at all sites except for Lompolojänkkä (figure 9a). Later, the effect of reduced CO\(_2\) uptake will dominate, causing a warming effect at these sites. Lompolojänkkä, with opposite changes in GHG fluxes as compared to other mires, shows an initial warming and a subsequent cooling effect. The switchover of the instantaneous RF from cooling to warming takes place 15–50 years after the drought year for the mires which experienced a water table drawdown (figure 9b), while at Lompolojänkkä the transition was from warming to cooling (figure 9c).

4. Discussion

The 2018 drought caused a widespread water table drawdown across North European mire ecosystems. This is a reflection of the dry and warm conditions during summer of 2018. In Sweden, precipitation deficit was observed in nearly the whole country from May to July, with Southern Sweden experiencing the highest deficit [1]. Furthermore, May and July were much warmer than the long-term average for the whole of Sweden [1], while June was somewhat warmer in the south and colder in the north [1]. In Finland, the early summer precipitation deficit was more pronounced in the southern part of the country [2], with warmer than average summer for the whole county [3]. However, local hydrological features related to e.g. topographical position can cause some mires to be less sensitive to climatic variations, as seen at the Lompolojänkkä mire.

We observed similarities in the change of annual GHG fluxes at all the mires with a water table drawdown, with a reduction of both CO\(_2\) uptake and CH\(_4\) emission. Three out of the four mires with lowered water table turned from CO\(_2\) sinks to sources during 2018. The reduction of CH\(_4\) emission was more moderate, the change being mostly less than 20% of the emission during the reference year, with the exception of Mycklemossen (42%). Mycklemossen is the southernmost
of the mire sites in this study and is located within the area most affected by the 2018 drought. It also experienced drier than average conditions in 2016 and 2017, the effects of which may have carried over to 2018. Furthermore, Mycklemossen has most ombrotrophic bog characteristics while the other mires show more minerogenic fen characteristics (table 2). As bogs typically have a lower water table as compared to minerogenic fens and have a lesser coverage of aerenchymatous plants, their CH4 emission may be more sensitive to dry conditions.

We could not establish statistically significant correlations between the changes of annual CO2 exchange and annual CH4 emission with summertime temperature or water table level. However, the apparent dependence of CH4 emission on peat temperature shows a clear 2018-to-reference difference in all mires with a lowered water table. Similar differences in the apparent temperature dependence of CH4 emission have also been observed previously [33,34]. At Lompolojänkkä, where the water table was not drawn down, the temperature response of CH4 emission was similar in 2018 and the reference year. The high peat temperature at Lompolojänkkä in 2018 can explain the very high CH4 emission in that year. On the other hand, at Degerö, which also had relatively high peat temperatures in 2018, the CH4 emission was clearly lowered due to the lower water table. Thus, it seems obvious that both the water table level and peat temperature play a role in this variation.

The use of such dependencies e.g. for upscaling the climatic effects of droughts would additionally require establishing a relationship between water table and precipitation, and peat temperature and air temperature, as water table position and peat temperatures are not parameters commonly measured by weather observation networks.

As the CH4 emissions were reduced, this change first dominated the radiative forcing effects over the reduction in CO2 uptake and resulted in a temporary cooling effect. According to our RF analysis, this cooling was in most cases limited to the first 15–50 years after the drought year. The length of this period depends on the ratio of the changes in the two GHG fluxes, while the strength of the cooling and warming effects depend on the magnitude of these changes. At Siikaneva and Degerö, with a small reduction in CH4 emission as compared to a reduction in CO2 uptake, the cooling period is short, whereas for Kaamanen, with a small change in CO2 uptake, cooling lasts longer. Mires with a large change in CH4 fluxes showed a large initial change in the instantaneous RF. Siikaneva, with the largest reduction in CO2 uptake, showed the largest warming after the switchover from cooling to warming.

The GWP20- and GWP100-based metrics, which essentially represent RF integrals, reflect the RF-based analysis.

The short-term climatic effect as shown by both the GWP and RF approaches is very sensitive to the changes in CH4 fluxes. As the variation in annual CH4 emissions from northern mires can be ca. 2 g C m−2 [10], the selection of reference years can have a large effect on the estimated short-term climatic forcing, which is affected more by CH4 than CO2. Ideally, we should compare the CH4 emissions during a drought year to a long-term average. Currently, however, very few CH4 emission time series exceed 10 years. Thus, the development of long-term flux measurement networks, such as ICOS, is expected to lead to more representative datasets and improved understanding of these climate feedbacks.

5. Conclusion

The dry conditions in Northwestern Europe in 2018 led to a lowering of water table position at most, but not all, flux measurement sites on mire ecosystems. The lowered water table led to a reduction of both summertime CO2 uptake and CH4 emission, and annual exchange of these GHGs. The apparent temperature dependence of CH4 fluxes was clearly affected by the lowered water table, but also temperature effects were obvious. Due to the different atmospheric residence times of these GHGs, the cooling effect due to the reduction of CH4 emission dominates for the first 15–50 years, whereas for CO2, the warming effect lasts longer. Mires with a large change in CH4 fluxes showed a large initial change in the instantaneous RF. Siikaneva, with the largest reduction in CO2 uptake, showed the largest warming after the switchover from cooling to warming. The GWP20- and GWP100-based metrics, which essentially represent RF integrals, reflect the RF-based analysis.
years after the drought, after which the warming effect by the reduced CO₂ uptake will dominate.

Data accessibility. The data from Degerö and Lompolojänkkä is available through ICOS Carbon Portal (https://www.icos-cp.eu/). Suikaneva data is available through Avaa portal (https://avaa.tdata.fi/web/smart/smear/search). Mycklemossen data is available through SITES portal (https://data.fieldsites.se/portal/). Data from Kaamanen is available at zenodo (https://zenodo.org/record/3975733). The climate data is publicly available from SMHI and FMI smart portals (https://www.smhi.se/data/meteorologi/; https://en.ilmatieteenlaitos.fi/download-observations#!/).

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Endnotes
1https://www.smhi.se/data/meteorologi/
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Figure 9. (a) Time evolution of instantaneous radiative forcing (RF) due to the change in net CO₂ uptake (ΔFCO₂) and CH₄ emission (ΔFCH₄) during 2018, as compared to the reference period. (b,c) The dependence of timing of the RF switchover time (sign change) on the ΔFCO₂/ΔFCH₄ ratio for sites with a negative ΔFCO₂ and a positive ΔFCO₂ (b) and a positive ΔFCH₄ and a negative ΔFCO₂ (c). The arrows indicate the ΔFCO₂/ΔFCH₄ ratio for each site and the corresponding cooling and warming periods.
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