Dear reviewers,

we appreciate your thoughtful and detailed reviews! Your constructive comments certainly helped to improve our manuscript and particularly the discussion. We took your comments (black) into consideration as described below (blue):

Point-by-point response to reviewer 1:

General comments

This is a carefully done study about the production, oxidation and emission of CH_4 in Patagonian bog, the results are of considerable interest and the paper is well written. However, some points need clarifying and certain statements require further justification.

Specific comments

1. the authors should not ignore that acetogenesis might be important in anaerobic environments when H_2 partial pressures are high and temperatures are low. Acetogens can outcompete methanogens at low temperature, as many acetogens seem to have a higher growth rate at low temperature than most methanogens (Kotsyurbenko et al., 1996, 2001). If acetogenesis process is active in the bog, the δ3C value of actetate in the porewater will be largely decreased because of the substantial fractionation during acetate production from CO_2 and H_2. And resultantly, the 13C value of CH_4 will also be lower and resulted in larger apparent isotopic fractionation factor (ac) between CO_2 and CH_4. Therefore, it's difficult to determine the relative importance of acetoclastic versus hydrogenotrophic methanogenesis pathway without the 13C value of acetate in this study.

We agree with the reviewer, that the d13C-CH4 signal was surprisingly low and therefore needs an explanation. Indeed, a strong effect of only methanotrophy should result in a less negative signature of d13C in CH4. We attempt to explain the low d13C-CH4 signal by the occurrence of microsite that create a mixed isotopic signal from methane production and consumption. As the reviewer correctly points out, the occurrence of acetogenesis is a reasonable explanation for the surprisingly negative d13C-CH4 signatures. Reviewer 2 suggests occurrence of hydrogenotrophic methanogenesis as a possible explanation. We agree that both pathways could explain the pattern in the d13C-CH4 signal, although we propose in accordance with the reviewer that hydrogenotrophic methanogenesis was probably relatively more important below pools while acetoclastic methanogenesis in combination with acetogenesis seemed to contribute more below Astelia lawns. But as we did not quantify other parameters such as labile organic matter from roots, acetate concentrations or its carbon isotopic signatures, we cannot clearly determine the relative importance of both pathways for our study, as the reviewer correctly states.

In the revised discussion, we emphasize that the depleted d13C-CH4 signal is an unexpected result (page 14, lines 6-8, and lines 34-2 on page 15). We explain possible sources for depleted 13C-CH4 within the rhizosphere and discuss the possibility of the occurrence of acetogenesis (page 14, lines 16-22; page 15, line 2). The difficulties to separate the isotopic effects arising from methanogenic pathways are now mentioned (page 14, line 18 and page 15, lines 3-5). We tried to balance the suggestions of both reviewers by discussing the arguments for both, hydrogenotrophic and acetoclastic methanogenesis and acetogenesis, carefully (page 15, lines 2-11).

2. In the first page, line 26-28, it's stated that: "Below the rhizosphere. . .. . .CH_4 was predominantly produced by hydrogenotrophic methanogenesis". In fact, data in Figure 4def showed that the hydrogenotrophic pathway had higher contribution to CH_4 in the pool, while the acetoclastic pathway must play relatively more important role for the CH_4 production below the rhizosphere of Astelia Lawn. This is consistent with the supply of labile organic carbon from

the root exudates of Astelia. To sum up, I think it's difficult to conclude that CH4 is mainly produced from the hydrogenotrophic pathway below the rhizosphere of Astelia.

We agree with the reviewer that hydrogenotrophic methanogenesis was probably relatively more important below pools while acetoclastic methanogenesis seemed to contribute more below Astelia lawns. This seemed to have been even true below the rhizosphere of Astelia lawns, but is a result hard to explain from the data obtained in our study. As the reviewer correctly points out, labile organic matter from roots could be a possible explanation. But as we did not quantify other parameters such as labile organic matter from roots, acetate concentrations or its carbon isotopic signatures, we cannot clearly determine the relative importance of both pathways for our study, as the reviewer correctly states in the general comment 1.

In the revised abstract, we rephrased that sentence on page 1, line 26-28. We emphasize in the discussion that the depleted d13C-CH4 signal is an unexpected result (page 14, lines 6-8, and lines 34-2 on page 15). We explain possible sources for depleted 13C-CH4 and discuss the possibility of the occurrence of acetogenesis (page 14, lines 16-22; page 15, line 2). The difficulties to separate the isotopic effects arising from methanogenic pathways are now mentioned (page 14, line 18 and page 15, lines 3-5). We tried to balance the suggestions of both reviewers by discussing the arguments for both, hydrogenotrophic and acetoclastic methanogenesis and acetogenesis, carefully (page 14, lines 18-20; page 15, lines 2-11).

3. It's stated that mean root lifetimes of A. pumila has been estimated to be ~3-4 years. So, whether the production and oxidation of CH4 will be strongly affected in case of the turnover of large amounts of roots?

It is an interesting point that turnover i.e. presence and activity of roots should largely determine the occurrence of microsites. One could expect that temporal and spatial expansion of microsites is not static but varies with root life time and turnover. However, as reviewer 2 pointed to a partly speculative discussion about microsites in the former version of the manuscript, we only briefly included this aspect into the revised discussion (page 14, lines 13-14).

4. Please check Table 3, the data in the last three columns are in wrong places.

Yes, the reviewer was correct. We corrected Table 3 accordingly. The data presented in this table are part of a larger dataset that is still analyzed at the moment. During this analyses we decided to re-analyze some peat samples to improve the data quality. Thus, some values slightly changed and the data in the table were updated.

Point-by-point response to reviewer 2:

General comments

The MS of Münchberger and co-authors contributes to the knowledge on processes of methane turnover (production+oxidation) and transport in rarely studied southern bogs. Authors combined field sampling with the advanced analytics (porewater chemistry and stable isotope analyses) to report relationships and peculiar mechanisms between microrelief forms, dominating vegetation communities and the net processes affecting the CH4 efflux from the Patagonian peatland during two consecutive summer seasons. Field-based studies are critically important for understanding processes related to functioning of ecosystems and therefore interesting for the broad scientific community. Accepting the field experiments typically operate with much larger spatial and temporal variability in measured parameters (and as the result, relatively lower statistical power as compared to controlled conditions), still there are several issues which I would like to point out for the discussion and improvement. Below authors find general comments while specific recommendations and technical corrections are incorporated directly in the draft file attached.

1. First of all, the MS is rather long and too repetitive and descriptive. Thus, the Introduction is definitely too extended, especially regarding the common knowledge about methane in the very beginning and peatlands in general. Authors could immediately start the story of the importance of southern peatlands and have the necessary information on peatlands' biochemistry and vegetation specialty in there. Then the information on the isotope issue would be sufficient to formulate hypotheses without any loss of logic.

We understand your concern and appreciate your suggestions of how the topic of the manuscript could be introduced in a more straightforward way. However, the strength of our dataset is the combination of both, a comprehensive chamber measurement campaign and advanced pore water chemistry. To address our manuscript to the readers of both communities, researcher focusing on gas exchange in peatlands as well as those mainly dealing with biogeochemical processes in the peat, we decided to shortly introduce the main mechanisms of both research areas. Southern peatlands are introduced only towards the end of the introduction since the rhizosphere effects on methane dynamics due to aerenchymatic vascular plants are of relevance for other peatlands with a dense cover of vascular plants such as rushes and sedges. We believe that starting the introduction with the importance of southern peatlands would result in a too narrowed topic of the manuscript. Therefore, and as reviewer 1 did not comment on the structure and length of the introduction, we hope that reviewer 2 could agree with our positions here.

Nevertheless, we agree that in parts the introduction could be substantially shortened. Descriptive parts as well as passages dealing with common knowledge about methane in the introduction are rephrased now. We thereby reduced the number of words in the introduction by about 200 words. Please see

- *page 2: line 4, line 7, lines 10-18, line 24*
- *page 3: lines 7-9, lines 28-4 on page 4*

As we also agree that parts of the discussion were too repetitive and descriptive, we shortened the discussion by another 100 words despite the interpretation of the d13C-CH4 signal concerning methanogenic pathways required more explanation as suggested by both reviewers. We kindly refer to our answer to general comment 4 to 7 below for details on this aspect.

2. In the proposed hypotheses, it has to be clearer why pools are so much different from lawns in terms of methanogenesis pathways. This was not strait forward from the introduction; I suggest to omit statements as "remains less affected" because they are more confusing then explanatory; please, rephrase.

We added some more information, in particular that pools are only scarcely vegetated (page 3, line 12). Hypotheses II was rephrased to "pore water CH4 and DIC concentration profiles and its carbon isotopic signatures below densely-rooted Astelia lawns reflect a distinct CH4 oxidation effect contrary to sparsely- or even non-rooted peat below pools" (page 2, lines 8-9) and in hypotheses III we changed "non-rooted" to "sparsely- or even non-rooted" (page 4, lines 8-9 and lines 11-12). Furthermore, "non-rooted" was changed to "sparsely- or even non-rooted" throughout the whole text.

3. In the Methods section, I was confused with relatively short time (3 min) of chamber exposition even under the conditions of rather low atmospheric temperatures and low fluxes expected. Why also transparent and not opaque chambers were used for CH4 fluxes measurement?

Indeed, chamber measurements with a chamber not connected to a fast gas analyzer need up to 30 minutes or more to determine methane fluxes. The chamber used in our study was connected to a portable gas analyzer (Ultraportable Greenhouse Gas Analyzer, 915-001, Los Gatos Research) with a 1 hz sampling rate. The instrument accuracy according to the manufacturer was < 2 ppb. Therefore, this instrument provides the opportunity to determine concentration changes even at low CH4 concentrations and within a short period of time (see for example McEwin et al., 2015; Berger et al., 2018 or Mastepanov et al., 2013 who used a similar gas analyzer with 1 hz sampling rate). Test measurements with a prolonged closure time and instantaneous on-site monitoring of gas concentrations changes within the chamber proved that a short measurement time was sufficient to determine the CH4 fluxes also at our study site. From this, we could furthermore exclude that zero fluxes are a methodological artifact.

And indeed, despite the short measurement time and low fluxes, only 105 of 537 flux measurements showed a concentration increase with a slope not significantly different from zero (page 7, lines 12-13). During all other measurements (at least a small but) significant concentration change was observed already during the short measurement time down to absolute values of 0.01 mmol CH4 m-2 d-1 (page 9, lines 27-28).

We are also confident that low or zero fluxes were not an artifact despite the short measurement time and at low temperatures. Otherwise collars with low or zero fluxes would have shown a response to temperature. We kindly refer to figure S02 in the supplement provided to the manuscript. This figure show that most individual collars did not show any response to temperature. Please compare also to the explanation on page 7, lines 16-20.

We used transparent and opaque chambers since the Los Gatos gas analyzer can measure CH4 and CO2 simultaneously. Thus, our measurement campaign was designed to determine also the NEE. As the CH4 fluxes did not differ systematically between light and dark measurements, we included also the light measurements in our data set to increase the sample size for CH4 fluxes.

4. Discussion section contains repetitive and partly speculative information and therefore is currently too long. For instance, in the discussion of results on 13C-CH4 depth profile (page 14, lines 5-8) authors seemingly "oversell" their results: "scattered between" may also indicate no significant difference (this is not clear from the data). Indeed, Fig. 4d demonstrates rather narrow d13C-CH4 range along the whole depth profile. So, in fact, d13C-CH4 signal alone was not informative enough to approve the strong oxidative properties of rhizosphere of A. pumila. I agree that both methanogenesis and oxidation may co-exist in close vicinity, but still it may not explain lack of d13C-CH4 variation between upper and lower horizons unless CH4 produced in the rhizosphere region is even more depleted in 13C than in deeper layers. The explanation of this phenomenon because of "more reduced...microsites" is not fully clear. More than below the rhizosphere? Why?

We understand that parts of the discussion are too repetitive and partly speculative. The comparatively small shift of the mean d13C-CH4 signature to more enriched values within the rhizosphere was a surprising and unexpected result also to us, so we intended to discuss *this more thoroughly – probably going too far. Indeed, a strong effect of only methanotrophy should result in a less negative signature of d13C in CH4 compared to the signature below the rhizosphere. Therefore we completely agree with the reviewer, that the d13C-CH4 signal alone does not provide a clear indication for oxidative effects in the rhizosphere. Taking into account the near-zero CH4 emissions, high DIC:CH4 ratios and a d13C-CH4 depth pattern not following the d13C-CO2 and a depleted d13C-CO2 signal, we can nevertheless only explain these results by a strong effect of methanotrophy.*

In addition, we attempted to explain the lack of variation in the mean d13C-CH4 signal. Throughout the rhizosphere, the d13C-CH4 signal was associated with a wider standard variation of replicate samples compared to deeper peat layers. Our possible explanation for this is that the mean d13C-CH4 signal represents a mixed signal from methane production and consumption and, thus, indicates a co-existence of locally distinct aerobic and anaerobic microsites. Maybe our explanations were too detailed here and thus became speculative. In fact, the word scatter was indeed used incorrectly here to describe the wider standard variation.

As the reviewer correctly points out, the occurrence of hydrogenotrophic methanogenesis is a possible explanation for surprisingly negative d13C-CH4 signatures. Reviewer 1 suggests occurrence of acetogenesis as a further possible explanation. We agree that both pathways could explain the pattern in the d13C-CH4 signal, although we propose in accordance with reviewer 1 that hydrogenotrophic methanogenesis was probably relatively more important below pools while acetoclastic methanogenesis in combination with acetogenesis seemed to contribute more below Astelia lawns. But as we did not quantify other parameters such as labile organic matter from roots, acetate concentrations or its carbon isotopic signatures, we cannot clearly determine the relative importance of both pathways for our study. We kindly refer to our answer to general comment 5 below for more details.

In the revised discussion, we replaced “scatter”/”scattering” by “range”/”ranging”/”variation” (page 11, line 27; page 14, line 5 and 11). By merging paragraphs in section 4.2 (please see the “specific comments section, comment 3 on page 14), repetitive and speculative information in the discussion were reduced. We mention that the lack of d13C-CH4 variation between upper and lower horizons resulting in a comparatively negative δ13C-CH4 signature throughout the rhizosphere is an unexpected result (page 14, lines 6-8, and lines 34-2 on page 15). We discuss now which processes may have resulted in such 13C-CH4 signatures (page 14, lines 16-22) and tried to balance the suggestions of both reviewers by discussing the arguments for both, hydrogenotrophic and acetoclastic methanogenesis and acetogenesis, carefully (page 15, lines 2-9). The misleading statement “more reduced... microsites” was removed.

5. Contribution of acetoclastic pathway to methanogenesis in the rhizosphere of A. pumila was not convincingly verified (e.g. page 14, lines 23-27) and looks therefore speculative: having acetoclastic methanogenesis and co-existence of oxidation should generate much more enriched d13C-CH4 values in comparison to deep peat. Fig. 4d cannot support this. Seemingly, change of fractionation factor with depth was not significant either. The available data are not enough to approve existence of acetoclastic methanogenesis, and this has to be acknowledged.

We agree with the reviewer, that a clear effect of methanotrophy and acetoclastic methanogenesis on the d13C-CH4 signature should result in an enriched d13C-CH4 signal and a distinctly lower fractionation factor throughout the rhizosphere compared to deeper peat layers. We were thus surprised by the small (and probably not statistically significant) change in the fractionation factor. Thus, we attempt to explain a fractionation factor in the overlap range of ac from hydrogenotrophic and acetoclastic methanogenesis.

As already observed for the d13C-CH4 signal, also the fractionation factor shows a wider standard variation of replicate samples within the rhizosphere. The standard variation of the fractionation factor even tended to be larger with increasing depth down to the lower boundary of the rhizosphere. This pattern comes along with a presumably with depth decreasing root density (Fritz et al., 2011) in these depths. We therefore interpret this as a further indication for the occurrence of microsites as lower root density makes a more *heterogeneous peat matrix more likely and thus a higher variation in the fractionation factor between sampling sites.*

We agree with the specific recommendation on page 15, comment 1 that occurrence of hydrogenotrophic methanogenesis at elevated H2 levels in surface peat layers might be a possible source for depleted 13C and an explanation for only small changes and a comparatively higher standard variation in the fractionation factor. Another reasonable explanation is the occurrence of acetogenesis, as suggested by reviewer 1.

We underline in the revised discussion that only small changes in the fractionation factor between upper and lower horizons are an unexpected result if methanotrophic effects are assumed (page 14, line 4). We explain possible sources for depleted 13C-CH4 within the rhizosphere and discuss the possibility of the occurrence of acetogenesis now (page 15, lines 2). The difficulties to separate the isotopic effects arising from methanogenic pathways are mentioned (page 14, line 18 and page 15, lines 3-5). As we did not quantify other parameters such as labile organic matter from roots, acetate concentrations or its carbon isotopic signatures, the possibility of both, hydrogenotrophic and acetoclastic methanogenesis is discussed (page 15, lines 5-11).

6. Another critical point is again a speculative discussion of the results on pools and lateral flows on the site (page 15, lines 23-35). Explanations on gas diffusion along gradient were clear for me (from pools to lawns) but water movement is not the same. Pools are local depressions, so water should flow from lawns into pools. If this flow is so low, then the gas diffusion in opposite direction can be stronger, but this means almost standing water. In case there is a lateral flow of water (what is very natural), then the gas flow can’t be counter to it. Therefore, I could understand the inflow of oxygen from lawns into pools, but not CH4 from pools to lawns. The overall picture may change if there is a slope, but then lawns and pools have to be arranged accordingly. Pools will get matter of those lawns which are exposed higher and transfer it downwards to other lawns. If there is a slope on the site, then the conceptual figure should somehow reflect it. Such important information was not provided in Mat&Meth or any other parts of MS.

We thank the reviewer for this careful and critical examination of our concept. We attempted to explain low CH4 concentrations in the pore water below pools, as the isotopic signals below pools did not indicate a methanotrophic effect. Upward diffusion of CH4 against the concentration gradient is not possible and CH4 emissions were low, so we can only explain this by lateral exchange of CH4.

Indeed, pools are local depressions in the micro-relief, and we therefore agree that water should flow from lawns into pools. Nevertheless, the micro-relief is not very pronounced at our study site with Astelia lawns being elevated by only about 5-20 cm above the water table and the pool surface. This is indicated in the conceptual figure. We therefore assume, that the micro-relief does not exert much impact on the water flow in deeper peat layers and water flow from lawns to pools should be restricted to the uppermost decimeters of the peat profile. In contrast, the rhizosphere stretches over almost 2 m within highly decomposed peat. So we propose that there is a large zone with negligible water flow throughout the rhizosphere. Due to low water movement, diffusive transport dominates and both, CH4 transport from pools to lawns and O2 transport from lawns to pools could be reasonable.

Some information about the flat micro-relief is now included in the site description (page 4, line 27). We specify in the revised discussion that CH4 may be transported by diffusion and that the micro-relief is not pronounced (page 15, lines 29-32). Furthermore, repetitive explanations in section 4.3 were shortened by about 60 words.

7. The section 4.4. is rather long and at several places contains repetitive text (e.g. page 17, lines 15-17, 21-23, 27-28; the effect of A. pumila roots was very clear, no need to repeat many times). I recommend condensing text strongly.

We understand that the interpretation of the observed emission pattern is repetitive concerning biogeochemical processes in the peat. We carefully shortened repetitive explanations in paragraph 4.4., starting in line 12 on page 17 by 150 words.

8. Depending on the available information from authors, the conceptual Fig. 6 can be changed (see more detailed comments in the text).

We kindly refer to our answer to general comment 6.

Specific recommendations and technical corrections incorporated in the draft file of the manuscript

Page 1

- Comment 1, line 25: How was this tested? If so, how far from root surface the "suppressive effect" is possible?

This was not tested and, thus, this conclusion was removed here.

- Comment 2, lines 30-32: Please, rephrase the sentence in a more simplistic way. Too difficult to read and understand.

Was rephrased.

Page 2

- Comment 1, lines 6-7: Please, check whether this value is still relevant. There is no recent reference cited.

References were checked, but no recent reference was found splitting CH4 emissions from wetlands into sources from different types of wetlands explicitly mentioning peatlands. Instead, even very recent publications like Rinne et al. (2018) still cite Aselmann and Crutzen (1989) as a reference for CH4 emissions from a specific type of wetland. Furthermore and for example, Dlugokencky et al. (2011) cite Bousquet et al. (2006) who give an estimate of 30% of wetlands contributing to global CH4 emissions (in agreement with Kirschke et al, 2013) of which bogs and tundra make up 9% and swamps 21%. To conclude, we believe the estimate given here is still reasonable and there is – to the best of our knowledge - no recent reference for the contribution of peatlands to global annual CH4 emissions.

- Comment 2, line 7: 28-fold

This technical correction was changed accordingly.

- Comment 3, lines 10-12: What about low temperatures? I am not sure bogs do exist in tropics (excluding mountain regions).

Some information about the importance of temperature was added.

- Comment 4, line 17: This is not clear: is this prerequisite for the oxidation? Not trapped=not oxidized? If so, how exactly could CH4 be trapped and how does CH4 oxidation occur in e.g. rice paddies?

The sentence was rephrased.

- Comment 5, line 30: (delta 13C)

Was added.

- Comment 6, line 32: Actually, values could go even to positive range.

The range was changed to “-25 to +10‰”.

Page 4

- Comment 1, line 17: Not clear. Do authors mean, reflect the signal of methanogenesis type? Please, rephrase.

The hypothesis was changed. Please refer to the “general comments” section, comment 2.

- Comment 2, lines 19-20: How is this known? From the introduction above, it is not clear the pools are without (vasular) vegetation. Northern pools often contain aerenchimatous plants of different species compared to lawns and hummocks, or at least Sphagnum. Please, clarify above.

This comment was already answered above in the “general comments” section, comment 2.

- Comment 3, line 23: I find the Introduction a bit too extended, especially regarding the common knowledge about methane in the very beginning and peatlands in general. Authors could immediately start the story of the importance of southern peatlands and have the necessary information on peatlands' biochemistry and vegetation specialty in there. Then the information on the isotope issue would be sufficient to formulate hypotheses without any loss of logic.

This comment was already answered above in the "general comments" section, comment 1.

Page 5

- Comment 1, line 4: Not any more? Should it be in Present Tense as the previous sentence?

The tense was corrected in the description of the study site.

- Comment 2, line 5: Does this mean pools were nevertheless vegetated? If so, which species dominated? What was the bottom of such pools?

The vegetation in the pools is described in more detail now.

- Comment 3, line 6:

The tense was corrected in the description of the study site.

- Comment 4, line 7: Liter of what, peat? For peat, could you provide other volumetric dimensions, e.g. dm-3?

The dry weight is given as liter of peat soil and this information was added. The volumetric dimension was not changed in order to stick to the units given in the cited reference.

Page 7

- Comment 1, line 16: This could be too short time for CH4 flux measurement especially if outside temperatures were relatively low. How was it determined? Could zero fluxes be the reason of short exposure time?

This comment was already answered above in the "general comments" section, comment 3.

Page 8

- Comment 1, line 4: was

"Was" was added and the sentence split into two parts to improve readability.

- Comment 2, line 24: How? What was the volume of the sample? 3 ml? For such small volumes a separate device (Small volume unit) is necessary. Please, expalin.

Yes, the reviewer is correct. The missing information in the description of the device and measurement routine was added (page 8, lines 19-20).

- Comment 3, line 30: Confusing: organic or inorganic? Please correct.

Was changed to "dissolved inorganic carbon".

Page 9

- Comment 1, line 22: Again, liter is not clear for peat as volume containing roots.

"Liter of peat" was added.

- Comment 2, line 23: Please, provide here a value with the reference to study (studies). This will help better compare the differences between plant species.

This information was added.

Page 10

- Comment 1, line 1:

Was changed accordingly.

- Comment 2, line 1: This is confusing: zero flux is not detectable (otherwise it is a positive or negative). Please, rephrase. I am still wondering if outside air temperature is -0.5 C, how could 3 min be enough to measure any CH4 flux.

We rephrased this phrase explaining that despite near-zero fluxes we were still able to detect these low magnitude fluxes. Nevertheless, below a certain range, fluxes were set to zero as they did not differ significantly from zero (page 9, lines 27-28). Concerning a short *measurement time at low temperature, we refer to our answer to comment 3 in the "general comments" section.*

Page 11

- Comment 1, lines 26-27: There was no rhizosphere below pools, so what then caused the gradient?

The upward diffusion from deep peat below pools was caused by low pore water CH4 concentrations in upper peat layers below pools. Here, we changed "within the rhizosphere" to "throughout the rhizosphere of Astelia lawns and in corresponding depths below pools". We attempt to explain low pore water CH4 concentrations below pools by lateral transport of CH4 from pools to lawns (see section 4.3 in the discussion).

- Comment 2, line 28: Suggest to rephrase: Carbon isotopic values in pore water and apparent fractionation.

The section title was rephrased.

Page 12

- Comment 1, line 7: fractionation

This technical correction was changed accordingly.

- Comment 2, line 22: with?

We added "in" here.

Page 13

- Comment 1, lines 30-31: Please, check the definitions: typically, "alternative" means alternative to oxygen. So, oxygen cannot be alternative to itself.

This phrase was changed accordingly.

Page 14

- Comment 1, lines 6-7: With this, authors attempt to oversell their results: "scattered between" seemingly indicate no significant difference. Indeed, Fig. 4d demonstrate rather narrow d13C-CH4 range along the whole depth profile. So, in fact, d13C-CH4 signal alone was not informative enough to approve the strong oxidative properties of rhizosphere of A. pumila. I agree that both methanogenesis and oxidation may co-exist in close vicinity, but still it may not explain lack of d13C-CH4 variation between upper and lower horizons unless CH4 produced in the rhizosphere region is even more depleted in 13C than in deeper layers. The explanation of this phenomenon because of "more reduced...microsites" is not fully clear. More than below the rhizosphere? Why?

This comment was already answered above in the "general comments" section, comment 4.

- Comment 2, line 17: According to this oxidation concept, the most 13C enriched CH4 has to be allocated at the shallowest depth. However, in contrast, it is ca. 10‰ more depleted than next depth levels (20-50 cm). In addition, d13C-CO2 is relatively more enriched that in deeper layers. How is this possible?

We inspected again our dataset to explain this. During a measurement, the isotopic signal of each sample is determined repetitively. So in fact, the signal determined from one sample is a mean of many measurements. To further improve the data quality, we excluded the isotopic signal of one sample with an elevated SD. This results now in a less enriched mean of d13C-CO2 and a slightly lower ac value in the uppermost peat layer. Figure 4e and 4f were corrected accordingly.

The sampling devices were installed below the water table, but only mean of water table is given in the figures. Thus, the line denoting the water table in the figures was not exactly at the correct position. This line was slightly shifted and figures 4 and 5 updated accordingly. So, in the uppermost depth not much influence from roots can be expected. Accordingly, the CH4 was not enriched due to methanotrophic effects, but comparatively depleted by methanogenesis (please compare to answers to comment 4 and 5 in the general comment section).

- Comment 3, lines 17-22: This information is already repetition of the message above. I suggest to merge both parts telling the story as here but with the reference to results as in the previous paragraph. Otherwise, it is excessive.

We followed the helpful suggestion of the reviewer and merged both paragraphs.

- Comment 4, lines 23-26: This contradicts to the data measured: having acetoclastic methanogenesis and co-existence of oxidation should generate much more enriched d13C-CH4 values in comparison to deep peat. Fig. 4d cannot support this. Seemingly, change of fractionation factor with depth was not significant either. The available data are not enough to approve existence of acetoclastic methaogenesis. Please, discuss this

This comment was already answered in the “general comments” section, comment 4 and 5.

- Comment 5, lines 27-28: Again, there is not enough evidence to support the hypothesis. As it is stated, this is speculation and should be rephrased.

We changed “supports” to “would support” and kindly refer to our answer to general comment 5 in the “general comments” section.

- Comment 6, lines 29-30: Yes, but it was small below the rhizosphere too! Speculation!

This comment was already answered in the “general comments” section, comment 4 and 5.

- Comment 7, line 32: They also increased at the very top of profile. No information about significance of differences in fractionation factor between depths is provided.

This comment was already answered in the “general comments” section, comment 5.

Page 15

- Comment 1, line 6: This may also mean occurrence of hydrogenotrophic methanogenesis in anaerobic rhizosphere zones. For example, Galand et al. (2002) FEMS, demonstrated dominance of H2-trophic methanogens in upper peat layer in a boreal northern peatland. Is there any evidence for southern peatlands too? This may partly explain relatively depleted d13C values of CH4 in the rhizosphere zone.

We included this explanation and kindly refer to our answer to general comment 4 and 5 in the “general comments” section for more details.

- Comment 2, lines 17-18: This can be misleading: 2nd hypothesis specified processes based on isotopic values, whereas here authors refer more to the concentrations/fluxes thereby considering rather 1st hypothesis. The latter, however was not supported. Please, rephrase. Also regarding the 2nd hypothesis, "less affected" is not appropriate for the hypothesis. Please, check the respective comment above.

This was clarified and the discussion concerning pools better linked to the hypotheses.

- Comment 3, lines 19-21: This is not clear: How could roots of A. pumila appear under pools? Was this observed during coring? If so, then the conceptual diagram should demonstrate that roots of A. pumila expand below pools. Check and correct accordingly.

It is possible, but we do not know whether the roots appear under pools. Therefore we did not include this in the conceptual figure. We clarified that roots control CH4 dynamics below pools only by releasing O2 that is used to consume CH4 thereby maintaining concentration gradients. Please refer to the “general comments” section, comment 6 for further details.

- Comment 4, line 22: Of what, CH4 or oxygen?

Of CH4, this is specified now. Please refer to the “general comments” section, comment 6 for details.

- Comment 5, lines 23-26: This statement is unclear: whereas gas diffusion along gradient is clear for me (from pools to lawns) water movement is not the same. Pools are local depressions, so water should flow from lawns into pools. If this flow is so low, then the gas diffusion in opposite direction can be stronger, but this means almost standing water. In case there is a lateral flow of water (what is very natural), then the gas flow can't be counter to it. Therefore, I could understand the inflow of oxygen from lawns into pools, but not CH4 from pools to lawns. The overall picture may change if there is a slope, but then lawns and pools have to be arranged accordingly. Pools will get matter of those lawns which are elevated and transfer it downwards to other lawns.

If there is a slope on the site, then the conceptual figure should somehow reflect it. Check!

This comment was already answered above in the "general comments" section, comment 6.

- Comment 6, lines 28-30: What is meant, suppression of methanogenesis or CH4 oxidation? This is important in context of measured isotope values. Please, specify.

We did not check know whether the roots appear under pools, but it would be reasonable. Therefore, here suppression of methanogenesis is meant as an explanation for low CH4 concentrations in pools. This is specified in the revised discussion. Please refer to the "general comments" section, comment 6 for further details.

Page 16

- Comment 1, lines 8-9: This is not fully clear: the limiting factor for hydrogenotrophic methanogenesis is typically H2 which is very reactive, since C source is CO2. H2 was sufficient, CO2 concentrations were also available, so why was then H2-reduction methanogenesis although dominating (depleted d13C-CH4) but not intensive? Maybe other anaerobic processes (sulfate reduction) outcompeted methanogenesis?

We changed the sentences stating that despite H2 concentrations and DIC:CH4 ratios suggest methanogenic conditions, CH4 production seemed to be limited below pools even at peaking H2 levels. Very negative d13C values suggest that methanogenesis was thermodynamically unfavorable. We included that methanogenesis might instead have been outcompeted by other electron accepting processes, such as sulfate reduction as suggested by the reviewer. Peaking H2 concentrations indicate that fermentation processes were active, but suggest that methane was produced only very locally if at all. Please refer to page 16, lines 10-16.

Page 17

- Comment 1: The section 4.4. is rather long and at several places contains repetitive text (e.g. page 17, lines 15-17, 21-23, 27-28; the effect of A. pumila roots was very clear, no need to repeat many times). I recommend condensing text strongly.

This comment was already answered above in the "general comments" section, comment 7.

Page 26

- Comment 1, lines 4-5:
- Comment 2, line 5: On the figure (f), platform 3 instead platform 2 is denoted. Check!

Was changed to platform a and b as actually in the field, we determined water table fluctuations at platform 1 and platform 3 constructed for chamber measurements.

Page 30

- Comment 1: It was discussed a lot about lateral flows, which how, are not reflected in this conceptual diagram. It is also not clear if the site has elevation/slope property. In such a case, please demonstrate the respective relationships.

This comment was already answered above in the "general comments" section, comment 6.

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List of most relevant changes made in the manuscript

- Descriptive parts as well as passages dealing with common knowledge about methane in the introduction are rephrased now (page 2: line 4, line 7, lines 10-18, line 24; page 3: lines 7-9, lines 28-4 on page 4).
- Hypotheses II was rephrased (page 2, lines 8-9).
- In the revised discussion we
  - Point to the surprising pattern of d13C-CH4 signature and the difficulties to separate the isotopic effects arising from methanogenic pathways (page 14, lines 2-8, line 18 and page 15, lines 3-5).
  - Tried to balance the suggestions of both reviewers by discussing the arguments for both, hydrogenotrophic and acetoclastic methanogenesis and acetogenesis, carefully (page 14, lines 18-20; page 15, lines 2-11).
  - We specify our concept about lateral exchange of CH4 throughout the upper 2 m of peat (page 15, lines 29-32).
  - Reduced repetitive, descriptive and speculative information in paragraph 4.2, 4.3, 4.4 by altogether about 200 words.
- We corrected the data in Table 3.

Zero to moderate methane emissions in a densely rooted, pristine Patagonian bog - biogeochemical controls as revealed from isotopic evidence

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Abstract. Peatlands are significant global methane (CH_4) sources, but processes governing CH_4 dynamics have been predominantly studied on the northern hemisphere. Southern hemispheric and tropical bogs can be dominated by cushion-forming vascular plants (e.g. *Astelia pumila*, *Donatia fascicularis*). These cushion bogs are found in many (mostly southern) parts of the world but could also serve as extreme examples for densely rooted northern hemispheric bogs dominated by rushes and sedges. We report highly variable summer CH_4 emissions from different microforms in a Patagonian cushion bog as determined by chamber measurements. Driving biogeochemical processes were identified from pore water profiles and carbon isotopic signatures. An intensive root activity throughout a rhizosphere stretching over 2 m depth accompanied by molecular oxygen release created aerobic microsites in water-saturated peat leading to a thorough CH_4 oxidation (< 0.003 mmol L^{-1} pore water CH_4, enriched $\delta^{13}C\text{-}CH_4$ by up to 10‰) and negligible emissions (0.09 ± 0.16 mmol CH_4 m^{-2} d^{-1}) from *Astelia* lawns. In sparsely or even non-rooted peat below adjacent pools similar pore water profile patterns as obtained under *Astelia* lawns were found which emitted very few amounts of CH_4 (0.23 ± 0.25 mmol m^{-2} d^{-1}). Below the *A. pumila* rhizosphere pore water concentrations increased sharply to 0.40 ± 0.25 mmol CH_4 L^{-1} and CH_4 was predominantly produced by hydrogenotrophic methanogenesis. Few *Sphagnum* lawns and – surprisingly – one lawn dominated by cushion-forming *D. fascicularis* were found to be local CH_4 emission hot spots with up to 1.52 ± 1.10 mmol CH_4 m^{-2} d^{-1} presumably as root density and molecular oxygen release dropped below a certain threshold. The spatial distribution of root characteristics supposedly causing such pronounced CH_4 emission pattern was evaluated on a conceptual level aiming to exemplify scenarios in densely rooted bogs. We conclude that presence of cushion vegetation as a proxy for negligible CH_4 emissions from cushion bogs needs to be

interpreted with caution. Nevertheless, overall ecosystem CH_4 emissions at our study site were probably minute compared to bog ecosystems worldwide and widely decoupled from environmental controls due intensive root activity of e.g. *A. pumila*.

1 Introduction

Peatland ecosystems are significant natural methane (CH_4) sources on the global scale responsible for about 10% of global annual CH4 emissions (Aselmann and Crutzen, 1989; Mikaloff Fletcher et al., 2004). CH_4 has a 28-fold higher global warming potential over a 100-year time horizon compared to carbon dioxide (CO_2) (IPCC, 2014) and, thus, processes governing CH_4 dynamics in peatlands receive much attention to estimate global greenhouse gas emissions.

The slowdown of decomposition and accumulation of C in rainwater-fed peatlands (bogs) results from e.g. a high water table, anoxic conditions, recalcitrant peat forming litter, low temperatures, inactivation of oxidative enzymes and an accumulation of decomposition end-products (Beer and Blodau, 2007; Limpens et al., 2008; Bonaiuti et al., 2017). Once methanogenic conditions are established, CH_4 production is mainly controlled by substrate supply of labile organic matter (Hornibrook et al., 1997; Whalen, 2005). Then, slow diffusive transport along the concentration gradient from deep anoxic peat layers to the atmosphere leads to CH_4 release. In upper, unsaturated and oxic peat zones that typically extent only about few decimetres (Whalen, 2005; Limpens et al., 2008), CH_4 might get consumed by methanotrophic microbes (Chasar et al., 2000; Whalen, 2005; Berger et al., 2018). Consequently, water table position and fluctuations strongly control the amount of emitted CH_4 (Blodau and Moore, 2003; Whalen, 2005). While CH_4 oxidation suppresses CH_4 emissions in diffusion dominated systems, ebullition by fast release of gas bubbles or plant-mediated transport by aerenchymatic roots can substantially increase CH_4 emissions (Fechner-Levy and Hemond, 1996; Joabsson et al., 1999 and references therein; Chasar et al., 2000; Colmer, 2003; Whalen, 2005; Knoblauch et al., 2015; Burger et al., 2016; Berger et al., 2018). With a high share of ebullitive fluxes, vegetated or open water pools in peatlands are considered as strong CH_4 emitters (Hamilton et al., 1994; Blodau 2002; Burger et al., 2016) that have, however, received less attention than the vegetated surfaces (Pelletier et al., 2014). Pools can even turn the peatlands' C balance into a source (Pelletier et al., 2014), but examples of low emission pools have been also reported (Knoblauch et al., 2015).

Carbon isotopic signatures ($\delta^{13}C$) are a valuable tool for identifying mechanisms and pathways of CH_4 dynamics. Carbon isotopic signatures in pore water of northern hemispheric bogs (hereafter termed northern bogs) vary typically between -80 to -50‰ and -25 to +10‰ for CH_4 and CO_2, respectively (e.g. Whiticar et al., 1986; Hornibrook et al., 1997; Chasar et al., 2000; Hornibrook et al., 2000; Beer et al., 2008; Steinmann et al., 2008; Corbett et al., 2013). Depending on the available substrate for methanogenesis, it was mostly observed that either the acetoclastic or hydrogenotrophic pathway predominates, resulting in distinctive carbon isotope signatures of CH_4 (acetate fermentation $\delta^{13}C$-CH_4 ~ -65 to -50‰, CO_2 reduction $\delta^{13}C$-CH_4 ~ -110 to -60‰) (Whiticar et al., 1986). Methane is prevailingly produced by acetoclastic methanogenesis when fresh, labile organic matter is available whereas the production pathway shifts towards hydrogenotrophic methanogenesis when organic matter becomes increasingly recalcitrant (Hornibrook et al., 1997; Popp et al., 1999; Chasar et al., 2000; Conrad, 2005). A predominance of the latter pathway is indicated by strong fractionation between $^{12}C/^{13}C$ resulting in relatively depleted $\delta^{13}C$-

CH_4 corresponding to a fractionation factor α_c between 1.055 and 1.090 (Whiticar et al., 1986) and a $\delta^{13}C$-CH_4 isotopic signature following that of $\delta^{13}C$-CO_2 (Hornibrook et al., 2000). Subsequent methanotrophy alters the isotopic signature of CH_4 by discriminating against ^{13}C and the residual CH_4 remains enriched while produced CO_2 becomes depleted in ^{13}C (Chasar et al., 2000; Popp et al., 1999). As both, acetoclastic methanogenesis and methanotrophy, result in a $\delta^{13}C$-CH_4 signature enriched in ^{13}C and a small apparent fractionation factor (Whiticar et al., 1986; Conrad, 2005), the acetoclastic pathway cannot be clearly separated from methanotrophic conditions based on carbon isotopes only (Conrad, 2005).

The majority of studies elucidating CH_4 dynamics in peatlands have been conducted on the northern hemisphere (e.g. Blodau, 2002; Limpens et al., 2008; Yu, 2012 and references in these), whereas only little research deals with CH_4 dynamics in bogs on the southern hemisphere (hereafter termed southern bogs) (Broder et al., 2015). Contrary to northern bogs, southern bogs are not only vegetated by *Sphagnum* mosses, dwarf shrubs or few graminoids such as the rush-like species *Tetroncium magellanicum*, but also by vascular plants (Kleinebecker et al., 2007) that can densely root upper peat layers (Fritz et al., 2011; Knorr et al., 2015). Another feature that can be found in both systems are pools with sparse or no vegetation (Fritz et al., 2011; González Garraza et al., 2018). The vascular plants, for instance of the genus *Astelia* (Asteliaceae), *Donatia* (Stylidiaceae) or *Oreobolus* (Cyperaceae), independently developed a cushion life form to protect from harsh climate in cold environments (Gibson and Kirkpatrick, 1985; Boucher et al., 2016). Bogs dominated by cushion-forming vascular plants (hereafter termed cushion bogs) can be found in many (mostly southern) parts of the world, for instance all along the high Andes (Coombes and Ramsay, 2001; Benavides et al., 2013; Fonkén, 2014) down to southernmost Patagonia (Ruthsatz and Villagran, 1991; Heusser, 1995; Kleinebecker et al., 2007; Grootjans et al., 2014), in highlands of eastern Africa (Dullo et al., 2017) as well as in New Guinea (Hope, 2014), New Zealand and Tasmania (Gibson and Kirkpatrick, 1985; Ruthsatz and Villagran, 1991) and some sub-Antarctic islands (Ruthsatz and Villagran, 1991). These cushion bogs could also be regarded as extreme examples for densely rooted northern bogs that are dominated by rushes and sedges.

To our knowledge, only two studies reported CH_4 emissions from southern vascular-plant dominated bogs with quite inconsistent results. Over a New Zealand bog dominated by the evergreen "wire rush" *Empodisma robustum*, CH_4 emissions exceeded those commonly reported from northern bogs (Goodrich et al., 2015), while emissions from a Patagonian cushion bog dominated by *Astelia pumila* were negligible (Fritz et al., 2011). Both, high and negligible CH_4 emissions, were mainly explained by the extensive aerenchymous roots of the prevailing plant species: The aerenchyma might function as a conduit for CH_4 from deep peat layers to the atmosphere in the first case, whereas in the second case pronounced O_2 supply by roots might have resulted in a thorough oxidation of pore water CH_4 and enhanced organic matter decomposition. However, Fritz et al. (2011) were the first to investigate CH_4 dynamics below *Astelia* lawns and determined emissions only sporadically without considering all predominant microforms and plant communities. Thus, general conclusions about CH_4 emissions from this type of ecosystem are so far restricted. Furthermore, more knowledge on biogeochemical processes throughout the peat column of *Astelia* lawns as a model plant for cushion-forming, aerenchymous plants and in other microforms is needed to extent our limited understanding of these first insights into CH_4 dynamics in cushion bogs. Despite the variety of bogs dominated by densely rooted, aerenchymous plants on the northern and southern hemisphere, there is some evidence from latest research that very low CH_4 pore water concentrations could be a more common phenomenon in those ecosystems (Dullo et al., 2017; Agethen et al., 2018; Knorr et al., 2015). In general, promotion or suppression of CH_4 production should be determined by the ratio of root density and activity associated with O_2 release versus presence of labile root organic matter or exudates accompanied with O_2 consumption (Blodau, 2002; Agethen et al., 2018).

Here, we quantified austral summer CH_4 emissions from dominant microforms in a Patagonian cushion bog and examined possible environmental and biogeochemical controls. We hypothesized that (I) emissions from cushion plant vegetation dominated by *Astelia pumila* or *Donatia fascicularis* are negligible while pools and *Sphagnum* lawns emit CH_4 in considerable amounts, and that (II) pore water CH_4 and DIC concentration profiles and its carbon isotopic signatures below densely-rooted *Astelia* lawns reflect a distinct CH_4 oxidation effect contrary to sparsely- or even non-rooted peat below pools, and that (III) besides by methanotrophy, isotopic composition of pore water CH_4 could also be affected by a predominance of acetoclastic methanogenesis throughout the rhizosphere of *Astelia* lawns shifting towards CO_2 reduction with peat depth and in sparsely- or even non-rooted peat below pools. Biogeochemical controls of CH_4 emissions from *Sphagnum* lawns were not subject of this study, as they have been intensively studied in northern bogs (e.g. Hornibrook et al., 1997; Beer and Blodau, 2007; Steinmann et al., 2008; Corbett et al., 2013) and even southern bogs with mixed vegetation in absence of notable cushion plant coverage (Broder et al., 2015).

2 Material and Methods

2.1 Description of the study site

The study was conducted at a cushion bog on the Peninsula Mitre in southernmost Patagonia, Tierra del Fuego (Moat, 54°58'S, 66°44'W, Fig. 1). Peatlands of the Peninsula Mitre provide the nowadays rare opportunity to study carbon dynamics under pristine conditions as they can be considered as largely undisturbed by human activities such as drainage, agriculture or elevated atmospheric nitrogen deposition (Kleinebecker et al., 2008; Fritz et al., 2011; Grootjans et al., 2014; Paredes et al., 2014). About 45% of this area are covered by peatlands (Iturraspe, 2012) while little is known about these ecosystems because of their poor accessibility (Iturraspe, 2012). The study site at Moat belongs to a complex system of sloping mires, blanket bogs, fens and – in coastal areas - cushion bogs (Iturraspe, 2012; Borromei et al., 2014). The studied cushion bog is located in exposed proximity to the Beagle channel with harsh winds (Grootjans et al., 2014) resulting in an oceanic climate with average daily temperatures of 6°C and annual precipitation of 500 mm (Fritz, 2012).

Large areas of the cushion bogs in Moat are characterized by a comparatively flat micro-relief and covered by the cushion-forming plants *Astelia pumila* and *Donatia fascicularis*. The vegetation of the studied bog is composed of a mosaic of different plant communities characterized by specific plant species with lawns of *A. pumila* being the prevailing microform. *Sphagnum magellanicum* or *D. fascicularis* grow in small lawns (patches of few square meters) at pool margins where *S. magellanicum* supposedly benefits from protection against desiccation. *Tetroncium magellanicum*, a rush-like herb that does not form cushions but presumably establishes aerenchymous roots as it tolerates inundation (von Mehring, 2013), is associated predominantly with *Sphagnum* lawns but also with *Astelia* and *Donatia* lawns or sporadically inhabits pools. These sparsely vegetated pools of different size (< 0.5 m² - ~10 m²) and ~0.5 m depth are embedded in *Astelia* lawns. Pool sediments are inhabited by cyanobacteria (Arsenault et al., 2018; González Garraza et al., 2018) and submerged *Sphagnum* mosses such as *Sphagnum cuspidatum* (Kleinebecker et al., 2007; Kip et al., 2012). Peat formation started ~11000 years ago (Borromei et al., 2014), and previously, the bog was dominated by *S. magellanicum* while *A. pumila* invaded the area around 2600 years before present as determined by pollen analyses (Heusser, 1995). The peat below *Astelia* lawns is densely rooted with on the average 2.15 g DW L of peat^{-1} down to 1.7 m (Fritz et al., 2011). Mean root lifetimes of *A. pumila* has been estimated to be ~3-4 years indicating a high root turnover (Knorr et al., 2015).

2.2 Sampling and analysis of solid peat and root biomass

Peat coring in *Astelia* and *Sphagnum* lawns (data not shown) was done using a Russian peat corer (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) down to a maximum depth of 7.5 m in *Astelia* lawns. Roots of *A. pumila* in *Astelia* lawn cores were sorted out and treated separately. The density of *D. fascicularis* root biomass was determined by cutting three 0.1 x 0.1 m sods down to a depth of 0.4 m. Peat and root biomass samples were oven dried at 70°C until constant weight to calculate peat bulk density and porosity as well as *D. fascicularis* root density. Total C and N contents together with abundance of ^{15}N and ^{13}C in the solid peat were determined using an elemental analyser (EA 3000, EuroVector, Redavalle, Italy) connected to an isotope ratio mass spectrometer (IRMS, NU instruments, Wrexham, UK).

2.3 Environmental variables

Environmental variables were determined during two measurement campaigns in 2015 and 2016 at half-hourly intervals. Photosynthetic active radiation (PAR, HOBO S-LIA-M003, Onset, USA, up to 2500 µmol m^{-2} s^{-1}) and air temperature (HOBO S-TMB-M0x, Onset, USA) were recorded by a weather station (HOBO U30 NRC, Onset, USA) in both years during austral summer months. Water table fluctuations at two replicate sites in *Astelia* lawns (Levelogger Edge 3001 and Barologger Edge, Solinst, Canada; both installed in perforated PVC tubes) and soil temperature in four depths of 0.05, 0.1, 0.3 and 0.5 m (HOBO TMCx-HD and HOBO U-12-008, Onset, USA) were measured continuously.

2.4 Chamber measurements and analyses of soil-atmosphere CH_4 fluxes

2.4.1 Field measurements

The closed chamber technique was used to determine CH_4 fluxes during two measurement campaigns in austral summer from December 2014 to March 2015 and in February and March 2016. One week prior to measurements, PVC collars with a height of 0.2 m were permanently installed ~0.15 m into the peat of the dominant microforms characterized by a specific plant species and a particular plant community (*Astelia* lawns: 2015 N = 3, 2016 N = 5; *Sphagnum* lawns: 2015 N = 3, 2016 N = 5; *Donatia* lawns: 2016 N = 3). The exact installation depth and the micro-relief of the surface within each collar was determined repeatedly to calculate the exact headspace volume for CH_4 flux estimation. The collars were equally arranged around three wooden platforms constructed in January 2014 to minimize disturbance during measurements and distributed over the study site to account for spatial variability. Different numbers of replicates between the two campaigns and the different microforms are the result of logistical constraints.

A cylindrical, transparent chamber with a basal area of 0.13 m^2 and a height of 0.4 m was used for soil-atmosphere flux measurements. The chamber was equipped with a fan to ensure mixing of the headspace air, a PAR sensor (HOBO S-LIA-M003, Onset, USA) and a temperature sensor (HOBO S-TMB-M0x, Onset, USA). A second temperature sensor recorded ambient temperature (HOBO S-TMB-M0x, Onset, USA) and all sensor data were logged in 1s-intervals to a data logger (HOBO U30 NRC, Onset, USA). This set-up allowed us to control air temperature inside the chamber within approximately 3°C deviation of the ambient air temperature. If necessary, ice packs were installed inside the chamber to avoid temperature increase. Due to strong wind conditions we decided against the installation of a vent tube. An opening in the top of the chamber avoided overpressure during chamber placement. This opening was closed immediately after the chamber was gently placed on a collar for at least 3 minutes to conduct measurements. Collars were equipped with a water-filled rim to ensure a gas-tight seal between chamber and collar during measurements. Pool fluxes were performed with a floating chamber of identical dimension and design on four pools located at each platform. The chamber wall extended approximately 0.04 m into the water during measurements.

All measurements were performed under a broad range of irradiance between 7:00 am to 22:00 pm (local time) to determine diurnal variations in CH_4 fluxes. At least once during each sampling period of two to three consecutive days, all selected microforms and pools were measured under dark conditions. Opaque, reflective material was used to cover the chamber for dark conditions. Measurements were taken every two weeks during the first campaign in 2015 (N = 405 measurements) and during two occasions in 2016 (N = 132 measurements). A more regular measurement routine throughout the whole season was constrained by harsh weather conditions and the remoteness of our study site.

The chamber was connected by a 2 mm inner diameter polyethylene tubing to a gas analyser (Los Gatos Ultraportable Greenhouse Gas Analyser 915-001, Los Gatos Research) to record the increase of CH_4 concentrations over time at a rate of 1 hz. Between measurements, atmospheric background concentrations were achieved inside the chamber. The gas analyser was equipped with an external pump providing a flow rate of 2 L min^{-1} and pumping the analysed gas back to chamber creating a closed system. Prior to each campaign, the instrument was recalibrated.

We estimated the cover of plant species within each collar to the nearest 5% and counted the number of *T. magellanicum* shoots to further characterize the different microforms (Table 1). In 2015, vegetation surveys were conducted at the beginning and at the end of the measurement campaign. Since no change in vegetation was observed, surveys were conducted only once during the campaign in 2016. For each collar, the position above the water table was determined once during each sampling period of consecutive days to account for different positions in the micro-relief and to determine a specific water table position. Additionally, we determined the area of each individual microform patch in which a collar had been installed.

2.4.2 CH_4 flux calculation and statistical analyses

Soil-atmosphere CH_4 fluxes were calculated from the gas concentration increase over time within the chamber using the software package (MATLAB Release R2015a) routine described in Eckhardt and Kutzbach (2016) and Kutzbach et al. (2007). Gas concentration was modelled either as a linear or an exponential function of time. Models performance was compared using Akaike's Information Criterion (AIC) as a measure of goodness-of-fit. This routine resulted in 90% of cases in a linear function of time (N = 485) and in 10% of cases in an exponential function of time (N = 52).

We visually inspected all concentration increases over time and none of the measurements showed a stepwise concentration increase indicative of ebullient events. Of the 3 minutes measurement time, 50 - 180 s (mostly around 90 s) were selected for the CH_4 flux calculation to exclude unstable conditions due to e.g. chamber placement particularly at the beginning of the measurement. Fluxes with a slope not significantly different from 0 (tested with an F-Test, $p > 0.05$) were set to zero (20% of cases, N = 105).

Normal distributions of CH_4 flux datasets were checked by a Kolmogorov-Smirnov test. Due to non-normality, the Kruskal-Wallis analysis of variance followed by multiple comparison U-tests adjusted by the Bonferroni method were applied to determine significant differences between CH_4 fluxes of different microforms and collars. The relationships between CH_4 fluxes and environmental variables (soil temperature, water table depth fluctuations) as well as additional features of individual collars were evaluated by Spearman's rank correlation (Table 2). A response of CH_4 emissions to the investigated environmental variables was identified only for a few individual collars. Therefore, no seasonal or annual ecosystem emissions were calculated. Statistical analyses were performed using Matlab (MATLAB Statistics Toolbox Release R2017a). All flux data were reported as mean ± standard deviation.

2.5 Depth profiles of peat pore water concentrations

2.5.1 Sampling and field measurements

Multilevel piezometers (MLP), as described in Beer and Blodau (2007), were installed during both measurement campaigns in austral summer 2015 and 2016 to determine pore water concentrations in depth profiles. The MLPs provided a spatial sampling resolution of either 0.1 or 0.2 m and were equipped with diffusive equilibration samplers made of permeable silicone tubes providing 4 mL gas sample volume together with a 5 mL crimp-vial filled with deionized water and covered with a permeable membrane (Supor-200 0.2 µ, Pall corporation, Pall life sciences). To collect gas samples, MLPs were stepwise retrieved and the gas volume extracted from the equilibration sampler with a 3 mL syringe was transferred into nitrogen-flushed 5 mL crimp vials. The crimp vials were capped with a butyl stopper with an aluminium crimp seal. MLPs were installed in *Astelia* lawns and pools in three replicates at each platform where closed chamber measurements were performed.

In January 2015, MLPs were installed in *Astelia* lawns (0.2 m resolution, 2 m depth) and pools (0.1 m resolution 0-1 m, 0.2 m resolution below down to a maximum depth of 4 m) for five weeks equilibration time. From gas samples pore water concentrations of CH_4, dissolved inorganic carbon (DIC) and hydrogen (H_2) were determined. To measure sulfate concentrations, a potential electron acceptor originating from sea spray and affecting competitiveness of methanogenesis (Broder et al., 2015), a pore water subsample obtained from each crimp-vial was transferred to a storage vial and stored frozen until analysis. An aliquot of each remaining pore water sample was measured in-situ with a pH/EC-meter (Combo HI 98129/130, Hannah instruments, Germany).

In January 2016, MLPs were installed to a depth of 3 m in pools (resolution as in 2015) for three weeks equilibration time and afterwards again in *Astelia* lawns (0.1 m resolution in transition zone from rooted to non-rooted peat in 1-2 m depth) for nine weeks of equilibration time. In 2016, equilibration samplers were used to collect CH_4 and CO_2 samples and determine their carbon stable isotopic signatures. Pore water samples obtained from crimp-vials were used to measure O_2 concentrations in-situ with a planar trace oxygen minisensor (Fibox 3, Presens, Germany).

2.5.2 Analytical procedures

Gas samples were transported to Germany and analysed within four weeks. Gaseous CH_4 and CO_2 concentrations were measured with a gas chromatograph (8610C, SRI Instruments, USA) equipped with a methaniser and flame ionization detector (FID). Hydrogen concentrations were analysed on a H_2-Analyzer (Ametek TA 3000 H_2 Analyser, Trace Analytical TA 3000r). Sulfate concentrations were obtained by ion chromatography (883 Basic IC plus, Metrohm, Herisau, Switzerland).

Stable carbon isotopic signatures of CH_4 and CO_2 were simultaneously determined by Cavity Ring-Down Spectroscopy (CRDS; Picarro G2201-I connected to a small sample isotope module (SSIM, model A0314), Picarro Inc., USA). As this set-up required a minimum sample volume of 20 mL, samples were diluted with nitrogen prior measurements. The instrument was calibrated in the beginning of every measurement day using two working standards of CH_4 (1000 ppm, -42.48‰) and CO_2 (1000 ppm, -31.07‰). Isotopic signatures are given in δ-notation relative to Vienna Peedee belemnite (VPDB). As samples were stored for several weeks and $\delta^{13}C$-CO_2 values were biased in case of high CH_4 concentrations in the sample, a correction procedure was applied following Berger et al. (2018).

2.5.3 Calculations and statistical analyses

Pore water concentrations of CH_4, dissolved inorganic carbon (DIC) and H_2 were re-calculated from gaseous concentrations obtained from equilibration samplers by applying Henry's law following Eq. (1):

$$c = K_H * p \tag{1}$$

where c is the concentration in mol L^{-1}, p the pressure in atm and K_H the Henry-constant that was corrected according to Sander (1999) for mean soil temperatures of 10°C in February 2015 and 2016 as well as 7°C in April at a depth of 0.5 m. DIC concentrations at prevalent pH conditions were calculated with respect to carbonate speciation considering equilibrium constants following Stumm and Morgan (1996). All pore water data were reported as mean ± standard deviation (N = 3). Zones of CH_4 production and consumption in the peat column were visually identified based on observed pore water concentration gradients. For a quantitative evaluation of pore water concentration gradients, steady-state conditions as well as a dominance of diffusive gas transport would have to be assumed; this may only partly apply to the system under study here, given the large root biomass. Nevertheless, we additionally applied a software routine using inverse modelling (PROFILE, Berg et al., 1998) for zone identification. This modelling approach supported the results obtained visually, but provided further rough estimates for production and consumption zones due to the complex diffusivity in the rhizosphere of highly rooted peat and, thus, results are presented in the appendix only.

An apparent isotopic fractionation factor α_c was determined (Whiticar et al., 1986; Hornibrook et al., 2000) to assess the predominant methanogenic pathway and / or methanotrophic activity following Eq. (2):

$$\alpha_c = \frac{\delta^{13}C_{CO_2} + 1000}{\delta^{13}C_{CH_4} + 1000} \tag{2}$$

3 Results

3.1 Characteristics of solid peat and root biomass

Roots of *A. pumila* were present in the upper profile down to a depth of 1.8 m (rhizosphere) in *Astelia* lawn cores. Throughout the rhizosphere, we observed a highly decomposed and amorphous peat supposedly originating from *A. pumila* that developed above *Sphagnum* peat. Peat below *Sphagnum* lawns was continuously formed predominantly by *Sphagnum*. Total C and N contents in the peat together with natural abundance of ^{15}N and ^{13}C are given in Table 3. Root density of *D. fascicularis* was 0.014 ± 0.010 g DW L of peat^{-1} at 0.35 m depth while root density of *A. pumila* was not determined once again as it has been already quantified with > 4 g DW L of peat^{-1} in around 0.5 m depth (Fritz et al., 2011).

3.2 Environmental conditions and potential controls on CH_4 fluxes

The study site was characterized by daily mean PAR values up to ~700 µmol m^{-2} s^{-1} with maximum values exceeding 2000 µmol m^{-2} s^{-1} and daily mean air temperatures ranging from -0.5°C to 17°C during the measurement campaigns in austral summer from January to April (Fig. 2). Soil temperature in summer reached maximum daily average values of 15°C and 12°C at 0.05 m depth and 0.5 m depth, respectively. Concurrently, the water table fluctuated close to the surface between -0.03 m and -0.23 m and differed consistently about few centimetres between the two water table measurement sites in *Astelia* lawns. CH_4 fluxes approached zero in many cases, but differed significantly from zero down to absolute values of 0.01 mmol CH_4 m^{-2} d^{-1}. Fluxes below absolute values of 0.01 mmol CH_4 m^{-2} d^{-1} did not differ significantly from zero and were therefore set to zero. For collars exhibiting low magnitude fluxes neither seasonal trends (data not shown) nor a relationship to water table and soil temperature fluctuations could be identified (Table 2). Yet, significant relationships between water table fluctuations or variations in soil temperatures were established for those few lawns with considerable emissions (Table 2).

3.3 Soil-atmosphere CH_4 fluxes and features of microforms possibly affecting CH_4 emissions

Summer CH_4 emissions in a South Patagonian cushion bog were highly variable among the dominant microforms *Astelia* lawns, *Sphagnum* lawns and *Donatia* lawns characterized by specific plant species as well as pools and showed a pronounced spatial pattern even within microforms. Compared to all other microforms, only *Sphagnum* lawns showed considerable emissions with 1.52 ± 1.10 mmol CH_4 m^{-2} d^{-1} while *Astelia* lawns emitted nearly no CH_4 with 0.09 ± 0.16 mmol m^{-2} d^{-1} (Fig. 3). Methane emissions from pools were also low (0.23 ± 0.25 mmol m^{-2} d^{-1}) and not significantly different from intermediate *Donatia* lawn fluxes (0.66 ± 0.96 mmol CH_4 m^{-2} d^{-1}). During some occasions, we determined even significant, negative CH_4 fluxes, mainly from *Astelia* lawns (Fig. 3a, Table 2). Most of these negative fluxes as well as the majority of fluxes (41%) that were set to zero were obtained from one individual collar throughout the whole measurement campaigns precluding the possibility of a measurement artefact.

As indicated by high standard deviations, CH_4 emissions between replicates of all microforms were not consistent. Field observations suggested that CH_4 emissions of a microform were not only controlled by the predominant plant species, but might have been associated with additional features of the respective microform. Therefore additional microform features (i.e. number of *T. magellanicum* shoots, cover of *D. fascicularis*, extend of the microform in which a specific collar was installed) were assessed. However, as we did not expect such small-scale spatial variability between emissions of individual collars, the results of this survey given in Table 2 are of rather explorative, preliminary character as the low number of replicates (3 to 5 collars) in combination with several outliers barely allows any sound statistical analysis. Nevertheless, collars with elevated or comparatively high emissions had some features in common: Emissions from one *Astelia* lawn were with ~0.3 mmol CH_4 m^{-2} d^{-1} (significantly) higher in both sampling years compared to fluxes measured from the other *Astelia* lawns. This *Astelia* lawn collar with elevated emissions was characterized by (I) the presence of many *T. magellanicum* shoots together with a high share of *D. fascicularis* and (II) placed in a lawn with small extent surrounded by a mosaic of small pools and *D. fascicularis* patches (both smaller than 1 m^2). Surprisingly, also one *Donatia* lawn was a substantial CH_4 source of 2.10 ± 0.14 mmol m^{-2} d^{-1}, even exceeding the highest emissions observed from *Sphagnum* lawns on all measurement occasions in 2016. Similar to the *Astelia* lawn with elevated emissions, the collars of *Donatia* and *Sphagnum* lawns with high emissions were characterized by (I) a high amount of *T. magellanicum* shoots and (II) placed in lawns surrounded by small pools and other patches of *D. fascicularis* with no *A. pumila* nearby. Emissions obtained from one *Sphagnum* lawn were with less than 0.3 mmol CH_4 m^{-2} d^{-1} in both sampling years significantly lower compared to emissions from other *Sphagnum* lawns. Vice versa, this collar with low *Sphagnum* emissions was characterized by (I) the lowest number of *T. magellanicum* shoots among all *Sphagnum* lawn collars and (II) installed in a small *Sphagnum* lawn surrounded by *A. pumila*.

3.4 Pore water CH_4 and DIC concentration profiles

Pore water profiles in peat columns below *Astelia* lawns and pools showed similar trends in pore water concentrations and during both sampling years. CH_4 concentrations were almost zero in the upper pore water profile below *Astelia* lawns (< 0.003 mmol L^{-1}) down to a depth of around 1.5 m, which corresponds to the zone where the rhizosphere was most pronounced (Fig. 4a). Below this depth, CH_4 concentrations sharply increased up to 0.25 ± 0.08 mmol L^{-1} at 3 m depth. CH_4 concentrations in pore water profiles below pools resembled profiles obtained under *Astelia* lawns on elevated levels. Throughout the upper profile down to 1.5 m, CH_4 concentrations were ~0.03 mmol L^{-1} with a peak around 0.3 m depth (0.06 ± 0.06 mmol L^{-1}) and increased steeply to 0.40 ± 0.25 mmol L^{-1} in 3 m depth. Maximum concentrations in comparable depths reached similar levels in both sampling years below *Astelia* lawns, but maximum concentrations below pools were about 3times higher in 2015 compared to 2016.

DIC predominantly occurred as dissolved CO_2 because of the low pH ranging from 3.36 to 4.77. Contrary to CH_4, DIC concentrations increased constantly with depth from around 1 mmol L^{-1} near the surface to 2.60 ± 1.0 mmol L^{-1} in 2 m depth below *Astelia* lawns and 2.94 ± 1.1 mmol L^{-1} in 3 m depth below pools (Fig. 4b). With depth, DIC converged with CH_4 concentrations, which was reflected by DIC:CH_4 ratios that were extremely high in the rhizosphere below *Astelia* lawns exceeding 100 (Fig. 4c). Beneath the rhizosphere, ratios steeply approached values below 40. Under pools, ratios slightly decreased with depth but were mostly around 40 down to 1.5 m with two distinct peaks of very little CH_4 at the surface and around 0.8 m depth. In deep peat layers below the rhizosphere, DIC:CH_4 ratios detected under *Astelia* lawns and pools converged and reached lowest ratios of ~10 and ~5, respectively.

Visual inspection of concentration profiles but also modelling of CH_4 production and consumption rates indicated a predominance of CH_4 consumption throughout the whole rhizosphere below *Astelia* lawns and in roughly corresponding depths under pools (Fig. 4a, Fig. 6). Maximum CH_4 consumption was identified in the lower rhizosphere around 1.5-2 m where the increase in CH_4 concentration was most pronounced. Deep peat layers below the rhizosphere of *Astelia* lawns and similar depths below pools were considered as CH_4 sources. In these depths, the high concentration levels of CH_4 (up to 0.40 ± 0.25 mmol L^{-1}) sustain substantial upward diffusion of CH_4 following the concentration gradient into the consumption zone throughout the rhizosphere of *Astelia* lawns and in corresponding depths below pools.

3.5 Carbon isotopic values in pore water and apparent fractionation

Values of $\delta^{13}C$ in CH_4 did not show a clear depth trend below *Astelia* lawns and ranged in the upper profile down to 2 m depth between -87.2 ± 10.1 to -72.1 ± 10.3‰ (Fig. 4d). Isotopic $\delta^{13}C$-CH_4 values below pools became less negative with depth from -93.4 ± 9.2 to -73.7 ± 1.2‰ with a minimum peak in upper peat layers around 0.3 m of -101.0 ± 5.6‰. In the upper meter of the profile, values of $\delta^{13}C$-CH_4 were thus up to 25‰ more negative below pools compared to *Astelia* lawns while the isotopic values of both profiles converged in deep peat layers below 2 m at -80‰. Values of $\delta^{13}C$ in CO_2 below *Astelia* lawns became more negative with depth in the upper profile down to 1 m reaching values as low as -32.4 ± 0.8‰ and increased to -19.5 ±

1.0‰ in 3 m depth. Below pools, values became less negative with depth throughout the whole profile from -21.2 ± 0.4 to -6.0 ± 1.5‰ (Fig. 4e).

Apparent fractionation factors varied only slightly and showed opposite trends below the two microforms. Values increased slightly from 1.060 to 1.066 below *Astelia* lawns, peaking at 1.045 in 0.5 m depth. Below pools, apparent fractionation factors decreased with depth from 1.079 to 1.073 with a maximum of 1.091 around 0.3 m depth (Fig. 4f).

3.6 Hydrogen, oxygen and sulfate concentrations in pore water profiles

Hydrogen concentrations were mostly below 3 nmol L^{-1} below *Astelia* lawns while they were elevated below pools, ranging between 3 and 10 nmol L^{-1} (Fig. 5a). Maximum concentrations were reached in the upper profile of *Astelia* lawns with up to 11.83 ± 17.88 nmol L^{-1} and, besides a peak at the surface, below pools from 1 to 2 m depth with up to 41.61 ± 64.63 nmol L^{-1}. Molecular oxygen concentrations were mostly below 5% saturation and tended to be higher in the upper profile down to 2 m below *Astelia* lawns compared to pools (Fig. 5b). Sulfate concentrations were similar below both, *Astelia* lawns and pools, and reached highest values near the surface with up to 16.43 ± 11.85 µmol L^{-1}. With depth, concentrations decreased and approached zero below 1 m (Fig. 5c).

4 Discussion

This study is among the first dealing with CH_4 dynamics in an austral, vascular-plant dominated cushion bog. We aimed to reveal patterns of CH_4 emissions and their environmental as well as potential belowground biogeochemical controls. We furthermore attempted to elucidate the CH_4 dynamics in the peat below the four predominant microforms on a conceptual level based on the results presented here and in previous studies.

4.1 Environmental controls on CH_4 emissions

Summer CH_4 emissions of a South Patagonian cushion bog dominated by *A. pumila* were low albeit spatial heterogeneity was pronounced with small patches of *Sphagnum* or *Donatia* lawns being local emission hot spots. The variation of CH_4 fluxes was mainly controlled by the dominant plant species of each lawn microform which emitted significantly different amounts of CH_4. We found only few significant responses of CH_4 fluxes to water table fluctuations or variations in soil temperatures (Table 2). Such weak coupling between environmental variables and CH_4 emissions is not surprising as fluxes from most individual collars were relatively low. Furthermore, the water table fluctuated only slightly near the surface (Fig. 2) and may thus not serve as a primary control on CH_4 emissions. Stronger effects may only be expected when amplitude and duration of fluctuations affect peat redox conditions substantially (Blodau and Moore, 2003; Knorr et al., 2009). Under such stable moisture conditions and as long as methanogenesis is not limited by substrate supply, the sensitivity of methanogenic microbial consortia to temperature should become apparent (Whalen, 2005). Variations in landscape CH_4 fluxes have indeed been related to soil temperature previously (Rinne et al., 2007; Jackowicz-Korczyński et al., 2010; Goodrich et al., 2015) which is in accordance with the present study. The temporal variability of CH_4 emissions over the two investigated seasons was rather low (data not shown) due to low seasonality in both, temperature and precipitation, in the study region. Measurement campaigns extending over shoulder seasons and comparing years of contrasting weather conditions would be necessary to reveal the impact of more pronounced water table fluctuations or temperature regimes on CH_4 fluxes in South Patagonian cushion bogs.

4.2 *Astelia* lawns – zero emission scenario

Emissions from *Astelia* lawns were minute (0.09 ± 0.16 mmol m^{-2} d^{-1}) and significantly lower than from all other microforms (Fig. 3) verifying our first hypothesis. The near-zero emissions were well explained by near-zero CH_4 concentrations (< 0.003 mmol L^{-1}) in the rhizosphere down to around 1.8 m. Only below, concentrations increased sharply to 0.2 mmol L^{-1} in 2 m depth (Fig. 4a). The low CH_4 concentrations even turned some *Astelia* lawns into a small sink for atmospheric CH_4 as shown by negative fluxes that were obtained sporadically throughout the whole measurement campaigns, confirming earlier results (Kip et al., 2012). These findings agree with previous research by Fritz et al. (2011) who observed CH_4 emissions from *Astelia* lawns in a comparably low magnitude as presented here and presented a similar CH_4 concentration depth profile. Extremely low CH_4 concentrations have also been obtained by Dullo et al. (2017) in upper peat layers of an Ethiopian cushion bog. Nevertheless, in deep peat layers below the rhizosphere, CH_4 concentrations of our study approached magnitudes reported for Chilean bogs with mixed vegetation consisting of *Sphagnum* mosses and *A. pumila* (Broder et al., 2015). This is in the lower range of concentrations described from northern bogs mostly around 0.5 mmol L^{-1} (e.g. Blodau and Moore, 2003; Beer and Blodau, 2007; Beer et al., 2008; Corbett et al., 2013) but even reaching up to 5 mmol L^{-1} in comparable depths (Steinmann et al., 2008).

A CH_4 concentration profile as observed at our site yet suggests that in deep peat layers below the rhizosphere (> 2 m) CH_4 was produced at substantial rates and comparably low oxidation, as indicated by DIC:CH_4 ratios notably smaller than 40 (Fig. 4c). Subsequently, CH_4 got almost completely oxidized on its diffusive way to the atmosphere as visualized on a conceptual level (Fig. 6). Ratios of DIC:CH_4 under methanogenic conditions in northern bogs are typically around 5 (e.g. Hornibrook et al., 1997; Blodau and Moore, 2003; Corbett et al., 2013), but can be as high as 30 (Steinmann et al., 2008). Notably higher ratios throughout the rhizosphere suggested methanotrophic activity and availability of either alternative electron acceptors or O_2 from aerenchymous roots suppressing methanogenesis (Colmer, 2003; Mainiero and Kazda, 2005; Knorr et al., 2008a, Fritz et al., 2011; Dullo et al., 2017). Diffusion and plant-mediated transport as pathways for upward CH_4 transport would have caused higher emissions and ebullition requires supersaturation of at least ~350 mmol CH_4 L^{-1} in the pore water (Fechner-Levy and Hemond, 1996; Beer et al., 2008). The sharp drop in CH_4 concentrations from -2 to -1.5 m depth characterized this peat layer as a zone of strongest methanotrophic activity, as supported by modelled consumption zones.

Carbon isotopic values obtained from pore water profiles reflected rhizosphere processes, although the δ^{13}C-CH_4 signature alone did not provide a clear indication for oxidative effects in the rhizosphere as proposed in our second hypothesis. A strong effect of only methanotrophy should result in a shift of the mean δ^{13}C-CH_4 signature to more enriched values and distinct changes in the fractionation factor from lower to upper horizons. Methane isotopic signatures were close to -80‰ in deep peat layers while above 2 m depth values ranged from -90 to -70‰ throughout the rhizosphere (Fig. 4d) while the fractionation factor increased slightly (Fig. 4f). These surprisingly negative δ^{13}C-CH_4 values throughout the rhizosphere along with a comparatively small shift and a wider standard variation of replicate samples are an unexpected result that needs further explanation.

We can only explain the pronounced variation in replicate δ^{13}C-CH_4 values to be associated with the presence of aerenchymous roots and the mean δ^{13}C-CH_4 depth pattern by a co-existence of aerobic and anaerobic microsites that would both support such strong variation within short spatial scales. The occurrence of small-scale aerobic microsites attached to roots releasing O_2 into water-saturated (peat) layers has been previously suggested (Colmer, 2003), also for peatlands on the northern hemisphere (Popp et al., 1999; Knorr et al., 2008a; Corbett et al., 2013). Life time and activity of *A. pumila* roots are highly dynamic (Knorr et al., 2015) and supposedly governed temporal and spatial expansion of microsites. Within these microsites, labile organic matter and CH_4 were rapidly consumed by aerobic respiration and methanotrophy resulting in CH_4 enriched in ^{13}C by up to 10‰ (Fig. 4d). This δ^{13}C-CH_4 signature and the apparently small ^{12}C/^{13}C fractionation observed throughout the rhizosphere (Fig 4f) revealed the influence of a strongly fractionating process such as CH_4 oxidation. Although based on ^{13}C isotope fractionation alone CH_4 oxidation cannot be clearly separated from acetoclastic methanogenesis (Whiticar et al., 1986; Conrad, 2005), oxidative effects in the rhizosphere were very likely since diffusion or plant-mediated transport were excluded as sinks for CH_4. Methanotrophy leaves CH_4 in the pore water enriched by ~10‰ while produced CO_2 becomes depleted (Chasar et al., 2000; Popp et al., 1999) as observed here throughout the rhizosphere with less negative signatures occurring only at greater depths (Fig. 4e). Also values of δ^{13}C-CO_2 of less than -30‰ that were substantially lower than the source organic matter material around -26‰ (Table 3) can only be explained by the influence of ^{13}C depleted carbon from oxidation of ^{13}C depleted CH_4. Substantial rates of root respiration were a further source for depleted CO_2 in the pore water (Corbett et al., 2013) as suggested by high DIC:CH_4 ratios mostly exceeding 100 throughout the prevailingly water-saturated rhizosphere (Fig. 4c). Nevertheless, O_2 release by roots still exceeded consumption, as demonstrated by O_2 saturation reaching up to 10% (Fig 5b). This O_2 supply may thus not only fuel CH_4 oxidation but also heterotrophic respiration using molecular oxygen or other electron acceptors regenerated by this O_2 input (Colmer, 2003; Mainiero and Kazda; 2005). Likely further sources of CO_2 could have been dissimilatory sulfate reduction in anaerobic microsites of surface peat layers down to 0.4 m (Fig. 5c) with sulfate originating e.g. from sea spray (Kleinebecker et al., 2008; Broder et al., 2015). Taking together these results obtained from CH_4 and DIC concentration profiles and its carbon isotopic signatures, the second hypothesis stating that pore water concentrations below *Astelia* lawns reflect a distinct CH_4 oxidation effect was confirmed.

Enriched CH_4 being only a leftover from CH_4 oxidation should result in a δ^{13}C-CH_4 depth pattern following that of the δ^{13}C-CO_2 profile (Hornibrook et al., 2000), but such pattern was not observed in our study (Fig. 4d and e). The surprisingly negative

$\delta^{13}C$-CH_4 signature throughout the rhizosphere is likely explained by production of few amounts of CH_4 in anaerobic microsites in absence of living roots. Either hydrogenotrophic or acetogenesis and subsequent acetoclastic methanogenesis cause large fractionation (Steinmann et al., 2008) and could add depleted CH_4 to the rhizosphere. As we did not quantify other parameters such as labile organic root matter or root exudates, acetate concentrations or its carbon isotopic signatures, we cannot clearly determine the relative importance of both pathways for our study. Elevated H_2 concentrations in surface peat layers (Fig. 5a) indicated high H_2 production by fermentation compared to consumption by e.g. sulfate reduction or hydrogenotrophic methanogenesis, presumably due to high root litter input and root exudates (Knorr et al., 2009; Estop-Aragonés et al., 2013). But as acetogens can outcompete hydrogenotrophic methanogens at low temperatures especially when H_2 is available, (Kotsyurbenko et al., 2001), we propose that acetoclastic methanogenesis was the more important pathway here. Together with the probably high amounts of labile organic matter available to serve as substrate for methanogenesis throughout 2 m of rhizosphere, this explanation would support our third hypothesis. With depth, root density presumably decreased (Fritz et al., 2011) and a slight increase in $^{12}C/^{13}C$ fractionation indicated a shift to a predominance of hydrogenotrophic methanogenesis and, below 2 m depth, absence of microsites (Fig. 4f) as α_c-values of replicate samples varied less and increased towards 1.065 (Whiticar et al., 1986; Conrad, 2005).

4.3 Pools – low emission scenario

Pools exhibited with 0.23 ± 0.25 mmol CH_4 m^{-2} d^{-1} second lowest emissions of the microforms under study (Fig. 3). Such low emissions were contrary to our first hypothesis and somewhat surprising since they have been previously reported to be similar to *Sphagnum* lawns (Fritz et al., 2011) and were expected to be relevant CH_4 sources because of prevailing anoxic conditions (Blodau, 2002). Moreover, other studies identified pools as hot-spots of CH_4 emissions from peatlands (Hamilton et al., 1994; Pelletier et al., 2014; Burger et al., 2016). This was clearly not the case here, as emissions were in the same order of magnitude as pool fluxes in South Patagonian *Sphagnum* bogs (Lehmann et al., 2016).

Low emissions were associated with CH_4 pore water concentrations surprisingly resembling those below *Astelia* lawns on slightly elevated levels (Fig. 4a). These low pore water concentrations in sparsely- or even non-rooted peat below pools were not supported by our second hypothesis and require another explanation. The $\delta^{13}C$-CH_4 signature was depleted compared to *Astelia* lawns down to 2 m depth, followed largely that of $\delta^{13}C$-CO_2 (Fig. 4d, e) and, thus, did not indicate a methanotrophic effect. As upward diffusion of CH_4 against the concentration gradient is impossible, we can only explain low pore water concentrations by lateral exchange of CH_4. We suggest that root O_2 release by *A. pumila* controlled even CH_4 dynamics below adjacent microforms as visualized on a conceptual level in Figure 6. The thorough CH_4 oxidation below *Astelia* lawns may establish a lateral concentration gradient of CH_4. Thereby, CH_4 from adjacent microforms may diffuse to the rhizosphere of *Astelia* lawns where it was consumed. As the micro-relief is not pronounced at our study site, we propose that there is a large depth zone throughout the 2 m rhizosphere of *Astelia* lawns and in corresponding depths below pools with negligible water flow and a predominance of diffusive transport. In this depth zone, we observed a highly decomposed and amorphous peat as previously described for cushion bogs (Ruthsatz and Villagran, 1991; Fritz et al., 2011) indicating a very high water permeability that would together with a high water table position facilitate such lateral exchange (Baird et al., 2016). The assumption of lateral exchange was supported by a peak in DIC:CH_4 ratios accompanied by very low CH_4 concentrations around 0.8 m below pools (Fig. 4c) inhibiting upward diffusion. Lateral root ingrowth and O_2 supply from adjacent *Astelia* lawns could furthermore supress methanogenesis and keep CH_4 concentrations below pools low, in particular if pools are small.

Patterns of carbon isotopic signatures, levels of H_2 concentrations ~10 nmol L^{-1} sufficient to maintain hydrogenotrophic methanogenesis (Heimann et al., 2010), and low DIC:CH_4 ratios suggested methanogenic conditions over the whole profile (Fig. 4c, 5c). Methanogenesis was especially indicated by a slight peak of CH_4 concentrations associated with lower DIC:CH_4 ratios and elevated H_2 ratios around 0.3 m depth. However, even high activity of fermentation processes as indicated by peaking H_2 levels from 1 to 2 m depth did not translate to changes in fractionation factor (Fig. 4f, 5a), but suggest that CH_4 was produced only very locally if at all. Low substrate supply from highly decomposed organic matter and thus unfavourable thermodynamic conditions seemed to limit CH_4 production as suggested by very negative $\delta^{13}C$-CH_4 signatures (Fig. 4d) accompanied with peaking α_c-values in the upper profile (Fig. 4f) (Knorr et al., 2008b; Hornibrook et al., 1997). Instead, methanogenesis might have been outcompeted by other electron accepting processes, such as sulfate reduction (Fig. 5c). If produced at all, CH_4 was rapidly consumed around 0.3 m depth by methanotrophic bacteria inhabiting submerged *Sphagnum* mosses that provided recalcitrant organic matter on pool bottoms (Kleinebecker et al., 2007; Kip et al., 2012; Knoblauch et al., 2015), or associated with cyanobacteria (Arsenault et al., 2018; González Garraza et al., 2018). Within the open water of pools which was well-mixed by strong winds, CH_4 production and excess of H_2 were diminished due to electron acceptor availability for consumption (e.g. O_2, sulfate). Thus, the pools at our study site belonged to examples of low emission pools as described in Knoblauch et al. (2015).

4.4 *Sphagnum* and *Donatia* lawns – low to moderate emission scenario

CH_4 emissions from *Sphagnum* and *Donatia* lawns were most variable among microforms ranging from near-zero to local emission hotspots. *Sphagnum* lawns showed significantly higher CH_4 emissions of 1.52 ± 1.10 mmol m^{-2} d^{-1} than all other microforms (Fig. 3). Substantially higher fluxes from *Sphagnum* lawns at our study site have been previously described by Fritz et al. (2011) and emissions reported here were in the same order of magnitude as determined for *Sphagnum* lawns in South Patagonian bogs dominated by *Sphagnum* mosses (Broder et al., 2015; Lehmann et al., 2016). Highest emissions obtained in the present study from *Sphagnum* and *Donatia* lawns were at intermediate levels compared to northern bogs (Blodau, 2002; Laine et al., 2007; Limpens et al., 2008).

We present the first CH_4 emission data obtained from *Donatia* lawns. Contrary to our expectations, *Donatia* lawns emitted 0.66 ± 0.96 mmol CH_4 m^{-2} d^{-1} and had thus second highest CH_4 emissions of our study. One lawn even exceeded emissions of the strongest *Sphagnum* lawn source (Fig. 3c, Table 2) on all measurement occasions. As these comparatively high emissions could be well reproduced, we conclude that an artefact can be excluded. Therefore, our first hypothesis, that cushion plants emit negligible amounts of CH_4, could retrospectively only be partly confirmed, as it depends on the specific cushion-forming plant species. We conclude that the presence of cushion plants as a proxy for negligible CH_4 emissions from cushion bogs needs to be carefully interpreted.

The spatial distribution of vascular plant root characteristics and its oxidative effects apparently controlled CH_4 dynamics in the study site as suggested by the pronounced spatial variability of emissions associated with our preliminary observations of microform features (Table 2). *D. fascicularis* established a deep and aerenchymous, but with < 0.05 g DW L of peat^{-1} a substantially less dense rooting system compared to *A. pumila* with > 4 g DW L of peat^{-1} in around 0.5 m depth (Fritz et al., 2011). The lower root density of *D. fascicularis* was probably below a specific threshold at which O_2 release did not suppress emissions any more. Instead, the roots might have accelerated CH_4 production by presence of labile organic matter while facilitating emissions (e.g. Joabsson et al., 1999; Blodau, 2002; Colmer, 2003; Whalen, 2005; Agethen et al., 2018). As root O_2 release promotes nutrient mobilization (Colmer, 2003), this assumption of little if any O_2 release by *D. fascicularis* is in line with Schmidt et al. (2010) who found nutrient concentrations in *D. fascicularis* to be almost as low as in *S. magellanicum* while *A. pumila* contained significantly higher amounts of nutrients.

Sphagnum and *Donatia* lawns that showed substantial CH_4 emissions were beyond the sphere of influence by *A. pumila* roots. Although not measured here, pore water CH_4 concentrations below *Sphagnum* and *Donatia* lawns with remarkably higher emissions probably increased steeply below the water table (Fig. 6), like common depth profiles in northern (e.g. Beer and Blodau, 2007; Limpens et al., 2008; Corbett et al., 2013) or southern bogs (Broder et al., 2015). This explanation implies that the pore water below those lawns was not well-connected to pore water influenced by *A. pumila* roots. A spatial variability of peat physical properties on the ecosystem scale was suggested by water table records (Fig. 2) demonstrating that one site responded faster than the other to, for instance, precipitation events.

We speculate that the biogeochemistry below *Sphagnum* and *Donatia* lawns with near-zero emissions was, likewise to pools, influenced by root activity of nearby *A. pumila* (as visualized in Fig. 6). This assumption was supported by previous research in our study site. Fritz et al. (2011) showed that below *Sphagnum* lawns pore water CH_4 concentrations can be substantially lowered throughout rhizosphere-influenced peat layers. Further research should be undertaken to investigate why CH_4 emissions from *Sphagnum* and *Donatia* lawns appear to be highly variable in order to understand CH_4 dynamics in under-researched cushion bogs.

4.5 Implications for ecosystem CH_4 emissions from Patagonian cushion bogs

Highest summer emissions in the present study were considerably lower compared to maximum austral summer fluxes of ~150 mg CH_4 m^{-2} d^{-1} (9.4 mmol m^{-2} d^{-1}) determined for a New Zealand bog dominated by the vascular evergreen “wire rush,” *Empodisma robustum* (Goodrich et al., 2015). The authors explained such high CH_4 emissions by comparatively wet conditions and a high density of aerenchymous vegetation providing a gas conduit for CH_4 transport in their study site. Compared to CH_4

emissions of northern bogs ranging from 3 to 53 mg m^{-2} d^{-1} at intermediate levels in wet bogs to up to 80 mg m^{-2} d^{-1} (Blodau, 2002; Laine et al., 2007; Limpens et al., 2008; 0.2 to 2.2 and up to 5 mmol m^{-2} d^{-1}), highest summer emissions in the present study represent a pronounced CH_4 source. Nevertheless, overall ecosystem CH_4 emissions would probably be among the lowest described for pristine bog ecosystems worldwide when taking into account the high proportion of the surface area where *Astelia* lawns prevailed.

While *Donatia* lawns covered only small parts of our study site, we observed other parts of the complex bog system in the whole study area to be widely dominated by *D. fascicularis* instead of *A. pumila* which is in line with previous studies (Heusser, 1995; Grootjans et al., 2014) who described the cushion bogs in the Moat landscape to be covered by both, *A. pumila* and *D. fascicularis*. Thus, amounts of emitted CH_4 could be significant also on the ecosystem scale once *D. fascicularis* dominates. For instance, a predominance of *D. fascicularis* is typical for later vegetation succession stages in cushion bogs of Tierra del Fuego (Heusser, 1995) or Chile (Ruthsatz and Villagran, 1991; Kleinebecker et al., 2007).

5 Conclusion

We conclude from our study that the spatial distribution of cushion-forming *A. pumila* root density and activity and associated O_2 supply strongly controlled CH_4 production and consumption in a pristine Patagonian cushion bog. Thereby, CH_4 emission were reduced to near-zero levels and largely decoupled from environmental controls. The high root density even regulated CH_4 dynamics below adjacent microforms with less or non-rooted peat such as pools, *Sphagnum* lawns or lawns dominated by cushion-forming *D. fascicularis* by maintaining lateral concentration gradients in upper peat layers. Nevertheless, when root density dropped below a certain threshold, CH_4 production might have been accelerated by presence of labile root organic matter or exudates accompanied with O_2 consumption along with facilitated CH_4 transport by aerenchymatic roots of e.g. *D. fascicularis*. Under such circumstances, CH_4 emissions increased to intermediate levels compared to northern bogs. Therefore, the presence of cushion plants as a proxy for negligible CH_4 emissions from cushion bogs should be interpreted carefully. As cushion bogs can be found in many (mostly southern) parts of the world and only very limited knowledge about CH_4 dynamics from these systems exist, future research should take into account a possibly high spatial variability of CH_4 emission from bogs dominated by cushion plants. We demonstrated an extreme scenario for how a spatial distribution of root density in the peat can lead to a pronounced pattern of CH_4 emissions. Yet, the underlying ratio between root characteristics and O_2 supply determining this emission pattern should be applicable to other densely rooted peatlands in general. Further research should be undertaken to prove relationships that have been developed here on a conceptual level in order to extend our knowledge on CH_4 dynamics in under-researched cushion bogs.

Data availability. The data can be accessed by email request to the corresponding authors.

Author contributions. CB, TK and WM designed the study. WM, CB, TK and VAP conducted field work and sample analyses with the help of KHK. WM performed data analyses and prepared the manuscript with contributions from KHK, TK and VAP.

Competing interests. The authors declare that they have no conflict of interest.

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Figures

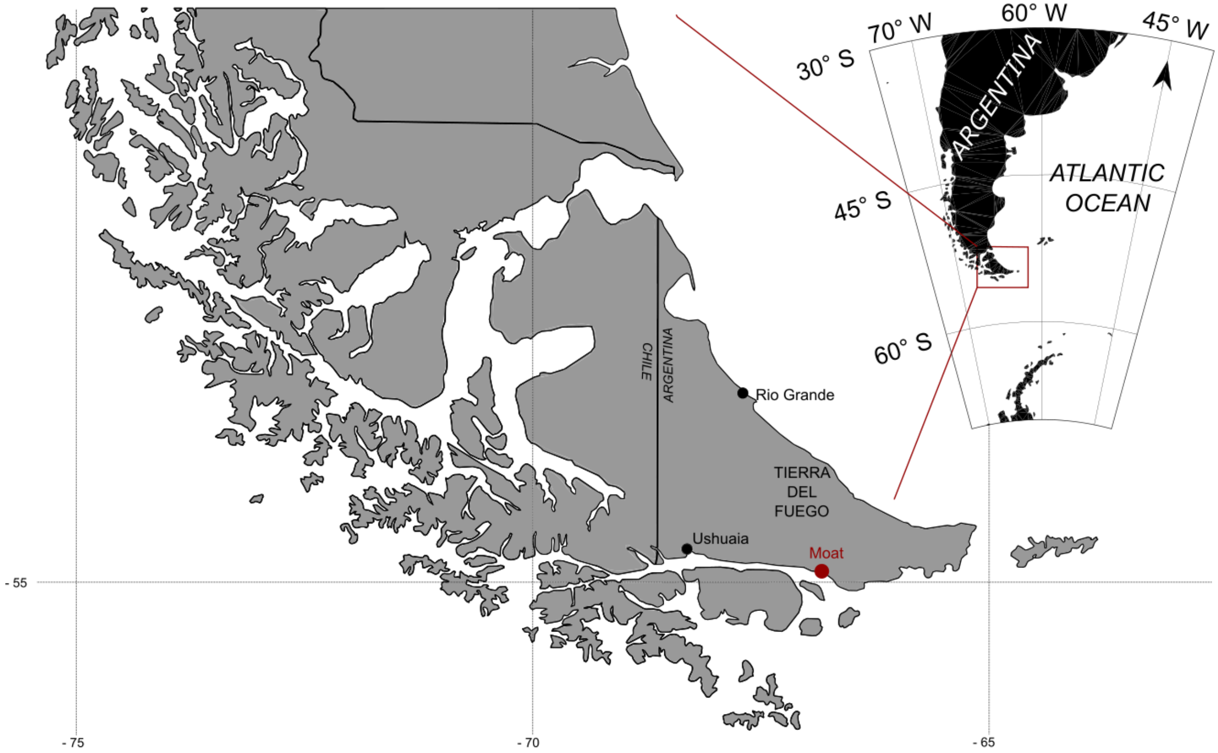

Figure 1. Location of the study area in southernmost Patagonia. The investigated cushion bog in Moat is located 130 km eastern of Ushuaia (Argentina). The map was created at http://www.simplemappr.net accessed on 11.12.2017 and in Matlab (MATLAB Mapping Toolbox Release R2017a).

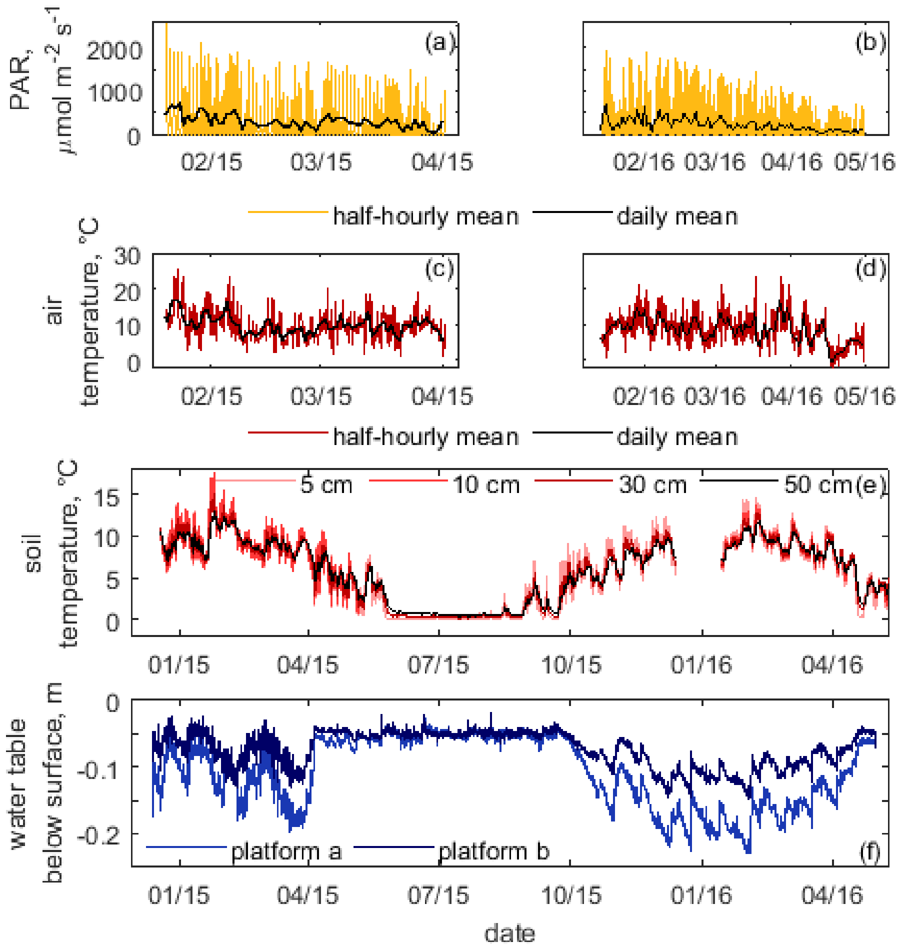

Figure 2. Time series of environmental variables during the study period. Photosynthetic active radiation (PAR, a, b) and air temperature (c, d) are presented as half-hourly and daily means during two austral summer periods. Soil temperature (e) and water table position below surface (f) were continuously recorded and are shown as half-hourly means. Note the difference in response time between platform a and platform b where water table fluctuations were recorded.

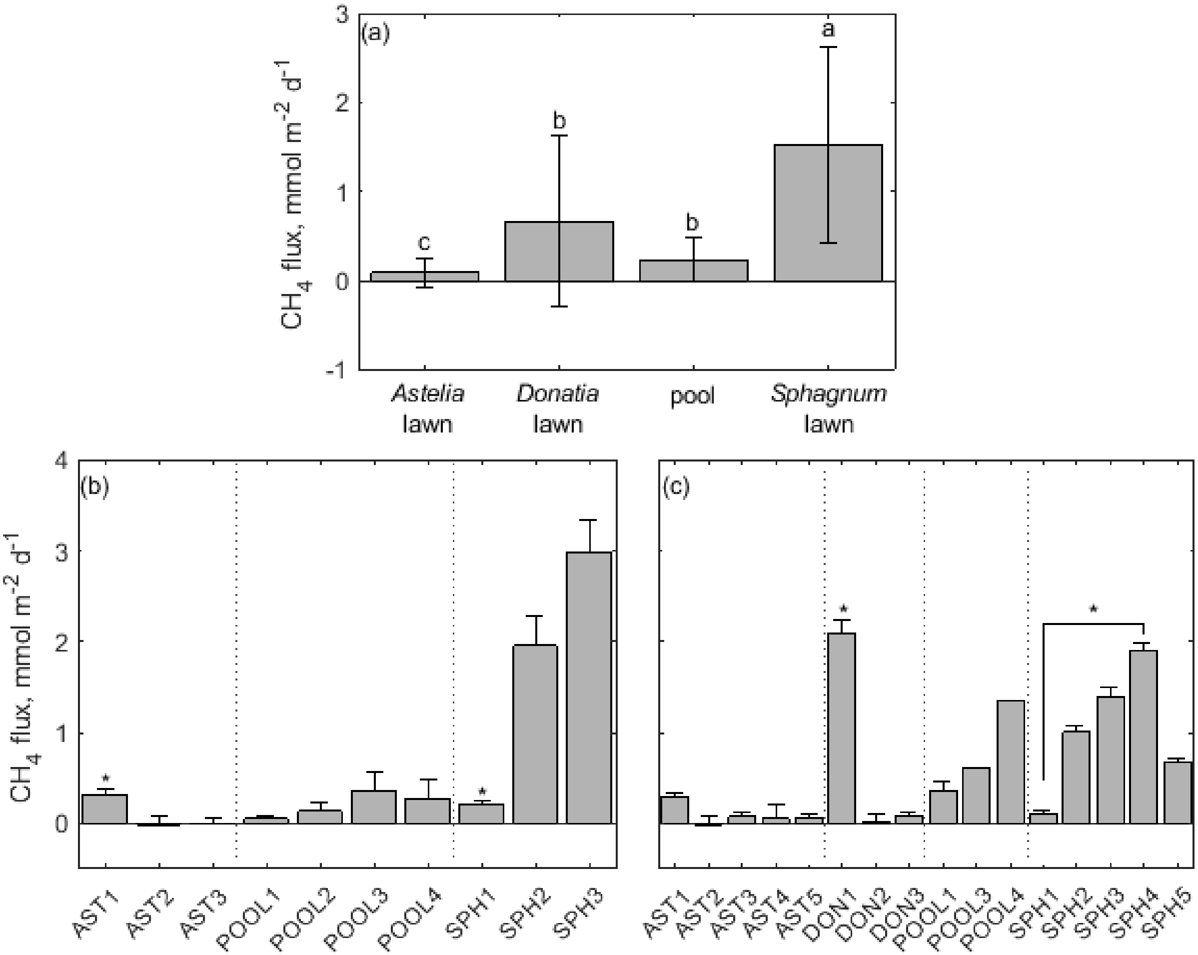

Figure 3 a-c. Mean CH_4 emissions and their standard deviation determined from dominant microforms (a) and individual collars during the two measurement campaigns (b, c) in a Patagonian cushion bog. Different letter superscripts denote significantly different amounts of emitted CH_4 between microforms despite variability within microforms was substantial (a) or from collars within one microform (b, c) that were identified by Kruskal-Wallis analysis of variance and multiple comparison U-tests with Bonferroni adjustment.

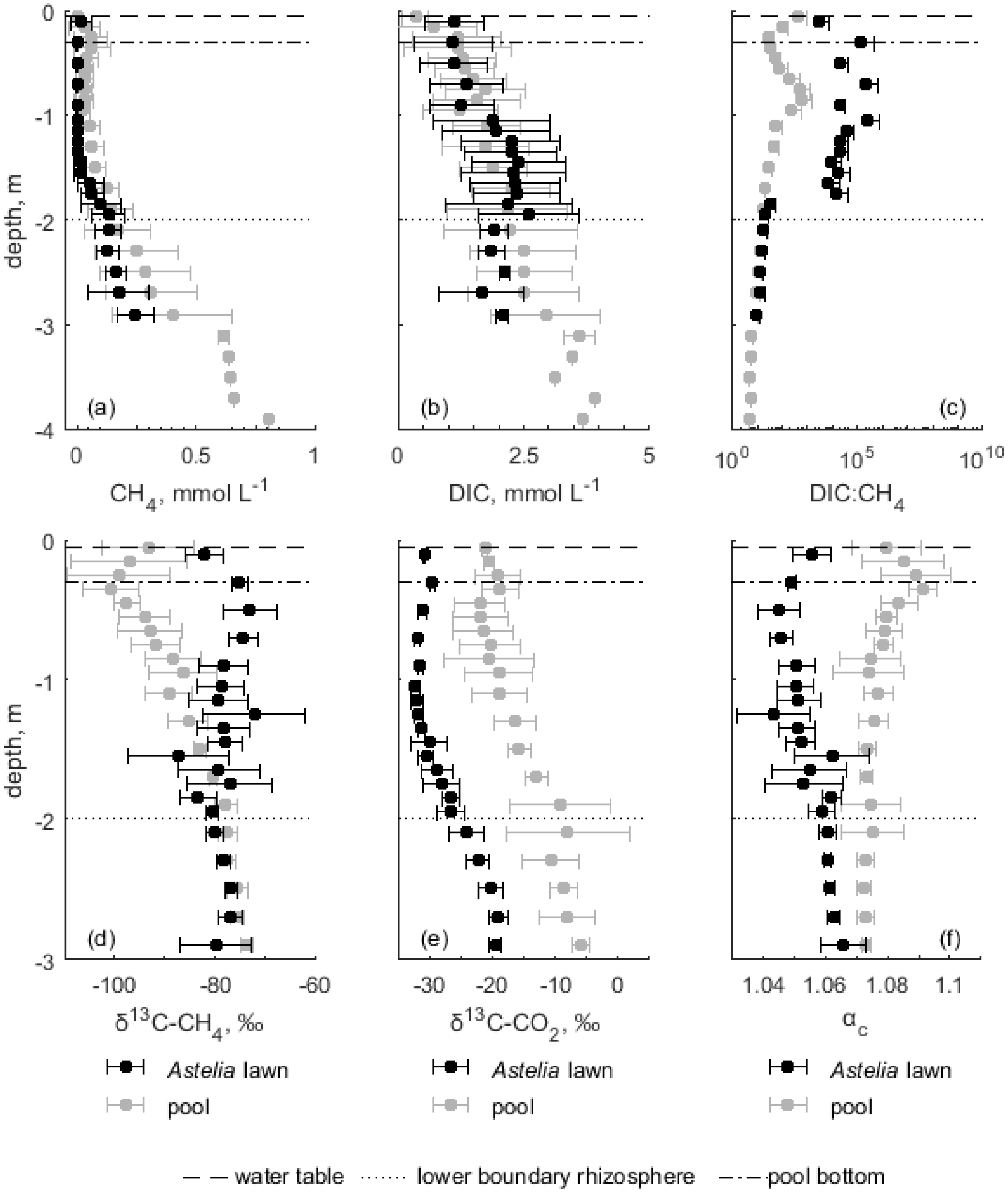

Figure 4 a-f. Pore water composition in depth profiles obtained from MLPS (N = 3) installed in *Astelia* lawns and pools during two sampling campaigns in austral summer 2015 and 2016. Mean values and their standard deviation are presented. CH_4 (a) and DIC (b) concentrations as well as related DIC:CH_4 (c) ratios were determined during both sampling events while carbon isotope values of CH_4 (d) and DIC (e) and corresponding fractionation factors (f) were investigated only during the second campaign. DIC:CH_4 ratios are shown on a logarithmic scale without negative standard deviation for *Astelia* lawns and pools. Displayed depths represent the centre of a MLP segment and had to be standardized because of different sampling resolution in both years. The water table position and approximate maximum rooting depth (rhizosphere) refer to *Astelia* lawns only. Note the different scale of the y-axis in the upper and lower three panels.

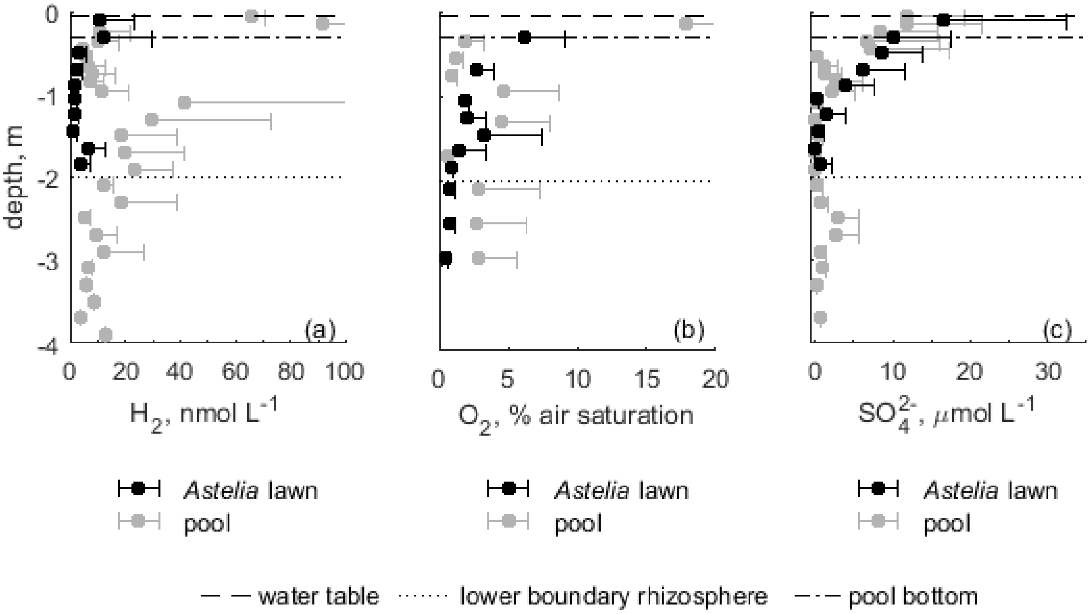

Figure 5 a-c. Profiles of H_2 (a), O_2 (b) and sulfate (c) pore water concentrations obtained from MLPs (N = 3) installed in *Astelia* lawns and pools during two sampling campaigns in austral summer 2015 and 2016. Mean values and their standard deviation are presented. Displayed depths represent the centre of a MLP segment and had to be standardized because of different sampling resolution in both years. The water table position and approximate maximum rooting depth (rhizosphere) refer to *Astelia* lawns only.

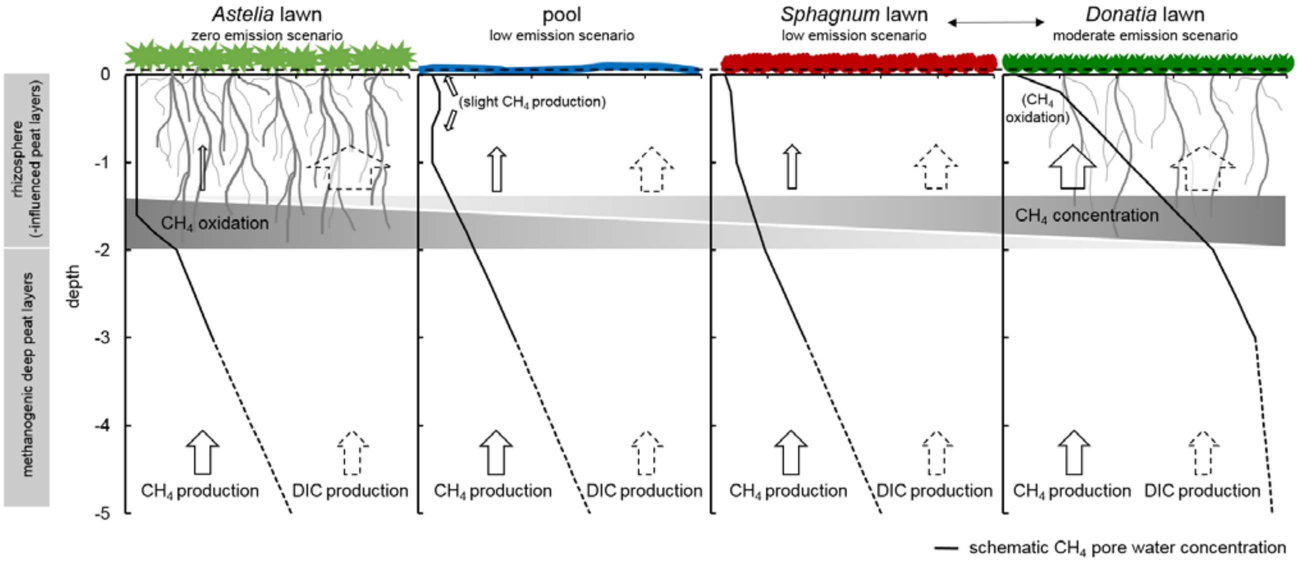

Figure 6. Schematic CH_4 concentration profiles below the four dominant microforms in a Patagonian cushion bog. The shape of profiles was derived from data obtained in the present study together with those by Limpens et al. (2008), Fritz et al. (2011) and Broder et al. (2015). The size of arrows represents the relative magnitude of either a CH_4 or CO_2 flux following the diffusion gradient. The water table position is displayed by a dashed line near the surface. CH_4 oxidation by root O_2 release resulted in near-zero CH_4 pore water concentrations in densely rooted peat below *Astelia* lawns. With increasing distance from densely rooted peat, CH_4 oxidation decreased while CH_4 concentration increased until reaching a depth profile typical for those of northern peatlands with less if any roots in water-saturated peat layers. Exemplary sequence of microforms, derived from observed amounts of emitted CH_4. Other sequences of microforms are reasonable as microforms occur in various combinations in the field.

Tables

Table 1. Characteristic plant species of dominant microforms in a Patagonian cushion bog. Species composition was determined during the second measurement campaign within collars where closed chamber measurements were conducted. Mean cover (%) and its standard deviation of characteristic were given and plant species with a mean cover < 5 % were listed with +.

	microform		
species	*Astelia* lawn	*Sphagnum* lawn	*Donatia* lawn
Astelia pumila	84 ± 16		
Donatia fascicularis	8 ± 10	+	90 ± 9
Sphagnum magellanicum		94 ± 4	
Tetroncium magellanicum	+	7 ± 2	+
Caltha dioneifolia	+	+	6 ± 5
Empetrum rubrum	+		
Gaultheria antarctica	+	+	+
Myrteola nummularia	+		

Table 2. CH_4 fluxes determined from individual collars installed in dominant microforms of a Patagonian cushion bog. Number of flux measurements, their mean and standard deviation are presented. Significantly different fluxes from collars within one microform were identified by Kruskal-Wallis analysis of variance and multiple comparison U-tests with Bonferroni adjustment. Results of computing Spearman's rank correlation coefficient rho for the relationships between CH_4 fluxes and possible environmental controls, namely water table depth determined separately for each collar and soil temperature in 0.05 m depth, are given. Furthermore, characteristics of collars and results of computing Spearman's rank correlation for the relationships between mean CH_4 fluxes during the second campaign and each feature are shown. Microform size refers to the extent of a microform in which a specific collar was installed. P-values < 0.05 indicate a correlation significantly different from zero.

year	micro-form		Kruskal-Wallis analysis			water table depth, m		soil temperature, °C		presence *T. magellanicum*			presence *D. fascicularis*			microform size		
			N	mean flux, mmol CH_4 m^{-2} d^{-1}	p	rho	p	rho	p	number of shoots	rho	p	cover, %	rho	p	size, m²	rho	p
2015	*Astelia* lawn	1	60	0.32 ± 0.05	< 0.05	-0.22	n.s.	n.d.	n.d.									
		2	64	-0.02 ± 0.09	n.s.	-0.21	n.s.	0.17	n.s.									
		3	55	-0.01 ± 0.07	n.s.	0.03	n.s.	-0.08	n.s.									
	Sphagnum lawn	1	62	0.21 ± 0.05	< 0.05	-0.21	n.s.	n.d.	n.d.									
		2	64	1.96 ± 0.33	n.s.	0.41	< 0.05	0.52	< 0.05									
		3	54	2.99 ± 0.35	n.s.	0.2	n.s.	0.6	< 0.05									
	pool	1	13	0.05 ± 0.03	n.s.			n.d.	n.d.									
		2	12	0.14 ± 0.08	n.s.			0.4	n.s.									
		3	10	0.36 ± 0.2	n.s.			0.64	< 0.05									
		4	11	0.28 ± 0.2	n.s.			-0.01	n.s.									
2016	*Astelia* lawn	1	7	0.29 ± 0.04	n.s.	0.27	n.s.	-0.13	n.s.	15	0.67[a]	n.s.	25	0.01	n.s.	1.12	-0.10	n.s.
		2	11	-0.02 ± 0.1	n.s.	-0.22	n.s.	-0.16	n.s.	0			4			4.45		
		3	8	0.07 ± 0.05	n.s.	-0.68	n.s.	-0.31	n.s.	0			0			26.66		
		4	11	0.06 ± 0.15	n.s.	-0.09	n.s.	0.13	n.s.	0			8			3.38		
		5	11	0.06 ± 0.04	n.s.	-0.44	n.s.	0.14	n.s.	6			2			4.55		
	Donatia lawn	1	9	2.1 ± 0.14	< 0.05	-0.82	< 0.05	0.74	< 0.05	30	1.00[a]	n.s.	80	-1.00[a]	n.s.	0.26	0.50	n.s.
		2	11	0.01 ± 0.09	n.s.	0.29	n.s.	-0.64	< 0.05	9			97			0.15		
		3	10	0.08 ± 0.04	n.s.	-0.46	n.s.	-0.2	n.s.	18			92			0.96		
	Sphagnum lawn	1	9	0.09 ± 0.05	< 0.05	0.68	n.s.	-0.78	< 0.05	66	0.40	n.s.	0	0.71[a]	n.s.	0.43	0.00	n.s.
		2	11	1.01 ± 0.06	n.s.	0.15	n.s.	-0.42	n.s.	165			0			2.38		

	3	11	1.39 ± 0.1	n.s.	-0.05	n.s.	-0.05	n.s.	175	0	2.7
	4	9	1.9 ± 0.08	< 0.05	-0.44	n.s.	0.25	n.s.	108	4	0.38
	5	10	0.68 ± 0.03	n.s.	0.17	n.s.	-0.22	n.s.	120	0	0.65
pool	1	2	0.35 ± 0.11	n.s.			n.d.	n.d.			
	3	1	0.6 ± 0	n.s.			n.d.	n.d.			
	4	1	1.35 ± 0	n.s.			n.d.	n.d.			

n.s. = not significant, n.d. = not determined, [a] = despite a (relative) high absolute value of Spearman’s rho, p-values did not indicate a significant correlation, probably because of outliers.

Table 3. Summary of peat characteristics obtained from two peat cores taken in *Astelia* lawns in a Patagonian cushion bog. Data were averaged over the respective depths sampled in 0.1 m resolution.

peat characteristics	depth, m	bulk density, g cm^{-3}	N, %	C, %	CN	$\delta^{15}N$	$\delta^{13}C$
amorphous, highly decomposed cushion peat with many living *Astelia* roots, only close to the surface (0-0.4 m) with recognizable plant material	0-1	0.03	1.42	49.31	37.62	-1.24	-25.63
	1-2	0.06	1.83	52.45	28.69	1.24	-26.18
Sphagnum peat, with depth increasingly amorphous and decomposed	2-3	0.06	1.52	51.37	34.38	1.12	-26.33
	3-4	0.06	1.22	50.49	41.98	0.22	-25.78
	4-5	0.11	1.17	47.86	41.45	-1.59	-26.43
	5-6	0.10	1.18	47.56	40.67	-1.62	-26.77
	6-7	0.15	1.28	50.27	44.34	-1.97	-27.08

Supplement of

Zero to moderate methane emissions in a densely rooted, pristine Patagonian bog and their biogeochemical controls as revealed from isotopic evidence

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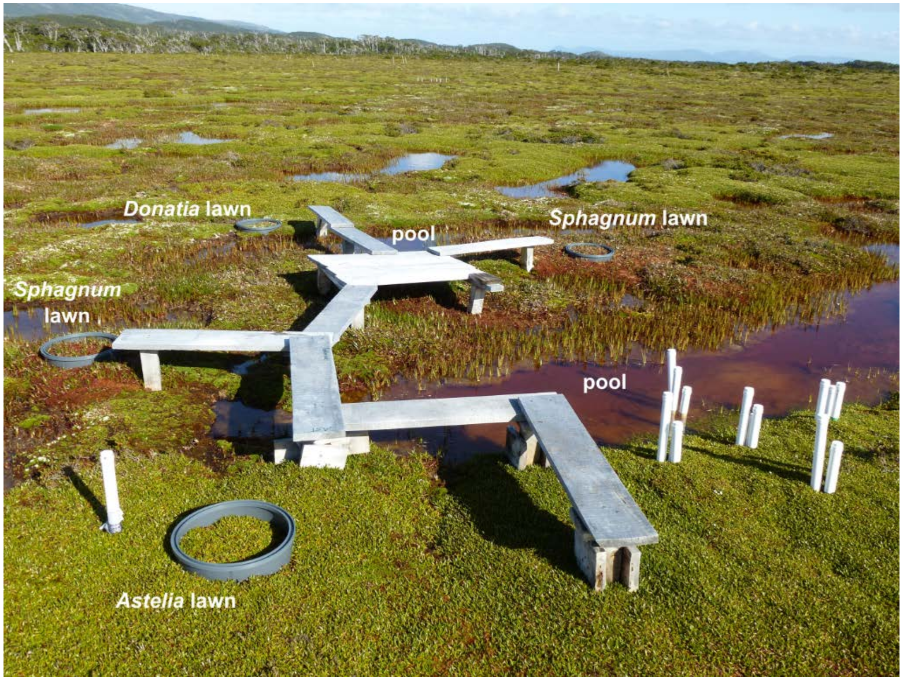
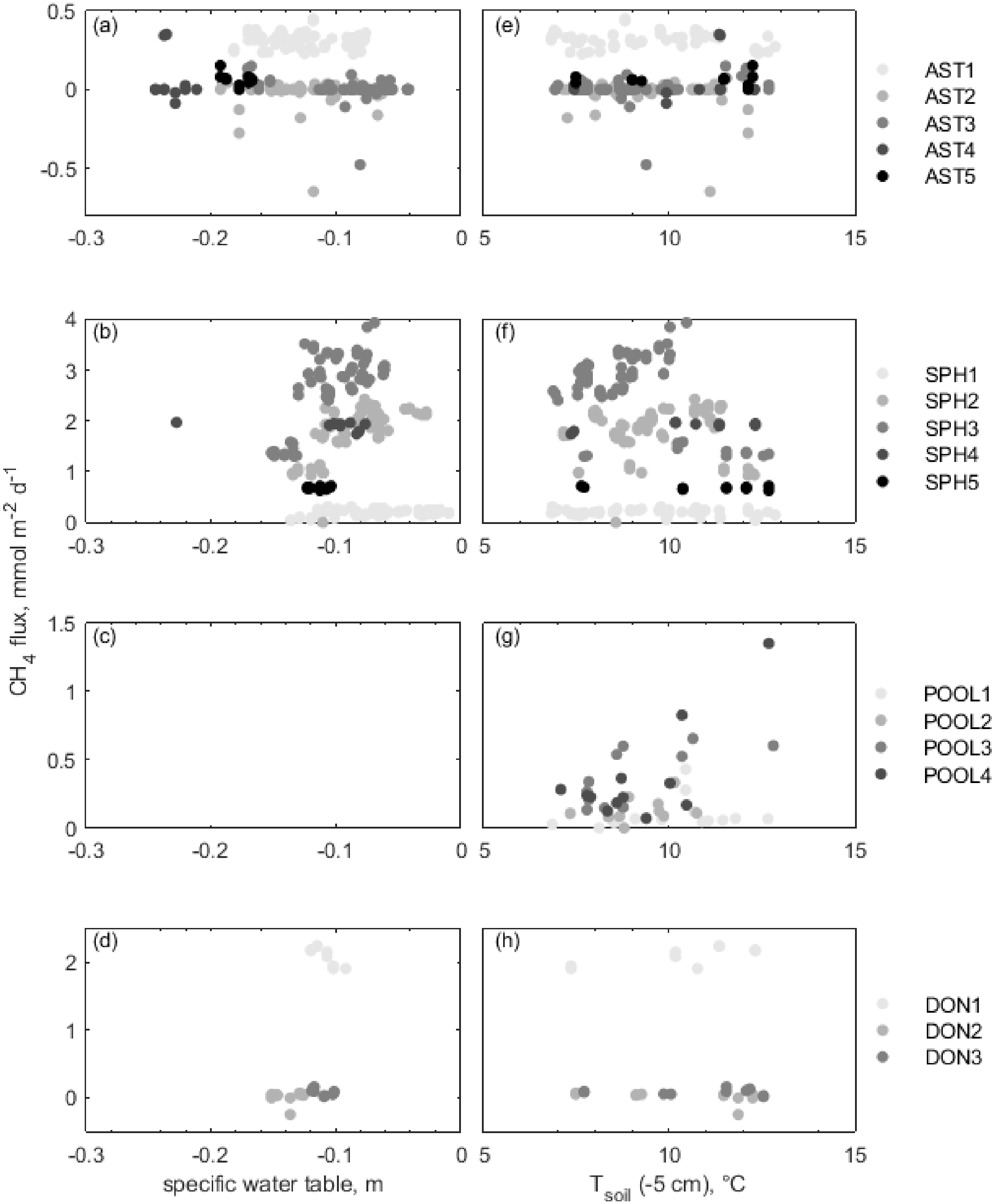


Figure S01. Arrangement of collars at platform 3 in the study site. Boardwalks were not installed between platforms to minimize disturbance of the cushion vegetation surface. Picture taken by Isabella Närdemann. Note the different types of microforms.



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
0.5
0
-0.5
4
3
2
1
0
1.5
1
0.5
0
2
1
0
-0.3
-0.2
-0.1
0
5
10
15
CH$_4$ flux, mmol m^{-2} d^{-1}
specific water table, m
T$_{soil}$ (-5 cm), °C
AST1
AST2
AST3
AST4
AST5
SPH1
SPH2
SPH3
SPH4
SPH5
POOL1
POOL2
POOL3
POOL4
DON1
DON2
DON3

Figure S02 a-h CH_4 fluxes measured from individual collars of dominant microforms (*Astelia* lawns (a,e), *Sphagnum* lawns (b,f), pools (c,g) and *Donatia* lawns (d,h)) in a Patagonian cushion bog plotted against water table depth and soil temperature. CH_4 emissions were mostly decoupled from environmental controls probably since CH_4 fluxes were negligible in many cases. Obviously, individual collars of microforms with non-zero emissions released different amounts of CH_4.

Identification of CH_4 production and consumption zones applying PROFILE

Methods

Zones of CH_4 production and consumption in the peat column were quantitatively identified by inverse modelling based on pore water profiles of CH_4 concentrations using the software routine PROFILE (Berg et al., 1998). Steady-state conditions as well as a dominance of diffusive gas transport over ebullient events and aerenchymatic transport would have to be assumed. Given the large root biomass, this may only partly apply to the system under study here. Therefore, the modelling approach provided only rough estimates for production and consumption zones due to the complex diffusivity in the rhizosphere of highly rooted peat. Nevertheless, diffusion coefficients for CH_4 were derived from Lermann (1988) and corrected for mean soil temperatures (of 10°C in February 2015 and 2016 as well as 7°C in April at a depth of 0.5 m) as well as porosity. Porosity ϕ was calculated as (Eq. A1)

$$\varphi = 1 - \frac{\rho_{\mathrm{bulk}}}{\rho_{\mathrm{particle}}}$$

where ρ bulk is the bulk density (g cm^{-3}) and ρ particle the particle density (g cm^{-3}). Particle density was assumed to be 1.5 g cm^{-3} (Weiss et al., 1998). Below *Asteli*a lawns, the porous media available for diffusion was reduced by presence of roots and porosity was calculated considering the average root biomass throughout the rhizosphere. The software input requires equal depth zones and thus data were averaged to get a 0.2 m resolution over the whole profile, if necessary. The model results were evaluated at a significance level of 0.05.

Results and discussion

The lower rhizosphere of *Astelia* lawns was the most pronounced sink of CH_4, while in the upper rhizosphere production of (small amounts) of CH_4 was balanced by CH_4 oxidation (fig. A3, a-f). Zones of CH_4 consumption below pools (fig. A3, g-l) roughly corresponded to zones of CH_4 consumption of *Astelia* lawns while near the surface net production also approached zero. These zones of CH_4 consumption in relatively great depths below pools support our assumption of a lateral concentration gradient distributing e.g. CH_4 and O_2 along adjacent microforms. The pool sediment was identified as a zone of CH_4 production in two cases, possibly due to the availability of degradable organic matter from submerged

Sphagnum. The near-zero diffusive CH_4 flux was consistent with low emission measured by chambers. Deep peat layers below those sampled would probably indicate intense CH_4 production.

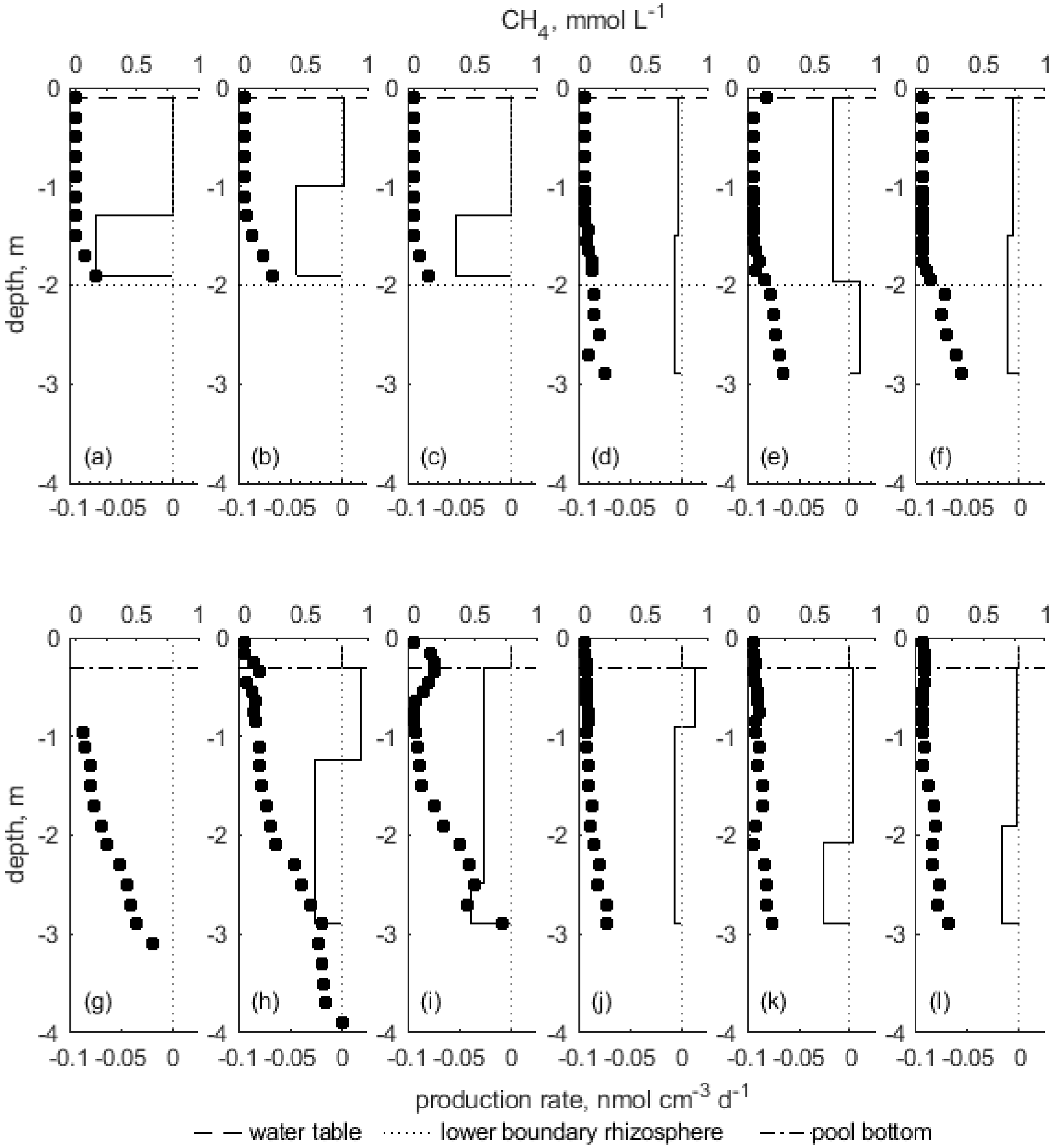

CH$_4$, mmol L^{-1}
0 0.5 1
depth, m
0 -1 -2 -3 -4
(a) (b) (c) (d) (e) (f)
(g) (h) (i) (j) (k) (l)
-0.1 -0.05 0
production rate, nmol cm^{-3} d^{-1}
water table
lower boundary rhizosphere
pool bottom

Figure S03 a-l CH_4 pore water concentration depth profiles obtained from MLPs installed in *Astelia* lawns and pools during two sampling campaigns in austral summer 2015 and 2016. Displayed depths represent the centre of a MLP segment. Note that no data were available for the upper profile of pool 1 and that modelling of production rates did not include all data obtained from pool 2 in 2015 for depth consistency. Concentrations are given per volume of pore water while production rates are given per volume of peat.

References

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