Greenhouse gas released from the deep permafrost in the northern Qinghai-Tibetan Plateau

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Deep carbon pool in permafrost regions is an important component of the global terrestrial carbon cycle. However, the greenhouse gas production from deep permafrost soils is not well understood. Here, using soils collected from 5-m deep permafrost cores from meadow and wet meadow on the northern Qinghai-Tibetan Plateau (QTP), we investigated the effects of temperature on CO2 and N2O production under aerobic incubations and CH4 production under anaerobic incubations. After a 35-day incubation, the CO2, N2O and CH4 production at −2 °C to 10 °C were 0.44~2.12 mg C-CO2/g soil C, 0.0027~0.097 mg N-N2O/g soil N, and 0.14~5.88 μg C-CH4/g soil C, respectively. Greenhouse gas production in deep permafrost is related to the C:N ratio and stable isotopes of soil organic carbon (SOC), whereas depth plays a less important role. The temperature sensitivity (Q10) values of the CO2, N2O and CH4 production were 1.67–4.15, 3.26–5.60 and 5.22–10.85, without significant differences among different depths. These results indicated that climate warming likely has similar effects on gas production in deep permafrost and surface soils. Our results suggest that greenhouse gas emissions from both the deep permafrost and surface soils to the air will increase under future climate change.

High-mountain environments experience more rapid changes in temperature than those at lower elevations1. In the past decades, permafrost degradation accompanying climate warming has been widely detected in mountain permafrost regions as well as in the high-latitude Arctic regions. This degradation is evident from the deepening of the active layer thickness2,3, ground temperature increases4,5, and thermokarst terrain formations6. Permafrost thaws accelerate the rates of carbon and nitrogen released by the soil into the atmosphere and cause a significant positive climate-change feedback7. A large amount of soil organic carbon is stored in mountainous permafrost regions, and the carbon pools of these regions are very sensitive to temperature increases8,9.

Soil organic matter (SOM) decomposition in permafrost-affected soils is controlled by a complex interplay of environmental parameters such as temperature, soil water content, oxygen and nutrient availability10. In particular, temperature has a strong positive effect on aerobic and anaerobic soil respiration rates in permafrost regions11,12. Since permafrost degradation typically presents as a gradual increase in soil temperature from below 0 °C, to near 0 °C and then to above 0 °C, incubation experiments using permafrost soils at colder (<0 °C) and warmer temperatures (10 °C)13–15 can provide insights into the changes of greenhouse gas release that accompany permafrost degradation. The Qinghai-Tibetan Plateau (QTP) is the largest low-latitude mountainous permafrost area and has special thermal characteristics; e.g., the ground temperature is considerably higher than that in high-latitude regions, often being near 0 °C. The soil organic carbon (SOC) pools of the QTP have been estimated to approximately 28 Pg in the upper 2 m of soil and approximately 160 Pg for the upper 25 m soils. More than half of the SOC is stored in the soils under meadow and wet meadow16. Therefore, obtaining an understanding of greenhouse gas release under these two land cover types is important. The soil respirations in the upper soils, such as the upper 10 cm, has been shown to vulnerable to decomposition and to have a high sensitivity to temperature17. However, few studies have been performed to determine the CO2 emissions of the deep permafrost on the QTP1. Furthermore,
the deep permafrost produces unknown amounts of CH\textsubscript{4} and N\textsubscript{2}O, which are also important greenhouse gases that can be released into the atmosphere\textsuperscript{7}.

Permafrost cores can contain a broad range of soil water contents from the active layer to the permafrost table and to the deep permafrost-affected soils\textsuperscript{8}. In the permafrost regions on the QTP, the SOM has been well preserved due to the low decomposition rates. Climate warming can stimulate microbial decomposition of the SOM and lead to greenhouse gas emissions under both aerobic and anaerobic conditions. We hypothesized that 1) the production of greenhouse gas, including CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O, of the different permafrost layers is comparable to that in high-latitude permafrost regions throughout the deep soils; 2) the production of greenhouse gas in the deep permafrost is sensitive to temperature increases independent of depth; and 3) the production of greenhouse gas is related to the water-extractable organic carbon (WEOC) content. To test these hypotheses, we collected \~5 m long soil cores from meadows and wet meadows in the permafrost region of the QTP (Table 1) and then measured the greenhouse gas emissions of the soils sampled at different depths of these cores. Soil incubation experiments were conducted under aerobic (to measure CO\textsubscript{2} and N\textsubscript{2}O production) and anaerobic (to measure CH\textsubscript{4} production) conditions at temperatures of \textdegree C, 5 \textdegree C and 10 \textdegree C, and the relationships among the soil parameters of the deep permafrost were examined.

### Results

#### Carbon and nitrogen characteristics.

Soil samples from three deep cores were collected and analyzed (Fig. 1). The deep cores of \#A, \#B and \#C exhibited considerable variations in soil water content, TN, SOC, WEOC and \textsuperscript{13}C-SOC\textsubscript{‰} (Fig. 2). Soil water content, TN and SOC content were higher in core \#C, which was taken in a wet meadow, than in the cores from meadow (cores \#A and \#B). Soil water content in cores \#A, \#B and \#C had ranges of 14.7–45.7\%, 4.9–58.7\%, and 51.2–91.0\%, respectively. Regarding the stable isotope signatures, the \textsuperscript{13}C-SOC\textsubscript{‰} values of deep cores \#A (−22.9~−28.0\‰) and \#B (−22.8~−27.8\‰) showed greater vertical changes than did those of core \#C (−25.2~−26.3\‰).

| Site | Latitude(°) | Longitude(°) | Altitude(m) | MAGT(°C) | Aspect | Topography | Land cover | Active layer (m) | Above ground biomass (kg·m\textsuperscript{−2}) |
|------|-------------|--------------|-------------|----------|--------|------------|------------|-----------------|-----------------------------------------------|
| \#A  | 98.9627     | 38.9548      | 4153        | −1.71    | Southeast | PS | Meadow     | 2.0            | 0.464                                        |
| \#B  | 98.9630     | 38.9030      | 3970        | −1.64    | Northeast | PSP | Meadow     | 2.3            | 0.512                                        |
| \#C  | 100.9163    | 37.9979      | 3691        | −0.70 (19 m) | North | PS | Wet meadow | 1.4            | 0.791                                        |

Table 1. Summary of Borehole Site details. MAGT = mean annual ground temperature; PS = piedmont slope; PSP = piedmont sloping plain; The above ground biomass was measured in August 2014 using the harvesting method, and the active layer thicknesses were determined based on monitoring the ground temperatures of the drill holes from 2013 to 2015.

Figure 1. Study area and locations of deep permafrost cores (\#A, \#B and \#C) on the northern Qinghai-Tibetan Plateau. The map was created using ArcGIS 9.3 (https://www.esri.com/en-us/home).
Greenhouse gas emissions and their temperature sensitivities. After a 35-day incubation, there were similar trends in the CO₂, N₂O and CH₄ emissions with depth at temperatures of −2 °C, 5 °C and 10 °C (Fig. 3). The production of greenhouse gas was obviously higher at 10 °C than at 5 °C or −2 °C. For core #A, the highest CO₂ production was 4.86 mg C-CO₂/g soil C, which was recorded at a depth of 0.3 m. Below this depth, CO₂ production was typically lower than 2 mg C-CO₂/g soil C. The highest CO₂ production was 6.58 mg C-CO₂/g soil C, observed in soil core #B. For cores #B and #C, the mean CO₂ production at 10 °C was 2.12 and 1.32 mg C-CO₂/g soil C, respectively. N₂O production at the three temperatures showed similar patterns. At 10 °C, the mean values were 0.097, 0.062, and 0.017 mg N-N₂O/g soil N for cores #A, #B and #C, respectively. The CH₄ production at −2 °C and 5 °C was similar, but the values increased considerably at 10 °C. The CH₄ emissions of core #C were lower than those of cores #A and #B. At 10 °C, the mean CH₄ emissions for cores #A, #B, and #C were 3.36, 5.88, and 1.64 μg C-CH₄/g soil C.

The temperature sensitivity (Q₁₀) values of the greenhouse gas emissions of cores #A, #B and #C exhibited similar trends, with the Q₁₀ values of the CH₄ emissions being higher than those of the N₂O emissions and the lowest values observed for the CO₂ emissions (Fig. 4). The Q₁₀ values for the CO₂ emissions for cores #A, #B and #C had ranges of 2.38~3.79, 2.26~4.15 and 1.67~3.93, respectively. The Q₁₀ values of the N₂O emissions for cores #A, #B and #C had ranges of 3.26~4.44, 3.82~5.60 and 3.76~4.40, respectively. For the CH₄ emissions of cores #A, #B and #C, the Q₁₀ values had ranges of 5.62~7.75, 5.22~9.82 and 5.69~10.85, respectively. For the same greenhouse gas, there were no significant differences among the Q₁₀ values at different depths (t-test, p > 0.05, n = 3).

Factors influencing greenhouse gas production. Across the three cores, there was no significant relationship between depth and production of any of the greenhouse gases. When the greenhouse gas emissions were expressed using a dried soil base, all of the emissions were significantly correlated with soil water, SOC and TN contents (Table 2, supplementary information Dataset 1). When the gas emissions were expressed using a soil carbon base, CO₂ production was significantly positively correlated with WEOC content, which was negatively correlated with depth. N₂O and CH₄ production were both negatively correlated with soil water content, SOC...
content, and TN content. N$_2$O production was significantly correlated with the C:N ratio, and CH$_4$ production was significantly correlated with CO$_2$ production (Table 2).

**Discussion**

**Soil carbon and nitrogen in permafrost layers.** In most soils, the SOC and TN contents decrease with depth. Vertical decreasing trends of SOM have been observed in the arid areas of the QTP$^{18}$. In this study, the SOC and TN contents were negatively correlated with depth, but these negative correlations were not statistically
significant. This result might be explained by the effects of permafrost on SOM: SOM content can be high in deep soils when the SOM has been protected from microbial decomposition by permafrost19. Cryoturbation processes can also bury some organic layers in deep soils20.

The 13C‰ and WEOC showed significant relationships with depth. WEOC is typically characterized by low molecular weight compounds, which can be directly transported across microbial cell membranes, and thus mainly consists of labile fractions21. In addition, the decomposition of organic matter fractionates the isotopic signal of the SOC since the respired CO2 must be 13C depleted22–24. For example, microorganisms may preferentially respire CO2 that is 13C-depleted relative to the substrate25. Therefore, the remaining SOC in deep soils has a more enriched 13C-signature. The 13C‰ distribution over different depths might also be explained by the significant correlation of WEOC with depth; i.e., the labile C pool (WEOC) decreased with depth, thus causing an increase in 13C-signature with depth. The significant relationships between soil water content and each of SOC and TN reflect the fact that a high soil water content limits the decomposition of SOM because it reduces the oxygen availability for microbial decomposition26,27.

Greenhouse gas emissions. Temperature is one of the important controls of organic matter decomposition6. In this study, greenhouse gas emissions increased with temperature during both the aerobic and anaerobic incubations. The greenhouse gas emissions were the mean values from the triplicate measurement during the incubation.

| Soil water | 13C‰ | SOC | TN | C:N | WEOC | CO2 | N2O | CH4 | Depth |
|------------|------|-----|----|-----|------|-----|-----|-----|-------|
| Soil water | 1.00 |     |    |     |      |     |     |     |       |
| 13C‰ | 0.00 | 1.00 |
| SOC | 0.84** | −0.06 | 1.00 |
| TN | 0.83** | −0.03 | 0.99** | 1.00 |
| C:N | −0.31 | −0.34 | −0.29 | −0.36 | 1.00 |
| WEOC | −0.16 | −0.21 | −0.19 | −0.20 | 0.14 | 1.00 |
| CO2 | −0.17 | 0.06 | −0.23 | −0.22 | −0.15 | 0.46* | 1.00 |
| N2O | −0.49** | 0.03 | −0.64** | −0.67** | 0.68** | 0.08 | 0.16 | 1.00 |
| CH4 | −0.47* | 0.38* | −0.55** | −0.50** | −0.20 | 0.22 | 0.59** | 0.29 | 1.00 |
| Depth | 0.00 | 0.46* | −0.16 | −0.11 | −0.02 | −0.42* | −0.34 | 0.27 | 0.09 | 1.00 |

Table 2. Relationships among soil variables and greenhouse gas emissions (for 10 °C). *p < 0.05, **p < 0.01, n = 28. The greenhouse gas emissions were the mean values from the triplicate measurement during the incubation.
**Table 3.** Greenhouse gas emissions of previously published works and our study. *The 35 day emissions were calculated from the reported emissions with the assumptions that the production rates were constant. The emissions expressed using the SOC and TN bases were calculated according to the reported SOC and TN contents when the reported emissions were expressed for dry soil weights.*

| Area                         | SOC/TN content | Incubation temperature | Reported emissions | 35 day production* | References               |
|------------------------------|----------------|------------------------|--------------------|--------------------|-------------------------|
| **CO₂ emissions**            |                |                        |                    |                    |                         |
| Siberian tundra              | 5–11% SOC      | 4 °C                   | 3.5–15 mg C-CO₂/g C/60 days | 2.0–8.8 mg C-CO₂/g C | Walz et al., 2017       |
| Alaskan tundra               | 1–16% SOC      | 15 °C                  | 1–3.5 mg C-CO₂/g C/500 days | 2.0–9.0 mg C-CO₂/g C | Lee et al., 2012        |
| Northern China peat          | 22–41% SOC     | 5 °C, 15 °C            | 0.5–8 mg C-CO₂/kg soil/h | 1.5–22 mg C-CO₂/g C | Wang et al., 2014       |
| Qinghai-Tibet Plateau wet meadow | 4–12% SOC      | 5 °C                   | 0.25–2 mg C-CO₂/g C/7 days | 1.3–10 mg C-CO₂/g C | Ma et al., 2016         |
| Our study                    | 0.3–11% SOC    | –2 °C, 5 °C, 10 °C     | 0.0007–0.58 mg C-CH₄/g soil/500 days | 0.049–4.06 mg C-CH₄/g C | Lee et al., 2012        |
| **CH₄ emissions**            |                |                        |                    |                    |                         |
| Alaskan tundra               | 1–16% SOC      | 15 °C                  | 0.05–0.3 g C-CH₄/g C/60 days | 0.03–0.175 mg C-CH₄/g C | Walz et al., 2017       |
| Siberian tundra              | 5–11% SOC      | 4 °C                   | 0.05–0.3 g C-CH₄/g C/60 days | 0.03–0.175 mg C-CH₄/g C | Walz et al., 2017       |
| Our study                    | 0.3–11% SOC    | –2 °C, 5 °C, 10 °C     | 0.14–5.88 μg C-CH₄/g C |                    |                         |
| **N₂O emissions**            |                |                        |                    |                    |                         |
| Greenland wetland            | 0.05–0.2% TN   | 7 °C                   | 1.6 ugN-N₂O/kg soil/h |                    | Elberling et al., 2010  |
| Northern China peat          | 1.4–1.9% TN    | 5 °C, 15 °C            | 0.05–1.5 ugN-N₂O/kg soil/h | 0.004–0.1 mgN-N₂O/g N | Wang et al., 2014       |
| Our study                    | 0.02–1.5% TN   | –2 °C, 5 °C, 10 °C     | 0.003–1.35 mgN-N₂O/g N |                    |                         |

The Q₁₀ values in our study confirm that the greenhouse gas production is sensitive to increased temperature. For deep permafrost soils, the average Q₁₀ values of the CO₂ and N₂O emissions were 2.9 and 4.3, respectively. These values are higher than those (2.0–2.2) observed in the high-latitude peat and fen permafrost regions of northern China. The Q₁₀ values of the CO₂ emissions were similar to those (3.4–6.1) observed in Siberian tundra soils. The Q₁₀ values of N₂O production in our study were in the range (1.5–6.9) of those reported for Canadian agricultural soils. The Q₁₀ values of CH₄ are generally higher than those of CO₂, although there is large variation (ranging from 1.7 to 28) among different temperature conditions. In an experiment using paddy soils, the Q₁₀ value of CH₄ was approximately 7.4 times higher than that of CO₂. In this study, the Q₁₀ values of CH₄ production ranged from 5.22 to 10.85 and were higher than the values observed for CO₂ and N₂O production. The high Q₁₀ values of CH₄ likely result from several mechanisms. First, CH₄ oxidation is less sensitive to temperature than is methanogenesis due to its lower optimum temperature such that the CH₄ emissions show high Q₁₀ values. Second, the solubilities of CH₄ and O₂ decrease with increased temperature, further limiting the oxidation of methane. Third, higher temperatures promote microbial activity and thus provide more substrates for CH₄ production. Increasing temperature might also shift the composition of the archaean community and the pathways of methanogenesis towards hydrogenotrophic methanogenesis. Overall, the greenhouse gas emissions of the deep permafrost soils of the QTP are sensitive to temperature increases.

**Relationships between greenhouse gas emissions and soil variables.** The greenhouse gas emissions expressed using a soil mass base were significantly correlated with soil water, SOC and TN contents, indicating that more substrates supply favors the greenhouse gas production. We mainly focused on the CO₂ emissions expressed using a SOC base because these emissions can potentially be used to estimate greenhouse gas emissions based on the global permafrost carbon pools. Consequently, the CO₂ emissions expressed by a soil C base were negatively correlated with the SOC contents. Although the WEOC represents a labile carbon pool, there was no significant relationship between WEOC content and greenhouse gas production. This result confirms that the mechanisms of microbial decomposition are very complicated.

There was a significant positive correlation between CH₄ production and ¹³C‰, which can potentially be attributed to the different effects of soil depth on CH₄ production and ¹³C‰. ¹³C‰ was significantly positively correlated with depth (¹³C becomes increasingly enriched with depth), whereas CH₄ production showed no decreasing trend with depth. Additionally, the acetoclastic hydrogenotrophic pathways of methanogenesis allow for microbial activities that are more independent of the ¹³C‰ values of SOM. Previous studies suggested that the availability of labile substrates is one of the limiting factors for methanogenesis due to its lower optimum temperature such that the CH₄ emissions show high Q₁₀ values. Second, the solubilities of CH₄ and O₂ decrease with increased temperature, further limiting the oxidation of methane. Third, higher temperatures promote microbial activity and thus provide more substrates for CH₄ production. Increasing temperature might also shift the composition of the archaean community and the pathways of methanogenesis towards hydrogenotrophic methanogenesis. Overall, the greenhouse gas emissions of the deep permafrost soils of the QTP are sensitive to temperature increases.
emissions were affected by the labile fractions of SOM. The temperature sensitivities of the CO₂ emissions ranged from 2.9 to 4.3 across the soil cores, suggesting that the production of CO₂ in the soils beneath the meadows and wet meadows of permafrost regions is sensitive to temperature increases. The sensitivity of CH₄ production to temperature was considerably greater than that of CO₂, which is consistent with previous studies of many soils [4,5,37]. The temperature sensitivity of N₂O production was within the range of sensitivity values observed for circum-Arctic regions. The greenhouse gas emissions in deep permafrost regions are related to the C:N ratio and stable isotopes of SOC, whereas depth plays a less important role. Our results also showed the SOM below 2 m can contribute to global greenhouse gas emissions in permafrost regions.

Methods

Sampling and analysis. In 2012–2014, three permafrost boreholes of various lengths were collected using machine drilling. The cores, #A, #B and #C, were located in the northern QTP, northwestern China (Fig. 1). The area is characterized by an alpine semi-arid climate, has an annual mean precipitation of 433 mm and has a mean annual temperature of 1.5 °C. The three sites had alpine meadow and alpine wet meadow ground conditions; the dominant species was Kobresia tibetica Maxim. The vegetation types, average ground temperatures and other geomorphic features are shown in Table 1.

Cores of the active and permafrost layers, which were up to 4.0–5.3 m in length and had diameters of 15 cm, were collected. The collected cores were wrapped, labeled, and stored in a freezer at −20 °C and transferred to the laboratory. All frozen cores were cut in half lengthwise. Then, one-half of each core was analyzed for its physical and chemical characteristics, and the other half was incubated under aerobic and anaerobic conditions.

Sampling and analysis. The soil water content was determined by drying the soils at 105 °C for 8 h and measuring the soil weights before and after drying. The SOC, total carbon, and total nitrogen (TN) of the pulverized homogenized samples were quantified by dry combustion using a Vario EL elemental analyzer (Elementar, Hanau, Germany). For the measurement of the WEOC, the soil samples were taken from the −20 °C freezer and put into flasks. The soils were kept at 4 °C for 4 h to thaw the soils. Then, the WEOC was determined by shaking 20 g of moist field soil with 100 ml of deionized water for 5 h; the suspension was then centrifuged and filtered. The stable carbon isotopes in the SOC were analyzed using an OI Analytical Analyzer (Picarro, California, USA).

Incubation experiments. Frozen samples from cores #A, #B and #C were slowly thawed from −20 °C to −2 °C in a refrigerator. The soil samples were incubated at constant temperatures of −2 °C, 5 °C and 10 °C under aerobic and anaerobic conditions. The samples used for the aerobic incubations were weighed, placed into pre-weighed mason jars with airtight lids, and then placed in the incubator (Thermo, USA). For the anaerobic incubations, the headspaces of the anaerobic samples were filled with N₂. The CO₂ and N₂O emissions under aerobic conditions and the CH₄ emissions under anaerobic conditions were calculated using the changes in the headspace gas concentrations over time (adjusted for headspace volume) [4]. The incubation experiments were performed for 35 days at each temperature, and the gas concentrations were measured on days 7, 14, 21, 28 and 35.

The CO₂ concentrations were measured with a Licor-7000 infrared gas analyzer (Li-Cor, Lincoln, NE, USA) with nitrogen used as the carrier gas. At each measurement point, three 20 ml headspace samples were collected using a syringe through a rubber septum in the container lid over a 48-hour period and were analyzed for their CO₂ concentrations. After each measurement, the mason jars were maintained in the open position for 12 hours to allow the headspace CO₂ to equilibrate with the atmosphere. The CH₄ and N₂O concentrations were measured using a gas chromatograph (GC, Agilent 7890 A, Agilent Technologies Inc., Santa Clara, CA). The GC was equipped with a flame-ionization detector (FID) and an electron capture detector (ECD). The FID, ECD and column temperatures were held at 200 °C, 330 °C and 55 °C, respectively. High-purity nitrogen was used as the carrier gas for the FID and ECD systems at a flow rate of 30 and 35 ml/min, respectively. During the incubation period, the jars were weighed weekly to determine the amount of water lost through evaporation. When necessary, water was added to bring the soil samples to their initial weights.

Statistical analysis. The values of Q₁₀ were calculated by fitting Equation (1) to estimate of the temperature sensitivities of the greenhouse gas:

\[ P = A e^{BT} \]

where \( P \) is the rate of greenhouse gas production, \( T \) is the temperature, \( e \) is an exponential function, \( A \) and \( B \) are fitted parameters, and the \( Q₁₀ \) was calculated as:

\[ Q₁₀ = e^{10B} \]

The CO₂ and CH₄ emissions were expressed based on SOC, and N₂O emissions were expressed based on TN. We also calculated these greenhouse gas emissions based on dried soil weight (supplementary information Dataset 1). The data analyses were performed in R.3.3.3 (https://www.r-project.org/). The greenhouse gas emissions are presented as mean values and standard deviations, and a one-way ANOVA with post-hoc Tukey’s test was used to compare the \( Q₁₀ \) values at different depths.

Data availability. All relevant data are available from the corresponding author upon request.
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**Author Contributions**

C.M., L.L., Q.Z. Performed field work. C.M., X.W. performed the laboratory work and data analysis. X.W. and T.Z. designed the study. All the authors wrote the paper.

**Additional Information**

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