Antarctic Permafrost Degassing Revealed By Extensive Soil Gas and Co_2 Flux Survey in Taylor Valley

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Abstract

McMurdo Dry Valleys comprise 10% of the ice-free soil surface areas in Antarctica. Permafrost stability plays an important role in C-cycle as it potentially stores considerable quantities of greenhouse gases. While the geomorphology of the Dry Valleys reflects a long history of changing climate conditions, comparison with the rapidly warming Northern polar region suggests that future climate and ecosystems may change more rapidly from permafrost degradation. In Austral summer 2019/2020 a comprehensive sampling of soil gases and CO_2 flux measurements was undertaken in the Taylor Valley, with the aims to identify potential presence of soil gases in the active layer. The results obtained show high concentrations of CH_4, CO_2, He and an increasing CO_2 flux rate. We identify the likely source of the gas to be from dissolved gases in deep brine moving from inland (potentially underneath the Antarctic Ice Sheet) to the coast at depth beneath the permafrost layer.

Highlights

- First extensive soil gas and CO_2 flux survey in Antarctica.
- Discovering of multigas anomalies zones.
- First CO_2 emission estimation in Taylor Valley.
- Abiotic origin identified for the CO_2.
- Baseline for future monitoring surveys.

1 Introduction

Permafrost is any ground (soil or rock and any ice and organic material inclusions) that remains completely frozen (0°C or colder) for at least two years[1]. Its thaw and the microbial decomposition of previously frozen organic carbon is considered one of the most likely positive climate feedbacks from terrestrial ecosystems to the atmosphere in a gradually warming planet[2,3]. Permafrost is present in both hemispheres at high latitudes and its temperature, thickness, and continuity are controlled by the geographic setting and, to a large extent, by the surface energy balance and thus vary strongly with latitude and it is present in both hemispheres at high latitudes[4]. Climate warming effects are going to impact these regions in the upcoming decades[5,6] and all three types of permafrost below 1000 m elevation (dry, ice-cemented, and massive ice) may be susceptible to warming-related degradation depending on future emission pathways, for example through slumping of melt-lubricated sediments and surface ablation by sublimation-driven ice removal[7,8]. Measurements of CO_2 and CH_4 soil concentrations and fluxes are essential to understand the C cycle in terrestrial ecosystems, although less is known about controls over CO_2 flux (φCO_2) in ecosystems lacking vascular vegetation, including polar deserts (such as the McMurdo Dry Valleys, thereafter MDV) and some hot deserts, where autotrophic inputs are low and abiotic factors tend to dominate in determining φCO_2[9].

In the Arctic and boreal regions, permafrost is found in Greenland, Alaska, Canada, Northern Europe, Russia and China[4], and represent 22% of the exposed land surface[10]. Studies carried out on permafrost soils in these ecosystems have shown how these areas store almost twice the carbon currently present in the

atmosphere[4,11]. These regions are rich in frozen organic matter, that would lead to an increase of the production of CO_2 and CH_4 by microbial activities in case of thawing[4]. Furthermore, part of the released carbon could easily dissolve in water and, through solar radiation, produce CO_2 by the photomineralization process[12]. Large methane deposits currently stored at high latitude regions are either frozen within permafrost or trapped below impermeable buffer zones[13]. Current and future warming will significantly affect polar and sub-polar regions triggering the melting of ice-bound sediments, releasing methane in to the Earth's atmosphere. Methane has a global warming potential 28 times higher than that of CO_2 on a 100-year time horizon[14]. It is therefore imperative to provide estimates of methane and other gases released from the high-latitude regions. In remote and scarcely monitored regions soil gas release can endure for decades or even centuries before being detected and quantified.

In the Southern Hemisphere, permafrost is found in the Sub-Antarctic islands, in the Antarctic Peninsula, at high elevations, and in the ice-free areas of the Antarctic region. Since Antarctica is much colder than the Arctic, it has limited organic content in soils[4] and its ice-free area represents only 0.35% of the continent[15], the degradation of permafrost has not been widely studied[16]. Nevertheless, if the temperature warms in Antarctica, the potential total amount of carbon contribution could be significant even at a fraction of the Northern Hemisphere. Also, the role of bacteria was in the past underestimated, and is potentially more important in Antarctica than previously believed. Indeed, microbial activity affects the amount of total organic carbon and is more susceptible to weak temperature variations[4]. The MDV are the largest ice-free regions in Antarctica[17]; their geomorphology reveals how the landscape is strongly controlled by climate processes[18]. Attempts to quantify CO_2 emissions in the Antarctic continent have been carried out in the MDV soils, highlighting that φCO_2 is driven primarily by physical factors such as soil temperature and moisture, indicating that future climate change may alter the soil C cycle[17,19–23]. The lack of mechanistic understanding makes it difficult to predict the contribution of soil φCO_2 to the C-cycle due to climate change in the polar deserts of Antarctica. In the MDV, φCO_2 has been used to characterize a variety of ecosystem processes and properties, including soil C turnover, the functional role of differing origins of organic matter supporting C cycling, and biotic distribution and activity[24–28]. In situ φCO_2 in MDV soils is low and spatially variable[29], and it is therefore difficult to separate the biological processes (e.g. C-fixation) from physical factors (e.g. carbonate dissolution). Parsons et al.[30] hypothesized that in extreme desert environments, abiotic factors, like temperature gradients, parent material and soil water dynamics, may have the same magnitude of the biological processes influencing φCO_2 rates; on the contrary, in lowest latitude ecosystems the physical φCO_2 is negligible. Recent studies have revealed a diffuse subsurface brine system in the MDV area, occurring preferentially near the coast and under the surface sediments of the main valleys that could be carried from beneath the East Antarctic Ice Sheet[31]. The presence of this deep fluid circulation could also promote the uprising of geogenic gases. Soil gas measurements in the MDV were performed by Gregorich et al.[29] and by MacIntyre et al.[23] but both works provide few measurement points and were focused on biological process and temporal variability, respectively. In order to understand better the different mechanisms of production and migration of gas species in this environment, it is necessary to carry out a comprehensive survey. To date, no studies have been completed to investigate the soil gas spatial distribution in relation to possible fault and/or fracture systems and characterize seepage for both CO_2 and CH_4 in Antarctica. Soil gas geochemistry

is an alternative powerful approach that is widely used to detect diffusive/advective gas emissions and identify preferential migration pathways such as buried faults and fractured areas[32–38]. Permafrost is generally a barrier to the migration and leakage of endogenous gaseous species. However, the presence of faults, fractures and the thawing, could allow surface migration of anomalous concentrations of endogenous gaseous species. The challenge and the goal of this research is to understand the greenhouse gas potential that is trapped by MDV permafrost and, therefore, how much of these greenhouse gases would be released during thawing events. The rate of carbon release from permafrost soils is highly uncertain[39]. More accurate estimates are crucial to predict the impact and timing of this carbon-cycle feedback effect, and thus how significant permafrost thaw will be for climate change this century and beyond. We report here the first large scale soil gas survey in Antarctica targeting the Taylor Valley as ideal locality for such type of study (Fig. 1). The sampling strategy was developed considering the logistical constraints and finalized to obtain the most representative results of the study area. Our work evaluates the magnitude and spatial distribution of the concentrations of some gases in the soil and of φCO_2 emission from permafrost and/or thawing shallow strata. The goal is to provide a first total CO_2 emission estimate for the lower Taylor Valley that can be used for future monitoring surveys and extrapolated more broadly across the continent.

2 Results

2.1 Soil gas composition and flux magnitude of the lower Taylor valley

Soil gas and flux surveys were carried out between 20 December 2019 and 25 January 2020. A total of 157 soil gas samples and 159 φCO_2 measurements were collected in an area of 21.6 km^2 with an average density of 7.3 samples/km^2 (Fig. 2).

The main statistics obtained for soil gas concentrations and φCO_2 are reported in Table 1. All gas species highlight broadly skewed distributions with the presence of few outliers (see SD and SK in Table 1). By comparing the mean and median values, the presence of outliers is particularly evident for H_2 and CH_4 (mean values > median values). The difference between the mean and median values also suggests a log-normal distribution for φCO_2, CO_2, CH_4 and H_2.

To understand better the magnitude and the significance of the soil gas concentrations measured in Antarctica, calculated mean values are compared with the average concentrations of the same gaseous species present in the atmosphere, in the soil-atmosphere interface and in soil gases from the literature (Table 2). In Taylor Valley, O_2, N_2 and Ne concentrations are broadly equal to their atmospheric concentration. In contrast, H_2, CO_2 and CH_4 concentrations are higher than atmospheric concentrations. CO_2 mean concentration is twice as high as those normally measured in the soil gas. He concentrations highlight a mean value lower than the atmospheric concentration, and as evidenced by the 90% percentile, and only less than 10% of the total samples shows higher concentrations than the atmosphere.

2.2 Spatial distribution of soil gas concentrations and φCO_2 values

The soil gas and φCO_2 distributions were investigated to detect potential permafrost, or to identify the possible presence of faults and fractures, which may provide gas migration pathways. NPPs highlighted the following anomaly threshold values: 5.4 ppmv for He, 18.8 ppmv for Ne, 4 ppmv for H_2, 9 ppmv for CH_4, 0.5 vol% for CO_2 and 3 $gm^{-2}d^{-1}$ for φCO_2. In Fig. 3A CH_4 spatial distribution shows higher values (up to 18,447 ppmv) in the NE and E sectors, and weak anomalies in the other sectors except for the central part of the study area where only background values occur. The contour map of CO_2 (Fig. 3B) shows diffuse anomalous values (> 0.5 vol%) to the S, SW and central sectors of the study area, while in the E sector background values dominate. Some weak anomalies are in close correspondence with those from CH_4. The spatial distribution of φCO_2 is shown in Fig. 3C. Large anomaly zones are located in the NE and SE sectors, while higher anomalous values are in the central south part of the study area; weak anomalies are also present in the SW sector. H_2 distribution (Fig. 3D) shows small anomalous values scattered throughout the study area. However, some of the H_2 anomalies correspond with those observed for CH_4 and CO_2. Regions with high concentrations of He (Fig. 3E) are distributed along N and S borders of the study area. Ne concentrations (Fig. 3F) largely increase together with He and are mostly located along the N edge of the study area.

3 Discussions

In the MDV, very limited data about soil gas concentrations are available (only CO_2 and CH_4), while for the most part they concern CO_2 and CH_4 flux measurements. In 2003-2005 austral summers, Gregorich et al.[29] measured up to 0.55 vol% of CO_2 and up to 5780 ppmv of CH_4 in Garwood valley. In January 2014, MacIntyre et al.[23] measured a maximum value of 0.044 vol% of CO_2 in the lower Taylor Valley, near Howard Glacier (Fig. 1). Both studies found CO_2 concentrations 1-2 orders of magnitude lower than the maximum value measured in this study (3.44 vol%, Table 1). The highest CH_4 value reported in Gregorich et al.[29] is in the same order of magnitude as found in this study, although more than three times lower than our maximum value (18,447 ppmv, Table 1). Both referenced studies, however, collected a limited number of measurements and focused on temporal variability rather than spatial variability. Worldwide, CO_2 and CH_4 soil gas data are numerous, and measured in different environments: in the Arctic Finnish Lapland, Voigt et al.[42], measured CO_2 max value about 6 vol% and CH_4 max value about 300 ppmv. In Italy, CO_2 mean values of about 3 vol% for Tyrrhenian basins, 1.57 vol% for Apennine Intermontane plains and 1.09 vol% for foredeep basins, based on more than 10,000 samples[43].

In contrast, φCO_2 has been measured in Antarctica since 1994 (see Table 3). The φCO_2 measurements in this study are up to 3 orders of magnitude higher than previous studies, therefore, the highest measured in the MDV hereto. φCO_2 measurements in this work in Taylor Valley are on average comparable with the values measured in the Arctic[25,44], desert[25,45] and alpine[46] areas and lower than other areas of the globe[25,47] (Table 3).

The distribution of the positive anomalies for CH_4, CO_2, H_2 and φCO_2 are consistent in the NE, NW and S sectors of the study area, while He shows a good correlation with CO_2 and CH_4 anomalies in the S and N sectors, respectively. He detected in shallow soil is generally indicative of deep sources[32,38], and is typically

associated with CO_2 and CH_4 emissions that act as carrier gas for trace gases (i.e., He, Rn) [35,48]. The source of these gas anomalies could be linked with shallow depth hypersaline fluids[31,49] that during summer periods can release the dissolved gases after permafrost thawing. These gases can then easily migrate toward the surface through permeable layers, as well as local fractures and/or buried faults. These may act as preferential migration pathways thus resulting in the linear multigas anomalous zones observed in the study area[35,37,48] (Fig. 4). Figure 4 shows gas anomalies aligned in ENE-WSW direction in the S and N sectors of the study area, respectively. At the northern boundary, the anomalous zone does not appear as continuous as that occurring in the southern boundary of the area because of the presence of the Commonwealth Glacier and related wetlands and streams (Fig. 2), that most likely prevent gas upwelling.

As for the southern sector, there are also two physical factors that may increase permafrost degradation: solar radiation and soil albedo. Solar radiation is more intense on North facing slopes than South facing slopes and in summer time soil temperatures increase in this sector[18,50]. On the southern slope, south of Commonwealth Glacier is an area rich in dark basalt and anorthoclase phonolite[51]. Campbell et al.[52] found the greatest heating on dark colored basalt soils. The combination of these phenomena may enhance the superficial degradation of the permafrost in the southern sector (i.e. where the major gaseous anomalies have been identified).

Regarding the origin of the atmospheric gases, the scatterplot of Fig. 5 shows the comparison between CO_2, O_2, and N_2 concentrations. The linear trend of the samples in the graph shows the existence of a dilution process of atmospheric gases (N_2 and O_2) by CO_2. This effect leads to exclude a biological or atmospheric contribution to the soil system, but may be linked to a different intake of CO_2, for example, geological and/or abiotic contributions[53]. These hypotheses can be confirmed only with isotope analyses of gas samples. In the literature, the origin of CO_2 in Antarctic soils is suggested to be linked to biological activity, favored by soil alkalinity and by shallow abiotic processes (CO_2 solubility), soil moisture content and soil temperature variations[19,21,23,29,30]. Shanhun et al.[9] and Risk et al.[54] suggested an abiotic origin of CO_2 based on the isotopic analyses, reporting very high positive φCO_2 values that cannot be explained by normal microbial activity. We suggest that the measured high anomaly values, originate from the subsurface brine system[31,49], and are linked to permafrost cap discontinuities at the edges of the valley (fractures or buried local faults). The spatial distribution of these anomalous zone could also be locally influenced by shallow permafrost thawing.

Although the samples were collected at shallow depths (i.e. permafrost is often reached at 30 cm depth) and are potentially affected by atmospheric gas dilution[55,56], the anomalous values of He, CH_4, CO_2 and φCO_2 cannot entirely be explained by biological activity and/or superficial physical processes. Another aspect concerns the presence of soil moisture which prevents both sampling and gas rising[55,56]. In Taylor Valley, the wetlands represent an area where water permeates the pores of the soil but does not emerge on the surface. Within these areas (Fig. 2) we managed to complete some sampling stations, however it should be noted that the gas concentrations are certainly underestimated compared to those conducted in dry and ventilated soil conditions. In these areas, of about 2.1 km^2 (equal to 10% of the total area) 16 soil gas samples and φCO_2 were collected. Statistical analyses (Table S1) confirm the low values in these areas.

Figure 6 shows the ranging and average values of φCO_2 measured over time in Antarctica. It should be noted that the reported measurements were conducted using various methods and in different environments, e.g. there are measurements on dry soil, near and from lakes and from the Ross Sea. Data collected in Dec 2019 - Jan 2020 from Taylor Valley show that the average value is in the same order of magnitude of those reported from the Garwood Valley[29]. The maximum values measured in this work, instead, is at least one order of magnitude higher than those previously reported. Focusing on Taylor Valley, various measurements have been carried out over the years, both in the soils[9,25] and around the three lakes[30]. The comparison of these data shows that our values are two orders of magnitude greater than those previously measured.

The total CO_2 gas emission rates over the surveyed area (A = 21.6 km^2) have been computed following a statistical approach (see 2.3 Statistical and geostatistical analysis) and, the calculated average CO_2 output is 14.95 t d^{-1} (Table S2). The calculated total CO_2 emission considering the three summer months, is about 1,345.5 t. This value is also considered as the total annual CO_2 emitted, providing a conservative estimate for the warmest months expecting much lower emissions during the rest of the year. Then, the estimated emission factor in the study area is 62.3 t km^{-2} y^{-1}. Comparing this value, for example, with those estimated for the central Apennines in Italy, ranging from 350 to 1,050 t $km^{-2}y^{-1}$[57], it is evident that the fluxes reported herein are remarkably lower, even compared with others reported worldwide[58]. This discrepancy is due to both climate/environmental differences and organic content and biological activity usually present in the soils of the other continents. Although our emission values are low, forecasting that ice-free regions in Antarctica are likely to expand with gradual warming, this amount will tend to increase and should be counted in the global CO_2 budget estimations.

To conclude, we provide the first spatial distribution maps of soil gas concentrations and φCO_2 in a large area (> 20 km^2) of the Taylor Valley, Antarctica. The calculated CO_2 emission output during the summer period is 1,345.5 t. Our results emphasize that extensive surveys are necessary to properly evaluate greenhouse gas (GHG) emissions in regions with permafrost. We also established the first extensive baseline maps that can be used to compare and monitor soil gas concentrations and CO_2 emissions in the region. The collected data identified areas characterized by multigas anomalies where permafrost partial melting may occur during the summer period and where fluids migrate to the surface through structures/fractures aligned with the main direction of the valley. We suggest that the gases originate from the subsurface brine system that is rich in dissolved gasses. The superficial melting of the permafrost and the presence of permeable zones inside it, allowed these gases to migrate to the surface.

4 Methods

4.1. Site description and sampling strategy

The MDV feature a mosaic of ice-covered lakes, ponds, ephemeral streams, valley glaciers and glacial, fluvial, lacustrine and aeolian sediments. Mean annual air temperature in the valleys is −17°C, and annual precipitation (snow water equivalent) spans 3–50 mm[59], making the MDV a cold, polar desert[60]. Continuous permafrost, by definition, is a regional land surface with temperatures below 0°C on interannual timescales,

and underlies 90–100% of the MDV. This permafrost is predominantly ice-cemented (ranging from ice-saturated to weakly cemented), although overlying “dry-frozen” (ice-free) permafrost is common in the upper ~1 m along valley walls[20]. Massive buried ice (ground ice) is common in the MDV and has been mapped in the Quartermain Range, in Victoria Valley, and in extensive ice-cored Ross Sea drift deposits emplaced during the last glacial maximum[20,61,62]. Taylor Valley (77°37' S, 163°15' E) is the southernmost of the three large Dry Valleys in the Transantarctic Mountains and extends WSW-ENE for ~29 km from Taylor Glacier to the McMurdo Sound (Fig. 1). Our study area is located in the eastern sector of the valley and extends for 6 km to the east of the Lake Fryxell bordering the southern part of the Commonwealth glacier (Fig. 2). The area is characterized by hummocky moraines, lacustrine deposits, and outwash fans where ephemeral streams and water tracks are active during summer. Recent studies also documented the presence of shallow underground brine systems [31,49].

4.2 Soil gas and φCO_2 measurements

Typically soil gas survey samples are collected from the soil pore air by pounding a steel probe in the soil at a depth of about 0.6-0.8 m[55,56]. However, in the presence of a shallow permafrost cap, our soil gas samples were collected at the bottom of the active layer that was present to depths ranging between 0.15 to 0.5 m (average depth of about 0.3 m). Elemental gas composition was then analyzed at Scott Base (at Pram Point on Ross Island) two weeks after collection to determine the concentrations of He, Ne, H_2, O_2, N_2, CH_4, CO_2. We used a MicroGC Varian 4900 CP, equipped with two Thermal Conductivity Detectors (TCD), responding to the difference in thermal conductivity between the carrier gas (Ar) and the sample components.

φCO_2 measurements were measured directly in the field by using a West System™ portable fluxmeter equipped with an IR Spectrometry detector (LICOR–LI820), with high accuracy in the range from 0 up to 600 mol m^{-2} d^{-1} (0 - 26400 g m^{-2} d^{-1}).

The concentration change over time is converted into CO_2 flux in g m^{-2} d^{-1} considering the pressure and temperature variations measured during the day, together with volume (0.0028 m^3) and surface (0.0306 m^2) of the accumulation chamber, using the formula:

(φCO_2 * (86400 * P * (V/A)) / (1000000 * R * T)) * M

where φCO_2 is the soil flux expressed in ppm/sec; P is the pressure in mbar; V is volume (m^3) and A is surface area (m^2) of the accumulation chamber; T is the temperature in K; M is molecular weight; R = 0.08314472 in bar L $(K\ mol)^{-1}$ that is used to calculate the volume in L of an ideal gas from its temperature in K, pressure in bar and mole number.

4.3 Statistical and geostatistical analysis.

Exploratory Data Analysis (EDA) (numerical and graphical techniques) was applied to elaborate soil gas data in terms of main statistical parameters, distribution type, background, and anomalous values. Normal probability plots (NPP) were interpreted according to the Sinclair method[63] in order to distinguish different populations and statistical anomaly threshold values for each gas species (see Fig. S1). Subsequently,

geostatistical analysis (e.g., variogram analysis and kriging[35,43]) was applied to construct contour maps to represent the spatial distribution of gas concentrations in the surveyed area. Furthermore, φCO_2 measurements were used to estimate the total output of CO_2 emission from the soil to the atmosphere in the investigated area[64]. This emission rate (expressed in t d^{-1}) was calculated by multiplying the average flux value of each population recognized in the NPP by the respective area estimated in the contour map. The contributions of the different populations (excluding background values) where then summed to obtain the total φCO_2 (see table S2).

Declarations

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Authors Contributions

L.R. and A.S. led the conceptual development of the study and designed the project. L.R., A.S., A.M., F.F., G.W., C.M., M.C.T., J.T.H.A., R.W. and V.R. data collection. A.S. and M.C.T. analyzed the data. L.R., A.S., G.C. and A.M. interpreted the data. L.R., A.S. and G.C. wrote original manuscript. L.R., A.S., A.M., J.T.H.A, F.F., G.W., R.S. and S.B. drafted the paper. L.R. Principal Investigator of the SENECA project.

Competing interests

The authors declare no competing financial interests.

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Tables

Table 1. Descriptive statistics of He, Ne, H_2, O_2, N_2, CH_4, CO_2 soil gas concentration and φCO_2 measurements carried out in the Lower Taylor Valley.

	N	Mean	Median	Min	Max	LQ	UQ	P10%	P90%	SD	SK
He (ppmv)	157	5.08	5.06	4.20	6.49	5.0	5.13	4.74	5.24	0.30	1.77
Ne (ppmv)	157	17.61	17.48	15.23	22.12	17.15	17.84	16.98	18.39	0.83	2.15
H_2 (ppmv)	157	3.57	1.79	0.15	36.95	1.02	2.73	0.65	9.51	5.60	3.59
O_2 (vol%)	157	20.82	20.88	19.52	21.09	20.75	20.94	20.59	20.99	0.20	-3.07
N_2 (vol%)	157	76.18	76.25	74.23	77.19	75.95	76.54	75.50	76.77	0.53	-1.03
CH_4 (ppmv)	157	220.3	3.7	1.8	18447	3.2	4.4	2.9	25.3	1553	10.7
CO_2 (vol%)	157	0.53	0.20	0.04	3.44	0.06	0.78	0.05	1.52	0.69	2.01
φCO_2 (g $m^{-2}d^{-1}$)	159	1.73	1.20	-0.74	11.36	0.74	2.08	0.42	4.11	1.63	2.22

N: number of observations; LQ: lower quartile; UQ: upper quartile; P10%: percentile 10%; P90%: percentile 90%; SD: standard deviation; SK: skewness.

Table 2. Comparison of gas content measured in the Lower Taylor Valley and air composition at different layers in the surficial environment. Typical average values of soil gas concentration of Ne, O_2, N_2, H_2O, Ar, CO_2, He, CH_4, and H_2 in the Taylor Valley (this work), atmospheric air, atmosphere-soil interface and soil gas.

	Taylor Valley (this work)	Atmospheric air	Atmosphere-soil interface	Soil gas
N_2 (vol%)	76.18	78.08	78.08	79.2
O_2 (vol%)	20.82	20.95	20.94	20.6
H_2O (%)	-	0.1 – 4	na	na
Ar (%)	-	0.93	0.93	na
CO_2 (vol%)	0.53	0.035	0.031	0.25
Ne (ppmv)	17.61	18	na	na
He (ppmv)	5.08	5.24	5.22*	na
CH_4 (ppmv)	220.3	1.4	1.4	na
H_2 (ppmv)	3.57	0.5	0.5	na

Modified from Rose et al.[40]; *Holland & Emerson[41]

Table 3. Summary table of φCO_2 measured in different terrestrial environments. Soil emission rates in g m^{-2} d^{-1} from Antarctic, Arctic, and other ecosystems (e.g., Alpine and sub-alpine, Mediterranean, desert and tropical climates).

Study site	Date	CO_2 rate (g $m^{-2}d^{-1}$)
Antarctic		
Taylor Valley[25]	1994-1997	0,1
Ross Sea[65]	1997-2003	-0.35 — -0.02
Lake Fryxell, Taylor Valley[30]	2001-2002	-0.3 — 0.57
Lake Hoare, Taylor Valley[30]	2001-2002	-0.38 — 0.42
Lake Bonney, Taylor Valley[30]	2001-2002	0.004 — 0.08
Upper moraine; Garwood Valley[19]	2003	0.0005
Delta; Garwood Valley[19]	2003	0.0006
Sand dune; Garwood Valley[19]	2003	0.00045
Lower moraine; Garwood Valley[19]	2003	0.0009
Polygons; Garwood Valley[19]	2003	0.0007
Hill slope; Garwood Valley[19]	2003	0.0008
Stream edge; Garwood Valley[19]	2003	0.0024
Lake edge; Garwood Valley[19]	2003	0.0137
Garwood Valley[29]	2003	0.9504
Garwood Valley[29]	2005	1.59
Lake Mochou[66]	2007-2008	-1.70
Lake Tuanjie[66]	2007-2008	-0.89
Taylor Valley[9]	2008-2009 h13:00-15:00	0.097
Taylor Valley[9]	2008-2009 h06:00-08:00	-0.09
Hidden Valley[54]	2011	0.02 – 1.56
Taylor Valley (this work)	*2019-2020*	*1.73*
Arctic		
Subarctic fens, Canada[67]	-	0.09 — 1.28
Bog, Canada[68]	-	0.05
Poor fen, Canada[68]	-	0.17

Drained swamp peatlands, Canada[69]	-	0 — 0.016
Toolik Lake, Alaska[47]	-	0.15 — 0.78
Arctic tundra[25]	-	1.59
Boreal peatland, Canada[44]	-	0.08
Other ecosystems		
Sub-alpine snowpack[46]	-	2.046
Alpine snowpack[46]	-	0.693
Desert scrub soil[25]	-	0.59
Deciduous forest soil[25]	-	2.5
Tropical soil[25]	-	3.34
Temperate[70]	-	1.9 - 30.41
Mediterranean[70]	-	1.9 - 10.26
Subtropical[70]	-	2.66 - 4.94
Rocky Desert[45]	-	6.17

Figures

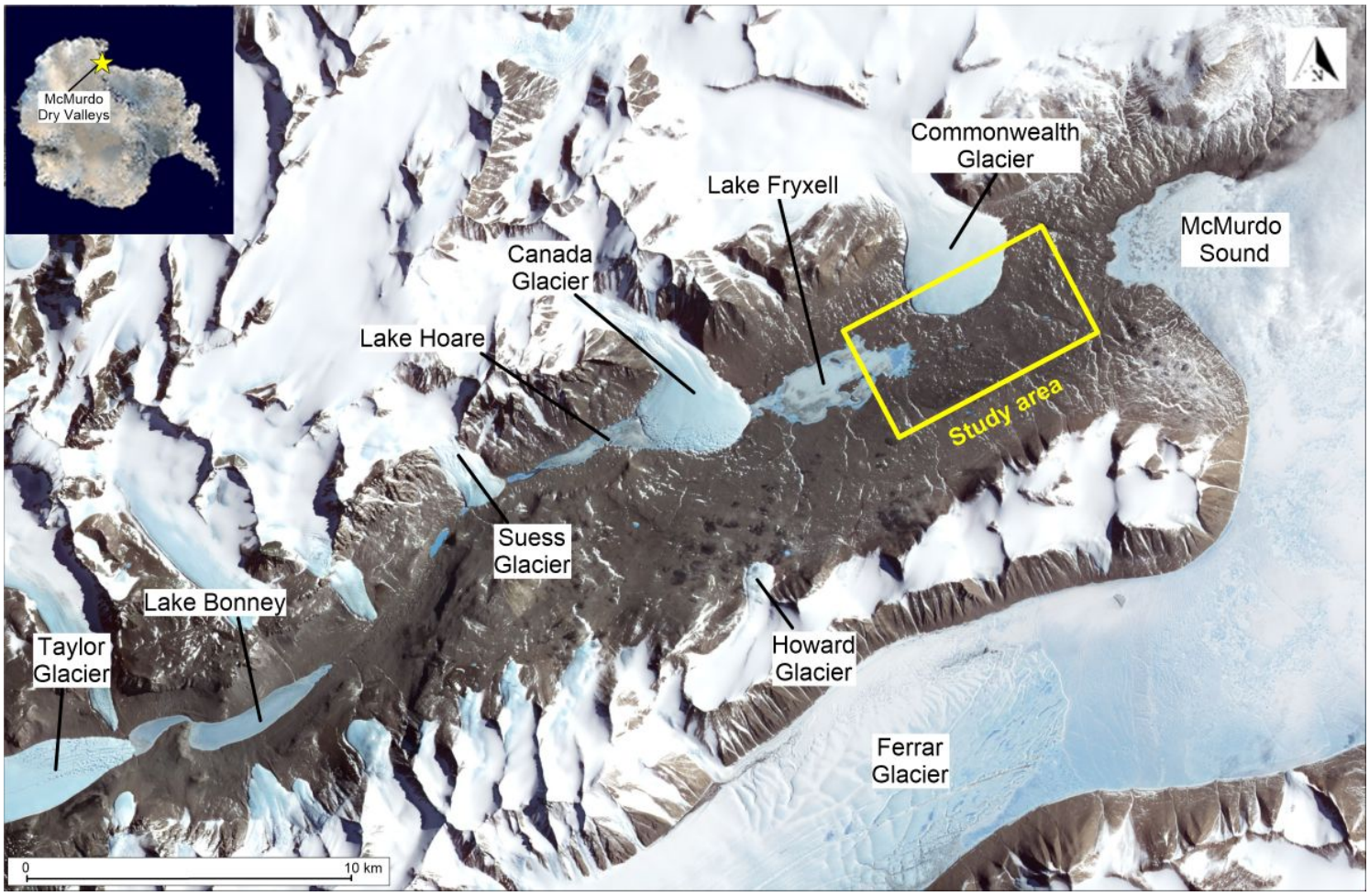

Figure 1

Location of the study area (yellow square) in the Taylor Valley, McMurdo Dry Valleys, Victoria land, West Antarctica. The inferred area is located among the Lake Fryxell, the Commonwealth Glacier and the McMurdo Sound. The inset indicates the location of the McMurdo Dry valleys. (credit: NASA).

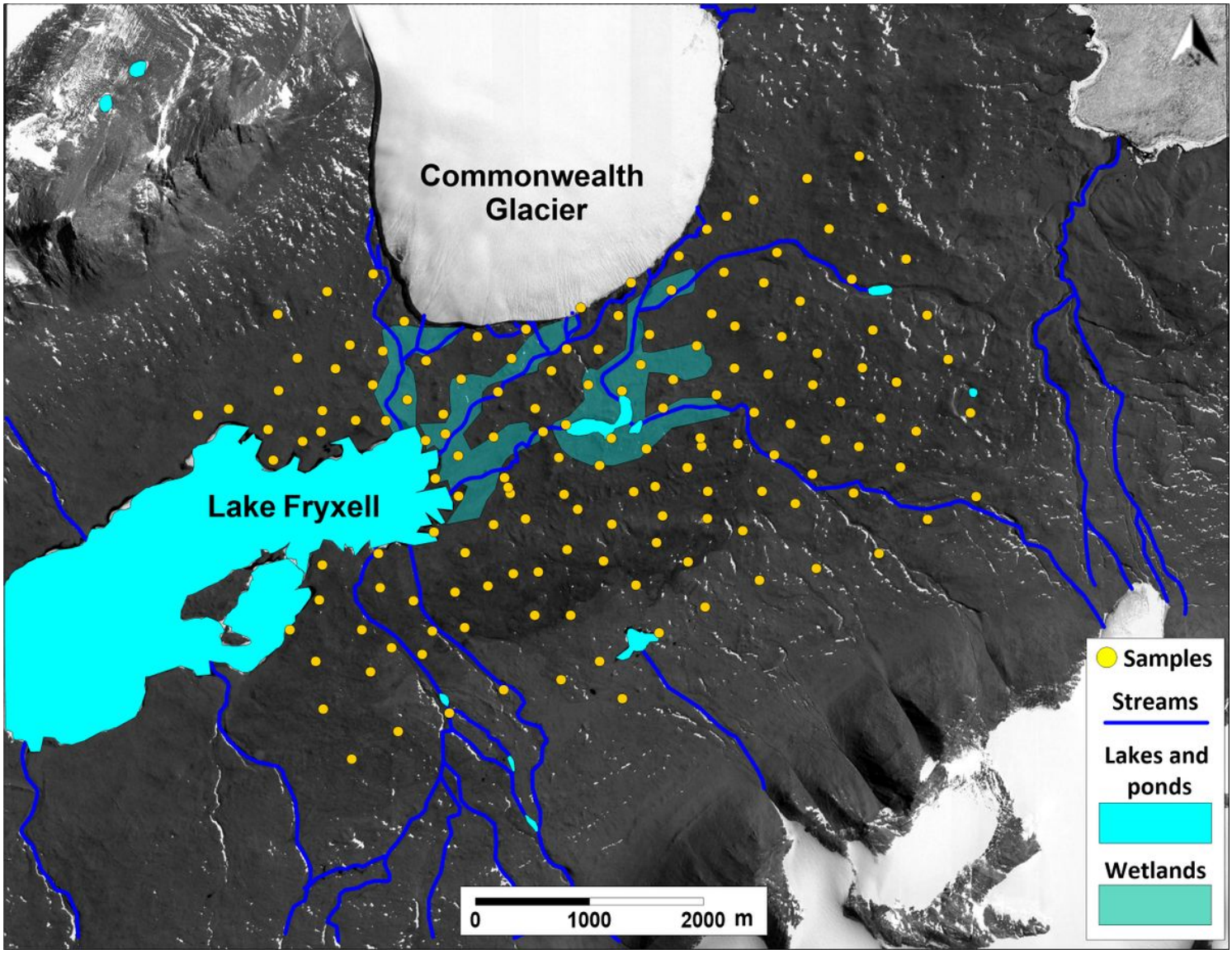

Figure 2

Location of soil gas and φCO_2 measurement points (yellow dots), of lakes and ponds (cyan areas), streams (blue lines) and wetlands (sea green areas) within Lower Taylor Valley.

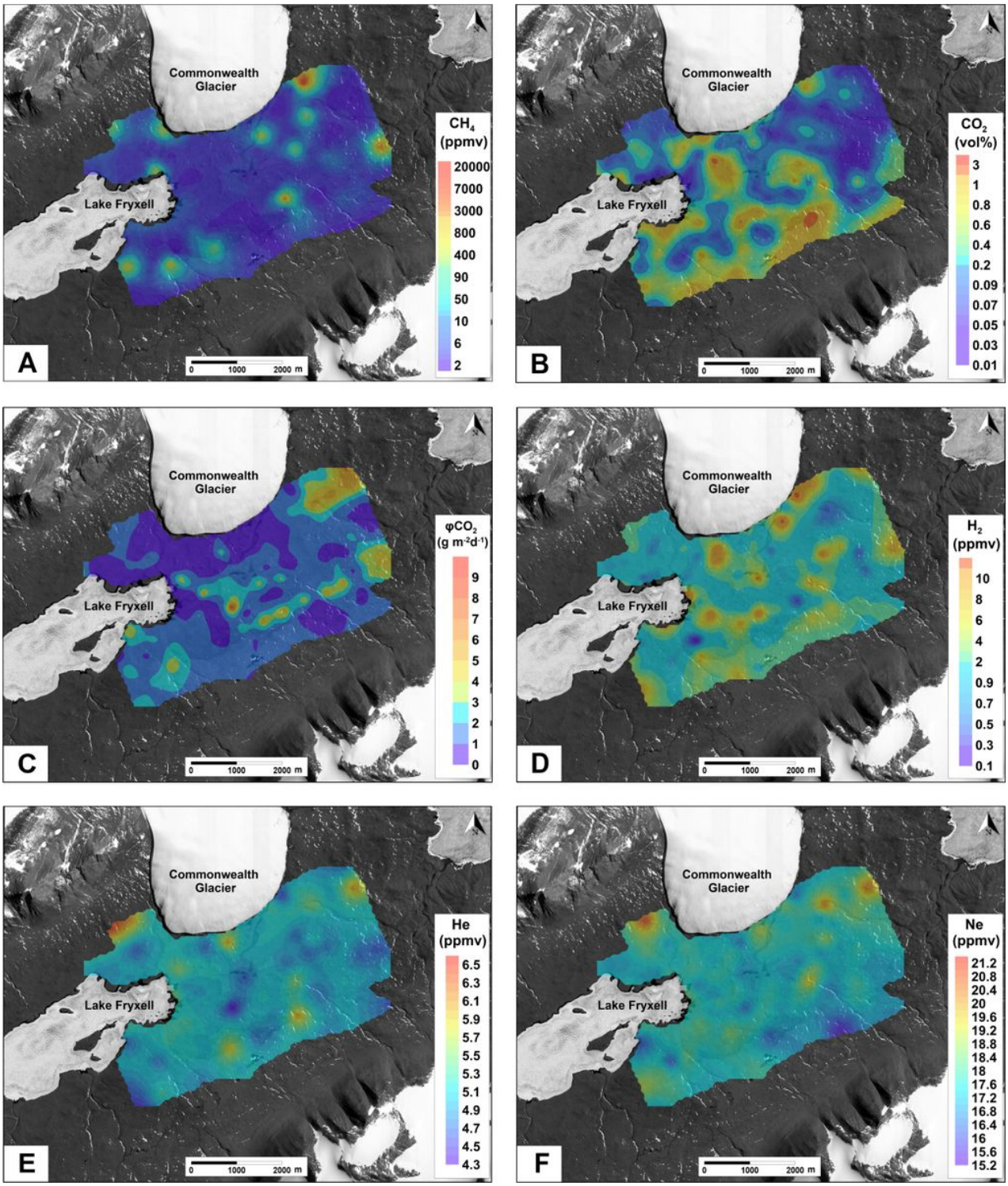

Figure 3

Contour maps of the analyzed gas species and the φCO_2. The figure shows the spatial distribution of CH_4 concentrations (A), CO_2 concentrations (B), φCO_2 (C), H_2 concentrations (D), He concentrations (E) and Ne concentrations (F) obtained by means of geostatistical analysis, in the Lower Taylor Valley.

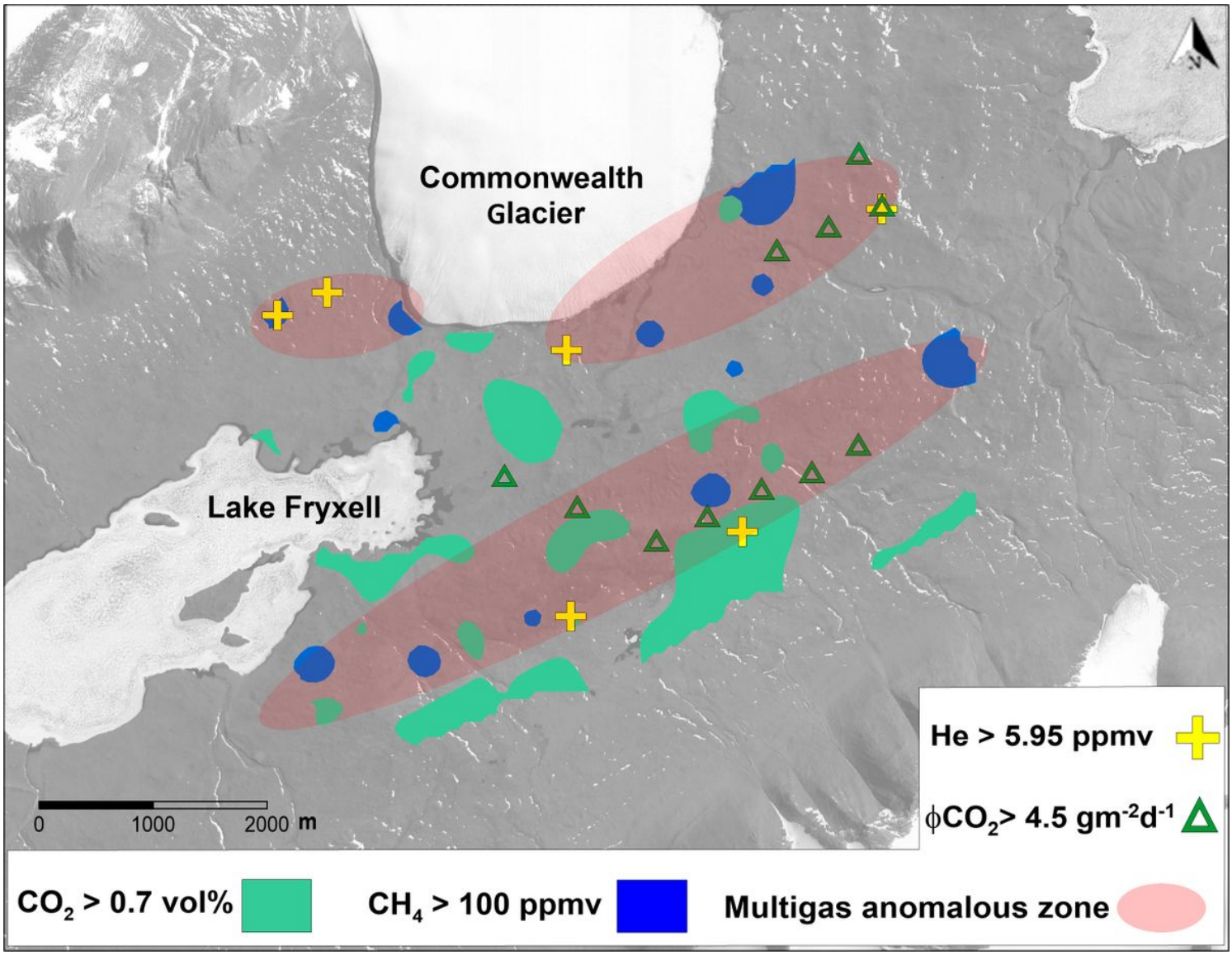

Figure 4

The map shows contour areas of CO_2 (green) and CH_4 (blue) concentrations higher than 0.7 vol% and 100 ppmv, respectively, samples with He higher than 5.95 ppmv (yellow crosses), φCO_2 higher than 4.5 g $m^{-2}d^{-1}$ (green triangles). The map also shows, in pink ellipsoid, the multigas anomalous zones recognized.

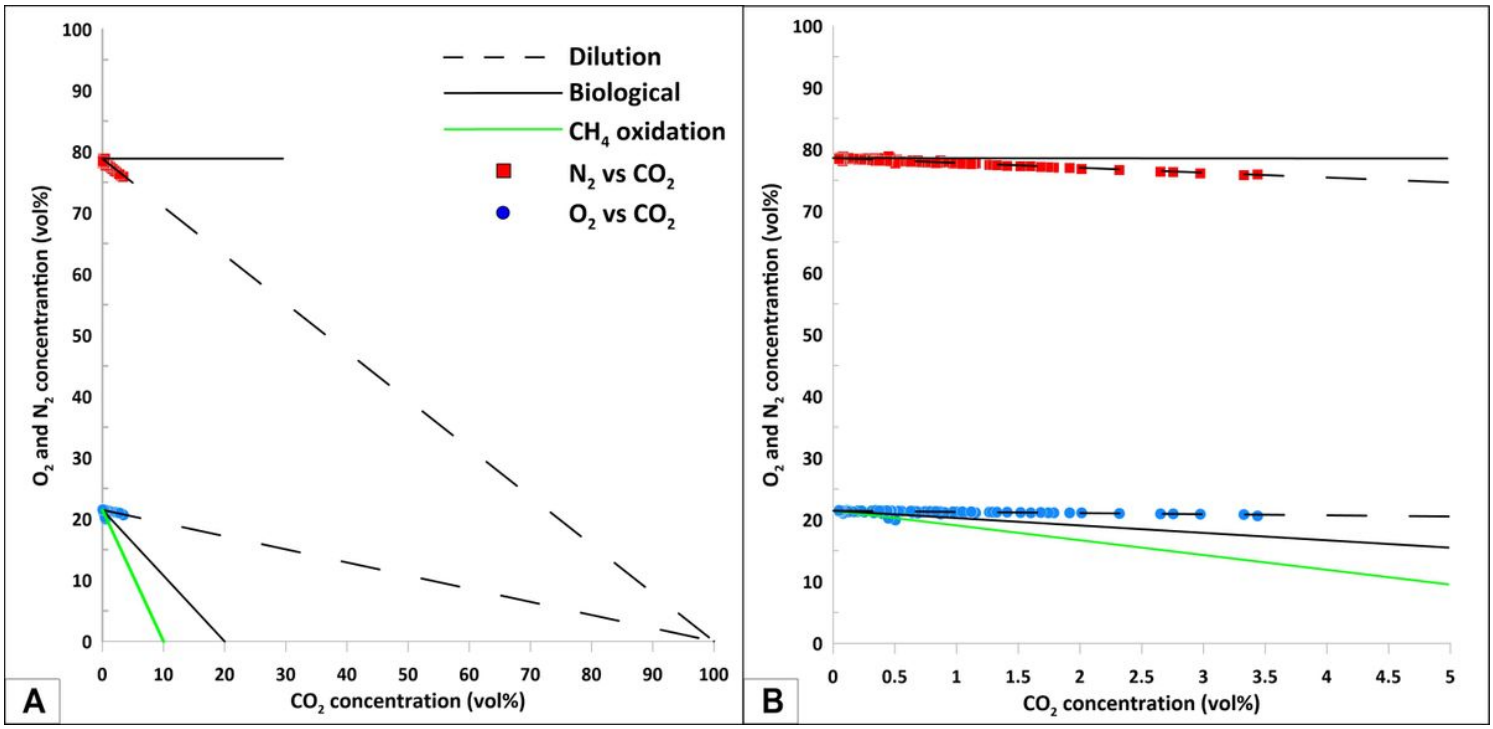

Figure 5

Scatter plot of O_2 and N_2 vs CO_2 (concentrations, vol%). The correlations between nitrogen and carbon dioxide, as well as oxygen and carbon dioxide, provide information about the tendency of data. Black solid lines highlight a biological source for the CO_2. Green lines show CO_2 derived by CH_4 oxidation, while dash lines indicate a dilution, an external contribution of CO_2 into the soil closed system (a). The same plot showing CO_2 concentrations up to 5% (b).

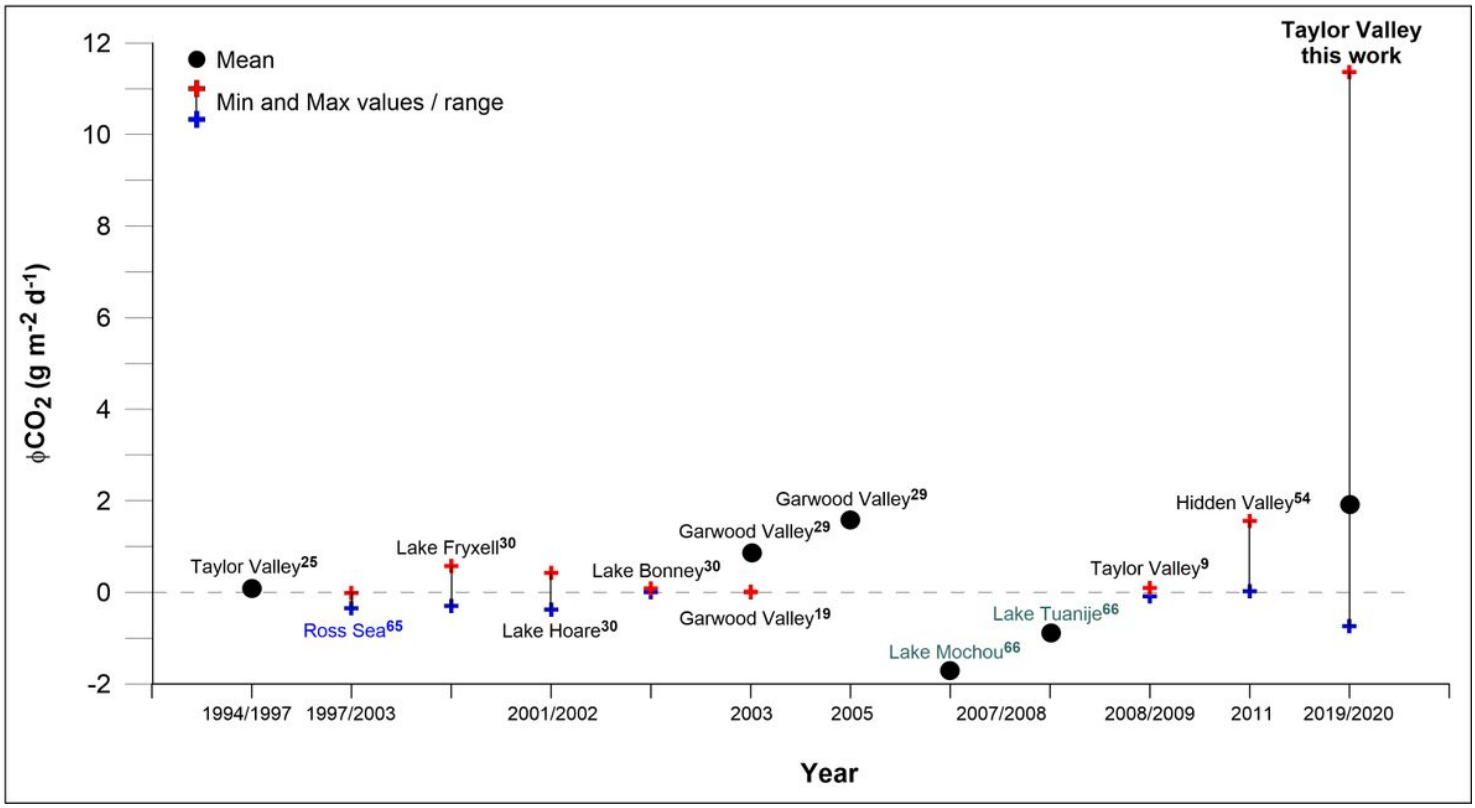

Figure 6

Summary diagram of φCO_2 measurements carried out since 1994 in Antarctica. The diagram shows CO_2 measurements performed in Antarctica by using various methods and in different environments. Measurements on dry soil (in black), lakes (in light blue) and the Ross Sea (in blue) are reported.

Supplementary Files

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