Soil methane production, anaerobic and aerobic oxidation in porewater of wetland soils of the Minjiang River estuarine, China

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Abstract

Wetlands are important sources of methane emission. Methane anaerobic oxidation, aerobic oxidation and production, and dissolved methane are important process of methane metabolism. We studied methane metabolism and the soil influencing factors. Potential soil methane production, anaerobic oxidation and aerobic oxidation rates, and dissolved methane in soil porewater changed seasonally and the annual average was 21.1±5.1 μg $g^{-1}d^{-1}$, 11.0±3.9 μg $g^{-1}d^{-1}$, 20.9±5.8 μg $g^{-1}d^{-1}$, and 62.9±20.6 μmol l^{-1}, respectively. Potential soil methane production and anaerobic and aerobic oxidation were positively correlated among them and with soil pH and negatively correlated with soil redox potential (Eh). Potential soil methane production and aerobic and anaerobic oxidation rates were negatively related to pore soil methane concentration. Thus, the more water saturated the soil (the lower Eh), the higher its capacity to methane production was, but even higher was soil potential capacity to methane oxidation both in the same anaerobic circumstances and when the soil was suddenly submitted to aerobic conditions. All these results suggested a buffer effect in the methane balance in wetland areas, the environmental circumstances favoring methane production are also favorable to methane anaerobic oxidation.

Keywords Methane production · methane anaerobic oxidation · methane aerobic oxidation · dissolved methane · Minjiang River estuarine wetland

Introduction

Although, the total area occupied by wetlands currently accounts for only 4.6% of the total land area (Costanza et al. 1997), their ecosystem services value accounts for 32% of the total value of the world, especially coastal wetlands whose ecosystem service value accounts for 17% of the global total value (Costanza et al. 1997). Wetland is sensitive to the external stress and becomes the ideal area for global change research (Simas et al. 2001). Methane is one of the important greenhouse gases affecting global climate change. Although, wetlands only represent a small fraction of the Earth's land surface, they are the main sources of methane to the atmosphere, representing between 20%-39% of global methane emissions (Laanbroek 2010). The relative increase of methane at the scale of 100-year is about 25 times than that of carbon dioxide (IPCC, 2007). Thus, improving the knowledge of methane metabolism in wetland soils warrants intense research.

Methane metabolism is in several phases: production, oxidation, dissolved methane, transport and emission (Buckley et al. 2008). Methane production, oxidation and dissolved methane in water have great impacts on the ultimate reduction of methane emissions in wetlands (Singh 2011). In the 21st century, methane anaerobic oxidation has become the core and hot issues (Raghoebarsing et al. 2006; Kniemeyer et al. 2007). However, the reports about methane anaerobic oxidation in coastal estuarine wetlands are few. Furthermore, the relationships between potential soil methane anaerobic oxidation capacity with potential soil methane production and with potential soil methane aerobic oxidation capacity are uncertain in wetland areas.

Whether relationships exist between the soil capacity to produce methane and the soil capacity to oxidize methane when the soil is in anaerobic conditions and whether between production and oxidation in wet conditions in dry-aerobic periods are two important questions that warrant research.

Methane metabolism in wetlands is strongly influenced by environmental factors that vary both spatially and temporally (Datta et al. 2013). The availability of electron acceptors and donors in soils plays a key role in regulating CH_4 production and consumption (Moran et al. 2008; Ettwig et al. 2010; Ro et al. 2011) and thereby controlling dissolved methane and the emission. Electron acceptors (e.g. Fe^{3+}, NO_3^-, and sulfate) are reduced during wet periods, but regenerated (oxidized) during dry periods (Neubauer et al. 2007). Soils can also provide carbon substrates to microbes for mediating CH_4 production and enhancing plant growth that in turn governs more than 90% of CH_4 transport (Le Mer and Roger 2001). Other environmental variables, include soil temperature, pH, redox potential (Eh) and salinity also influences CH_4 metabolism (Song et al. 2008; Wang et al. 2017). Better knowledge and characterization of CH_4 metabolism and transport of CH_4, are essential for better understanding and characterizing of GHG emissions from wetlands advancing in the knowledge of soil and soil pore water circumstances can favor the production and oxidation processes in soil media and thus, the final methane contents in soil-atmosphere interface and emission can give clues to choose between soil and plant community management strategies to diminish as much as possible the methane emissions. This information can also provide clues to improve the models and

82 projections of methane production and emissions on regional and global scale.

83 China has a coastline of 18,000 km in length, with numerous estuaries and bays
84 and a diversity of coastal wetlands which are important component of China's
85 wetlands, as well as the world's wetlands. Minjiang River estuarine wetland is the
86 main natural wetland of southeast coast of China. The wetland of Minjiang River
87 estuary is rich in biological species and abundant in waterbird resources (Liu et al.,
88 2006). Moreover, the Minjiang River estuary is an important tidal wetland ecosystem
89 due to its unique location at the transition between central and southern subtropical
90 climatic zones (Zheng et al. 2006). The tidal wetlands are rich in animal and plant
91 biodiversity (Zhou et al. 2006) being an excellent site representing the wide coastal
92 wetland areas of this part of China coast-

93 We studied the: (1) the seasonal variation potential of soil methane production,
94 soil methane anaerobic oxidation, soil methane aerobic oxidation, dissolved methane,
95 emission and the relationships among these variables and (2) the soil variables that
96 have significant relationships with methane-related variables in Minjiang River
97 estuarine wetland along the year. The results obtained in this study were also aimed to
98 provide a scientific basis for a suitable management of wetland avoiding as much as
99 possible CH_4 emissions.
100

101 ## Materials and Methods

102 **Study area**

103 This study was conducted in the Shanyutan wetland (26°01′46″N; 119°37′31″E,

Fig. 1), the largest tidal estuarine wetland (approximately 3120 ha) in the estuary of the Minjiang River.

The climate in this region is relatively warm and wet with a mean annual temperature of 19.6 ºC and a mean annual precipitation of 1346 mm (Zheng et al. 2006). The soil surface is submerged across the study site beneath 10-120 cm of water for 3-3.5 h during each tidal inundation. Soil surfaces of the entire wetland are exposed at low tide during 24 h and the weight percentage of water in the soil and soil redox potential are 116.39% and 12.57 mV respectively and soil remains flooded at some depths. The average salinity of the tidal water between May and December 2007 was 4.2 ± 2.5‰. *C. malaccensis* is one of the two dominant species of plants in this estuarine wetland. *C. malaccensis* is a native plant typically found in the upper (mid to high) portions of mudflats that grow between April and October, the highest population height is about 1.5 m and the density is about 1000 m^{-2}. Below-ground rhizomes are creeping growth in the topsoil layers.

Experimental design

Seasonal variation samples were collected from April in 2012 to March in 2013 from Shanyutan wetland in Minjiang River estuary. We established a plot of 900 m^2 in Shanyutan wetland and then collected the *C. malaccensis* wetland soil randomly after selecting three quadrats (100 m^2) within the big plot. Soil samples of 0-20 cm were collected with a small core sampler (length and diameter of 0.3 and 0.1 m). The sampling was conducted every month during one-year. Thus, a total of 36 soil

samples (one wetland type × one soil layer × twelve months' × three replicate plots) were thus collected.

Measurements of potential methane production

In each sampled soil, potential soil methane production rate was determined by placing 30 g of the fresh soil sample in a 120 ml incubation bottle and injecting 30 ml of distilled water (water: soil ratio was thus 1:1) (Wang et al. 2010; Bergman et al. 2000). The incubation bottles were filled with oxygen-free nitrogen through a small hole in the bottle stopper to eliminate the possibility of methane consumption caused by carrying oxygen during the sampling process and slowly equilibrated with the atmospheric pressure for 24 h to consume the residual oxygen in incubation bottles, which ensures the soil sample is in a strictly anaerobic environment (Smemo and Yavitt 2007; Wrede et al. 2012),. Three replicates were set and placed in an anaerobic incubator (YQX-Ⅱ, Shanghai Yuejin Medical Equipment Factory) in the dark place using the average soil temperature in situ. Then the gas samples were taken at 0, 24, 48, 72, and 96 h, and the sample incubation bottles were gently swirled for 1-2 min before gas sampling. Each extraction was 2 ml and supplemented with the corresponding volume of oxygen-free nitrogen. Methane concentration was determined by a GC-2010 gas chromatograph (Shimadzu Scientific Instruments, Kyoto, Japan). The potential methane production rate was calculated by the methane concentration increment during the incubation time in the incubation bottles.

Measurements of potential methane anaerobic oxidation

In each collected soil sample, potential soil methane anaerobic oxidation rate was

150 determined by placing 30 g of fresh soil sample in a 120 ml incubation bottles and
151 injecting 30 ml of 40 mmol l^{-1} of methane production inhibitor (BES,
152 bromoethanesulfonate) solution (Müller et al. 1993; Hoehler et al. 1994) at a water:
153 soil ratio of 1:1 (Bergman et al. 2000). The incubation bottles were filled with
154 oxygen-free nitrogen through a small hole in the bottle stopper to eliminate the
155 possibility of methane consumption caused by carrying oxygen during the sampling
156 process and slowly equilibrated with the atmospheric pressure for 24 h to consume the
157 residual oxygen in the incubation bottles, ensuring the soil sample is in a strictly
158 anaerobic environment (Smemo and Yavitt 2007; Wrede et al. 2012). Then, pure
159 Methane standard gas was injected into each incubation bottles so that the
160 concentration of methane in the incubation bottle was 10000 μmol mol^{-1}, and 3
161 replicates were set and placed in an anaerobic incubator (YQX-Ⅱ, Shanghai Yuejin
162 Medical Equipment Factory) in the dark place using the average soil temperature *in*
163 *situ*. Then the gas samples were taken at 0, 24, 48, 72, and 96 h, and the sampled
164 incubation bottles were gently swirled for 1-2 min before gas sampling. Each
165 extraction was 2 ml and supplemented with the corresponding volume of oxygen-free
166 nitrogen. Methane concentration was determined by a GC-2010 gas chromatograph
167 (Shimadzu Scientific Instruments, Kyoto, Japan). Potential methane anaerobic
168 oxidation rate was calculated by the methane concentration decrement as the
169 incubation time in the incubation bottles.

170 **Measurements of potential methane aerobic oxidation**

171 In each soil sampled potential soil methane aerobic oxidation rate was determined by
172 Krüger et al. (2002) and Supparattanapan et al. (2009), by placing 30 g of fresh soil
173 sample in a 120 ml incubation bottle and injecting 30 ml of distilled water into it, the
174 water: soil ratio was 1:1 (Wang et al. 2010; Bergman et al. 2000). Then, pure methane

standard gas was injected into each incubation bottles so that the concentration of methane in the incubation bottles was 10000 μmol mol^{-1}, and three replicates were set and incubation in the dark place using the average soil temperature in situ. Then the gas samples were taken at 0, 24, 48, 72, and 96 h, and the sampledincubation bottles were gently swirled for 1-2 min before gas sampling. Each extraction was 2 ml and supplemented with the corresponding volume of oxygen-nitrogen. Methane concentration was determined by a GC-2010 gas chromatograph (Shimadzu Scientific Instruments, Kyoto, Japan). Potential soil methane anaerobic oxidation rate was calculated by the methane concentration decrement as the incubation time in the incubation bottles.

Measurement (in situ) of porewater dissolved CH_4 concentration

Porewater was sampled *in situ* once each month. Three specially designed stainless steel tubes (2.0 cm inner diameter) were installed to a depth of 30 cm in each plot. Porewater samples were collected immediately after the measurements of CH_4 emission using 50-ml syringes to inject it into pre-evacuated vials (20 ml) and stored in a cooling box in the field. After transporting to the laboratory, the samples in the vials were stored at -20 °C until the analysis of CH_4 concentration. Before analysis, the vials were first thawed at room temperature and were then vigorously shaken for 5 min to equilibrate the CH_4 concentrations between the porewater and the headspace. The gas samples were taken from the headspace of the vials and analyzed for CH_4 concentration with the above gas chromatograph (Ding et al. 2003).

Determination of methane concentrations

Methane concentrations in the headspace air samples were determined by gas chromatography (Shimadzu GC-2010, Kyoto, Japan) using a stainless steel Porapak Q column (2 m long, 4 mm outer diameter, 80/100 mesh). A flame ionization detector (FID) was used for the determination of the methane concentrations. The operating temperatures of the column, injector and detector for the determination of methane concentrations were adjusted to 70, 200 and 200 °C. The gas chromatograph was calibrated before and after each set of measurements using 1.01, 7.99 and 50.5 μL methane L^{-1} in He (CRM/RM Information Center of China) as primary standards.

Calculation of potential methane production, anaerobic oxidation, aerobic oxidation, and porewater dissolved CH_4 concentration

Potential methane production, anaerobic oxidation, and aerobic oxidation rates were estimated by (Wassmann *et al*., 1998):

$$P = \frac{dc}{dt} \cdot \frac{V_H}{W_S} \cdot \frac{MW}{MV} \cdot \frac{T_{st}}{T_{st} + T}$$

where P is the potential rate of methane anaerobic oxidation, aerobic oxidation and production (μg^{-1} g^{-1} d^{-1}), dc/dt is the recorded change in the mixing ratio of C (methane) in the headspace over time (mmol mol^{-1} d^{-1}), V_H is the volume of the headspace (L), Ws is the dry weight of the soil (g), MW is the molecular weight of methane (g), MV is the molecular volume (L), T is the temperature (K) and T_{st} is the standard temperature (ºK).

The concentration of CH_4 dissolved in the porewater was calculated following (Ding et al. 2003):

$$C = \frac{Ch \cdot Vh}{22.4 \cdot Vp}$$

where *Ch* is the CH_4 concentration ($\mu l\ l^{-1}$) in the air sample from the vials, *Vh* is the volume of air in the bottle (ml), and *Vp* is the volume of the porewater in the bottle (ml).

Measurements of soil properties

Total soil porewater (collected by centrifugation at 5000 r min^{-1}) dissolved organic-C (DOC) concentration was measured using a TOC-V CPH total carbon analyzer (Shimadzu Scientific Instruments, Kyoto, Japan). Porewater (collected by centrifugation at 5000 r min^{-1}) NO_3^-, SO_4^{2-} and Cl^- concentrations were determined by ICS2100 ion chromatography (American Dionex Production, Sunnyvale, USA). Soil tempratue, Eh and pH were measured with an Eh/pH/temprature meter (IQ Scientific Instruments, Carlsbad, USA) and salinity was measured using a 2265FS EC Meter (Spectrum Technologies Inc., Paxinos, USA). Total Fe content was determined by digesting fresh soil samples with 1 mol HCl L^{-1}. Ferrous ions were extracted using 1,10-phenanthroline and measured spectrometrically (Wang et al. 2012). Ferric concentration was calculated by subtracting the ferrous concentration from the total Fe concentration.

Statistical analyses

The significance of the differences in potential methane production, anaerobic oxidation, aerobic oxidation and dissolved methane, soil variables and other properties among the seasonal variation were assessed by One-Way ANOVA. We analyzed the relationships of the potentials of soil methane production, soil methane anaerobic oxidation, soil methane aerobic oxidation and dissolved methane among them and with soil DOC, soil temperature, Eh, pH, salinity, soil NO_3^-, SO_4^{2-} and Cl^- concentrations and plant biomass. Plot and time of sampling (month) were introduced into the models as random factors. If a variable was non-normally distributed we transform it to normalize its distribution. In concrete soil nitrate and soil ferric concentrations were log-transformed to reach their normal distribution. We used the "*nlme*" (Pinheiro et al. 2016) and "*lme4*" (Bates et al. 2015) R packages with the "*lme*" and "*lmer*" functions to conduct the mixed linear models. We chose the best model for each dependent variable using Akaike information criteria. We used the MuMIn (Barton 2012) R package in the mixed models to estimate the percentage of variance explained by the model. We presented in significant relationships the total variance explained by the model including the fixed and random factors (R^2c) and also the variability explained by only the fixed factor (R^2m).

We used Principal component analyses (PCA) to assess the multiple correlations among total potential methane production, anaerobic oxidation, aerobic oxidation and dissolved methane and environmental factor and the analyzed soil variables and their relative importance in the separation of soil samples from different seasons. The PCA were performed using Statistica 6.0 (StatSoft, Inc. Tule, Oklahoma,

USA).

Results

Potential soil methane production, methane anaerobic oxidation, methane aerobic oxidation, and dissolved methane along the year

Potential soil methane production rates changed seasonally in the Shanyutan wetland of Minjiang River estuary (Figs. 2, 3), with a maximum value of 57.4±7.7 μg g^{-1} d^{-1} in January 2013 and a minimum value of 4.85±1.1 μg g^{-1} d^{-1} in August 2012. The annual average value was 21.1±5.1 μg g^{-1} d^{-1}. In general, potential soil methane production rate was significantly higher in winter than that of the summer (Fig. 3, $P<0.05$). However, there were not significantly different among other seasons (Fig. 3, $P>0.05$).

Potential soil methane anaerobic oxidation rates changed seasonally in the Shanyutan wetland of Minjiang River estuary (Figs. 2, 3), with a maximum value of 41.8±13.4 μg g^{-1} d^{-1} in January 2013 and a minimum value of 3.46±0.97 μg g^{-1} d^{-1} in August 2012. The annual average value was 11.0±3.9 μg g^{-1} d^{-1}. In general, potential soil methane anaerobic oxidation production rate was significantly higher in winter than those of spring and autumn (Fig. 3, $P<0.05$). However, there were not significantly different among other seasons (Fig. 3, $P>0.05$).

Potential soil methane aerobic oxidation rates changed seasonally in the Shanyutan wetland of Minjiang River estuary (Figs. 2, 3), with a maximum value of 70.2±24.5 μg g^{-1} d^{-1} in January 2013 and a minimum value of 6.55±1.42 μg g^{-1} d^{-1} in

May 2012. The annual average value was 20.9±5.8 μg g^{-1} d^{-1}. In general, potential soil methane aerobic oxidation production rate was not significantly different among seasons (Fig. 3, P>0.05).

Dissolved methane in soil porewater changed seasonally in the Shanyutan wetland of Minjiang River estuary (Figs. 2, 3), with a maximum value of 261±39 μmol l^{-1} in August 2012 and a minimum value of 7.52±0.37 μmol l^{-1} in January 2012. The annual average was 62.9±20.6 μmol l^{-1}. In general, dissolved methane in soil porewater was significantly higher in summer than other seasons (Fig. 3, P<0.05). However, there were not significantly different among other seasons (Fig. 3, P>0.05).

Relationship among potential soil methane production, methane anaerobic oxidation, methane aerobic oxidation and dissolved methane along the year

The linear mixed models showed that soil potential soil methane anaerobic oxidation, potential soil methane production and potential soil methane aerobic oxidation rates were positively related to each other (Table 1). The statistical models of the corresponding three relationships (including plots and time as random factors) had very high total significance (R^2c=0.99, P<0.0001) (Table 1). Methane concentrations in soil porewater were negatively correlated with potential soil anaerobic oxidation rates (R^2m=0.15, R^2c=0.91), potential soil methane production rates (R^2m=0.24, R^2c=0.99) and potential soil aerobic methane oxidation (R^2m=0.13, R^2c=0.94) (Table 1).

Seasonality in environment variables

Soil temperature changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 31.5±0.1 ℃ in September 2012 And a minimum value of 12.4±0.6 ℃ in February 2013. The annual average was 21.4±2.0 ℃.

Soil ferric concentration changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 87.0±9.9 mg g^{-1} in June 2012. In September 2012 which is the lowest value was 12.2±2.3 mg g^{-1}, and annual average was 37.8±6.9 mg g^{-1}.

Soil pH changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 7.62±0.01 in January 2013 and a minimum value of 6.30±0.02 in November 2012. The annual average was 6.72±0.11.

Soil Eh changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 41.1±0.7mV in November 2012. In January 2013 that had the lowest value, was -36.5±0.7 mV and annual average was 16.3±6.5mV.

Soil salinity changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 4.21±0.71 mS cm^{-1} in April 2012. In February 2012 the lowest value was 1.91±0.33 mS cm^{-1} and annual average was 3.08±0.21 mS cm^{-1}.

Dissolved sulfate in soil porewater concentration changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 362±36 mg l^{-1} in December 2012. In February 2013 the lowest value was 128±12 mg

l^{-1} and annual average was 227±25 mg l^{-1}.

Dissolved nitrate in soil porewater concentration changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 2.46±0.44 mg l^{-1} in December 2012. In October 2012 the lowest value were 0.106±0.039 mg l^{-1} and annual average was 0.828±0.212 mg l^{-1}.

Dissolved chloridion in soil porewater concentration changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 4595±279 mg l^{-1} in November 2012. In August 2012 the lowest value were 1412±92 mg l^{-1}, and annual average was 2821±283 mg l^{-1}.

Plant biomass changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 2313±657 g m^{-2} in December 2012. April 2012 had the lowest value were 759±320 g m^{-2}, and annual average was 1462±198 g m^{-2}.

Air temperature changed seasonally in the Shanyutan wetland of Minjiang River estuary (Fig. 4), with a maximum value of 35.5±0.0 ℃ in July 2012. February 2013 had the lowest value was 10.2±0.1 ℃, and annual average was 23.0±2.4 ℃.

Potential soil methane production, methane anaerobic oxidation, aerobic oxidation rates, dissolved methane, and their relationships with soil properties

The linear mixed models showed that potential soil methane production rates were positively related to soil pH (R^2m=0.15, R^2c=0.90) and negatively related to soil Eh (R^2m=0.15, R^2c=0.90) and with soil temperature (R^2m=0.13, R^2c=0.90) (Table 1).

Potential soil methane anaerobic oxidation rates were positively related to soil pH (R^2m=0.14, R^2c=0.99) and negatively with soil Eh (R^2m=0.15, R^2c=0.99) (Table 1). Finally, methane concentration in soil pore water was positively related to soil temperature (R^2m=0.32, R^2c=0.99) (Table 1).

The PCA analysis was completely consistent with the previous commented univariant analyses. Soil samples collected in summer were located across the PC1 axis coinciding with higher porewater methane concentrations, higher soil and air temperature and soil Eh and lower soil pH and potential soil methane production and oxidation rates, both anaerobic and aerobic (Fig. 5). Just the contrary patterns were related to soil samples collected in winter that were placed in the other side of the PC1 axis (Fig. 5).

Discussion

Seasonal variation of potential methane production, anaerobic oxidation, aerobic oxidation and dissolved methane

Potential soil methane production rate was higher in winter than in summer. In winter there are lots of the plant litter input and thereby the soil carbon concentration which is the most important substrate for methane production, increases (Yagi and Minami 1990), thereby promoting the soil methane production (Van der Gon and Neue 1995). Moreover, the optimum temperature of methane production is about 20 C (Wagner and Pfeiffer 1997) and in our study, the average temperature was 14.4 and 29.2 C in winter and summer, respectively, thus more closely to the optimum for soil methane production in winter than in summer. Moreover, in summer, the plant growth was

higher than in other seasons, and more O_2 was released into the soil, generating soil redox conditions which were not proper for methane production. Furthermore, in Fujian province the acid rain was high and the summer was main rainy season, so the soil pH decreased in summer and thereby inhibiting methane production. In contrast, winter was the dry season and had relatively higher pH, favoring methane production. In our study, the linear mixed models showed that potential soil methane production rates were positively related to soil pH and negatively related to soil Eh and temperature.

Potential soil methane anaerobic oxidation rates were also higher in winter than those of spring and autumn, and also than those of summer, although, not significantly different. As commented in Fujian province acid rain is high and the summer was the main rainy season, so in summer the soil pH decrease and thereby inhibited the methane anaerobic oxidation microbial activity. In contrast, winter was the dry season with relatively higher pH which was favorable to the growth of microbes involved in methane anaerobic oxidation. In our study, supporting these comments, the linear mixed models showed that potential soil methane anaerobic oxidation rates were positively related to soil pH. Moreover, Nauhaus et al. (2002) showed that the optimum temperature value was between 4-16 ° C for methane anaerobic oxidation. In our study, the average seasonal temperatures were 18.7, 29.2, 23.3 and 14.4 ° C for spring, summer, autumn and winter respectively, so obviously, the winter was the most suitable season for methane anaerobic oxidation.

Potential soil methane aerobic oxidation rate was not significantly different

among seasons. However, there was still a trend to higher values in winter than in the other seasons. The reason would be the same than for methane anaerobic oxidation, that winter was the dry season, with relative higher soil pH. In our study, the linear mixed models showed that potential soil methane aerobic oxidation rates were also positively related to soil pH. Moreover, Dasselaar et al. (1998) found that temperature promotion of the methane aerobic oxidation was higher when the temperature was 4~12℃ than when it was 12~18 ℃. In our study, the temperatures closer to 12℃ were those of winter.

Dissolved methane in soil porewater was instead higher in summer than in the other seasons, which had no significant differences among them. The dissolved methane in soil porewater resulted from many factors, such as methane production, oxidation and transportation, etc. The lower summer methane anaerobic and aerobic oxidation were likely the most determinant factors of these higher values of dissolved methane in summer.

The soils with highest soil pH and lowest Eh were those that showed the highest potentials of methane production and anaerobic oxidation. But the most interesting result was that soil samples with the highest soil pH and lowest Eh were also those that showed the highest potentials of aerobic methane oxidation. Consistently, with these results, Kettunen et al (1999) also observed that the maximum potential capacity to methane aerobic oxidation was higher in soils below than above table level. Similar results have also been observed in boreal pine fen areas (Saarino et al. 1998).

These results thus suggested a buffer effect in the methane balance in wetland

areas. Environmental and soil conditions favoring methane production are also more favorable for methane anaerobic oxidation during the same circumstances and also in drier periods, for aerobic methane oxidation. In fact alternation between wet-dry periods related to wetland source-sink of methane have been observed everywhere (Juutinen et al. 2003; Knorr et al. 2008; Brown et al. 2014; Goodrich et al. 2015). But the fact that as more favorable the conditions of soil are to produce methane higher is also its capacity to oxidize methane was observed in both flooded (anaerobic) and dry (aerobic) periods. This observation warrants future research to corroborate this possible general pattern.

Relationship among potential methane production, anaerobic oxidation, aerobic oxidation and dissolved methane

Potential methane anaerobic oxidation and potential methane production showed a very significant positive correlation. This pattern has been previously observed in tropical and boreal wet soils and peatlands where these two variables have also shown to be significantly correlated, in agreement with our results (Smemo and Yavitt 2011; Blazewicz et al. 2012). The relationship between methane anaerobic oxidation and methane production was mainly related to the functional microbial association, where anaerobic methanotroph (ANME) *archaea* was the main microorganism involved in methane production and can also participate in the methane anaerobic oxidation (Alperin and Hoehler 2009; Lloyd et al. 2011). Methane production *archaea* can

444 oxidize methane as observed in pure culture experiments (Moran et al. 2005; Joye and
445 Samarkin 2009; Roberts and Aharon 1994). In addition, there was a significant
446 positive correlation between methane anaerobic oxidation and methane aerobic
447 oxidation in this study. Recent studies have demonstrated that aerobic and anaerobic
448 methane oxidation bacteria can coexist in the same places, suggesting that the
449 proportion of different species can depend on the oxygen and methane availability and
450 also that diverse microbial activity was important to sustain methanotrophic activity
451 (Siniscalchi et al., 2017). Eller et al. (2005) observed the co-occurrence of methane
452 aerobic and anaerobic process in the same soil samples and water columns. Moreover,
453 potential methane aerobic oxidation and potential methane production processes
454 showed a very significant positive correlation as expected from methane being the
455 substrate of methane oxidation (Nesbit and Breitenbeck 1992). However, negative
456 relationships between methane concentrations in soil porewater and the studied
457 potential methane production rates and also potential soil methane oxidation, both in
458 anaerobic and aerobic conditions were then observed. These results suggest that
459 methane production was not the most determinant factor controlling the dissolved
460 methane in soil porewater. However, porewater dissolved methane was directly
461 limited by methane anaerobic oxidation and aerobic oxidation in Minjiang estuarine
462 wetland. These results were not in agreement with the fact that methane storage was
463 the key factor in the oxidation of methane in coastal sulphate-rich marine sediments
464 (Nauhaus et al. 2002; Treude et al. 2005; Orcutt et al. 2005). This possible
465 explanation was consistent with the linear mixed models showing the inverse

466 relationships between methane present in porewater and the soil potential capacity of
467 methane production and also of methane oxidation.
468
469 **Conclusions**
470 1. Potential methane production, anaerobic oxidation and aerobic oxidation were all
471 shown to be higher in winter than other seasons, however, the dissolved methane in
472 soil porewater was higher in summer than other seasons.
473 2. The concentration of soil pH and Eh are the studied factors that had the stronger
474 relationships with potential soil methane production and anaerobic and aerobic
475 oxidation rates. This showed thus, strong relationships among the different soil
476 metabolic methane processes and the basic potential chemical activities of soils.
477 3. The positive correlation between methane production, methane anaerobic oxidation
478 and methane aerobic oxidation suggested that at least some of the soil conditions and
479 of the overall set of microorganisms communities that favor methane production also
480 favor its oxidation.
481 4. The negative relationships between methane concentrations in soil porewater with
482 the potential soil of methane production and oxidation in anaerobic and aerobic
483 conditions suggest that the higher the soil potential to produce methane, the higher the
484 potential soil capacity to oxidize methane in aerobic and anaerobic conditions.
485
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Conflicts of Interest

The authors declare no conflicts of interest.

References:

Alperin MJ, Hoehler TM (2009) Anaerobic methane oxidation by archaea/sulfate-reducing bacteria aggregates: 1. Thermodynamic and physical constraints. American Journal of Science 309:869-957

Barnes RO, Goldberg ED (1976) Methane production and consumption in anaerobic marine sediment. Geology 4:297-300

Barton K (2012) MuM. In: Multi-model inference. R package version 1.7.2. http://CRAN. R-283 project.org/package=MuMIn. at http://cran.r-project.org/ package=MuMIn>

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67:1-48

Bergman I, Klarqvist M, Nilsson M (2000) Seasonal variation in rates of methane production from peat of various botanical origins: effects of temperature and substrate quality. FEMS Microbiology Ecology 33:181-189

Blazewicz S, Petersen DG, Waldrop MP, Firestone MK (2012) Anaerobic oxidation of methane in tropical and boreal soils: ecological significance in terrestrial

514 methane cycling. Journal of Geophysical Research 117:G02033.
515 Brown, BG, Humpherys ER, Moore TR, Roulet NT, Lefleur PM (2014) Evidence for
516 a nonmonotonic relationships between ecosystem-scale peatland methane
517 emissions and water table depth. Journal of Geophysical
518 Research-Biogeosciences 119:826-835
519 Buckley DH, Baumgartner LK, Visscher PT (2008) Vertical distribution of methane
520 metabolism in microbial mats of the Great Sippewissett salt marsh.
521 Environmental Microbiology 10:967-977
522 Costanza R, d'Arge R, de Groot RD, Farber S, Grasso M, Hannon B, Limburg K,
523 Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The
524 value of the world's ecosystem services and natural capital. Nature 387:253-260
525 Cassman, K. G. et al. (1998) Opportunities for increased nitrogen-use efficiency from
526 improved resource management in irrigated rice systems. Field Crops Research
527 56:7-39.
528 Crutzen P., The role of methane in atmospheric chemistry and climate, in: Von
529 Engelhardt W., Leonhard-Marek S., Breves G., Giesecke D. (Eds.), Ruminant
530 Physiology: Digestion, Metabolism, Growth and Reproduction, Ferdinand Enke
531 Verlag, Stuttgart, 1995, pp. 291-316
532 Dasselaar AP，Beusichen ML，Oenema O (1998) Effects of soil moisture content and
533 temperature on methane uptake by grasslands on sandy soils [J]. Plant Soil
534 204:213-222
535 Datta A, Yeluripati JB, Nayak DR, Mahata KR, Santra SC, Adhya TK (2013)
536 Seasonal variation of methane flux from coastal saline rice field with the
537 application of different organic manures. Atmospheric Environment 66:114–122
538 Deutzmann JS, Schink B (2011) Anaerobic oxidation of methane in sediments of lake
539 Constance, an oligotrophic freshwater lake. Applied and Environmental
540 Microbiology 77:4429-4436
541 Ding WX, Cai ZC, Tsuruta H, Li XP (2003) Key factors affecting spatial variation of
542 methane emissions from freshwater marshes. Chemosphere 51:167–173

543 Eller G, Kanel L, Kruger M (2005) Cooccurrence of aerobic and anaerobic methane
544 oxidation in the water column of Lake Plu*b*see. Applied Environment
545 Microbiology 71:8925–8928
546 Ettwig KF, Bulter MK, Paslier DL, et al. (2010) Nitrite-driven anaerobic methane
547 oxidation by oxygenic bacteria. Nature 464:543-548
548 Gauthier M, Bradley RL, Simek M (2013) Anaerobic methane oxidation may be more
549 prevalent in surface soils than was originally thought//EGU General Assembly
550 Conference Abstracts 15:14169
551 Goodrich JP, Campbell DI, Roulet NT, Clearwater MJ (2015) Overriding control of
552 methane flux temporal variability by water table dynamics in a southern
553 hemisphere, raised bog. Journal of Geophysical Research 120:819-831
554 Hartzell J L, Jordan R E. (2012) Shifts in the relative availability of phosphorus and
555 nitrogen along estuarine salinity gradients. Biogeochemistry 107:489-500
556 Hoehler TM, Alperin MJ, Albert DB, et al. (1994) Field and laboratory studies of
557 methane oxidation in an anoxic marine sediment-evidence for a
558 methanogen-sulfate reducer consortium. Global Biogeochemical Cycles
559 8:451-463
560 IPCC (2014). Intergovernmental Panel on Climate Change, IPCC, 2014. Climate
561 Change 2014: Mitigation of Climate Change. Contribution of Working Group III
562 to the Fifth Assessment Report of the Intergovernmental Panel on Climate
563 Change [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S.,
564 Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B.,
565 Savolainen, J., Schlömer, S., von Stechow, C., Zwickel T. & Minx, J. C. (eds.)].
566 Cambridge University Press, Cambridge, United Kingdom & New York, NY,
567 USA. 1435 p.
568 Iversen N, Blackburn TH (1981) Seasonal rates of methane oxidation in anaerobic
569 marine sediments. Applied and Environmental Microbiology 41:1295-1300
570 Joye SB, Samarkin VA (2009) Metabolic variability in seafloor brines revealed by
571 carbon and sulphur dynamics. Nature Geoscience 2:349-354
572 Juutinen S, Alm J, Larmola T, Huttunen JT, Moreno M, Saarnio S, Martikainen PJ,

573 Silvola J (2003) Methane (CH4) reléase from litoral wetlands of Boreal lakes
574 during an extended flooding period. Global Change Biology 9:413-424
575 Kettunen A, Kaitala V, Lehtinen A, Lohila A, Alm J, Silvola J, Martikainen PJ (1999)
576 Methane production and oxidation potentials in relation to water table
577 fluctuations in two boreal mires. Soil Biology and Biochemistry 31:1741-1749
578 Knorr KH, Oosterwoud MR, Blodau C (2008) Experimental drought alters rates of
579 soil respiration and methanogenesis but not carbon exchange in soil of a
580 temperate fen. Soil Biology and Biochemistry 40:1781-1791
581 Kniemeyer O, Musat F, Sievert SM, et al. (2007) Anaerobic oxidation of short-chain
582 hydrocarbons by marine sulphate-reducing bacteria. Nature 449:898-901
583 Krüger M, Eller G, Conrad R, et al. (2002) Seasonal variations in CH_4 oxidation and
584 pathways of CH4 production in rice fields determined by stable carbon isotopes
585 and specific inhibitors. Global Change Biology 8:265-280
586 Krüger M, Treude T, Wolters H, et al. (2005) Microbial methane turnover in different
587 marine habitats. Palaegeophy, Palaeoclimatology, Palaeoecology 227:6-17
588 Laanbroek HJ (2010) Methane emission from nature wetland: interplay between
589 emergent macrophytes and soil microbial process. Annals of Botany 105:141-153
590 Le Mer J., Roger P. (2001) Production, oxidation, emission and consumption of
591 methane by soils: a review. European Journal of Soil Biology 37:25–50
592 Liu JQ, Zeng CS, Chen N (2006) Research of Minjiang River estuary wetland.
593 Beijing: Science Press
594 Lloyd KG, Alperin MJ, Teske A (2011) Environmental evidence for net methane
595 production and oxidation in putative anaerobic methanotrophic (ANME) archaea.
596 Environmental Microbiology 13:2548-2564
597 Moran JJ, Beal EJ, Vrentas JM, et al. (2008) Methyl sulfides as intermediates in the
598 anaerobic oxidation of methane. Environmental Microbiology 10:162-173
599 Moran JJ, House CH, Freeman KH, et al. (2005) Trace methane oxidation studied in
600 several Euryarchaeota under diverse conditions. Archaea 1:303-309
601 Moran JJ, Beal EJ, Vrentas JM, Orphan VJ, Freeman KH, House CH (2008) Methyl
602 sulfides as intermediates in the anaerobic oxidation of methane. Environmental

603 Microbiology 10:162-173
604 Müller V, Blaut M, Gottschalk G. (1993) Bioenergetics of methanogenesis. In Ferry J
605 G, editor. Methanogenesis: ecology, physiology, biochenistry, and genetics.New
606 York: Chapman and Hall, pp. 360-406
607 Nauhaus K, Boetius A, Krüger M, Widdel F (2002) In vitro demonstration of
608 anaerobic oxidation of methane coupled to sulphate reduction in sediment from a
609 marine gas hydrate area. Environmental Microbiology 4:296-305
610 Nesbit SP，Breitenbeck GA (1992) A laboratory study of factors influencing methane
611 uptake by soils [J]. Agriculture Ecosystems and Environment 41:39-54
612 Neubauer SC, Toledo-Duran GE, Emerson D (2007) Returning to their roots:
613 iron-oxidizing bacteria enhance short-term plaque formation in the wetland-plant
614 rhizosphere. Geomicrobiology Journal 24:65–73
615 Neue, H. U. (1997) Fluxes of methane from rice ®elds and potential for mitigation.
616 Soil Use Management 13: 258-267.
617 Orcutt B, Boetius A, Elvert M, Samarkin V, Joye SB (2005) Molecular
618 biogeochemistry of sulfate reduction, methanogenesis and the anaerobic
619 oxidation of methane at Gulf of Mexico cold seeps. Geochimica et
620 Cosmochimica Acta 69:4267-4281
621 Pinheiro J, Bates D, DebRoy S, Sarkar D, Core TR (2016) *nlme*: Linear and Nonlinear
622 Mixed Effects Models. R *package* version 3.1-126, http://CRAN
623 Raghoebarsing AA, Pol A, van des Pas-Schoonen KT, Smolders AJP, Ettwig KF,
624 Rijpstra, WIC, Schouten, S, Damsté JSS, den Camp HJMO, Jetten MSM, Strous
625 M (2006) A microbial consortium couples anaerobic methane oxidation to
626 denitrification. Nature 440:918-921
627 Ro S, Seanjan P, Tulaphitak T (2011) Sulfate content influencing methane production
628 and emission from incubated soil and rice-planted soil in Northeast Thailand. Soil
629 Science and Plant Nutrition 57:833–842
630 Roberts HH, Aharon P (1994) Hydrocarbon-derived carbonate buildups of the
631 northern Gulf of Mexico continental slope: a review of submersible investigations.
632 Geo-Marine Letters 14:135-148

633 Saarnio S, Alm, Silvola J, Lohila A, Nykanen H, Martikainen PJ (1997) Seasonal
634 variation in CH_4 emissions and production and oxidation potentials at microsites
635 on an oligotrophic pine fen. Oecologia 110:414-422
636 Shima S, Thauer RK (2005) Methyl-coenzyme M reductase and the anaerobic
637 oxidation of methane in methanotrophic Archaea. Current Opinion in
638 Microbiology 8:643-648
639 Simas T, Nunes JP, Ferreria JG (2001) Effects of global climate change on coastal salt
640 marshes. Ecological Modelling 139:1-15
641 Singh JS (2011) Methanotrophs: the potential biological sink to mitigate the global
642 methane load. Current Science 100:29-30
643 Siniscalchi, L.A.B., Babelo Leite, L., Oliveira, G., Chernicharo, C.A.L., Calabria de
644 Araújo, J. (2017). Illumina sequencing-based analysis of a microbial community
645 enriched under anaerobic methane oxidation condition coupled to denitrification
646 revealed coexistence of aerobic and anaerobic methanotrophs. Environmental
647 Science Pollution Research 24:16751-16764.
648 Smemo KA, Yavitt JB (2011) Anaerobic oxidation of methane: an underappreciated
649 aspect of methane cycling in peatland ecosystems? Biogeosciences 8:779-793
650 Smemo KA, Yavitt JB (2007) Evidence for anaerobic CH_4 oxidation in freshwater
651 peatlands. Geomicrobiology Journal 24:583-597
652 Song CC, Zhang JB, Wang YY, Wang YS, Zhao ZC (2008) Emission of CO_2, CH_4 and
653 N_2O from freshwater marsh in north of China. Journal of Environmental
654 Management 88:428–436
655 Supparattanapan S, Saenjan P, Quantin C, et al. (2009) Salinity and organic
656 amendment effects on methane emission from a rain-fed saline paddy field. Soil
657 Science and Plant Nutrition 55:142-149
658 Tong C, Wang WQ, Huang JF, Gauci V, Zhang L.H, Sheng ZC (2012) Invasive alien
659 plants increase CH_4 emissions from a subtropical tidal estuarine wetland.
660 Biogeochemistry 111:677-693
661 Treude T, Krüger M, Boetius A, Jorgensen AB (2005). Environmental control on
662 anaerobic oxidation of methane in the gassy sediments of Eckernförde Bay

(German Baltic). Limnology and Oceanography 50:1771-1786

Van der Gon DHAC，Neue HU (1995) Influence of organic matter incorporation on methane emission from wetland rice field [J]. Global Biogeochemical Cycles 9:11-22

Wagner D，Pfeiffer EM (1997) Two temperature optima of methane production in a typical soil of the Elbe river marshland [J]. FEMS Microbiology Ecology 22:145-153

Wang WQ, Li PF, Zeng, CS, Tong C (2012) Evaluation of silicate iron slag as a potential methane mitigating method. – Advances in Materials Research 468:1626–1630

Wang C, Lai DYF, Sardans J, Wang W, Zeng C, Peñuelas J (2017) Factors Related with CH_4 and N_2O Emissions from a Paddy Field: Clues for Management implications. PLOS ONE 12:e0169254

Wang WQ, Tong C, Zeng, CS (2010) Stoichiometry characteristics of carbon, nitrogen, phosphorus and anaerobic carbon decomposition of wetland soil of different texture. – China Environment Sciences 30:1369–1374

Wassmann R, Neue HU, Bueno C, Lantin RS, Alberto MCR, Buendia LV, Bronson K, Papen H, Rennenberg H (1998) Methane production capacities of different rice soil derived from inherent and exogenous substrates. – Plant Soil 203:227–237

Wrede C, Brady S, Rockstroh S, et al. (2012) Aerobic and anaerobic methane oxidation in terrestrial mud volcanoes in the Northern Apennines. Sedimentary Geology 263:210-219

Yagi K，Minami K (1990) Effect of organic matter applications on methane emission from some Japanese paddy fields [J]. Soil Science and Plant Nutrition 36:599-610

Zheng CH, Zeng CS, Chen ZQ, Lin MC (2006) A study on the changes of landscape pattern of estuary wetlands of the Minjiang River. Wetland Science 4:29–34.

Zhou LJ, Tu YY, Song YC (2006) The biodiversity of wetland and its prevention measures in Min River Estuary. Ecological Science 25:330–334.

692 Table 1. Significant observed relationships of the potentials of soil methane
693 production, soil methane anaerobic oxidation and soil methane aerobic oxidation
694 among them and with soil properties. Plot and time of sampling (month) were
695 introduced in the models as random factors.

model <- lme(Variable~fixed factor, data=dades, random=~1|plot/time,method="REML")			
Variable	Fixed factor	Fixed factor statistics	Model statistics (R^2m=fixed factor, R^2c=fixed + random factor)
Potential soil anaerobic CH_4 oxidation	Potential soil CH_4 production	Estimates=0.578 F=43.7 *P*<0001	R^2m=0.56 R^2c=0.99
Potential soil aerobic CH_4 oxidation	Potential soil CH_4 production	Estimates=0.707 F=21.2 *P*<0001	R^2m=0.38 R^2c=0.99
Potential soil aerobic CH_4 oxidation	Potential soil anaerobic CH_4 oxidation	Estimates=1.14 F=49.0 *P*<0001	R^2m=0.58 R^2c=0.99
CH_4 pore-water soil concentration	Potential soil CH_4 production	Estimates=-0.029 F=11.8 *P*=0.0016	R^2m=0.24 R^2c=0.91
CH_4 pore-water soil concentration	Potential soil anaerobic CH_4 oxidation	Estimates=-0.42 F=6.31 *P*=0.017	R^2m=0.15 R^2c=0.91
CH_4 pore-water soil concentration	Potential soil aerobic CH_4 oxidation	Estimates=-0.46 F=5.09 *P*=0.031	R^2m=0.13 R^2c=0.94
Potential soil anaerobic CH_4 oxidation	Soil pH	Estimates=6.17 F=5.47 *P*=0.026	R^2m=0.14 R^2c=0.99
Potential soil anaerobic CH_4 oxidation	Soil Eh	Estimates=-0.016 F=5.89 *P*=0.021	R^2m=0.15 R^2c=0.99
Potential soil CH_4 production	Soil pH	Estimates=5.80 F=6.55 *P*=0.015	R^2m=0.15 R^2c=0.90
Potential soil CH_4 production	Soil Temperature	Estimates=-0.045 F=5.87 *P*=0.021	R^2m=0.13 R^2c=0.90
Potential soil CH_4 production	Soil Eh	Estimates=-0.015 F=6.76 *P*=0.014	R^2m=0.15 R^2c=0.90
CH_4 pore-water soil concentration	Soil Temperature	Estimates=0.082 F=16.4 *P*<0001	R^2m=0.32 R^2c=0.99

Figure legends

Fig. 1. Study area and sampling site (▲) in southeastern China.

Fig. 2. Monthly variation of potential soil methane production rate, potential soil methane anaerobic oxidation, potential soil methane aerobic rate, and dissolved methane concentration in soil porewater.

Fig. 3. Seasonal values of potential soil methane production rate (A), potential soil methane anaerobic oxidation rate (A), potential soil methane aerobic oxidation rate (A), and dissolved methane concentration in soil porewater (B). Different letters indicate significantly different among seasons.

Fig. 4. Monthly variation of soil properties (A), porewater properties (B), plant bimass (C), and air temperature (D).

Fig. 5. Principal component analyses (PCA) to observe the multiple correlations among potential soil methane anaerobic oxidation, potential soil methane production, potential soil methane aerobic methane oxidation and the environmental factors and the analyzed soil variables. We represented the position of different cases (soil samples) (a) and the loads of the commented variables (b) in the layout generated by the two first PCA axes (explaining together a 52.0% of the total variance). Ait T^a = Air temperature, Cl =concentration of Cl- in soil, Eh = soil potential redox, Fe^{3+} = Soil Fe^{3+} concentration, Maerox=Potential soil methane aerobic oxidation, Manaox=Potential soil methane anaerobic oxidation, Mprod=Potential soil methane production, Msoil=concentration of methane in soil porewater, pH = soilpH, salinity=soil salinity, Soil T^a =soil temperature, sulfate=soil sulfate concentration, aut

718 = autumn, su = summer, sp = spring, wi = winter.

745
746 **Fig. 1.**
747

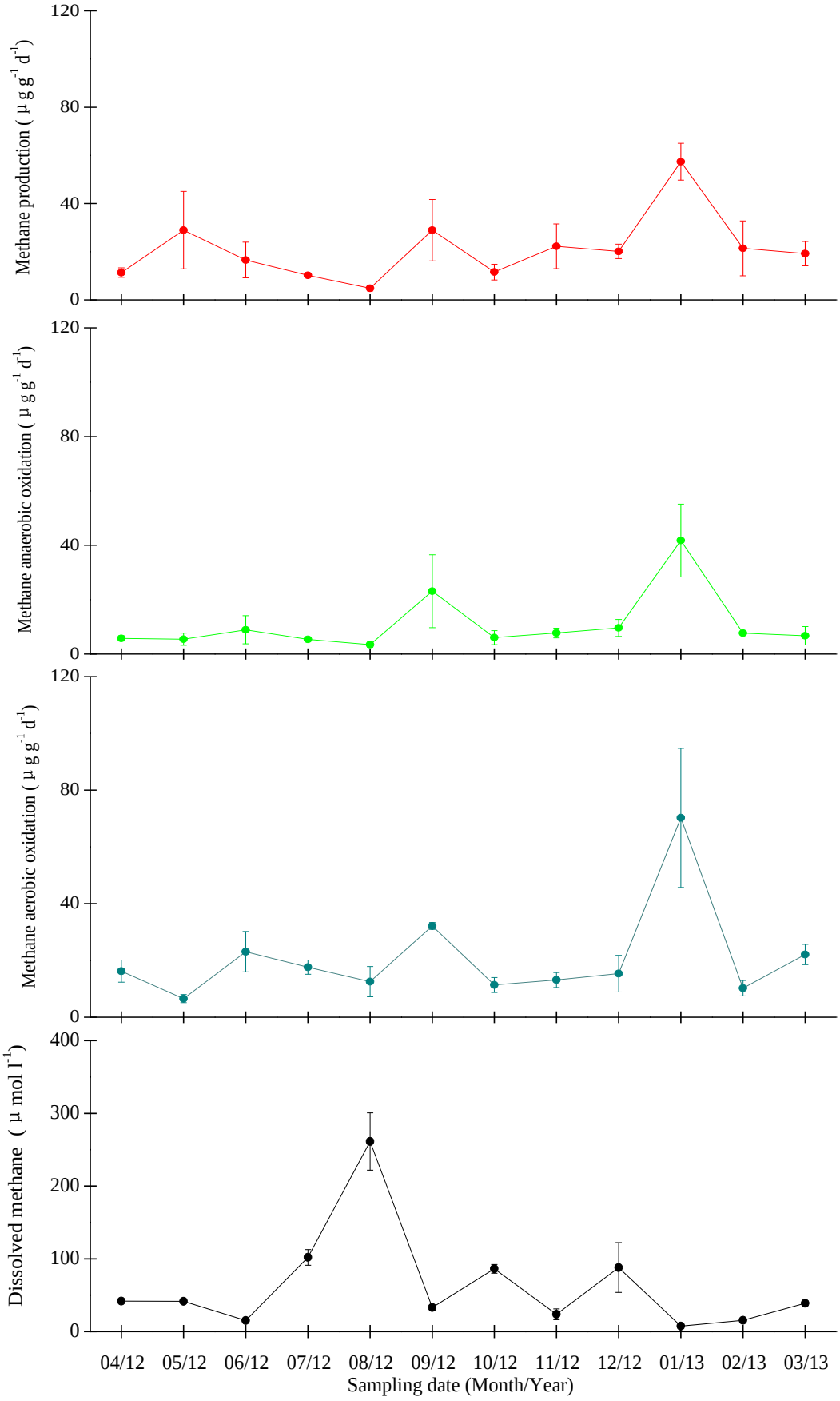
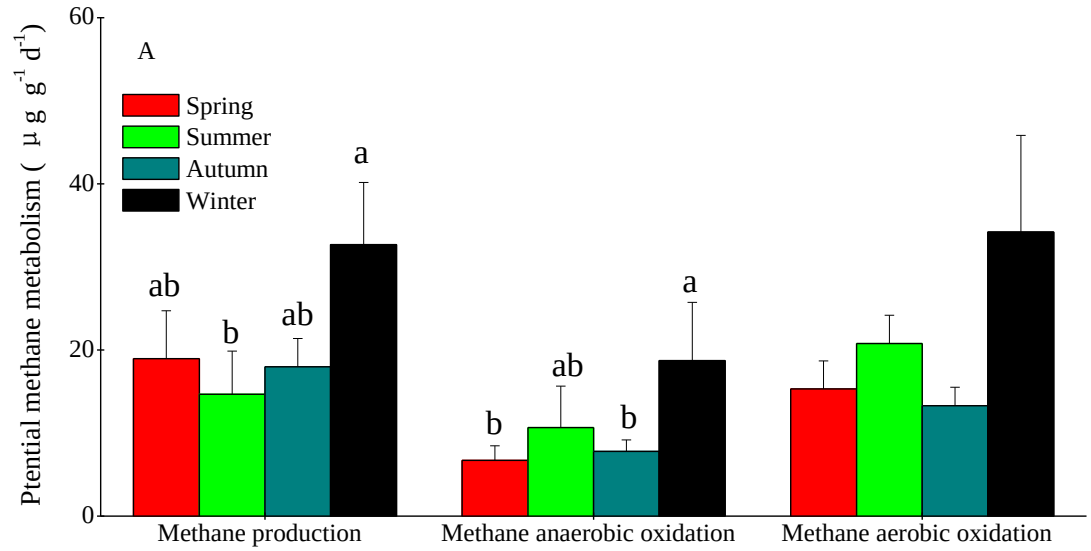

Methane production (μ g g^{-1} d^{-1})
Methane anaerobic oxidation (μ g g^{-1} d^{-1})
Methane aerobic oxidation (μ g g^{-1} d^{-1})
Dissolved methane (μ mol l^{-1})
0
40
80
120
100
200
300
400
04/12
05/12
06/12
07/12
08/12
09/12
10/12
11/12
12/12
01/13
02/13
03/13
Sampling date (Month/Year)

Fig. 2.


A
Spring
Summer
Autumn
Winter
Ptential methane metabolism (μ g g-1 d-1)
60
40
20
0
ab
b
ab
a
b
ab
b
a
Methane production
Methane anaerobic oxidation
Methane aerobic oxidation

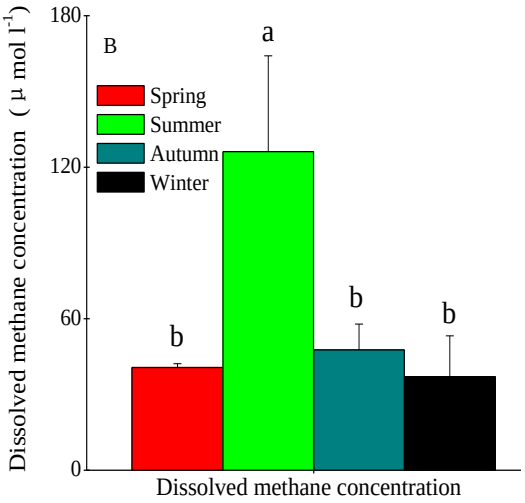
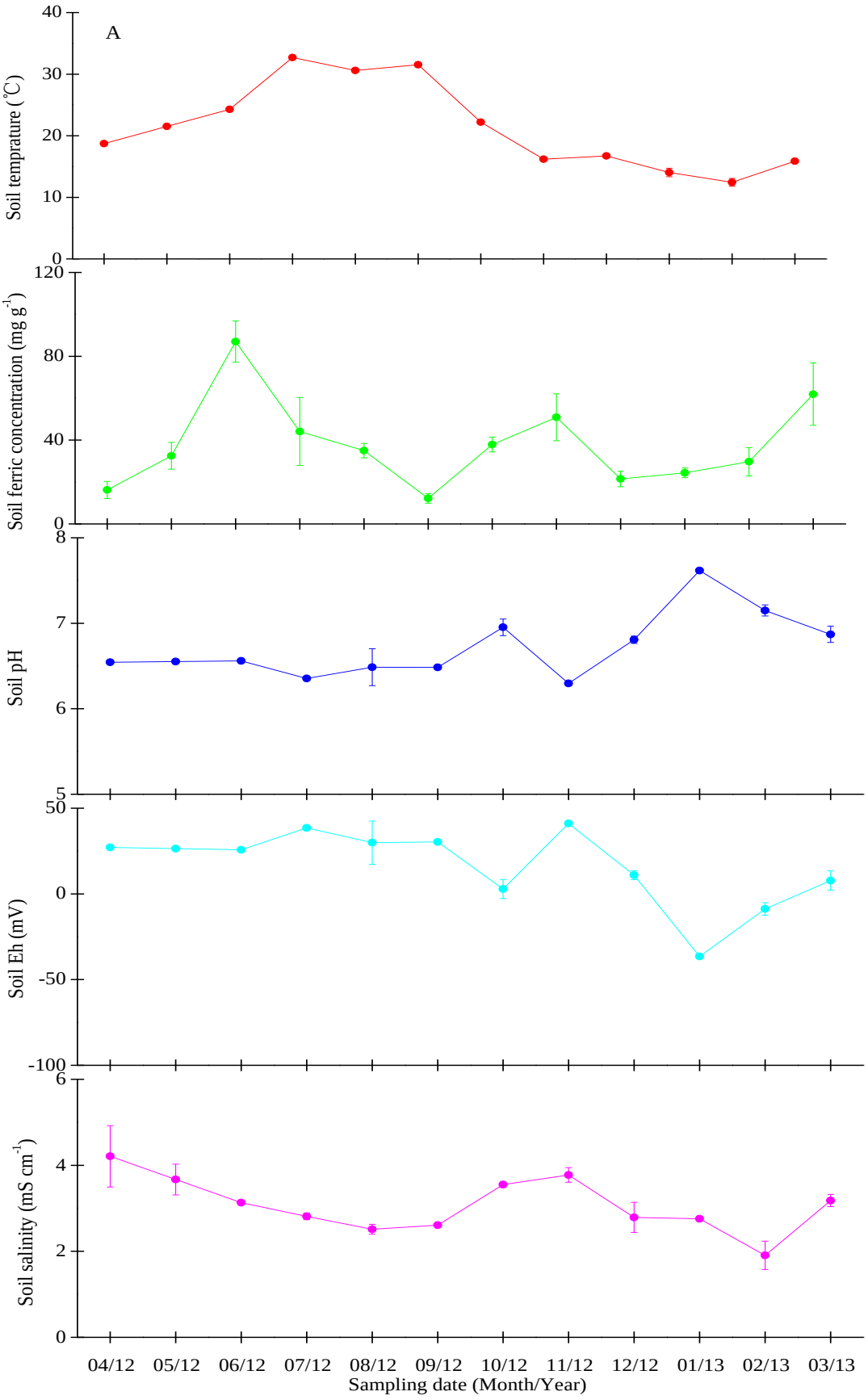
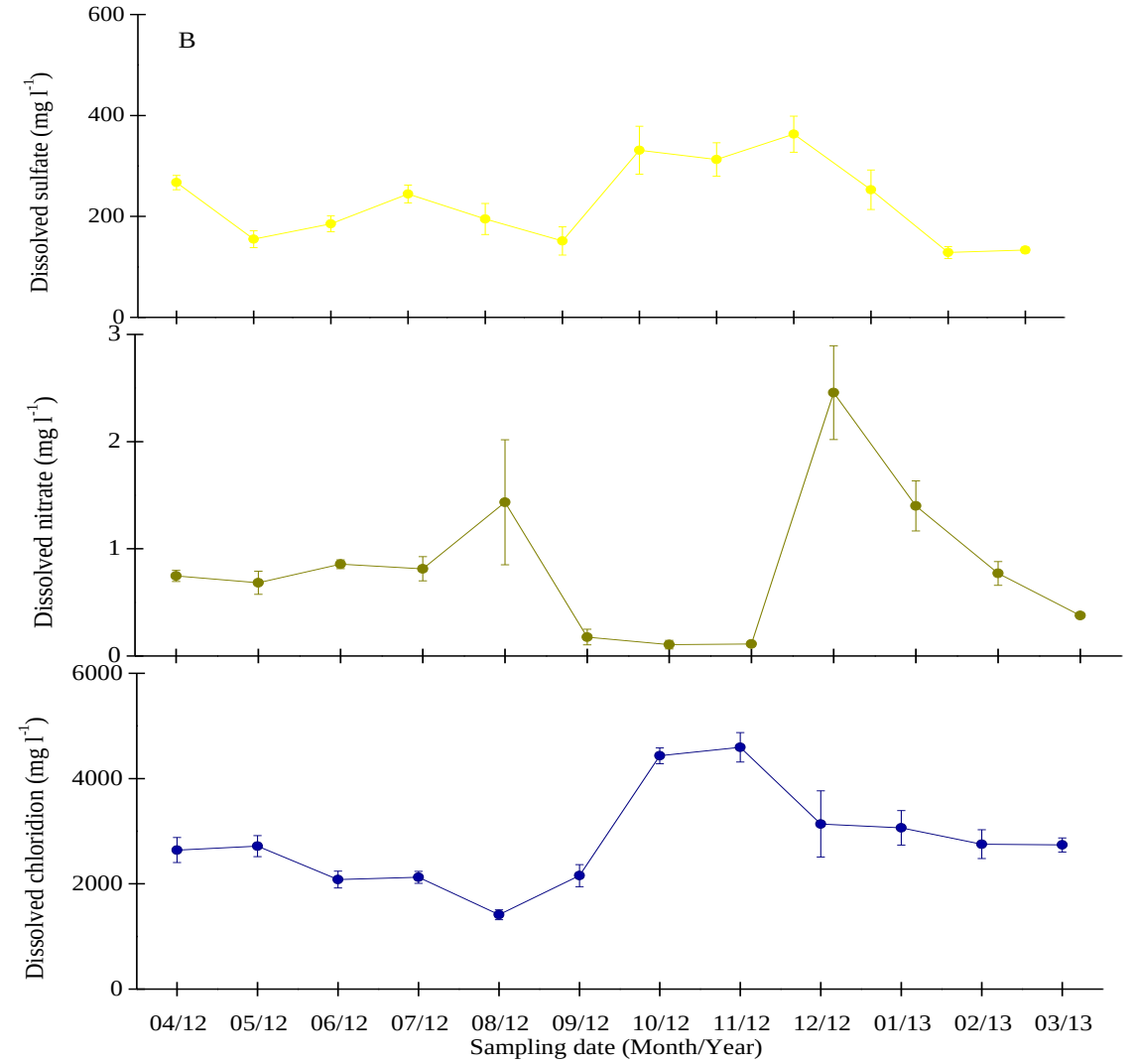
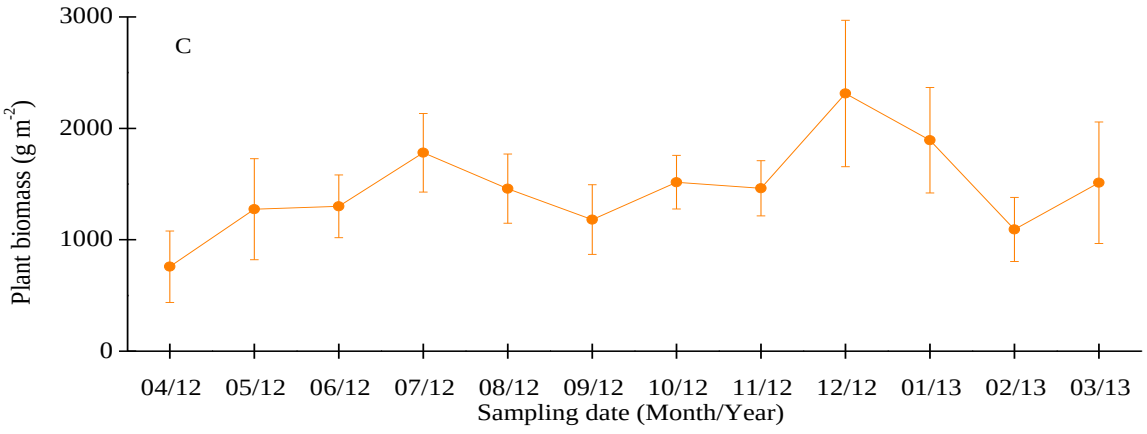

B
Spring
Summer
Autumn
Winter
Dissolved methane concentration (μ mol l-1)
180
120
60
0
b
a
b
b
Dissolved methane concentration

Fig. 3.


A
Soil temprature (℃)
Soil ferric concentration (mg g-1)
Soil pH
Soil Eh (mV)
Soil salinity (mS cm-1)
04/12
05/12
06/12
07/12
08/12
09/12
10/12
11/12
12/12
01/13
02/13
03/13
Sampling date (Month/Year)


B
Dissolved sulfate (mg l-1)
600
400
200
0
Dissolved nitrate (mg l-1)
3
2
1
0
Dissolved chloridion (mg l-1)
6000
4000
2000
0
04/12
05/12
06/12
07/12
08/12
09/12
10/12
11/12
12/12
01/13
02/13
03/13
Sampling date (Month/Year)


C
Plant biomass (g m-2)
3000
2000
1000
0
04/12
05/12
06/12
07/12
08/12
09/12
10/12
11/12
12/12
01/13
02/13
03/13
Sampling date (Month/Year)

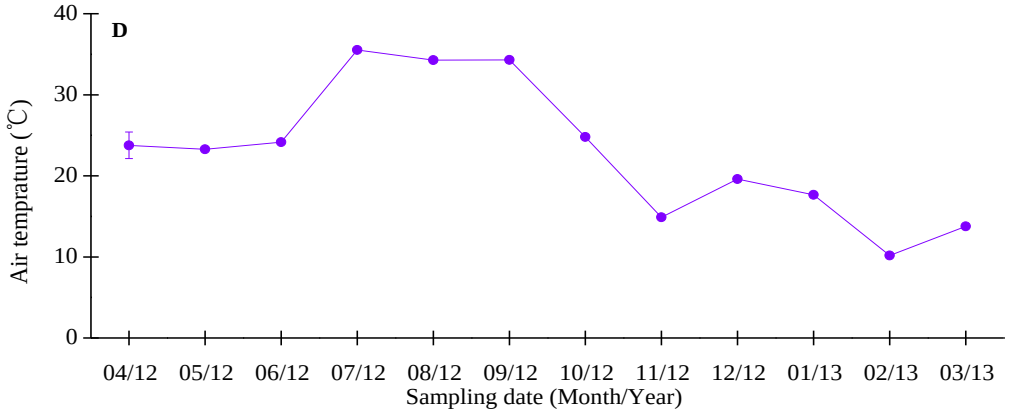

D
40
30
20
10
0
Air temprature (℃)
04/12
05/12
06/12
07/12
08/12
09/12
10/12
11/12
12/12
01/13
02/13
03/13
Sampling date (Month/Year)

Fig. 4.

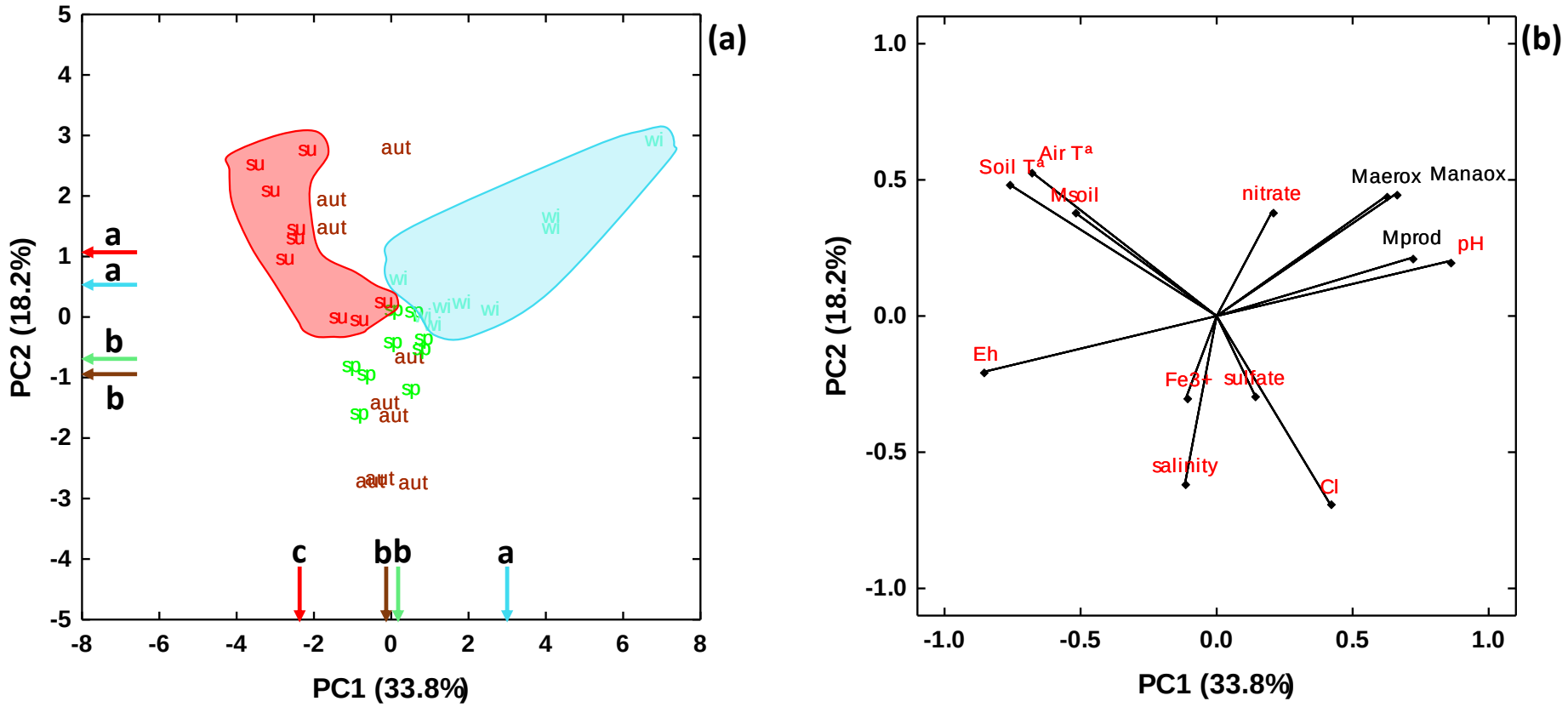

(a)
PC2 (18.2%)
PC1 (33.8%)
su
aut
wi
sp
a
a
b
b
c
bb
a
(b)
PC2 (18.2%)
PC1 (33.8%)
Soil Tª
Air Tª
Msoil
nitrate
Maerox
Manaox
Mprod
pH
Eh
Fe3+
sulfate
salinity
Cl

Fig. 5.

816

817