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Effects of Land Use Types on CH₄ and CO₂ Production Potentials in Subtropical Wetland Soils

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Abstract: Changes in land use types can alter the soil and environmental characteristics of wetlands, which in turn influence the magnitude of greenhouse gas production by soil microbes. However, the effects of land use change on the production potential of methane (CH₄) and carbon dioxide (CO₂) in subtropical wetland soils and the underlying controls are still largely unknown. In this study, we examined the soil CH₄ and CO₂ production potentials under five different land use types (natural mangrove, Gei Wai water channel, Gei Wai forest, reedbed, and freshwater pond) and their relationships with soil physico-chemical properties in a subtropical wetland in Hong Kong using aerobic and anaerobic laboratory incubation experiments. Our results showed an overall decreasing trend of CH₄ and CO₂ production potentials down the soil profile at all sites, which could be attributed to a reduction in the concentrations of soil organic matter (SOM), total Kjeldahl nitrogen (TKN) and ammonium nitrogen (NH₄⁺-N). Moreover, the soil CH₄ and CO₂ production potentials varied significantly in the surface soils among land use types, but were more similar across the sites in the deeper soils. The conversion of natural mangrove to other land use types significantly reduced both the aerobic and anaerobic CO₂ production potentials in the top 10 cm soils, except for Gei Wai forest, which demonstrated significantly higher CO₂ production rates (61.15–97.91 μg g⁻¹ day⁻¹). Meanwhile, the mean CH₄ production potential in the surface soils of natural mangrove (0.05 μg g⁻¹ d⁻¹) was significantly lower than that in the Gei Wai forest and Gei Wai channel (0.26–0.27 μg g⁻¹ day⁻¹) but slightly higher than that in the freshwater pond and reedbed (0.00–0.02 μg g⁻¹ day⁻¹). The high soil CH₄ and CO₂ production potentials observed in the Gei Wai forest could be explained by the high soil concentrations of SOM, TKN and NH₄⁺-N. On the other hand, the lower anaerobic CH₄ and aerobic CO₂ productions observed in the reedbed could be attributed to the lower concentrations of NH₄⁺-N and available phosphorus. Our findings highlighted the significant impacts of land use types on the CH₄ and CO₂ production potentials of subtropical wetland soils, which had practical implications for wetland management for climate change mitigation.

Keywords: carbon dioxide; gas production potential; greenhouse gas; land use; mangrove; methane; soil properties; wetland

1. Introduction

Carbon dioxide (CO₂) and methane (CH₄) are potent greenhouse gases (GHGs) in the atmosphere that can contribute significantly to global climate change. Wetlands, as the single largest natural CH₄ source, account for over 30% of the global CH₄ emissions and hence should not be neglected [1]. The net CH₄ emission rate from wetlands depends on the balance between CH₄ production, oxidation,

and transport (including diffusion, ebullition, and plant-mediated transport) [2]. CH₄ production in wetlands is predominantly caused by the anaerobic decomposition of organic matter originated from root exudates, crop residues, and dead photosynthetic biomass [2]. CH₄ can be produced by methanogens using various substrates, such as CO₂/H₂ and acetate [3]. The magnitude of soil CH₄ production depends on various factors including pH, temperature, and the availability of substrate, oxygen, and other alternative electron acceptors [4–7]. Most of the methanogens are known to grow within a narrow pH range of 6–8 [8], while the optimum pH for CH₄ production in the temperate and subarctic peat is found to range between 5.5 and 7.0 [9]. In a northern fen, a drop in pH from 7 to 5.5 caused a significant decrease in CH₄ production rate [7]. Numerous studies have shown a positive relationship between temperature and the rates of respiration and methanogenesis under both aerobic and anaerobic conditions [7,9–13]. Coles and Yavitt [14] found an increase in CH₄ production rates following the addition of carbon substrates (e.g., glucose, ethanol and acetate) to forested fen peat samples, which indicated substrate availability was a limiting factor of CH₄ production. Meanwhile, an increase in sulfate concentration and salinity can suppress methanogenesis, as sulfate-reducing bacteria can outcompete methanogens for the energy sources [15]. Nitrate nitrogen has been shown to increase the soil redox potential and decrease CH₄ production [16], while higher anaerobic CH₄ production rate was observed in peatlands with higher soil organic carbon (SOC) and nitrogen (N) concentrations [17].

Soil CO₂ production can occur during organic matter decomposition under both aerobic and anaerobic conditions as the wetland is exposed to air and flooded by water, respectively. CO₂ production potential is affected by various soil and environmental parameters, such as temperature, water table, oxygen, soil organic matter, and pH [18–20]. Inglett, Inglett, Reddy and Osborne [13] reported Q₁₀ values of anaerobic and aerobic soil CO₂ production in a subtropical freshwater marsh ranging between 1.3 and 2.5, and 1.4 and 2.2, respectively, illustrating the positive role of temperature on CO₂ production. Bergman, et al. [21] also found that both aerobic and anaerobic CO₂ production of peat samples significantly increased in response to a rise in temperature from 7 to 25 °C. Kim, et al. [22] showed that soil CO₂ production in boreal forests and peatlands was higher under non-flooded than flooded conditions owing to the greater oxygen availability. Soil organic matter quality is another important factor governing CO₂ production by affecting the substrate supply to microbes. A previous study has shown that the addition of glucose, a highly labile carbon compound, could increase CO₂ production in peatland soils by 2.9 and 1.5 times under anaerobic and aerobic conditions, respectively [18]. Moreover, a higher soil N concentration was shown to support a higher rate of anaerobic soil CO₂ production in peatlands [17].

Land use change can affect the species composition of plant communities and soil physico-chemical properties. Differences in biomass and litterfall among plant species can influence the soil organic C content, and subsequently the rate of soil GHG fluxes [23–25]. For instance, the Australian mangroves dominated by *Avicennia marina* had lower SOC than those dominated by *Rhizophora stylosa* [23]. In addition, the quality and quantity of root exudates produced by plants can vary between species, leading to differences in substrate supply for methanogenesis. Aulakh, et al. [26] reported that 61–83% of the carbon (C) from root exudates in paddy soils was converted to CH₄, indicating the significance of root exudates as a methanogenic substrate. Coastal mangroves in general have a much higher C stock per unit area than terrestrial forests in the tropical, temperate, and boreal regions, owing to their predominantly flooded environment, high primary productivity, and effective trapping of sediments [27]. They have a high ratio of belowground-to-aboveground C mass, with a large proportion of C being stored in dead roots and soils. However, global mangroves have been on a declining trend owing to aquaculture expansion, agricultural development, overharvesting, soil pollution, and climate change [28–30]. The net mangrove deforestation rates in the 1990s and in 2000–2005 were 0.72% and 0.66%, respectively [31]. Mangrove degradation and conversion could lead to substantial C losses, since a large quantity of C formerly stored in anaerobic soils are now exposed to aerobic conditions for an accelerated CO₂ emission [27]. Mangrove deforestation has resulted in

significant C emissions at the rates of 23.5–38.7 Tg year⁻¹ since 2000 [32]. The conversion of mangrove forests to shrimp ponds in Indonesia has resulted in CO₂ losses of 4.37 and 1.60 kg CO₂ m⁻² year⁻¹ from the walls and the floors of the ponds, respectively, to the atmosphere [33]. However, in the long run, the enhancement of soil CO₂ production in response to wetland conversion might decrease with time, as continual decomposition of soil organic matter leads to a reduction in SOC concentration. For example, the sediment organic content in the Caribbean mangroves decreased significantly by up to 50% around 8 years after clearing [34]. Lovelock, et al. [35] found that the soil CO₂ flux from the mangroves in Belize declined with post-clearing time, from 10,600 to 3000 t km⁻² year⁻¹ after one year and 20 years of clearing, respectively.

Coastal wetlands represent about 10% of the total area of natural wetlands in China, covering an area of 5.8 million ha [36]. Mangrove wetlands, which dominate the coastlines in southeast China, contain a large amount of organic matter, and are often highly eutrophic owing to the influence of urbanization and industrialization in the surrounding region [37]. The combination of high soil C stock and nutrient availability could potentially stimulate microbial activities and thus GHG production in soils. While Chen, et al. [38] reported high soil N₂O and CO₂ fluxes in eutrophic mangroves ranging between 0.1–6.3 mg m⁻² day⁻¹ and 1.1–9.3 mg m⁻² day⁻¹, respectively, the magnitude of soil greenhouse gas production potential in subtropical eutrophic wetlands and its response to land use change are still largely unknown. Hence, the objectives of this study are to: (1) quantify the anaerobic CH₄ and CO₂ production and aerobic CO₂ production potentials from the soils of a subtropical eutrophic wetland at different depths; (2) examine the impacts of mangrove conversion to other land use types on soil CH₄ and CO₂ production potentials; and (3) investigate the influence of soil physico-chemical properties on soil CH₄ and CO₂ production potentials. We hypothesize that: (i) the conversion of natural mangrove to other land use types (i.e., Gei Wai water channel, Gei Wai forest, freshwater pond, and reedbed) will reduce the SOC concentrations and soil CH₄ and CO₂ production potentials; (ii) the effects of land use change on soil CH₄ and CO₂ production potential will diminish with soil depth owing to decreasing SOC concentrations; and (iii) the variations in soil CH₄ and CO₂ production potentials are related to SOC, soil nitrogen concentration, salinity, and water table.

2. Materials and Methods

2.1. Study Site

The study was conducted in the 380-ha Mai Po Marshes Nature Reserve in Hong Kong, China (22°30' N, 114°01' E, Figure 1). This region is predominantly affected by a subtropical monsoonal climate, with mean annual temperature and precipitation of 23.3 °C and 2399 mm, respectively [39]. The highest monthly average temperature and rainfall occur during the summer period between June and August. Situated at the mouth of the Pearl River Estuary, this coastal wetland receives tidal water from Deep Bay and fresh water from the nearby Shenzhen and Shan Pui Rivers, and is generally influenced by semi-diurnal tides. Mangrove represents the dominant type of natural vegetation at this site. The soils in the natural mangrove have a depth of over 10 m, and the total C stock in the top 1 m soils is around 14 kg m⁻² (unpublished data). During the period between the 1940s and 1990s, around 50% of the natural mangrove forest was converted to several different land use types, such as shrimp ponds (Gei Wais), fish ponds, and reedbed, as a result of anthropogenic activities.

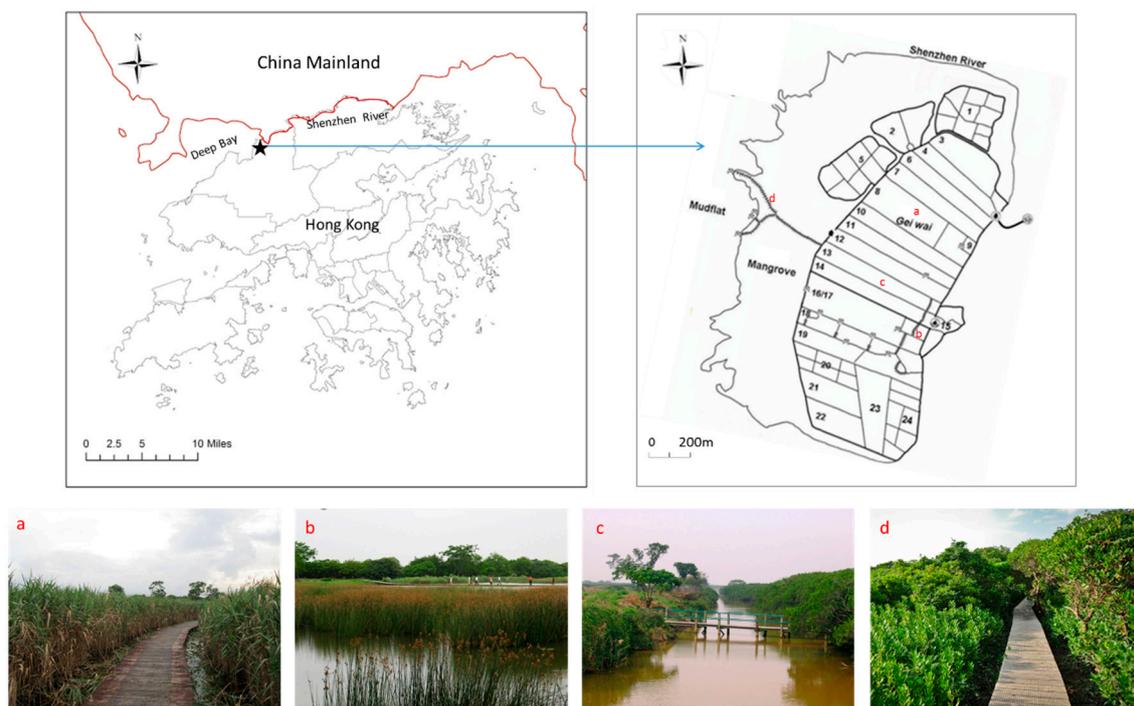


Figure 1. Locations of the five soil sampling sites: (a) Reedbed; (b) Freshwater pond; (c) Gei Wai forest and Gei Wai water channel; and (d) Mangrove.

Details about the dominant land use types in this coastal wetland site are as follows:

- (1) Mangrove: The natural mangrove is dominated by *Kandelia obovata*, which forms a continuous belt of approximately 500 m in width and 3 km in length [40]. It represents the original land use type at this site before human disturbances. The tallest *K. obovata* community in this mangrove has a mean canopy height of 6.5 m, a mean diameter at breast height of 7.6 cm, and a mean tree density of 0.7 m^{-2} [41];
- (2) Gei Wai: The tidal shrimp ponds (locally called Gei Wais) were converted from the natural mangrove in the 1940s. These brackish shrimp ponds, each with a size of around 10 ha, are surrounded by a water channel (~1.5 m deep, 10 m wide) around the four inner edges. Each pond has a central vegetated platform which is dominated by *K. obovata* (referred to as Gei Wai forest thereafter) and is occasionally flooded, similar to the high intertidal zone of the mangrove [42]. The pond is operated by a sluice gate that controls the water level, stocking of shrimp fries, and harvesting of shrimps;
- (3) Reedbed: The reedbeds are dominated by *Phragmites australis*, and are mostly found in the central platform of some Gei Wais. The reeds became dominant after the tidal Gei Wais were converted to permanently flooded ponds in the 1980s, leading to the drowning of existing mangrove vegetation [42]. The reedbeds in Mai Po now cover a total of 46 ha and is one of the largest in the Guangdong province in southern China [43];
- (4) Freshwater pond: It was converted from mangrove vegetation to shrimp pond in the 1940s, and then subsequently to a rain-fed freshwater pond dominated by *Scirpus subulatus* in 1997 to provide a freshwater habitat for enhancing biodiversity in this coastal wetland.

Table 1 shows the average water table, salinity, and pH values under the five land use types at Mai Po at the time of sample collection.

Table 1. Water table, soil pH, and soil salinity for the five land use types at the Mai Po Marshes (means \pm standard deviation, $n = 3$).

Land Use Type	Water Table	pH	Salinity
	cm		‰
Gei Wai forest	-18.00 ± 1.53	7.46 ± 0.14	5.33 ± 0.20
Gei Wai water channel	74.67 ± 2.40	8.10 ± 0.08	0.77 ± 0.00
Reedbed	0.70 ± 0.35	7.24 ± 0.12	7.10 ± 0.06
Freshwater pond	18.00 ± 2.52	6.91 ± 0.05	0.16 ± 0.00
Mangrove	-2.33 ± 0.67	7.23 ± 0.01	11.73 ± 0.27

2.2. Soil Sampling and Incubation

Soil cores in the top 0.5 m were collected in triplicate with a soil corer (1 m long, 10 cm diameter) for each of the five land use types (i.e., Gei Wai forest, Gei Wai water channel, freshwater pond, reedbed and mangrove) at the Mai Po Marshes (Figure 1). These cores were sub-sectioned in the field into four depth intervals, namely 0–10, 10–20, 20–30, and 30–50 cm, kept under 4 °C at field moisture content, and transported to the laboratory immediately for subsequent experiment [19]. The soils from the Gei Wai water channel and freshwater pond were kept with in-situ water for maintaining an anaerobic condition. The triplicate soil samples from each site were homogenized, and the roots and rocks were discarded in the laboratory before the incubation experiments. We conducted aerobic and anaerobic incubations for determining soil CH₄ and CO₂ production potentials, following the method of Moore and Dalva [19]. For anaerobic incubation, approximately 20 g of wet soils and 50 ml of distilled H₂O were placed in 300 ml glass bottles. The bottles were then sealed, evacuated with a vacuum pump, and flushed with O₂-free N₂ three times. These bottles were incubated anaerobically for 14 days under a temperature of 25 °C. At 0, 1, 3, 5, 7, 9, 11 and 14 days of incubation, 6 ml of headspace air sample was withdrawn from each bottle for the determination of CH₄ and CO₂ concentrations by gas chromatograph (7890A, Agilent, Santa Clara, CA, USA) [44]. After each sampling, 6 ml of O₂-free N₂ was added back into the bottle to maintain the same pressure. For aerobic incubation, approximate 20 g of wet soils and 10 ml of distilled H₂O were placed in 300 ml glass bottles, and then shaken on a rotary shaker to ensure that no anaerobic micro-sites were developed. The bottles were then flushed with room air and sealed for a total incubation period of 7 days. We collected 6 ml of headspace air sample from each bottle on a daily basis, and then added 6 ml of room air back to each bottle after sampling for pressure equilibration.

2.3. Measurement of Soil Properties

We measured soil temperature, soil moisture, pH, redox potential (Eh), and water level in triplicate for each of the five land use types simultaneously when soil samples were taken for incubation experiments. Soil temperature and moisture were measured with a thermometer (Fluke Corporation, Everett, WA, USA) and a soil moisture probe (HH2, Delta-T devices, Cambridge, UK), respectively. Soil pH and redox potential (Eh) were measured with a digital pH/ORP meter (Eutech Ion6+, Thermo Scientific, Waltham, MA, USA). Soil salinity was measured using a salinity meter (Model 140, Orion Research Inc., Jacksonville, FL, USA). Water table was measured by measuring the height of water inside a perforated PVC tube that was pre-installed into the soil.

We also measured the concentrations of ammonium nitrogen (NH₄⁺-N), nitrate nitrogen (NO₃⁻-N), available phosphorus (P), total Kjeldahl nitrogen (TKN) and soil organic matter (SOM) in the soils at the depths of 0–10, 10–20, 20–30 and 30–50 cm. Soil available P, NH₄⁺-N and NO₃⁻-N were extracted from fresh soils, and their concentrations were determined with a flow injection analyzer (FIA Star 5000, Hillerød, Denmark) following the methods of Black, et al. [45]. TKN was determined with the Kjeldahl method [45]. SOM concentration was determined by loss on ignition by combusting soils at 550 °C for 4 h following the method of Nelson and Sommers [46]. Sulfate concentration in the

top 10 cm soils was measured in situ by a plant root simulator (PRS, Western Ag Innovations Inc., Saskatoon, SK, Canada) equipped with a resin membrane that quantified the supply of cations and anions to the rhizosphere over a burial period of two weeks [47].

2.4. Determination of Soil C Fractions

The SOC concentration was determined by the Walkley–Black method as described in Nelson and Sommers [46]. In addition, we measured soil microbial biomass C (MBC), water-soluble carbohydrate C (WSC), readily mineralizable C (RMC), and acid hydrolyzable carbohydrate C (AHC) in the top 10 cm soils. MBC was determined by a modified chloroform fumigation method [48]. WSC was determined using the anthrone method after extracting the soils with 20 ml of deionized hot water at 80 °C for 24 h [49]. RMC was measured by wet digestion with dichromate after extraction with 0.5 M K₂SO₄ [50,51]. AHC was determined using the anthrone method after extraction with 1.5 M H₂SO₄ for 24 h [52].

2.5. Statistical Analysis

One-way ANOVA was used to test for significant differences in CH₄ and CO₂ productions and soil nutrients among land use types at each depth, as well as among depths for each land use type. The data were tested for normality and homogeneity of variance, and log-transformed if necessary. If significant differences were detected, post-hoc Duncan's multiple range test was further carried out for making multiple comparisons of CH₄ and CO₂ productions and soil nutrients among land use types or depths. Pearson correlation analysis was also conducted to establish the relationships between soil or environmental parameters and soil CH₄ and CO₂ productions. All statistical analyses were conducted using SPSS 19.0 for Windows (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Effects of Land Use Types on CH₄ and CO₂ Production Potentials

The anaerobic CH₄ (an-CH₄) production potentials in the top 10 cm soils differed significantly among land use types, with significantly higher values of 0.27 and 0.26 µg g⁻¹ day⁻¹ in the Gei Wai water channel and Gei Wai forest, respectively (Figure 2). The an-CH₄ production potentials were much lower in the mangrove, freshwater pond, and reedbed, with mean rates of 0.05, 0.02, and 0.004 µg g⁻¹ day⁻¹, respectively (Figure 2). At a depth of 10–20 cm, the an-CH₄ production was significantly higher in the Gei Wai water channel (0.05 µg g⁻¹ day⁻¹) and mangrove (0.06 µg g⁻¹ day⁻¹) than the other three land use types (0.00–0.03 µg g⁻¹ day⁻¹). At a depth of 20–30 cm, the mean an-CH₄ production potential was significantly higher in the Gei Wai water channel (0.06 µg g⁻¹ day⁻¹), followed by the Gei Wai forest and freshwater pond (0.01–0.02 µg g⁻¹ day⁻¹). With increasing soil depth, the site differences in an-CH₄ production were mitigated in the 30–50 cm soils. At a depth of 30–50 cm, the soil an-CH₄ production potentials were generally less than 0.01 µg g⁻¹ day⁻¹, with significantly lower values in the mangrove and reedbed.

Similarly, the anaerobic CO₂ (an-CO₂) production potentials in the top 10 cm soils showed significant differences among land use types (Figure 2), with significantly higher value (61.14 µg g⁻¹ day⁻¹) in the Gei Wai forest, followed by mangrove (22.23 µg g⁻¹ day⁻¹). Significantly lower mean values of an-CO₂ production were found in the reedbed and Gei Wai water channel (12.35–15.25 µg g⁻¹ day⁻¹), while the lowest value was seen in the freshwater pond (5.44 µg g⁻¹ day⁻¹). At a depth of 10–20 cm, the Gei Wai forest and mangrove also showed significantly higher soil an-CO₂ production (12.29–15.59 µg g⁻¹ day⁻¹) than the other three land use types. At a depth of 20–30 cm, the mean an-CO₂ production potential differed significantly among land use types in the order of: Gei Wai forest > Gei Wai water channel > mangrove > reedbed > freshwater pond. At a depth of 30–50 cm, the effects of land use types on soil CO₂ production became weak, with only mangrove showing a significantly higher value (8.95 µg g⁻¹ day⁻¹).

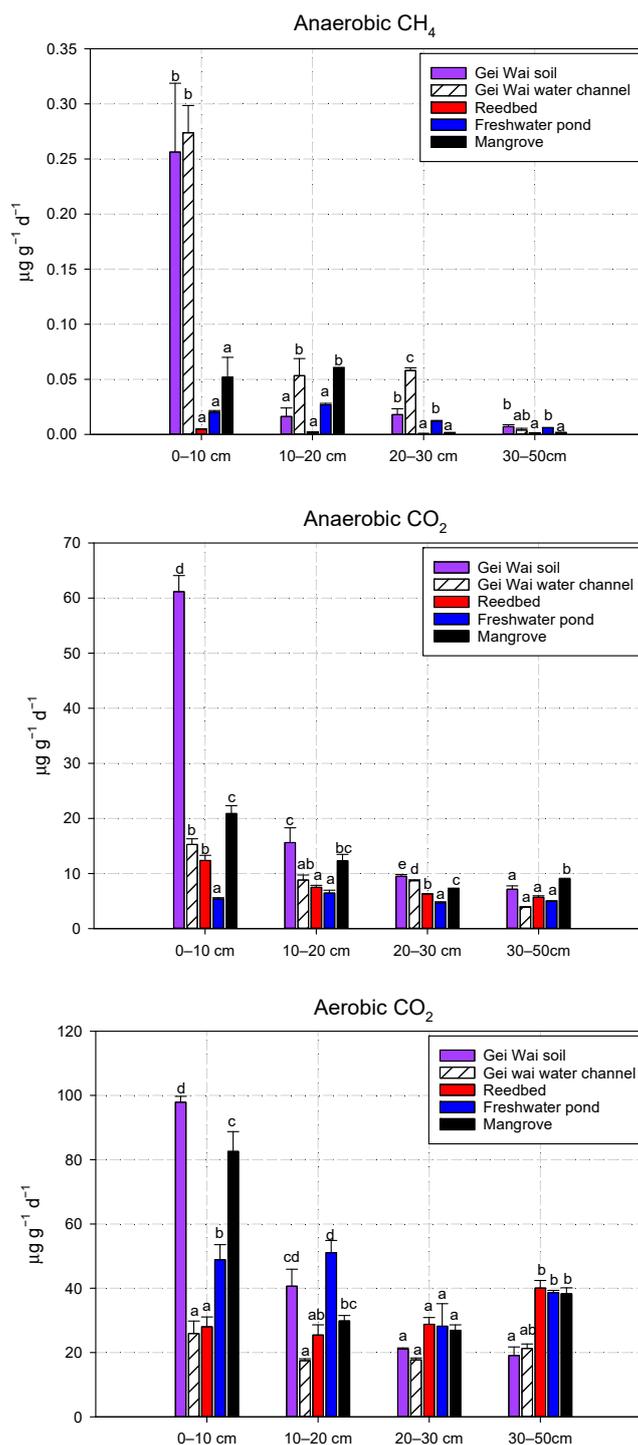


Figure 2. Mean anaerobic CH₄, anaerobic CO₂, and aerobic CO₂ production potentials at different soil depths for the five land use types. Data are means ± standard deviation. Different letters indicate significant differences in rates among the land use types at a given depth ($p < 0.05$).

The mean aerobic CO₂ (aero-CO₂) production potentials in the top 10 cm soils were significantly higher in the Gei Wai forest and mangrove (97.91 $\mu\text{g g}^{-1} \text{day}^{-1}$ and 82.56 $\mu\text{g g}^{-1} \text{day}^{-1}$, respectively), followed by the freshwater pond (48.88 $\mu\text{g g}^{-1} \text{day}^{-1}$). Significantly lower aero-CO₂ values were found in the Gei Wai water channel and reedbed (25.89 $\mu\text{g g}^{-1} \text{day}^{-1}$ and 28.00 $\mu\text{g g}^{-1} \text{day}^{-1}$, respectively, Figure 2). At a depth of 10–20 cm, the mean soil aero-CO₂ production potentials were significantly higher in the Gei Wai forest and freshwater pond (40.64–51.07 $\mu\text{g g}^{-1} \text{day}^{-1}$) than those in the Gei Wai

water channel and reedbed ($17.47\text{--}25.44 \mu\text{g g}^{-1} \text{ day}^{-1}$). However, there were no significant differences in mean soil aero- CO_2 production rates at a depth of 20–30 cm among land use types. At a depth of 30–50 cm, the mean aero- CO_2 production potentials were significantly higher in the reedbed, freshwater pond and mangrove ($38.27\text{--}40.02 \mu\text{g g}^{-1} \text{ day}^{-1}$) than in the Gei Wai forest ($19.06 \mu\text{g g}^{-1} \text{ day}^{-1}$).

3.2. Variations of Soil CH_4 and CO_2 Production Potentials with Depth

The mean soil an- CH_4 production potential showed a decreasing pattern with depth (Figure 3). The highest soil an- CH_4 production rates in the reedbed, Gei Wai forest, and Gei Wai water channel were observed in the top 10 cm, while those in the freshwater pond and mangrove sites were seen at a depth of 10–20 cm. On the other hand, the lowest an- CH_4 production potentials were found in the deeper soil layers, at a depth of 20–30 cm soil in the reedbed and mangrove, and a depth of 30–50 cm in the freshwater pond, Gei Wai forest, and Gei Wai water channel.

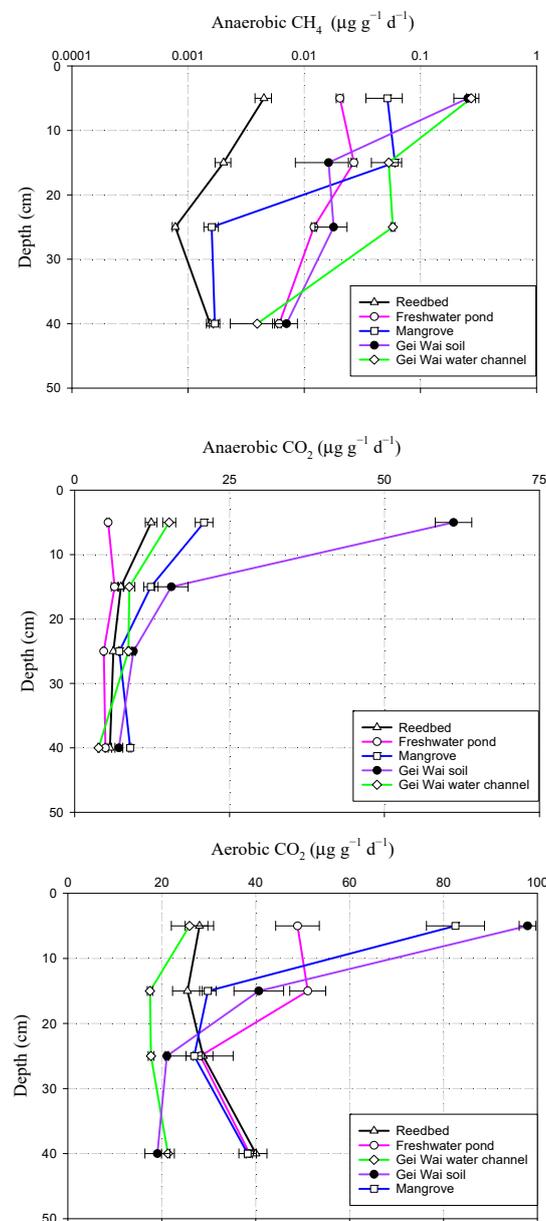


Figure 3. Depth profiles of anaerobic CH_4 , anaerobic CO_2 , and aerobic CO_2 production potentials for the five land use types. Data are means \pm standard deviation.

Similarly, the soil an-CO₂ production potential decreased generally with depth (Figure 3). The highest an-CO₂ production potentials were generally observed in the surface soils at depths of 0–10 and 10–20 cm, while the lowest an-CO₂ production rates were recorded in the deeper horizons at a depth of 30–50 cm in all land use types except mangrove. The aero-CO₂ production potentials showed a decreasing trend from a depth of 0–10 cm to a depth of 20–30 cm, and then increased again in deeper soils at a depth of 30–50 cm across all land use types except Gei Wai forest (Figure 3).

3.3. Relationships between Soil CH₄ and CO₂ Production Potentials

Across various land use types and soil depths, the mean an-CH₄ production potentials ranged from <0.01 to 0.27 µg g⁻¹ day⁻¹, which were considerably lower than the mean an-CO₂ production potentials that ranged from 3.85 to 61.14 µg g⁻¹ day⁻¹. The log-transformed anaerobic CO₂ and CH₄ production potentials were strongly and positively correlated ($p < 0.01$, Figure 4). Also, the log-transformed aerobic and anaerobic CO₂ production potentials were positively correlated ($p < 0.01$, Figure 4). The ratios between aerobic and anaerobic CO₂ production potentials ranged between 1.6:1 and 9.1:1, with an average value of 4.3:1.

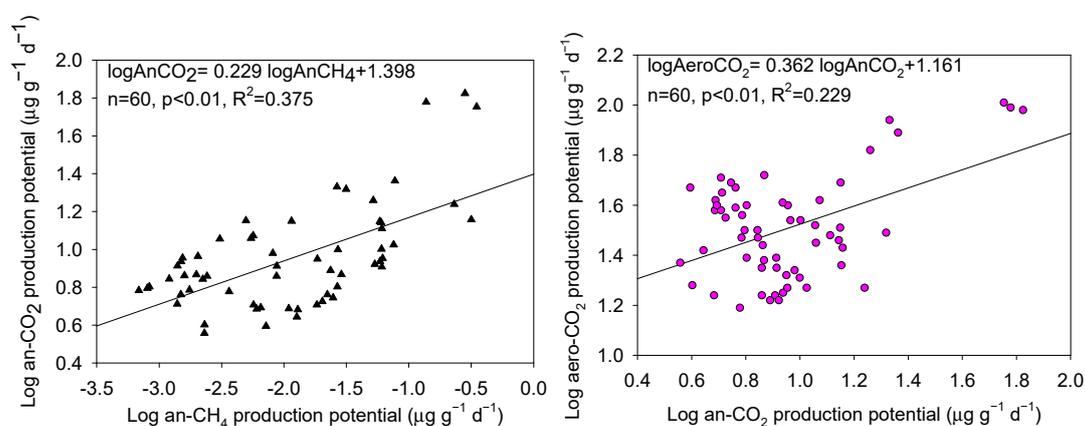


Figure 4. The relationships between anaerobic CO₂ production potentials and anaerobic CH₄ production potentials (left), and aerobic CO₂ production potentials (right).

3.4. Effects of Land Use Types on Soil Physico-Chemical Properties

As shown in Figure 5, the mean soil nutrient concentrations showed a decreasing pattern with depth similar to that of soil GHG production potentials. Soil NO₃⁻-N concentration was an exception with rather small variations along the soil profile, possibly because of the overall low concentrations in this coastal wetland (0.06–0.19 µg g⁻¹). Meanwhile, the mean soil nutrient concentrations differed significantly among land use types at a given depth, with the variations in SOM closely following those in TKN. In the top 10 cm soils, significantly higher SOM and TKN concentrations were observed in the Gei Wai forest, followed by reedbed and mangrove. The Gei Wai water channel and freshwater pond had significantly lower SOM and TKN concentrations. At a depth of 20–50 cm, the mean SOM and TKN concentrations were significantly higher in the reedbed and mangrove than in the Gei Wai forest and Gei Wai water channel. The mean soil NH₄⁺-N concentrations in the top 10 cm varied significantly among all five different land use types, but those at a depth of 20–50 cm were only significantly higher in the mangrove. The mean soil NO₃⁻-N concentrations were rather low with a range of 0.06–0.19 µg g⁻¹, and were generally similar across the land use types. Of the top 50 cm soils, the mean available P concentration was significantly greater in the mangrove (406–514 µg g⁻¹) than the other land use types (25.3–91.4 µg g⁻¹). The mean sulfate supply rate in the top 10 cm soil was significantly higher in the reedbed than in the Gei Wai forest and freshwater pond.

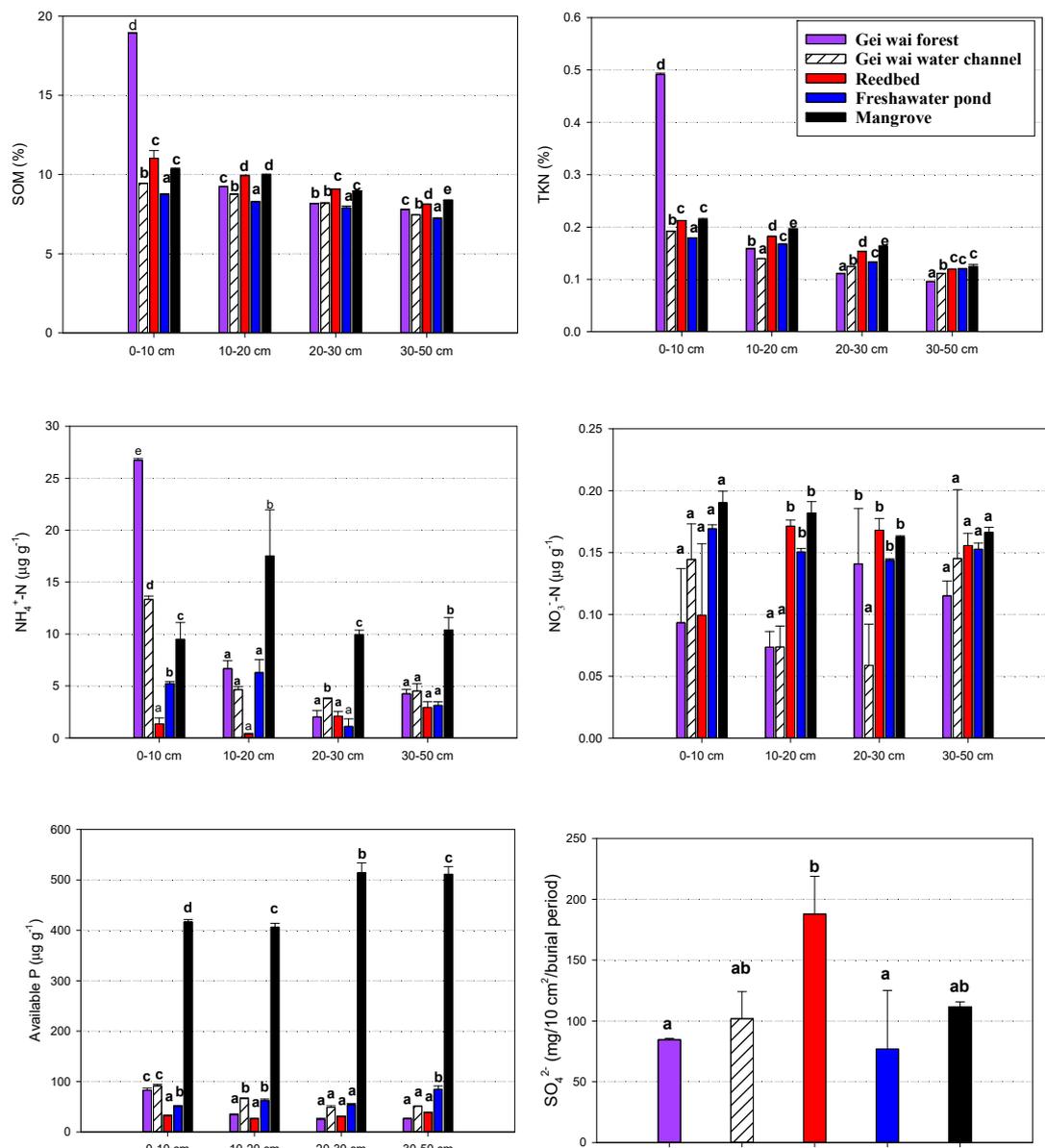


Figure 5. Mean SOM, TKN, NH₄⁺-N, NO₃⁻-N, available P concentrations and sulfate supply rate at different soil depths for the five land use types. Data are means ± standard deviation. Different letters represent significant differences in nutrient concentration among the land use types at a given depth (*p* < 0.05).

Table 2 shows the concentrations of various soil C fractions in the top 10 cm soils. Soil microbial biomass C concentrations were significantly higher in the Gei Wai forest (1724 mg kg⁻¹) than those in the reedbed and mangrove (1134–1218 mg kg⁻¹), which were, in turn, significantly higher than those in the Gei Wai water channel and freshwater pond (796–856 mg kg⁻¹). Similarly, the mean concentrations of water-soluble carbohydrate C, acid hydrolysable carbohydrate C, readily mineralizable C, and SOC were significantly higher in the Gei Wai forest, and significantly lower in the Gei Wai water channel and freshwater pond. All the C fractions were significantly correlated with SOC (*p* < 0.05), which contributed to the total soil labile C pool.

Table 2. Concentrations of various soil C fractions in the top 10 cm soils for the five land use types (means \pm standard deviation, n = 3).

Land Use Type	MBC	WSC	AHC	RMC	SOC
	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	%
Gei Wai forest	1724 \pm 86.0a	394 \pm 26.0a	1519 \pm 64.9a	699 \pm 22.6a	4.90 \pm 0.06a
Gei Wai water channel	856 \pm 258.3b	151 \pm 46.8b	587 \pm 116.1b	308 \pm 94.1b	2.50 \pm 0.42b
Reedbed	1218 \pm 103.0c	276 \pm 51.2c	1016 \pm 218.4c	510 \pm 47.4c	3.73 \pm 0.16c
Freshwater pond	796 \pm 55.7b	150 \pm 17.0b	664 \pm 106.1b	316 \pm 20.6b	2.28 \pm 0.13b
Mangrove	1134 \pm 60.9c	163 \pm 19.2b	975 \pm 164.9c	507 \pm 49.4c	2.58 \pm 0.18b

MBC: microbial biomass carbon; WSC: water-soluble carbohydrate carbon; AHC: acid hydrolyzable carbohydrate carbon; RMC: readily mineralizable carbon. Different letters indicate significant differences in mean concentrations among the land use types ($p < 0.05$).

3.5. Relationships between Soil Properties and GHG Production Potentials

Table 3 shows the results of correlation analysis between various soil chemical properties and the soil GHG production potentials for each land use type. At the Gei Wai forest, the soil concentrations of available P, NH₄⁺-N, SOM and TKN were all significantly and positively correlated with an-CH₄, an-CO₂ and aero-CO₂ production potentials. At the Gei Wai water channel, both an-CH₄, an-CO₂ production potentials were positively correlated with the concentrations of available phosphorous, NH₄⁺-N, SOM and TKN, while the aero-CO₂ production potential was only positively correlated with NO₃⁻-N concentration. Soil NO₃⁻-N concentration was negatively correlated with both an-CH₄ and an-CO₂ production potentials in the reedbed but positively correlated with both an-CH₄ and an-CO₂ production in the mangrove. Both SOM and the TKN concentrations were positively correlated with an-CH₄ and an-CO₂ production potentials in the reedbed as well as the mangrove. Soil available P concentration was positively correlated with aero-CO₂ production in the reedbed, but negatively correlated with an-CH₄ and an-CO₂ production in the mangrove. At the freshwater pond, an-CH₄ production potential was positively correlated with both SOM and TKN, while aero-CO₂ production was positively correlated with soil NH₄⁺-N concentration only. Moreover, we found that the higher concentrations of MBC, WSC, AHC and RMC in the Gei Wai forest and mangrove (Table 2) corresponded to the higher an-CO₂ and aero-CO₂ production potentials observed for these two land use types in the top 10 soils. However, the surface soils at reedbed had lower CH₄ and CO₂ production potentials in spite of the relatively high concentrations of labile C fractions.

Table 3. Correlation coefficients between gas production potentials and soil properties across all land use types and depths in the top 50 cm soils (n = 12).

Land Use Type	Production Potential	Available P	NH ₄ ⁺ -N	NO ₃ ⁻ -N	SOM	TKN
Gei Wai forest	An-CH ₄	0.950 **	0.908 **	n.s.	0.918 **	0.917 **
	An-CO ₂	0.985 **	0.981 **	n.s.	0.991 **	0.992 **
	Aero-CO ₂	0.972 **	0.982 **	n.s.	0.979 **	0.982 **
Gei Wai water channel	An-CH ₄	0.804 **	0.725 **	n.s.	0.722 **	0.788 **
	An-CO ₂	0.841 **	0.808 **	n.s.	0.924 **	0.930 **
	Aero-CO ₂	n.s.	n.s.	0.639 *	n.s.	n.s.
Reedbed	An-CH ₄	n.s.	n.s.	-0.663 *	0.744 **	0.736 **
	An-CO ₂	n.s.	n.s.	-0.691 *	0.780 **	0.861 **
	Aero-CO ₂	0.697 *	n.s.	n.s.	n.s.	-0.663 *
Freshwater pond	An-CH ₄	n.s.	n.s.	n.s.	0.792 **	0.875 **
	An-CO ₂	n.s.	n.s.	n.s.	n.s.	n.s.
	Aero-CO ₂	n.s.	0.645 *	n.s.	n.s.	n.s.
Mangrove	An-CH ₄	-0.887 **	n.s.	0.632 *	0.874 **	0.816 **
	An-CO ₂	-0.707 *	n.s.	0.600 *	0.815 **	0.771 **
	Aero-CO ₂	n.s.	n.s.	n.s.	n.s.	n.s.

** and *** indicate significant correlations at $p < 0.05$ and $p < 0.01$, respectively.

4. Discussion

4.1. CH₄ and CO₂ Production Potentials

The an-CH₄ production potentials in the top 50 cm soils at our coastal wetland ranged from <0.01 to 0.27 µg g⁻¹ day⁻¹, which were rather low when compared to the reported values in other wetlands (Table 4). Treat, Natali, Ernakovich, Iversen, Lupascu, McGuire, Norby, Roy Chowdhury, Richter and Šantrůčková [17] found that the maximum anaerobic CH₄ production rates in the boreal and tundra soils in the 0–20 cm and 20–100 cm layers were 7.87 and 1.2 µg g⁻¹ day⁻¹, respectively. One possible reason for the much lower an-CH₄ production potential observed in our study was that the SOC concentration in our surface soils was considerably lower than that in the northern peatlands (2.28–4.90% vs. 39.9%), which resulted in a more limited supply of labile organic C substrate for CH₄ production [53]. Meanwhile, the an-CH₄ production potential in the Gei Wai forest and the Gei Wai water channel was comparable to that in other coastal marshes [54,55]. The low an-CH₄ production potential in coastal wetlands was likely a result of the suppression of methanogenesis by sulfate-reducing bacteria under the prevailing high salinity and sulfate concentration [56].

The an-CO₂ production potentials ranged between 4.96 and 61.14 µg g⁻¹ day⁻¹ across all depths and land use types. We observed a strong correlation between an-CO₂ and an-CH₄ production potentials at our wetland site, which was similarly reported in some inland peatlands in Canada [13,57]. The ratios between an-CO₂ and an-CH₄ in the top 10 cm soils were 238:1, 56:1, 2751:1, 266:1, and 402:1 for the Gei Wai forest, Gei Wai water channel, reedbed, freshwater pond, and mangrove, respectively. A high an-CO₂ to an-CH₄ ratio indicates that methanogenesis using acetate or H₂/CO₂ may not be the only dominant microbial activity in soils. Anaerobic CH₄ oxidation may also occur through the actions of sulfate-reducing bacteria and anaerobic methanotrophic bacteria [58,59]. In marine environments, sulfate-dependent CH₄ oxidation can take place using sulfate, nitrite and iron as substrates by sulfate-reducing bacteria [60,61]. Our coastal mangrove was subjected to semi-diurnal tides from Deep Bay and thus the inputs of brackish water. This resulted in a relatively high soil sulfate supply in the mangrove than in the freshwater pond (111.71 vs. 77.00 mg/10 cm²/burial period). The reedbed had only biweekly tidal exchange and was submerged under brackish water for extended time periods, leading to a relatively high sulfate supply rate as well (187.94 mg/10 cm²/burial period). The higher availability of sulfate concentration in the reedbed and mangrove might have promoted anaerobic CH₄ oxidation, leading to the high an-CO₂ to an-CH₄ ratios.

The aero-CO₂ production potentials ranged between 19.06 and 97.91 µg g⁻¹ day⁻¹, which were considered low when compared to those reported in other studies (Table 4). We found a strong and positive correlation between the aero-CO₂ and an-CO₂ production potentials, which was in agreement with the findings of previous researches [19,57]. The ratios between aero-CO₂ and an-CO₂ production ranged from 1.6:1 to 9.1:1 across the five land use types, with an average value of 4.1:1. This average ratio fell within the range of 2:1 to 30:1 reported in other studies [12,19,21,57,62], and pointed to potentially greater production and emission of CO₂ from soils into the atmosphere when the coastal wetland was exposed to more aerobic conditions. The low an-CO₂ and aero-CO₂ production potentials observed at our study site could be attributed at least partly to the low SOM concentration (7.2–18.9%) as compared to the carbon-rich peatlands [13]. The low an-CO₂ production potential could also be partly attributed to the accumulation of metabolites in soils, which would inhibit CO₂ production under anaerobic conditions.

Table 4. A summary of reported values of soil CH₄ and CO₂ production potentials in wetlands.

Land Cover	Country	Depth	Incubation Period	Incubation Temperature (°C)	an-CH ₄	an-CO ₂	aero-CO ₂	Source
Sphagnum- and sedge-dominated boreal peatland	Sweden	0–60 cm	8 d	16	0–6 µg g ⁻¹ soil day ⁻¹	-	-	[4]
Peatlands of natural, harvested and restored sites	Canada	0–10 cm and depth near water table	4 d and 30 d for aerobic and anaerobic incubation, respectively	20	0.00–816, average of 21 µg g ⁻¹ soil day ⁻¹	10–290 µg g ⁻¹ soil day ⁻¹	40–150 µg g ⁻¹ soil day ⁻¹	[57]
Freshwater marsh with different vegetation	USA	0–10	28 d	20	5.3–19.6 µg g ⁻¹ soil day ⁻¹	50–95 µg g ⁻¹ soil day ⁻¹	400–660 µg g ⁻¹ soil day ⁻¹	[13]
Boreal forest, peatland, lakes, rivers and exposed bedrocks	Canada	0–5 and 5–15 cm	16 weeks	22	0.11–20.69 µg C g ⁻¹ C day ⁻¹	290–1500 µg C g ⁻¹ C day ⁻¹	160–2560 µg C g ⁻¹ C day ⁻¹	[22]
Peatlands of bogs, fens and swamps	Canada	0–110 cm	5 d	15 and 20	0.01–100, average of 11.37 µg g ⁻¹ soil day ⁻¹	70–5000, average of 1800 µg g ⁻¹ soil day ⁻¹	580–5000, average of 3700 µg g ⁻¹ soil day ⁻¹	[19]
Sphagnum-derived peat from Big Run Bog	USA	5–10, 20–25 and 40–45 cm depth	10 d	19	1.68 to 249.6 µg g ⁻¹ soil day ⁻¹ for surface soil	120–720 µg g ⁻¹ soil day ⁻¹ for surface soil	-	[63]
Peatlands of bogs, internal lawns, and permafrost mounds	Canada	0–100 cm	60 d	25	0.16 and 0.32–9.6 µg g ⁻¹ soil day ⁻¹ for permafrost and no permafrost bogs, 12.8 for lawns	120–260 µg g ⁻¹ soil day ⁻¹	-	[64]
Peatlands of bog and fen	Canada	0–10, 10–20 cm	3 d	0–25	0.10–0.27 µg g ⁻¹ soil day ⁻¹ for 20 and 25 °C	-	-	[9]
Freshwater marsh of wetland	China	0–60 cm		20	0.011–0.66 µg g ⁻¹ soil day ⁻¹	-	-	[65]
Estuarine brackish marshes	China	0–30 cm	3 d	20	0.058–0.142 µg g ⁻¹ soil day ⁻¹ at 30 cm	-	-	[54]
Coastal meadow, freshwater fen	Denmark	0–80 cm	6 d	24	0–0.8 µg g ⁻¹ C day ⁻¹ for meadow 0–3.84 µg g ⁻¹ C day ⁻¹ for fen	-	-	[55]
Hong Kong, China	China	0–10, 10–20, 20–30, 30–50 cm	14 d and 7 d for anaerobic and aerobic incubation, respectively	25	0.00–0.27 µg g ⁻¹ soil day ⁻¹	4.96–61.14 µg g ⁻¹ soil day ⁻¹	19.06–97.91 µg g ⁻¹ soil day ⁻¹	Our study

Care should be taken when comparing the incubation results in this study with those in other wetlands, as the difference in vegetation, pH, soil depth, incubation period and other factors might also affect the measured rates of GHG production. As shown in Table 4, studies examining soil GHG production potential in coastal wetland soils, especially in the subtropical region, are still very limited, and deserve further attention for improving the spatial representation of experimental results.

4.2. Effects of Land Use Types on Soil CH₄ and CO₂ Production Potentials

As mangrove was the natural and original land use type at our site before human disturbances, we used mangrove as the baseline reference for analyzing the effect of land use change on soil GHG production. In this section, we focused on the soil GHG production potentials in the top 10 cm soils, as the surface soil horizon was most sensitive to the effects of land use change. In general, mangrove conversion to other land use types reduced both aero-CO₂ and an-CO₂ production potentials, except for Gei Wai forest. The continual loss of soil C through soil respiration in response to wetland conversion could lead to a considerable reduction in SOM concentration after some years. Although the soil CO₂ production potential might exhibit a transient increase during the initial period of disturbance, it could decrease in the long run after mangrove conversion, owing to the exhaustion of C substrates [33–35]. In addition, the Gei Wai water channel and freshwater pond had significantly lower SOM and TKN concentrations in the top soils than the natural mangrove, which might also contribute to lower CO₂ production rates through a reduced supply of C and N substrates.

We observed significantly higher values of an-CH₄, an-CO₂ and aero-CO₂ production potentials in the top 10 cm soils in the Gei Wai forest than in the mangrove. The coastal mangrove received tidal floodwater twice a day, while the Gei Wai forest was only flooded occasionally. The higher salinity and sulfate concentration in the mangrove owing to the influence of brackish water contributed to the suppression of CH₄ production. In addition, the significantly higher soil concentrations of NH₄⁺-N, SOM and TKN in the Gei Wai forest could play a role in supporting higher CH₄ and CO₂ production, as supported by the strong and positive correlations between these soil properties and GHG production potentials (Table 3). A previous study has shown that NH₄⁺-N can facilitate CH₄ production and emission by decreasing the soil Eh [66]. Treat, Natali, Ernakovich, Iversen, Lupascu, McGuire, Norby, Roy Chowdhury, Richter and Šantrůčková [17] observed significantly higher an-CH₄ and an-CO₂ production in peatlands with higher SOC and N concentrations, which supported the importance of substrate supply for GHG production. Moreover, we found that in the Gei Wai forest and mangrove with higher an-CO₂ and aero-CO₂ production potentials, their soil MBC, WSC, AHC, and RMC concentrations were also higher than other land use types, indicating the importance of a labile C pool in promoting soil CO₂ production.

As compared to the natural mangrove, the Gei Wai water channel had significantly higher an-CH₄ production but significantly lower an-CO₂ and aero-CO₂ productions. The Gei Wai water channel was inundated for a long duration, leading to the development of strongly anaerobic conditions that facilitated CH₄ production and inhibited CO₂ production. The significantly higher soil NH₄⁺-N concentrations in the Gei Wai water channel might also have facilitated CH₄ production. Meanwhile, the significantly lower SOM and TKN concentrations observed in the top soils of the Gei Wai water channel could help explain the lower an-CO₂ and aero-CO₂ productions as compared to the mangrove.

In both the reedbed and the freshwater pond, an-CO₂ and aero-CO₂ production potentials in the top 10 cm soils were significantly lower than those in the mangrove, which could be related to the significantly lower concentrations of soil available P and NH₄⁺-N in supporting microbial respiration. The mean an-CH₄ production potential in the reedbed was close to zero, which might be related to the large availability of sulfate and oxygen in the soils that reduce the abundance of methanogens for CH₄ production [67].

4.3. Variations of CH₄ and CO₂ Production Potential with Depth

The an-CH₄ and an-CO₂ production potentials showed a decreasing pattern with depth in this study (Figure 3), which has also been shown in previous studies [17,62,68]. For example, Glatzel, Basiliko and Moore [57] found the largest an-CH₄ production in soil samples close to the peatland surface, with fresh peat accumulation and a high water table. In a grassland on peat soils in the Netherlands, the an-CH₄ production in the top 5 cm soils contributed to 70% of the total an-CH₄ production [62]. Treat, et al. [17] showed that an-CH₄ and an-CO₂ production in the permafrost zone decreased with depth, with the maximum CH₄ production detected in the top 20 cm. In this study, the maximum an-CH₄ and an-CO₂ production potentials were generally recorded in the top 10 cm soils across different land use types, except for the freshwater pond. From a depth interval of 10–20 cm to 20–30 cm, mean an-CH₄ production decreased substantially by 61.6%, 54.6%, and 97.4% in the reedbed, freshwater pond and mangrove, respectively. On the other hand, mean an-CO₂ production decreased over a range from 1.7% to 41.3% for the five land use types from a depth of 10–20 cm to 20–30 cm. From a depth interval of 20–30 cm to 30–50 cm, mean an-CH₄ production decreased by 60.7%, 93.2%, and 49.9% in the Gei Wai forest, Gei Wai water channel and freshwater pond, respectively. Meanwhile, average an-CO₂ production decreased over a range from 8.8% to 55.6% for all the land use types studied, except the freshwater pond. Meanwhile, soil aero-CO₂ production generally decreased from 0–10 cm to 20–30 cm depths, but increased again at a depth of 30–50 cm, except for the Gei Wai forest.

The decrease in soil CH₄ and CO₂ production potentials with depth was closely related to the variations in soil nutrients. Our results showed that SOM and TKN concentrations were significantly and positively correlated with both an-CH₄ and an-CO₂ production values in all land use types except the freshwater pond. With increasing soil depths, the supply of C substrates to soil microbes was diminished, which limited the anaerobic degradation of organic matter and, subsequently, the production of GHGs. Bergman, Lundberg and Nilsson [21] showed that the addition of starch and glucose as a C supply could increase CH₄ and CO₂ production in a peatland in Sweden. Given that soil available P and NH₄⁺-N concentrations were positively correlated with an-CH₄ and an-CO₂ productions in both the Gei Wai forest and Gei Wai water channel, the decreasing levels of available P and NH₄⁺-N with depth in these two sites might also help account for the reduction in anaerobic GHG production in the deeper soils.

5. Conclusions

The mean an-CH₄ production potentials ranged from <0.01 to 0.27 μg g⁻¹ day⁻¹ across land use types and depths in our coastal wetland, which were relatively low when compared to the values reported in other wetlands. This could be attributed to the low SOC concentration and high salinity that suppress methanogenesis at our site. The mean an-CO₂ production potentials ranged from 4.96 to 61.14 μg g⁻¹ day⁻¹ and were strongly and positively correlated with an-CH₄ production potential. The large ratio of an-CO₂ to an-CH₄ suggested that anaerobic CH₄ oxidation might occur, especially under the presence of sulfate. The mean aero-CO₂ production potentials ranged from 19.06 to 97.91 μg g⁻¹ day⁻¹, which were again in the low range among other wetlands. We found a strong correlation between aero-CO₂ and an-CO₂ production potentials, which implied the presence of some common controlling factors such as SOM and TKN concentrations.

CH₄ and CO₂ production potentials in the top 10 cm soils varied significantly among land use types. The conversion of mangroves to other land uses after a long time period reduced both aerobic and anaerobic CO₂ production potentials, except for the Gei Wai forest. This was contrary to the findings of other studies in which CO₂ emissions were enhanced in some newly cleared mangrove forests. Hence, future studies should carry out long-term monitoring of the response of soil GHG production to mangrove conversion. Moreover, in the top 10 cm soils, the highest an-CH₄ production rate was recorded in the Gei Wai water channel, while the highest an-CO₂ and aero-CO₂ production rates were obtained in the Gei Wai forest. The conversion of mangrove to Gei Wais (tidal shrimp ponds) should be carefully considered in future to minimize the soil production of GHGs and the

associated adverse climatic impacts. The effects of land use change on GHG production potentials were less significant in the subsurface soils (30–50 cm depth). Moreover, other biogeochemical processes (e.g., oxidation and transport) should be thoroughly investigated in order to provide a more complete picture of the impact of mangrove conversion on net GHG exchange. The an-CH₄, an-CO₂ and aero-CO₂ production potentials showed a decreasing pattern with depth, which was highly associated with the vertical variations of SOM and TKN concentrations in the soil profile. The reduction in soil's available P and NH₄⁺-N concentrations with depth also likely contributed to the lower an-CH₄ and an-CO₂ productions seen in both the Gei Wai forest and Gei Wai water channel.

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