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Salinity and Moisture Influence CO_2 and CH_4 Emissions From High-Latitude Coastal Soils

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Key Points:

- Greater salinity increased CO_2 emissions from saturated soil but suppressed CO_2 flux from partially saturated soil
- Greater salinity suppressed CH_4 emissions in saturated soil, but overall, CH_4 flux magnitude depended on whether the soil was saturated
- Largest C mobilization from these low-Arctic soils will occur at lowest elevations, which are most prone to near-future flooding

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Sea level rise and more frequent and larger storms will increase saltwater flooding in coastal terrestrial ecosystems, altering soil-atmosphere CO_2 and CH_4 exchange. Understanding these impacts is particularly relevant in high-latitude coastal soils that hold large carbon stocks but where the interaction of salinity and moisture on greenhouse gas flux remains unexplored. Here, we quantified the effects of salinity and moisture on CO_2 and CH_4 fluxes from low-Arctic coastal soils from three landscape positions (two Wetlands and Upland Tundra) distinguished by elevation, flooding frequency, soil characteristics, and vegetation. We used a full factorial laboratory incubation experiment of three soil moisture levels (40%, 70%, or 100% saturation) and four salinity levels (freshwater, 3, 6, or 12 ppt). Salinity and soil moisture were important controls on CO_2 and CH_4 emissions across all landscape positions. In saturated soil, CO_2 emissions increased with salinity in the lower elevation landscape positions but not in the Upland Tundra soil. Saturated soil was necessary for large CH_4 emissions. CH_4 emissions were greatest with low salinity, or after 11 weeks of incubation when SO_4^{2-} was exhausted allowing for methanogenesis as the dominant mechanism of anaerobic respiration. In partially saturated soil, greater salinity suppressed CO_2 production in all soils. CH_4 fluxes were overall quite low, but increased between 3 and 6 ppt in the Tundra. In the future, a small increase in floodwater salinity may increase CO_2 production while suppressing CH_4 production; however, where water is impounded, CH_4 production could become large, particularly in the landscapes most likely to flood.

Plain Language Summary

Coastal environments in northern regions are expected to experience more floods, with saltier floodwaters, as climate change raises ocean levels and increases the number and size of coastal storms. These changes will impact soils and vegetation on the coasts and may result in soils and vegetation taking up or releasing greenhouse gases, specifically carbon dioxide (CO_2) and methane (CH_4), two of the gases that contribute to climate change. We conducted an experiment investigating the effect of soil salinity and moisture, both independently and together, on the movement of CO_2 and CH_4 from soil to the atmosphere, from three different locations that vary in their elevation and history of flooding. We found that both salinity and moisture played an important role in determining the movement of greenhouse gases. In saturated soil, saltier floodwaters increase CO_2 emissions to the atmosphere in the lowest elevation regions, but not in the areas unaccustomed to flooding. In partially saturated soil, greater salinity suppressed CO_2 emissions. In the future, a small increase in floodwater salinity may increase CO_2 emissions but lower CH_4 emissions. CH_4 emissions will be largest when the landscape is flooded, particularly in the low-elevation landscapes most likely to flood.

1. Introduction

Climate change is increasing the exposure of coastal terrestrial ecosystems to storm surge and tidal flooding events as coastal regions experience relative sea level rise along with more frequent and intense storms (Cooley et al., 2022). Saltwater inundation in coastal soils rarely exposed to saline conditions alters soil biogeochemical processes, including the exchange of greenhouse gases (GHGs) such as CO_2 and CH_4 with the atmosphere (Chambers et al., 2011; Luo et al., 2019; Neubauer et al., 2013). As coastal terrestrial ecosystems hold large stocks of soil carbon, more frequent or intense flooding may alter ecosystem-wide fluxes of carbon to the atmosphere. The response of soils in low-relief Arctic coastal ecosystems is particularly critical because these ecosystems contain potentially vulnerable soil carbon (Hugelius et al., 2020; Kreplin et al., 2021), and relative sea level rise in this region is coupled with land subsidence from thawing permafrost (Jorgenson et al., 2018), greater frequency of storm surge-producing cyclones entering the Arctic (Parker et al., 2022), and a longer ice-free season (Meier &

Stroeve, 2022). All these factors together increase the likelihood of coastal flooding events in the near future. However, the effects of saltwater inundation on soil-atmosphere GHG exchange in the low-Arctic region, particularly the factors of floodwater salinity, soil moisture, and their interaction, remain unexplored.

Soil biogeochemical response to coastal flooding, including GHG emissions, depends on the ionic strength of floodwater and the introduction of SO_4^{2-}. High concentration of ions in soil water induces osmotic stress in microbes and can result in cell lysis and dehydration, which affects GHG emissions (Rietz & Haynes, 2003; Wichern et al., 2006). The introduction of SO_4^{2-} allows sulfate reducers to outcompete other anaerobic microbial functional groups (Mobilian et al., 2023), and as a result, saltwater inundation often reduces CH_4 emissions and increases CO_2 emissions from Wetland soils (Capone & Kiene, 1988; Chambers et al., 2011, 2013; Marton et al., 2012; Poffenbarger et al., 2011; Weston et al., 2006). However, in some coastal soils, salt exposure lowers CO_2 emissions (Chambers et al., 2014; Neubauer et al., 2013; Wang et al., 2017; Zhang et al., 2018) and the magnitude of CH_4 emissions is contingent on hydrologic conditions (Ardón et al., 2018) highlighting the influence of additional factors such as soil moisture on the effect of saltwater flooding on GHG emissions.

Soil moisture also acts as a control on both biological and physical soil processes in coastal environments (Stagg et al., 2017). Greater soil moisture typically increases CO_2 production via decomposition (Orchard & Cook, 1983) until a threshold at which high soil moisture limits diffusion of CO_2 out of the soil and O_2 into the soil (Millington, 1959; Risk et al., 2002; Skopp et al., 1990). In contrast, CH_4 emissions often increase with greater soil moisture as regions of anoxia within the soil create conditions conducive for methanogenesis (Cui et al., 2024; Yang et al., 2017). Soil moisture, and the resulting anoxia, is also an important control on the role of salinity on CO_2 and CH_4 emissions as SO_4^{2-} introduced by saline water can suppress methanogenesis (Luo et al., 2019). In rare instances, including hyper-saline environments, where methanogenesis is fueled by noncompetitive substrates, CH_4 production will continue in the presence of SO_4^{2-} (Bueno de Mesquita et al., 2023; King et al., 1983; Oremland & Polcin, 1982). However, in environments where methanogens must compete with sulfate reducing bacteria, methanogenesis is suppressed by saltwater due to the presence of SO_4^{2-}. As a result, soil moisture can alter both the magnitude of soil CO_2 and CH_4 emissions and also determine the impact of salinity on soil CH_4 fluxes.

The effects of changing soil moisture and salinity on soil biogeochemistry differ depending on the timescale over which they are observed because the immediate physical effects of increased soil moisture, versus the gradual change in microbial community in response to new environmental conditions (Bardgett & Caruso, 2020; Smith et al., 2018), occur on different timescales. The effects of salinity also depend on the timescale of exposure (Neubauer et al., 2013). In a freshwater Wetland exposed to saltwater, sulfate reduction became the dominant pathway of organic matter mineralization within 2 weeks and continued increasing through the first 4 weeks as the sulfate reducing community present in the soil adapted to the new saline conditions (Weston et al., 2006) indicating that a period of several weeks can be important in dictating Wetland response to salinity. Further, soils with prior saline exposure may have a more salt-tolerant microbial community than that of a soil rarely exposed to saline conditions (Ardón et al., 2018; Morrissey et al., 2014). In heterogenous coastal landscapes, there may be neighboring regions with contrasting saltwater exposure histories and microtopographic positions exposed to inundation for different lengths of time following flooding. Therefore, observing both the immediate and sustained soil biogeochemical response to saltwater exposure among landscape positions can provide useful insight into the nuances of how a landscape may respond to saltwater inundation.

The Yukon-Kuskokwim (Y-K) Delta in western Alaska, one of the largest high-latitude Wetland ecosystems in western North America (129,500 km^2), is experiencing widespread impacts of relative sea level rise and storm surge. The Y-K Delta is a model system to study the effects of seawater inundation on GHG emissions as it is a low-lying landscape and local microtopography creates distinct habitats across landscape positions that differ in elevation, frequency of flooding, and vegetation and soil characteristics (Figure 1). The most extreme floods of the last century occurred in 2005, 2006, 2011, 2018, and 2022, and all extended 21–32 km inland exposing the entire landscape, including the infrequently flooded Upland Tundra, to saltwater (Terenzi et al., 2014). Both low-lying Wetlands and the higher elevation Tundra are expected to experience more frequent inundation in the future; however, there is limited understanding of how saltwater inundation may have differential effects on GHG exchange across these gradients of historical saltwater exposure.

This study explores how exposure to altered salinity and soil moisture conditions affects potential CO_2 and CH_4 efflux from soils from three different landscape positions across a microtopographic gradient, using a laboratory

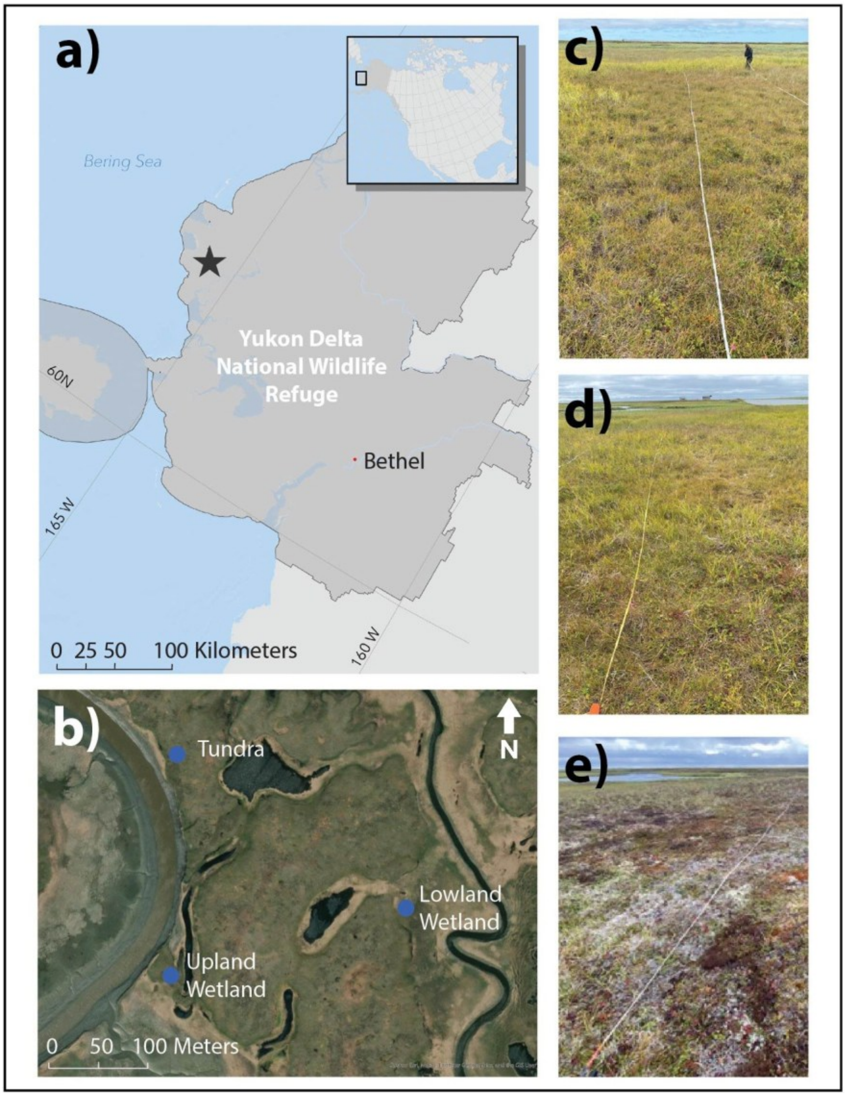

Figure 1. (a) Location of the field site including (b) the sampling locations in the Lowland Wetland, Upland Wetland, and Tundra and photographs of the sampling transects in (c) the Lowland Wetland, (d) the Upland Wetland, and (e) the Tundra.

microcosm incubation experiment. We tested the hypothesis that soil salinity and moisture will interact to control CO_2 and CH_4 flux from low-Arctic coastal soil. Specifically, we hypothesized that when the soil is saturated, greater salinity will increase CO_2 emissions but decrease CH_4 emissions, while in partially unsaturated soil, greater salinity will stimulate CO_2 emissions but have limited effect on CH_4 flux. We investigated the nature of this interaction among coastal soils that differ in their exposure to tidal and storm surge flooding, and across two different timeframes of analysis, 3 and 11 weeks, that we expect to span the timeline of sulfate depletion in soil with active sulfate reduction.

2. Materials and Methods

2.1. Study Site

Soil samples for incubation were collected from three landscape positions of the central coastal Yukon-Kuskokwim Delta, 19 km inland from the Bering Sea (Figure 1). This low-elevation, deltaic landscape is characterized by just 3 m of elevation gain within 40 km from the coast, and microtopographic gradients create local vegetative habitats including distinct soil and vegetation. This region has a cold oceanic climate with a summer (June–August) mean temperature of 12.5°C for the 30-year period 1991–2020 measured at Bethel, AK

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Table 1
Landscape Position Descriptions

	Lowland Wetland	Upland Wetland	Tundra
Elevation (m)	2.39 ± 0.02	2.56 ± 0.06	3.43 ± 0.06
Location (longitude, latitude)	−165.43916, 61.43637	−165.44336, 61.4354	−165.44395, 61.43738
Soil Characteristics			
Drainage class[a]	Very poorly drained	Poorly drained	Moderately well drained
Description of the amount of decomposition of soil organic material (Decomposition class)[b]	Plant material not easily distinguishable	Individual organic components (e.g. stems) breaking up; amorphous material is present	The structure and form of plant material remains complete
Botanical origin of soil organic fibers	Primarily graminoid	Primarily graminoid	Primarily Sphagnum moss
Bulk density	0.06 ± 0.01	0.14 ± 0.03	0.09 ± 0.04
Soil Chemistry			
Soluble salts (mmho/cm)	0.83 ± 0.13	0.48 ± 0.03	0.11 ± 0.01
OM (%)	57.76 ± 1.63	39.70 ± 1.45	60.30 ± 1.62
Sulfate—S (ppm)	133.80 ± 18.0	69.94 ± 6.29	31.02 ± 1.80
Vegetation	*Carex rariflora*, *Salix fuscescens*, *Calamagrostis spp.*, Eriophorum *vaginatum*, and *Potentilla palustre*	*Carex rariflora*, *Salix fuscescens*, *Carex lyngbyei*, *Empetrum nigrum*, and *Betula nana*	*Ledum palustre, Vaccinium vitis-idaea, Rubus chamaemorus, Betula nana,* and *Empetrum nigrum*

[a]"Soil Classification Working Group, 1998." [b]"Von Post Method of Decomposition as in Soil Classification Working Group, 1998."

(the nearest permanent long-term weather station, 200 km from the study site), and a winter (January–March) mean temperature of −12.2°C. Average annual precipitation was 499 mm (Palecki et al., 2021).

Soil was sampled from three landscape positions that are distinguished by elevation and the vegetation community: a Lowland Wetland, an Upland Wetland, and Tundra (Table 1). The Lowland Wetland is the lowest in elevation and has the highest salinity as a result of being inundated by oligohaline floodwaters during high tides at least annually. The soil of the Lowland Wetland is frequently saturated with standing water. The Upland Wetland is at an intermediate elevation between the Lowland Wetland and the Tundra, and the soil at this landscape position has intermediate salinity (Table 1), suggesting less frequent inundation than the Lowland Wetland but more frequent than the Tundra. This landscape position was inundated at least once during the 3 year study period. Finally, the Tundra is present at the highest elevation, and has the lowest soil salinity (Table 1). This landscape position is only inundated every 5–12 years during large storm events (Ravens & Allen, 2017). Previous research in this region suggests that fungal and prokaryotic communities are distinct across these three landscape positions (Foley, 2020).

2.2. Study Design

In August of 2022, soil was sampled every 5 m along a 15-m transect in each landscape position by collecting four 15 cm × 15 cm × 15 cm soil monoliths, each 1 m from the transect in every cardinal direction, yielding 12 monoliths per landscape position. To capture the most biological activity in the O horizon, each monolith was harvested to a depth of 15 cm below the transition from live to dead moss (top 2 cm) or below dead plant material (Hobbie et al., 2002; Neff & Hooper, 2002; O'Donnell et al., 2009). In the laboratory, soil monoliths were air-dried at room temperature, homogenized within landscape position, and sorted to remove roots larger than 2 mm. Subsamples of 20 g of dry, homogenized soil were placed into 236 mL glass microcosms.

Each microcosm was assigned to a factorial combination of a salinity treatment (0 parts per thousand [ppt], 3, 6, or 12 ppt) and a moisture treatment (40%, 70%, or 100% saturation), resulting in 12 different treatment combinations with 7 replicates for each landscape position (84 microcosms per landscape position and 252 total plus 12 "blank" microcosms that were incubated with no soil). The salinity treatments span the observed salinity of high tide floodwaters at the study site (0–5 ppt, Petit Bon et al., 2024) and the salinity at which prior work has observed that CO_2 and CH_4 emissions become inhibited (Wang et al., 2017). The soil moisture treatments bracket the range of conditions observed at the field site (Petit Bon et al., 2024).

The desired salinity for each treatment was obtained by adding seawater mix (NeoMarine Salt Mix, Brightwell Aquatics, USA) to deionized water, and fully saturating the soil in each microcosm to ensure that all samples in a given treatment received the same amount of salt. By tracking microcosm weights daily, soil was allowed to air-dry to the target moisture; then, microcosms were loosely covered in foil to maintain exposure to the atmosphere but limit drying throughout the experiment. Each microcosm was maintained at the target moisture by weighing microcosms weekly and adding deionized water to return the microcosm to its initial weight. The microcosms were incubated in a growth chamber (Percival Scientific, USA) at 18°C. This temperature is based on the 80th percentile of maximum daily air temperature in summer (Thornton et al., 2022), and was chosen to allow investigation of differences in greenhouse gas emissions potential from different landscapes under the influences of salinity and moisture by removing temperature limitations on gas production. Microcosms were incubated at 84% relative humidity, based on typical summer humidity conditions (Petit Bon et al., 2024). The position of each microcosm in the growth chamber was randomly rotated each week.

2.3. Greenhouse Gas Measurements

The flux of CO_2 and CH_4 from each microcosm was analyzed approximately once a week for 11 weeks. CO_2 and CH_4 flux from each microcosm was determined using the change in concentration of gas in the microcosm headspace over a period of 24 hr by securing lids fitted with rubber septa on each microcosm 24 hr before a measurement took place. At the time of measurement, 1 mL of gas was extracted from the headspace using a gastight syringe (Luer-Lok model, SGE) and injected into a Li-COR 7810 spectroscopic gas analyzer (model Li-7810, Li-COR Inc., Lincoln, NE, USA) equipped with a closed loop system to determine the concentration of gas in the microcosm. Standards of CO_2, CH_4, and zero air were used for calibration.

The concentration of gas in the microcosm headspace was calculated using the LI-Integrator program (Licor, 2025). To use the LI-Integrator program, gases of known concentration and volume were injected into a closed loop system to establish a relationship between concentration and "delta", difference in concentration in the loop pre- and postinjection. This relationship was then used to determine the concentration of gas from each microcosm headspace when a known volume was injected into the loop. CO_2 fluxes were calculated using the difference in gas concentrations from blank microcosms, which had no soil, and the concentration in the capped microcosms after 24 hr, using the following equation:

$$Fc = \frac{VP_0\delta[CO_2]}{\mathrm{RM}_s(T_0 + 273.15)\delta t}$$

where F_c is the soil CO_2 flux (µmol CO_2 g of dry soil^{-1} s^{-1}), V is the headspace volume in the microcosm (cm^3), P_0 is the initial pressure (kPa), R is the ideal gas constant (8.314×10^3 kPa cm^3 K^{-1} mol^{-1}), M_s is the soil mass (g), T_0 is the initial air temperature (°C), and $\frac{\delta[CO_2]}{\delta t}$ is the change in CO_2 over time (µmol mol^{-1} s^{-1}) between the time the microcosm was capped and the time of measurement 24 hr later (Liang et al., 2015). CH_4 fluxes were calculated using the same method but expressed as nmol CH_4 g of dry soil^{-1} s^{-1}. Cumulative flux was calculated for each microcosm using the trapezoidal integration approach with cumulative CO_2 fluxes reported in g CO_2-C g of dry soil^{-1} and cumulative CH_4 fluxes reported in µg CH_4-C g of dry soil^{-1}. We chose to report cumulative fluxes as we were interested in understanding difference in total gas emissions among treatments. To capture before and after the expected sulfate depletion in soil, cumulative flux was determined for two points of time during the incubation: start of incubation through week 3 and the start of incubation through week 11. Following the experiment, 5–10 mL of water from all 100% saturated samples was extracted using a filtration syringe and a suction system and subsampled to measure SO_4^{2-} concentration (Series 4500i ion chromatograph, Dionex, Sunnyvale, CA, USA).

2.4. Statistical Analyses

All statistical analyses were performed with R version 4.2.2 (R Core Team, 2022). Main and interactive effects between salinity and moisture on GHG cumulative flux were tested using a two-way analysis of variance (ANOVA) for each landscape position separately, for both cumulative fluxes after 3 weeks and for cumulative fluxes after 11 weeks. Cumulative fluxes for 3 and 11 weeks were not compared statistically; rather, we use the contrasting results at two timeframes to gain ecological insight about the system. Model residuals met

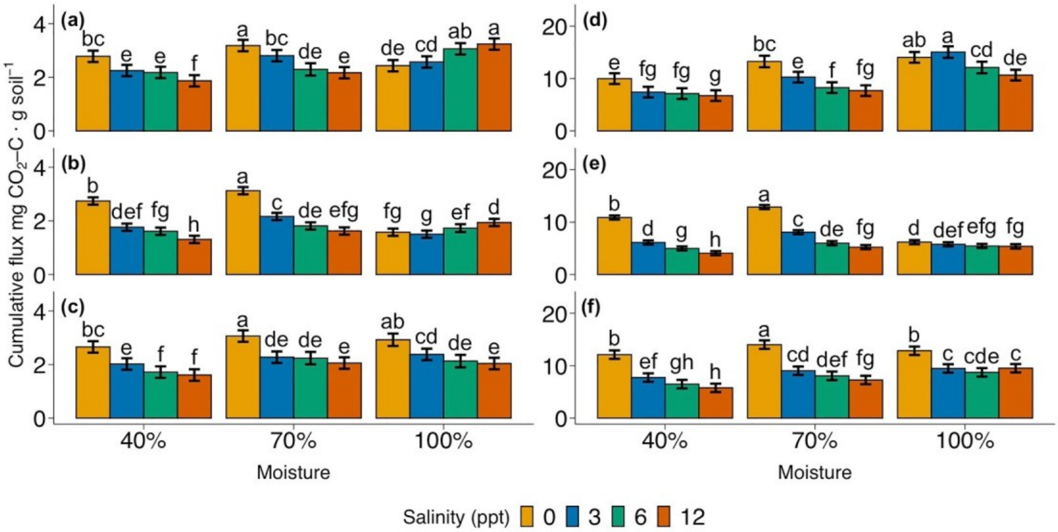

Figure 2. Model predictions for cumulative CO_2 flux following 3 weeks of incubation from the (a) Lowland Wetland, (b) Upland Wetland, and (c) Tundra and following 11 weeks of incubation from the (d) Lowland Wetland, (e) Upland Wetland, and (f) Tundra. Error bars represent 95% confidence intervals. Letters represent statistically significant cumulative flux means among salinities and moisture levels within each landscape position and incubation length ($p < 0.05$).

assumptions of normality and homogeneity. Model predictions and their confidence intervals for each treatment combination were extracted using the emmeans package (Lenth, 2023). Pairwise comparisons were conducted using the multcomp package (Hothorn et al., 2008) followed by post hoc Tukey test. Significant differences were determined as $p < 0.05$. Similarly, SO_4^{2-} concentrations were compared across salinity levels within each landscape position using a one-way ANOVA and post hoc Tukey test.

3. Results

3.1. Effects of Salinity and Moisture on Cumulative Soil CO_2 Emissions

The effects of salinity, moisture, and their interaction were highly significant in nearly all statistical models of greenhouse gas emissions, indicating a differential greenhouse gas response to salinity under different moisture conditions. Soil CO_2 emissions from all three landscape positions responded similarly to salinity and moisture except for the Tundra soil after 3 weeks where CO_2 emissions decreased with salinity under all moisture conditions (Figure 2, Table S1 in Supporting Information S1). The consistent response to salinity under all saturation conditions in Tundra soil is in contrast to both Upland and Lowland Wetland soils where salinity had opposing effects on cumulative CO_2 emissions in saturated versus unsaturated (40% and 70% saturation) conditions after 3 weeks. Specifically, CO_2 emissions from Wetland soils increased with greater salinity under saturated conditions but decreased with salinity under unsaturated conditions. In the Lowland Wetland, the mean cumulative CO_2 emissions for saturated soils with 0 ppt salinity was 25% lower than soils with 12 ppt salinity. Similarly, for the Upland Wetland site, the mean cumulative CO_2 emissions for soils with 0 ppt salinity was 19% lower than soils with 12 ppt salinity. Overall, after 3 weeks of incubation, the effect of salinity on CO_2 emissions was influenced by moisture in both Wetland soils, but not in the Tundra soil.

The response of soil CO_2 flux to differences in salinity after 11 weeks was largely similar to that after 3 weeks, except for saturated Lowland and Upland Wetland soil. After 11 weeks of incubation, greater salinity generally decreased cumulative CO_2 flux for all landscape positions and across all moisture levels (Figure 2, Table S2 in Supporting Information S1). Saturated soil exposed to the 12 ppt salinity treatment decreased CO_2 flux by 24%, 13%, and 26% relative to fluxes from the 0 ppt treatment in Lowland Wetland, Upland Wetland, and Tundra, respectively. The effect of salinity on CO_2 flux was also consistent across both fully and partially saturated soils. Partially saturated soil (40% saturation) exposed to 12 ppt salinity decreased CO_2 flux by 32%, 63%, and 52% relative to fluxes from the 0 ppt treatment across the three landscape positions, respectively, and the reductions

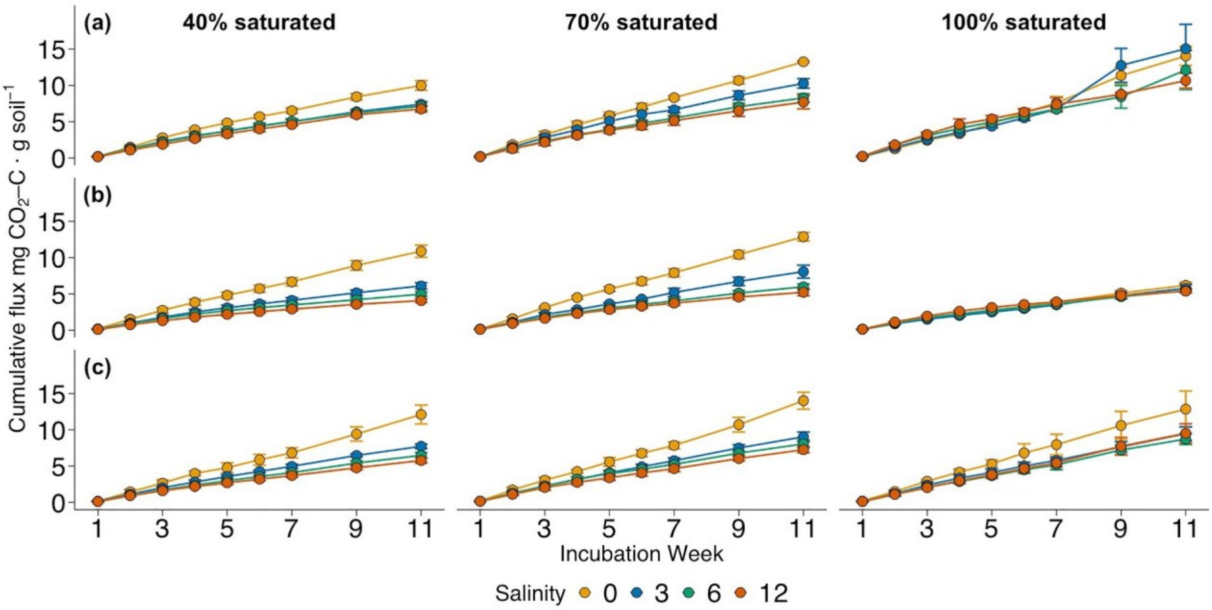

Figure 3. Mean cumulative soil CO_2 flux by salinity over 11-week incubation from the (a) Lowland Wetland, (b) Upland Wetland, and (c) Tundra across all three moisture levels. Error bars represent standard deviation.

from 70% saturated soil were similar. The magnitude of CO_2 flux was consistent over the entire incubation period for all soils (Figure 3).

3.2. Effects of Salinity and Moisture on Cumulative Soil CH_4 Emissions

After 3 weeks of incubation in saturated soils, cumulative CH_4 flux decreased with increased salinity in both Lowland and Upland Wetland soils, whereas CH_4 flux from Tundra soil was not affected by salinity (Figure 4, Table S3 in Supporting Information S1). Specifically, CH_4 flux from Lowland Wetland soil saturated with

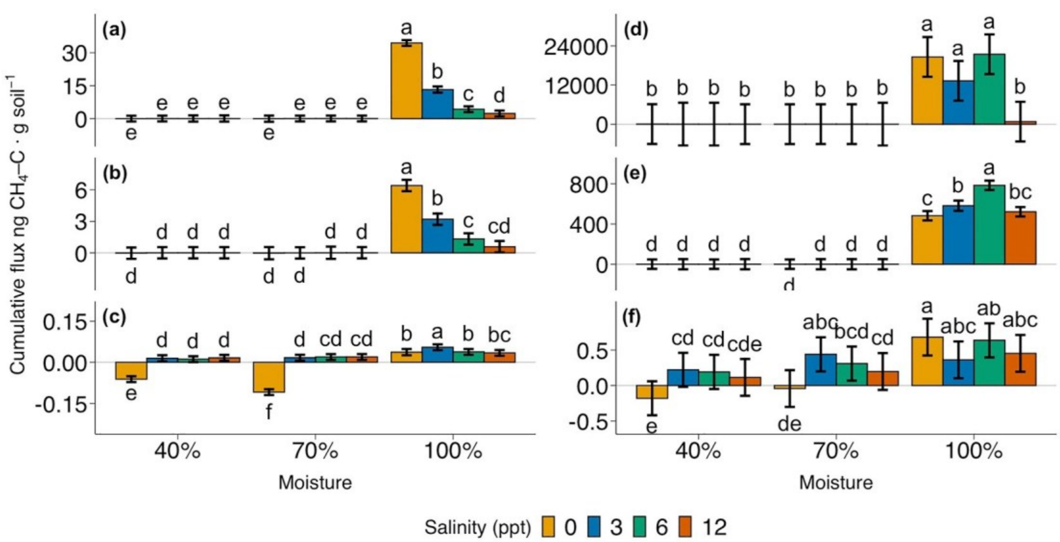

Figure 4. Model predictions for cumulative CH_4 flux following 3 weeks of incubation from the (a) Lowland Wetland, (b) Upland Wetland, and (c) Tundra and following 11 weeks of incubation from the (d) Lowland Wetland, (e) Upland Wetland, and (f) Tundra. Error bars represent 95% confidence intervals. Letters represent statistically significant cumulative flux means among salinities and moisture levels within each landscape position and incubation length ($p < 0.05$). The y-axes differ among plots.

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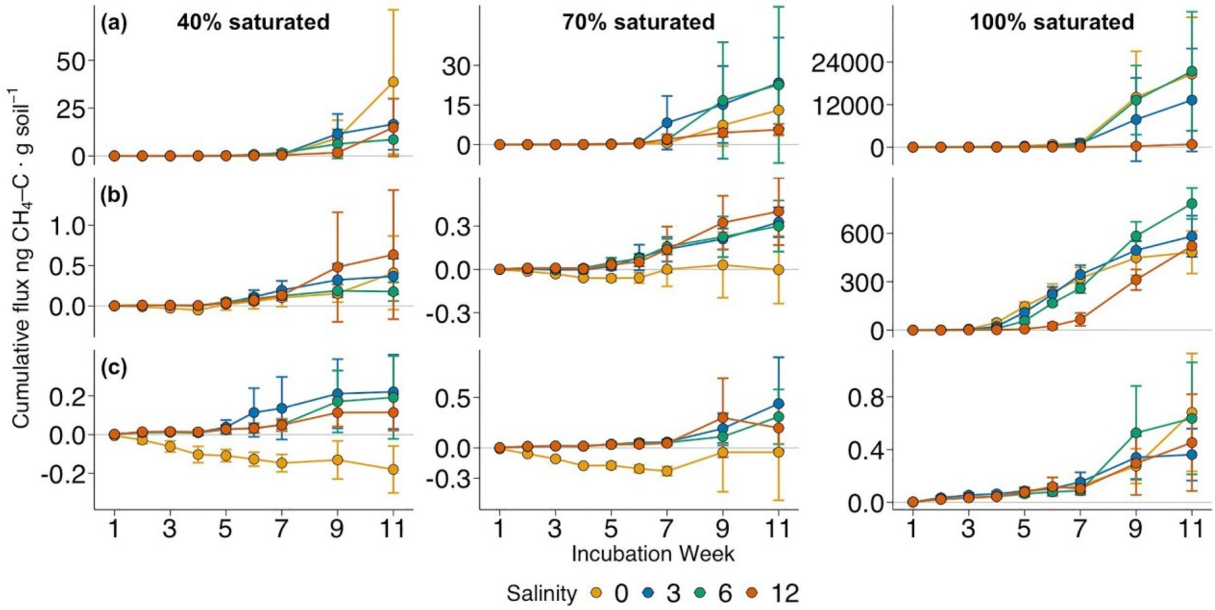

Figure 5. Mean cumulative CH_4 flux by salinity over 11-week incubation from the (a) Lowland Wetland, (b) Upland Wetland, and (c) Tundra across all three moisture levels. Error bars represent standard deviation. The *y*-axes differ among plots.

freshwater was ∼1,400% greater than CH_4 fluxes from soil saturated with 12 ppt salinity (Figure 4). Similarly, CH_4 flux from Upland Wetland soil saturated with freshwater was ∼900% greater than soil saturated with 12 ppt salinity. In contrast to the saturated samples, unsaturated samples had a CH_4 flux near zero in all landscape positions. CH_4 fluxes from unsaturated soil were much smaller than the fluxes from saturated soil.

Unlike CO_2, cumulative CH_4 flux following 11 weeks of incubation increased with higher moisture and had smaller and more complex effects from salinity (Figure 4, Table S4 in Supporting Information S1). Cumulative CH_4 flux for 100% saturated soils were greater than 40% and 70% saturated soils from the Lowland Wetland, Upland Wetland, and Tundra across all salinities, except the Tundra at 12 ppt. Further, CH_4 fluxes from Tundra soil at both 40% and 70% saturation increased between 0 and 3 ppt salinity (Figure 4). In contrast to the constant magnitude of CO_2 flux throughout the 11-week incubation, CH_4 flux dramatically accelerated in the middle of the incubation (around week 7) across all treatments and landscape positions (Figure 5) in saturated soil.

3.3. Effects of Salinity on Soil SO_4^{2-} Concentration

At the end of the incubation, SO_4^{2-} concentrations measured in the 100% saturated soils varied among landscape positions and salinity treatments (Table 2). Low concentrations of SO_4^{2-} remained after incubation across all salinity levels in the Lowland and Upland Wetland soils and did not differ from one another. In contrast, within the Tundra soil, SO_4^{2-} concentration was greater from freshwater through 3 and 6–12 ppt. The sulfate

Table 2
Mean Sulfate Concentration for Each Landscape Position and Salinity Level for 100% Saturated Samples at the End of the Experiment

	Average sulfate (SO_4^{2-}) concentration (ppm) ± standard deviation		
Salinity treatment (ppt)	Lowland Wetland	Upland Wetland	Tundra
0	4.02 ± 1.43 a	5.10 ± 2.78 a	1.77 ± 0.87 a
3	4.36 ± 1.62 a	3.47 ± 0.71 a	250.89 ± 35.42 b
6	4.18 ± 1.63 a	5.13 ± 4.15 a	359.55 ± 40.52 c
12	3.74 ± 1.25 a	6.25 ± 2.55 a	796.42 ± 90.63 d

Note. Different letters indicate significant differences ($p < 0.05$).

concentration in the 12 ppt salinity treatment was ∼450% greater than SO_4^{2-} concentration in the soil from the 0 ppt salinity treatment.

4. Discussion

Our results support the hypothesis that the effect of salinity on GHG fluxes is influenced by moisture in low-Arctic, coastal soils, but we observed complexity in these relationships across soils from different landscape positions with different histories of inundation. Greater salinity increased CO_2 and decreased CH_4 flux in saturated soil from the two Wetlands, but this trend was not observed in the Tundra soil. In partially saturated soil, greater salinity reduced CO_2 emissions from all soils but had little effect on CH_4 flux, which remained near zero. Finally, the role of salinity in saturated soils was diminished after 11 weeks relative to after 3 weeks, as SO_4^{2-} potentially present in the water was exhausted, thus promoting the role of moisture as more influential than salinity in soils exposed for longer periods of time. This trend, however, was only observed in the Wetland soils and conspicuously absent in Tundra soil, indicating Tundra soil GHG fluxes are governed by different biogeochemical processes than the adjacent wetlands, and will respond differently to future changes in flooding.

4.1. CO_2 Flux

CO_2 fluxes from saturated Lowland and Upland Wetland sites generally increased with greater salinity while in contrast, CO_2 flux from saturated Tundra soil generally decreased with greater salinity, after 3 weeks. A similar trend was observed after 11 weeks, with significant differences in emissions observed between 12 ppt and freshwater, but not among every level of salinity. Increasing CO_2 flux with greater salinity from saturated soil has been observed in other freshwater tidal marshes (Chambers et al., 2011; Marton et al., 2012; Wang et al., 2017) because SO_4^{2-} availability in saltwater can stimulate CO_2 emissions as sulfate reducers metabolize organic carbon and CH_4 (Beal et al., 2009; La et al., 2022). However, in contrast to the Wetlands, our observations from Tundra soil are a counter to this prevailing trend. Decreasing CO_2 flux with salinity, such as what we observed from Tundra soil, has been seen in freshwater soils known to have limited prior exposure to salinity (Ardón et al., 2018). As this Tundra is rarely exposed to seawater (only every 5–12 years, Ravens & Allen, 2017), it may not have the same communities of salt-tolerant microbes including sulfate reducers as the Wetland soils (Morrissey et al., 2014). Further, high SO_4^{2-} concentrations were found in the Tundra soil at the end of the experiment (Table 2) supporting lower rates of sulfate reduction in this soil, which is one of the mechanisms often responsible for increased CO_2 emissions with greater salinity (Chambers et al., 2011). Overall, these low-Arctic Wetland soils experience a transition in the dominant biogeochemical processes when the soil becomes saturated, altering the response of CO_2 flux to salinity, but the same transition does not take place in the Tundra.

Cumulative CO_2 flux from 40% to 70% saturated soil from all landscape positions decreased with increasing salinity across both timeframes investigated (Figures 1 and 2). Decreasing CO_2 flux in response to low levels of saltwater exposure has been observed previously in unsaturated soil (Brouns et al., 2014), and there are several potential explanations: the decrease maybe due to osmotic stress, which can dehydrate cells (even when freshwater soils are exposed to salinities as low as 3 ppt) (Setia et al., 2011), an increased ion toxicity (from Cl^- and SO_4^{2-} salts; Rath et al., 2016), or the two combined (Maucieri et al., 2017), which can inhibit soil microorganism growth and activity, reducing CO_2 emissions (Zhang et al., 2018). Because these soils were dried prior to incubation and incubated at 18°C, it is also possible that the microbial community of incubated soil differs slightly from field conditions. However such a difference is unlikely to be responsible for the response to salinity because (a) this same response to salinity has been observed in both samples that were previously dried (Brouns et al., 2014) and those that were not (Maucieri et al., 2017; Zhang et al., 2018) and (b) the effect of salinity on CO_2 flux is consistent among soils from all three landscape positions despite the fact that the Tundra soil is much more likely to experience warmer temperatures and regular drying than the Wetland soils.

4.2. CH_4 Flux

Saltwater exposure in saturated soil is widely understood to suppress soil CH_4 fluxes as the presence of SO_4^{2-} promotes sulfate reduction at the expense of methanogenesis (Chambers et al., 2011; Marton et al., 2012; Poffenbarger et al., 2011; Weston et al., 2006). This trend was supported in saturated Lowland and Upland Wetland soils over 3 weeks of incubation (Figure 3). Although this phenomenon is well established (Capone & Kiene, 1988; Luo et al., 2019; Weston et al., 2006), questions remain regarding the salinity threshold responsible for transitioning the relative magnitude of each metabolic pathway (sulfate reduction vs. methanogenesis), with suggested thresholds of 2–5 ppt (Marton et al., 2012) and 10–15 ppt (Wang et al., 2017). In the work reported here, CH_4 emissions from saturated Wetland soils declined most at salinities higher than 3 ppt, which is significant for this region as it is equal to observed high salinities of adjacent sloughs (Petit Bon et al., 2024). Therefore, these results indicate that even just a small increase in salinity from storm or tidal floodwaters may induce a threshold response that suppresses soil CH_4 emissions from these low-Arctic soils, particularly in the lower elevation landscape positions (Wetlands) that will likely experience more frequent flooding.

Saturated Tundra soil did not experience the same effects of salinity as saturated Wetland soils (Figure 3). While CH_4 flux from saturated Wetland soils decreased with greater salinity, CH_4 flux from saturated Tundra soil was consistently low among all salinity levels. Further, in Tundra soil, sulfate concentrations remained high after the experiment in the 3, 6, and 12 ppt treatment levels, with the greatest sulfate in the levels with greater salinity, indicating little to no sulfate depletion within the saturated Tundra soil (Table 2). There are several possible explanations why there is little difference in CH_4 emissions across salinity levels in Tundra soil. First, sphagnum peat from the Tundra landscape position can hold water amounts up to 2,500%–3,000% of their dry weight (Elumeeva et al., 2011), and may retain oxic soil microsites that support methanotrophy and never favor sulfate reduction or methanogenesis (Yang et al., 2017). Second, the Tundra soil may not have the same saline-tolerant microbial community as the more frequently flooded Wetland soils, and therefore, respiration is limited by the microbial communities present (Ardón et al., 2018; Bueno de Mesquita et al., 2024; Morrissey et al., 2014). Microbial analysis of similar Tundra soil in this region indicates low abundance of archaea, suggesting a low abundance of methanogens (Foley et al., 2021). Finally, the Tundra soil overall is composed of greater amounts of undecomposed material than the Wetland soils (Table 1), suggesting that limited substrate in the Tundra maybe limiting CH_4 emissions regardless of the salinity (Galand et al., 2005). These results demonstrate that saturated soil CH_4 responses to salinity are strongly contrasting across landscape positions, indicating that field fluxes likely also depend on site-specific soil properties and microbial communities.

The difference in CH_4 emissions observed over the 3-week versus 11-week timeframe highlights the potential for soil moisture to play a larger role in regulating CH_4 flux when soils remain saturated for longer periods of time, without being refreshed by saline water. After 3 weeks of incubation, saturated soil conditions produced a much larger CH_4 flux than unsaturated conditions, but the effect of suppressed CH_4 emissions at higher salinity was also clear (Figure 4, Table S4 in Supporting Information S1). In contrast, the relative role of soil moisture was greater after 11 weeks when emissions from saturated Upland Wetland soil were much greater than partially saturated soil from the same landscape position, and the effect of salinity was more convoluted (Figure 4). The declining importance of salinity over time suggests that the influence of salinity on CH_4 emissions decreases once SO_4^{2-} is depleted (Capone & Kiene, 1988; Lackner et al., 2020). This situation is relevant in the field where water from a storm surge event becomes impounded by local topography and the water remains present on the landscape for multiple weeks after the flooding event. However, in such an event, salt could remain on the landscape and potentially affect the ecosystem response (Lantz et al., 2015) even after sulfate has been exhausted. Finally, the rate of CH_4 emission increased in all soils around week 7 and after, with many not declining before the end of the experiment, suggesting that cumulative flux could be even higher if soils were exposed to these moisture conditions for longer and the microbial community composition experienced further changes in response to new conditions (Luo et al., 2019).

4.3. Future Implications

Arctic coastal environments are expected to experience increasing flooding frequency and intensity in coming decades. Our work suggests increased salinity and soil moisture from these floods, together and individually, and alter future potential soil GHG emissions, with the greatest effects of salinity observed in the two lowest landscape positions that already experience occasional saltwater inundation. There, more saline flooding in the future that saturates the soil will increase CO_2 emissions but decrease CH_4 emissions. Flooding events that leave the lowest elevation soil only partially saturated will have a similar magnitude effect on CO_2 emissions, but CO_2 emissions will decrease with salinity, while the CH_4 response from unsaturated soil will be much smaller. However, where inundation persists for longer, moisture will be more important than salinity in controlling CH_4 emissions, and the CH_4 flux may become quite large. This research highlights the interaction of soil moisture and salinity in controlling future GHG balance, particularly in high-latitude coastal environments that hold large and potentially vulnerable carbon stocks.

Global Research Statement

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Data Availability Statement

The gas flux data collected in this study are available at the Arctic Data Center via https://doi.org/10.18739/A27H1DP38 (B. N. Barr & Kelsey, 2024). The software for all statistical analyses is available at https://doi.org/10.5281/zenodo.15666106 (B. Barr, 2025).

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