Postprint: Persistent Dynamic Characteristics of Wetland Soil Gas Emissions in Response to Water Level Fluctuations

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Abstract

To explore the relationship between wetland water level fluctuations and soil gas emissions, dynamic monitoring was conducted on reed wetlands in the middle reaches of the Yellow River following half-flooding and full-flooding plot treatments, comparing differences in soil gas emissions during a 7-day water level change process. The results indicated that flooding induced significant differences in soil CO2 emission rates. With increasing soil temperature, emission rates of H2O, CO2, and H2S all exhibited upward trends (except for H2O in the full-flooding plot). The effects of half-flooding and full-flooding on H2O emission rates displayed a convergence-asynchrony-disappearance pattern: differences between the two treatments were essentially consistent during the early flooding stage (63.73 h), but diverged substantially in the later stage, with the influence of flooding persisting until after 125.64 h. Overall, flooding increased total H2O emissions by 76.3% and 31.3%, respectively. CO2 emission rates showed an asynchrony-convergence pattern: initial environmental changes from flooding caused a uniform reduction in CO2 emissions, with significant differences emerging between the two treatments from 37.69 to 68.66 h, and these differences persisted from 68.66 to 125.64 h despite water level recovery. Flooding reduced total CO2 emissions by 50.1% and 43.2%, respectively. H2S emission rates exhibited a no change-asynchrony-no change pattern, increasing total H2S emissions by 42.3% and 32.3%, respectively. This study tracked the dynamic processes of soil H2O, CO2, and H2S emission rate changes following water level rise, revealing that their impacts were characterized by asynchrony and persistence, with CO2 emission rates demonstrating a relatively long response cycle. The findings hold significant importance for research on the ecological functions of riverine wetlands. The response lag of wetland soil gas emissions to water level changes implies substantial impacts on wetland ecological functions, and their fluctuation processes require more precise investigation over extended time periods.

Full Text

Continuous Dynamic Characteristics of Wetland Soil Gas Emission Response to Water Level Changes

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Abstract: To explore the relationship between wetland water level changes and soil gas emissions, dynamic monitoring was conducted on reed wetlands in the middle reaches of the Yellow River under half-water-injection and full-water-injection treatments, and differences in soil gas emissions during the water level change process were compared. The results showed that water injection created significant differences in CO2 emission rates. With rising soil temperature, emission rates of all gases showed an upward trend (except for H2O under full injection). The impacts of half and full water injection exhibited a convergence-disappearance characteristic. For H2O emissions, the effects of half and full injection were basically consistent initially but diverged significantly in the later stage, with the influence not disappearing until 125.64 hours, causing overall increases of 76.3% and 31.3%, respectively. CO2 emission rates displayed asynchronous-convergence characteristics; the initial environmental change caused a consistent reduction in CO2 emissions, with significant differences appearing between 37.69-68.66 hours. Although water levels recovered from 68.66-125.64 hours, differences persisted, with water injection causing overall reductions of 50.1% and 43.2%, respectively. H2S emission rates exhibited a changeless-asynchronous-changeless pattern, with overall increases of 42.3% and 32.3%, respectively. This study tracked the dynamic processes of soil H2O, CO2, and H2S emission rate changes following water level rise, revealing that the impacts are asynchronous and persistent, with CO2 emission rates showing a particularly long response cycle. These results are significant for understanding the ecological functions of river wetlands, as the delayed response of wetland soil gas emissions to water level changes indicates important impacts on wetland ecological functions, and their fluctuation processes require longer-term precise monitoring.

Keywords: soil CO2 emission; wetland water level change; ecological function; water injection test

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1.1 Study Area Overview

The middle reaches of the Yellow River enter a canyon section below Togtoh County in Inner Mongolia, where the river cuts deeply with turbulent flow. However, in the Longmen to Tongguan section, the river surface widens and the flow becomes gentle, with extensive riparian wetlands on both banks [Figure 1: see original paper]. This section cuts across the Fenwei Plain, where the Fen River and Wei River tributaries converge into the Yellow River, with an average annual flow of 574.16 m^3/s. The zonal soils in the study area are cinnamon soil and loessial soil, with an average annual temperature of 12.7-15.6°C and annual precipitation of 390.7-592.2 mm. The region belongs to the warm temperate semi-humid monsoon climate zone, with deciduous broad-leaved forest development. Due to the influence of global climate change, upstream inflow varies significantly, and water levels fluctuate frequently, making the impact of water level changes on wetland ecological functions a new research priority.

1.2 Research Methods

To investigate the dynamic changes in gas emissions following water level variation, field plots were monitored with artificial water injection treatments compared against natural conditions. A typical reed wetland (Phragmites australis) was selected at the Yellow River floodplain in Hancheng City (110°28.03 E, 35°25.82 N). The reed community was located approximately 100-150 m from the river, with plant heights of 150-170 cm, stem diameters of 4-6 mm, and densities of about 50-60 plants/m^2. The vertical distance from the sample plots to the river surface was 50-60 cm, with water level variations of approximately 18 cm during the monitoring period.

On the sampling day, cultivation pits were excavated with specific dimensions shown in [Figure 2: see original paper], lined with perforated plastic anti-seepage film on the inner walls. The pits were arranged in a line along the river surface with spacing greater than 200 mm. A total of 9 cultivation pits were established across three treatments: 3 pits injected to -30 cm (half injection), 3 pits injected to the surface (full injection), and 3 untreated natural plots. Observations showed that water levels in both half and full injection pits returned to their original positions after 46.71 ± 3 hours of monitoring. Data collection began before injection, with initial sampling every 3-4 hours in the early stage and extended intervals in later stages. Monitoring continued for 160.85 hours, with 42 data collections per treatment type and three replicates per type.

1.3 Gas Emission Data Collection

Gas emission rates were measured using a WEST Systems portable soil CO2/H2O flux system with a chamber diameter of 200 mm. Sampling was conducted in inter-cluster open spaces, with the chamber edge compacted to ensure tight contact with the ground during dry plot sampling. Soil temperature was measured at 200 mm depth to represent soil thermal conditions.

1.4 Data Processing and Statistical Methods

Collected data were categorized and summarized using Excel. Two-factor ANOVA was employed to analyze significant differences among natural, half-injection, and full-injection plots. Emission rate comparison charts were generated for analysis.

2 Results and Analysis

Difference analysis revealed that water injection caused significant changes in CO2 emission rates, though the effect on H2S emission rates did not reach significance (Table 1). However, from the significance perspective, differences existed between half and full injection plots for H2O emissions, with half injection having a greater impact than full injection, while the opposite was true for H2S emission rates.

Table 1 Analysis of difference caused by water injection

Note: Sample size n=9; * indicates $P<0.05$.

During the monitoring process, regression analysis of 42 sequential data points with soil temperature showed that, except for H2O emission rates under full injection, all gas types exhibited upward trends with increasing soil temperature. The magnitude of increase followed the pattern H2O > CO2 > H2S. Compared with natural plots, both half and full injection caused varying degrees of reduction in CO2 emission rate increases. After injection, the relationship between soil temperature and gas emission rates was disrupted, with noticeable differences in linear regression equation slopes and goodness-of-fit. Water injection caused significant changes in total gas emissions, with half and full injection resulting in 31.3% and 50.1% increases in H2O emissions, respectively, and 43.2% and 42.3% reductions in CO2 emissions, respectively [Figure 4: see original paper].

Throughout the monitoring period, the impacts of half and full injection (represented as differences from natural plots) fluctuated with a daily periodicity, with greater effects at night than during the day. In the early monitoring stage (0-63.73 hours), differences between half and full injection were relatively small for all three gases. Between 63.73-125.64 hours, differences between half and full injection impacts became more pronounced, though both showed a convergence-disappearance trend [Figure 5: see original paper].

Figure 3 [Figure 3: see original paper] Relationship between soil temperature change and gas emission rate

Figure 4 [Figure 4: see original paper] Comparison of total emissions of H2O, CO2 and H2S

Note: The vertical coordinate represents the difference in emission rates between injection plots and natural plots for three gases.

Figure 5 [Figure 5: see original paper] Influence process of water injection on emission rate of the three kinds of gas

Note: Data were calculated using linear interpolation.

3.1 Characteristics of Soil H2O Emission Rate Changes After Water Injection

Water injection altered soil environmental conditions, triggering changes in soil gas emissions. Observations revealed that elevated soil water levels were only maintained for 1-2 days, while the soil underwent a biochemical adaptation process following physical injection. Due to the high permeability of Yellow River sandy soils and the delayed temperature response to water injection, H2O emission rates did not increase significantly in the early stage (0–63.73 hours). Although differences between half and full injection were initially consistent, they diverged markedly in the later stage despite water levels returning to natural conditions. Because of soil water retention differences, the effects persisted until 125.64 hours before disappearing. Consequently, H2O emission rates exhibited a convergence-disappearance trend after injection. While water injection increased soil moisture content, it reduced sensitivity to soil temperature. Combined with declining water levels in injection plots during monitoring, this ultimately resulted in poor fitting between H2O emission rates and soil temperature in injection plots.

3.2 Characteristics of Soil CO2 Emission Rate Changes After Water Injection

CO2 emissions originate from microbial degradation of organic matter, oxidation-reduction processes of organic and mineral components, and respiration of animals and plant roots. Higher soil temperatures can promote these processes in wetland soils, thereby increasing CO2 emission rates. In this study, CO2 emission rates showed a fluctuating decreasing trend overall. Differences between half and full injection plots and natural plots were basically consistent in the middle to late monitoring period (68.66–125.64 hours). However, significant differences occurred between 37.69–68.66 hours, indicating that water injection substantially impacted soil CO2 emissions.

The relationship between soil temperature and CO2 emissions proved complex: (1) Although water injection reduced CO2 emission rates, no direct correlation existed with injection volume. Total CO2 emissions during monitoring followed the pattern natural > full injection > half injection, with half injection having a greater impact than full injection. (2) Differences between half and full injection impacts on CO2 emission rates showed both divergence and convergence during monitoring, indicating complex influence processes. (3) The impacts were long-lasting; although water levels recovered to natural conditions after 2-3 days, differences remained. We propose that injected soils experienced saturation and recovery processes, triggering a series of environmental changes:

soil air shifted from anaerobic to aerobic conditions, soil organisms transitioned from antagonism to adaptation, and associated soil physicochemical processes changed accordingly.

The initial environmental change caused a consistent reduction in CO2 emission rates. However, due to differences in water level recovery time between full and half injection plots, asynchronous patterns emerged between 37.69–68.66 hours. From 68.66–125.64 hours, water levels in both half and full injection plots recovered to natural conditions, but soil CO2 emission rates indicated that soil moisture remained higher than in natural plots. During this stage, soils underwent water retention processes after saturation, with CO2 emission sources differing from natural plots and showing diurnal periodic variations. Although differences diminished after 125.64 hours, they persisted, likely because water injection disrupted the composition and quantity of soil CO2 sources. Water-soluble organic carbon (DOC), microbial communities, root respiration, and mineral physicochemical processes had not returned to natural levels after the disturbance, causing the persistence of injection effects. Previous studies have reported rebound phenomena in CO2 emission rates after water level rise, termed "Birch effects," and Moffett et al. found that tidal flooding significantly affected CO2 emission rates in salt marshes, supporting our conclusions.

3.3 Characteristics of Soil H2S Emission Rate Changes After Water Injection

Soil sulfur gas emissions primarily originate from dissimilatory sulfate reduction and degradation of sulfur-containing amino acids under microbial action, producing water-soluble and adsorbed forms. Soil moisture directly affects the availability of sulfate, gas diffusion rates, and microbial activity, indirectly influencing soil pH and redox potential, thereby affecting sulfur gas production and diffusion. Under stable high-moisture conditions, microorganisms in wetland soils undergo anaerobic decomposition of sulfur-containing materials, increasing H2S emission rates, with higher temperatures accelerating the process. Therefore, water injection caused overall increases in H2S emissions. However, in the early injection stage, changes in soil environment reduced rather than increased microbial activity and water-soluble sulfur, causing decreased H2S emission rates initially. As anaerobic conditions developed, H2S emission rates increased. Different water level decline rates between half and full injection created divergent impacts, though effects converged as conditions recovered. By the end of monitoring, H2S emission rates became similar to those in natural plots.

4 Conclusions

This study used artificial water injection to simulate the effects of water level rise on wetland soil gas emissions, demonstrating that water level rise significantly impacts wetland soil gas emissions. The main conclusions are:

1) Half and full water injection had differential impacts on the three gases, causing significant changes in CO_2 emission rates.

2) Except for H_2O emission rates under full injection, all gas types showed upward trends with increasing soil temperature, with the magnitude of increase following $H_2O > CO_2 > H_2S$.

3) Water injection caused increases in H_2O and H_2S emission rates and decreases in CO_2 emission rates. During monitoring, half and full injection resulted in 76.3% and 31.3% increases in H_2O emissions, respectively, and 50.1% and 43.2% reductions in CO_2 emissions, respectively, along with 42.3% and 32.3% increases in H_2S emissions, respectively.

4) Rapid water level changes from rise to fall created dynamic, persistent effects on gas emissions. H_2O emission rates showed a convergence-disappearance trend, CO_2 emission rates showed asynchronous-convergence-changeless trends, and H_2S emission rates showed changeless-asynchronous-changeless patterns. The impact of short-term water level changes on CO_2 emission rates did not disappear within 125.64 hours.

The impact of Yellow River water level changes on wetland soil gas emissions is dynamic, differing substantially from static water level conditions. This creates significant challenges for evaluating wetland air emissions. To address this, two approaches are recommended: first, conduct long-term monitoring under controlled laboratory conditions to eliminate interference from soil temperature and other factors; second, clarify the relationships between gas emissions and various soil source factors to establish regression models for the effects of different wetland water level changes on gas emissions.

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Note: Figure translations are in progress. See original paper for figures.