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Effects of Extreme Weather Events on Nitrous Oxide Emissions from Rice-Wheat Rotation Croplands

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Abstract

Nitrous oxide (N_2O) is a potent greenhouse gas, and agroecosystems, particularly rice-wheat rotation systems, are significant sources of its emissions. Climate change is increasing the frequency and intensity of extreme weather events (EWEs) such as droughts, heatwaves, and intense rainfall. This paper investigates the complex effects of these EWEs on N_2O fluxes in rice-wheat rotation croplands. Through a synthesis of existing literature and a proposed methodological framework for field-based research, this study posits that EWEs act as acute perturbations that disrupt the delicate balance between nitrification and denitrification processes, often leading to emission pulses that can offset long-term mitigation efforts. The review highlights that the impact is highly dependent on the timing, intensity, and duration of the event relative to key agronomic practices like fertilization and flooding. The proposed research methodology involves a combination of high-frequency automated chamber measurements, isotopic analysis, and microbial genomic sequencing to disentangle the underlying mechanisms. The anticipated conclusions underscore the need for adaptive nitrogen management strategies to enhance agroecosystem resilience in the face of a more variable climate.

Keywords: *Nitrous Oxide, Rice-Wheat Rotation, Extreme Weather events (EWEs), Climate Change, Denitrification.*

1. Introduction

1.1.The Dual Challenge: Food Security and Climate Change

The global agricultural system faces an unprecedented dual challenge: to feed a growing population projected to reach nearly 10 billion by 2050, while simultaneously mitigating its contribution to climate change. Central to this challenge is the management of nitrogen (N), an essential nutrient for crop productivity. The intensification of agriculture, particularly in Asia, has relied heavily on the application of synthetic nitrogen fertilizers to drive high-yielding cropping systems. Among these, the rice-wheat rotation (RWR) is paramount, covering approximately 26 million hectares across the Indo-Gangetic Plain and other parts of South and East Asia. This system is the bedrock of food security for hundreds of millions of people, producing staple carbohydrates that constitute a significant portion of the global caloric intake. However, this intensive management comes at a substantial environmental cost. Agroecosystems are the dominant anthropogenic source of nitrous oxide (N_2O), a greenhouse gas with a global warming potential approximately 298 times that of carbon dioxide over a 100-year period. Furthermore, N_2O is the primary stratospheric ozone-depleting substance emitted in the 21st century. In rice-wheat rotations, the unique hydrological transitions—from the flooded, anaerobic conditions of rice cultivation to the aerobic, upland conditions of wheat farming—create a dynamic biogeochemical environment that is highly conducive to both nitrification and denitrification, the two primary microbial processes responsible for N_2O production [1].

1.2.Extreme Weather Events: A New Frontier in Biogeochemistry

Climate change is not merely a gradual shift in average temperatures and precipitation patterns; it is fundamentally altering the variability and extremity of weather. The Intergovernmental Panel on Climate Change (IPCC) has concluded with high confidence that the frequency and intensity of extreme weather events (EWEs), including heatwaves, severe droughts, and extreme precipitation events, have increased since the 1950s and will continue to do so. These EWEs represent acute, short-term perturbations to ecosystems, contrasting with the chronic effects of gradual climate change. For agricultural systems, EWEs pose a direct threat to crop yields. However, their impact on soil biogeochemical processes, particularly nitrogen cycling and N_2O emissions, is less understood and represents a critical knowledge gap. The conventional understanding of N_2O emissions is built on long-term average fluxes, often measured under relatively stable, "normal" climatic conditions. This paradigm is ill-equipped to predict the episodic, high-magnitude emission pulses that often accompany EWEs. Such pulses, triggered by the rewetting of dry soils (the "Birch effect") or the rapid mineralization of organic matter following heat stress, can constitute a disproportionately large fraction of annual greenhouse gas budgets. Ignoring these acute events leads to significant underestimations of total N_2O emissions from agricultural landscapes [2].

1.3.Problem Statement and Research Rationale

Rice-wheat rotation systems are particularly vulnerable to EWEs due to their intensive management and hydrological sensitivity. For instance, a mid-season drought during the rice phase can induce unanticipated soil aeration, shifting the system from a denitrification-dominated regime to a nitrification-dominated one, potentially leading to a spike in N_2O. Conversely, an intense rainfall event following the application of nitrogen fertilizer to wheat fields can create transient anaerobic microsites, fueling denitrification and a burst of N_2O emissions. Heatwaves can accelerate the decomposition of soil organic matter and crop residues, releasing available nitrogen that is then susceptible to gaseous loss. The current body of research largely focuses on the effects of individual extreme events or on long-term climate trends, with limited integration. A holistic understanding of how the sequence, timing, and interactive effects of multiple EWEs influence N_2O emissions across the different phases of the rice-wheat rotation is critically lacking. Without this knowledge, the development of effective, climate-smart agricultural practices to mitigate N_2O emissions while maintaining resilience to extreme climate variability will be severely hampered [3].

1.4.Objectives of the Study

This research paper aims to address this knowledge gap by pursuing the following objectives:

- To synthesize existing literature on the effects of drought, heatwaves, and extreme precipitation on N_2O emissions in agroecosystems, with a specific focus on rice-wheat rotations.
- To propose a robust methodological framework for investigating the causal mechanisms driving N_2O pulses during EWEs, integrating high-resolution flux measurements, isotopic techniques, and molecular microbial ecology.
- To analyze and conceptualize the interactive effects of EWEs with key agronomic management factors (e.g., nitrogen fertilization timing, irrigation practices, residue management).
- To conclude by outlining adaptive management strategies and future research priorities to mitigate N_2O emissions from rice-wheat rotations under a more extreme climate [4].

2. Literature Review

2.1.Biogeochemistry of N_2O in Rice-Wheat Rotations

N_2O is produced in soils primarily through two microbial pathways: nitrification and denitrification. Nitrification is the aerobic oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), with N_2O produced as a byproduct. Denitrification is the anaerobic reduction of NO_3^- to dinitrogen gas (N_2), with N_2O as an obligate intermediate. The rice-wheat rotation creates a unique "biogeochemical seesaw." During the rice phase, prolonged flooding creates anaerobic conditions, favoring denitrification as the primary N_2O source. However, the N_2O produced is often further reduced to N_2, making net emissions relatively low during stable flooding. The major N_2O pulse in rice systems often occurs during mid-season aeration (drainage) events, which couple the production of NO_3^- from nitrification with subsequent denitrification in anaerobic microsites. The wheat phase, cultivated under aerobic conditions, primarily generates N_2O via nitrification and denitrification in transiently anaerobic hot spots, often following irrigation or rainfall events [5].

2.2.Impacts of Individual Extreme Weather Events

2.2.1. Drought and Rewetting

Drought is a major stressor in both phases of the rotation. In wheat, drought stress can inhibit plant nitrogen uptake, leaving surplus inorganic nitrogen (NH_4^+, NO_3^-) in the soil. This "N bottleneck" primes the system for large emissions upon rewetting. The "Birch effect" describes the rapid mineralization of microbial biomass and soil organic matter following the rewetting of dry soil, releasing a pulse of available carbon and nitrogen. This, combined with the re-activation of nitrifiers and denitrifiers, leads to a pronounced N_2O emission pulse. Studies have shown that such rewetting pulses can account for up to 30-50% of annual N_2O emissions in semi-arid and Mediterranean agroecosystems, a pattern that is increasingly relevant for the wheat-growing season in regions facing more frequent intermittent droughts.

2.2.2. Heatwaves

Heatwaves, defined as prolonged periods of excessively high temperatures, impact N_2O emissions through both direct and indirect mechanisms. Directly, elevated temperatures increase the metabolic rates of soil microbes, potentially accelerating both nitrification and denitrification, provided moisture is not limiting. Indirectly, heatwaves can induce plant stress, leading to root senescence and the exudation of labile carbon compounds into the rhizosphere. This carbon input can fuel denitrification, enhancing N_2O production. Furthermore, extreme heat can accelerate the decomposition of crop residues left on the field after harvest, releasing a flush of nitrogen that can be converted to N_2O before the subsequent crop establishes [6].

2.2.3. Extreme Precipitation and Flooding

While rice paddies are adapted to flooding, extreme precipitation events outside of the normal flooding period or during the wheat phase can have dramatic effects. Intense rainfall on fertilized, aerobic wheat fields can rapidly create waterlogged conditions. This induces denitrification and, if the N_2O reductase enzyme is inhibited (e.g., by low pH or high nitrite concentrations), can lead to a massive N_2O emission burst. In rice systems, unseasonal or excessive rainfall can disrupt managed drainage schedules, prolonging anaerobic conditions or causing unintended flooding during dry periods, altering the balance of N_2O versus methane (CH_4) emissions [7].

2.3.Interactive and Compound Effects

A significant gap in the literature is the study of compound events—the sequential occurrence of two or more EWEs. For example, a spring drought followed by a summer heatwave in the wheat phase, or a heatwave during the rice ripening stage followed by extreme rainfall at harvest. Such sequences can have non-additive effects. The legacy of one event (e.g., soil compaction from heavy rain, accumulation of labile substrates from a heatwave-killed cover crop) can prime the system for a vastly different response to a subsequent event. Current process-based models (e.g., DNDC, DayCent) are poorly parameterized to capture these legacy effects and the rapid biogeochemical transitions induced by EWEs.

2.4.Synthesis of Literature Gaps

The literature review reveals that while individual components are well-studied, there is a need for integrated research that:

- Simultaneously monitors N_2O fluxes across the entire rice-wheat cycle, capturing multiple EWE types.
- Moves beyond correlative studies to mechanistic understanding using advanced tools like stable isotope probing and metagenomics.
- Quantifies the contribution of short-term EWE-induced pulses to total annual emissions.
- Evaluates the effectiveness of adaptive management practices (e.g., controlled-

release fertilizers, optimized irrigation scheduling) in mitigating EWE-induced N_2O pulses [8].

3. Methodology

To address the outlined objectives, this section proposes a comprehensive methodology for a field-based study designed to capture the effects of EWEs on N_2O emissions.

3.1. Study Site and Experimental Design

The study would be conducted in a typical rice-wheat rotation region, such as the Indo-Gangetic Plain in India or the North China Plain. The experimental design would be a randomized complete block design with three treatments and four replicates (n=4).

- **Treatment 1:** Control (Ambient Conditions): Standard agronomic practices with no manipulation of weather.
- **Treatment 2:** Extreme Weather Manipulation: This treatment would involve a combination of passive and active manipulations to simulate compound EWEs:
- **Drought:** Rainout shelters (e.g., automated mobile roofs) would be used during the wheat season to exclude rainfall for a defined period (e.g., 4-6 weeks during the stem elongation stage), followed by a controlled rewetting event.
- **Heatwave:** During both rice and wheat seasons, infrared heaters or passive open-top chambers would be used to elevate canopy temperature by 4-6°C for a duration of 5-7 days, timed to coincide with sensitive growth stages (e.g., anthesis).
- **Extreme Precipitation:** A high-intensity, short-duration irrigation event (e.g., 100 mm in 2 hours) would be applied to the wheat plots following the drought period and again during the rice phase after a mid-season drainage event [9].
- **Treatment 3:** Adaptive Management: This treatment would be exposed to the same EWEs as Treatment 2, but with adaptive management interventions, such as the use of nitrification inhibitors (e.g., dicyandiamide, DCD) or split application of controlled-release nitrogen fertilizer.

3.2. N_2O Flux Measurement

High temporal resolution is critical. We will deploy an automated chamber system connected to a gas chromatograph or a cavity ring-down spectroscopy (CRDS) analyzer. This system will take measurements from all plots (n=12) at 4-hour intervals. This high-frequency sampling is essential to capture the rapid emission pulses that occur within hours of a rewetting or heat stress event, which would be missed by conventional weekly manual sampling.

3.3. Ancillary and Mechanistic Measurements

To understand the drivers of N_2O pulses, we will measure:

- **Soil Physicochemical Properties:** Soil moisture (volumetric water content), soil temperature (at multiple depths), and concentrations of soil NH_4^+, NO_3^-, and dissolved organic carbon (DOC) will be measured at high frequency (daily during events, weekly otherwise) [10].
- **Isotopic Analysis of N_2O:** The isotopic signature ($\delta^{15}N$ and $\delta^{18}O$) of emitted N_2O will be analyzed. This technique helps partition the contribution of nitrification versus denitrification to the total flux, providing a process-based understanding of the pulse.
- **Microbial Community Analysis:** Soil samples will be collected before, during, and after each simulated EWE. Quantitative PCR (qPCR) and metagenomic sequencing will be used to quantify the abundance of key functional genes (e.g., ‘AOA amoA’, ‘AOB amoA’ for nitrification; ‘nirK’, ‘nirS’, ‘nosZ’ for denitrification) and to assess shifts in microbial community structure.

3.4. Data Analysis

Data will be analyzed using a combination of linear mixed-effects models to assess the effects of treatments (EWE, management) and their interactions over time. Cumulative N_2O emissions will be calculated by integrating the high-frequency flux data. Structural equation modeling (SEM) will be used to explore the causal pathways linking EWEs, soil properties, microbial functional gene abundance, and N_2O fluxes. The contribution of EWE-induced pulses to the total cumulative emissions will be quantified by identifying and summing flux events exceeding a defined threshold (e.g., 2 standard deviations above the control mean).

4. Analysis (Anticipated Results and Conceptual Model)

Based on the proposed methodology, this section presents an anticipated analysis and conceptual framework for understanding the effects of EWEs.

4.1. Anticipated Findings

- **Pulse Emissions Dominate Annual Budgets:** We anticipate that the sequential EWEs (drought, heatwave, and extreme rain) will induce N_2O pulses that contribute to a disproportionately large fraction (potentially >50%) of the total N_2O emissions for the rotation period. The largest pulse is expected during the rewetting of the drought-stressed wheat field, particularly if it coincides with residual fertilizer N [11].
- **Pathway Shifts:** Isotopic analysis is expected to reveal a shift in N_2O production pathways during EWEs. For instance, during the drought period, nitrification might dominate as the soil dries. Upon rewetting, a rapid shift to denitrification would occur, driven by the flush of DOC and anaerobic microsite formation. Heatwaves may initially stimulate nitrification, but as plant stress increases, root exudates may fuel denitrification.
- **Microbial Legacy Effects:** Metagenomic analysis will likely show that EWEs do not just alter instantaneous activity but also reshape the microbial community. For example, drought may select for resilient, spore-forming bacteria, while the subsequent rewetting may favor fast-growing denitrifiers with the “nirS” gene, leading to a community structure that has a higher intrinsic potential for N_2O production for a legacy period after the event.

4.2. Conceptual Model

The synthesis of literature and anticipated results leads to the development of a conceptual model (Figure 1). This model posits that the "background" N_2O emissions under normal conditions are governed by routine agronomic management (fertilization, irrigation, flooding). Superimposed on this are EWE-induced pulses. The magnitude of the pulse is a function of:

- **The "Priming Potential":** The amount of available N and C substrates in the soil at the time of the event, determined by recent fertilization, residue decomposition, and the legacy of prior events [12 - 13].
- **The "Perturbation Strength":** The intensity and duration of the event (e.g., degree of drying, temperature increase).
- **“Ecosystem Resilience”:** The capacity of the soil-microbe-plant system to buffer the perturbation, which is mediated by factors like soil texture, organic matter content, and microbial diversity.

This model highlights that management interventions (e.g., nitrification inhibitors, residue retention) can influence the "Priming Potential" and "Ecosystem Resilience," thereby modulating the EWE-induced emission response.

Conclusions

This research paper has outlined the critical and underexplored link between extreme weather events and nitrous oxide emissions from the globally important rice-wheat rotation system. The detailed literature review and proposed methodology underscore that EWEs are not mere aberrations but are potent drivers of N_2O dynamics, capable of generating emission pulses that can dominate annual greenhouse gas budgets.

The key conclusions are:

- Extreme weather events (drought, heatwave, extreme precipitation) act as acute biogeochemical perturbations that disrupt the steady-state N cycling in rice-wheat rotations, leading to large, episodic N_2O pulses.
- The impact of EWEs is context-dependent, governed by the timing of the event relative to agronomic practices (especially N fertilization) and the legacy effects of previous events.

- Understanding the underlying mechanisms requires a multi-pronged approach that integrates high-frequency flux measurement with isotopic fingerprinting and molecular microbial ecology to move beyond correlation to causation.
- Current greenhouse gas inventories and process-based models are likely underestimating total N_2O emissions by not adequately accounting for the magnitude and frequency of EWE-induced pulses.

Implications for Adaptive Management

To mitigate N_2O emissions under a more volatile climate, agricultural management must become adaptive and resilient. Strategies include:

- **Precision Nitrogen Management:** Timing N applications to avoid large pools of available N coinciding with predicted high-risk periods (e.g., the onset of the monsoon or a forecasted drought-rewetting cycle).
- **Use of Enhanced-Efficiency Fertilizers:** Nitrification inhibitors and controlled-release formulations can decouple the availability of N from microbial activity, reducing the "priming potential" for N_2O production during an EWE.
- **Water Management:** In rice, alternate wetting and drying (AWD) can reduce methane emissions, but its interaction with N_2O during unseasonal drought or extreme rainfall needs careful management to avoid creating conditions for large N_2O pulses.

Future Research Directions

Future research should focus on:

- **Long-term, multi-event studies:** Establishing long-term experimental platforms that can capture the cumulative and interactive effects of multiple EWEs over several crop cycles.
- **Model development:** Incorporating the mechanisms of EWE-induced pulse emissions into next-generation biogeochemical models, with parameters derived from isotopic and genomic data.
- **Scaling up:** Developing methods to scale plot-level understanding of EWE-induced pulses to landscape and regional levels using remote sensing and machine learning techniques.

In conclusion, addressing the challenge of N_2O emissions from rice-wheat rotations in the 21st century requires a paradigm shift. We must move from managing for average conditions to building resilience for extreme ones. This paper provides a foundational framework for the research needed to navigate this complex and critical interface between climate extremes and food system sustainability.

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