

Article

Responses of Soil Nitrogen Transformation and N₂O Emission to Soil pH and Hydrothermal Changes

Yan Fu ^{1,2,3} , Xiao Ren ⁴ and Bo Zhu ^{1,2,*} 

¹ Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China; fuyan19@mailsucas.ac.cn

² Key Laboratory of Mountain Surface Process and Ecological Regulation, Chinese Academy of Sciences, Chengdu 610041, China

³ University of Chinese Academy of Sciences, Beijing 100049, China

⁴ College of Grassland Resources, Southwest Minzu University, Chengdu 610041, China; xren@swun.edu.cn

* Correspondence: bzhu@imde.ac.cn

Abstract: Soil nitrogen fate determines nitrogen availability for crops and their environmental impact, which is regulated by nitrogen transformation processes that are mediated through soil properties (e.g., pH) and environmental factors (e.g., hydrothermal conditions). Incubation experiments were conducted on soils with different pH levels (covering acidic to calcareous ranges) to study the effects of soil pH and hydrothermal conditions on nitrogen transformation and N₂O emissions. The results showed that the net ammonification rate was negatively correlated with soil pH, whereas the net nitrification rate, net nitrogen mineralization rate, and N₂O emission rate showed positive correlations. Structural equation modeling (SEM) indicated that soil pH and hydrothermal conditions exerted primary influences on soil net nitrogen transformation rates, consequently affecting N₂O emissions. Soil pH and hydrothermal conditions had 83% and 93% effects, respectively, on net nitrogen transformation rates, while they had 77% effects on N₂O emissions. Consequently, soil pH and hydrothermal conditions might be the key drivers influencing soil nitrogen transformation and N₂O emissions. Specifically, in subtropical regions characterized by high temperatures and abundant summer rainfall, regulating soil moisture could mitigate NO₃[−]-N accumulation and N₂O emissions, providing a targeted strategy for sustainable nitrogen management.



Academic Editor: Mingchu Zhang

Received: 18 March 2025

Revised: 19 April 2025

Accepted: 21 April 2025

Published: 22 April 2025

Citation: Fu, Y.; Ren, X.; Zhu, B. Responses of Soil Nitrogen Transformation and N₂O Emission to Soil pH and Hydrothermal Changes. *Agronomy* **2025**, *15*, 1005. <https://doi.org/10.3390/agronomy15051005>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: hydrothermal changes; net nitrogen transformation rate; N₂O emissions; purple soil

1. Introduction

Nitrogen is one of the key limiting nutrients for crop growth and development. Among its various forms, inorganic nitrogen—mainly ammonium ions (NH₄⁺) and nitrate (NO₃[−])—is especially important because it is directly available for plant uptake [1]. However, the concentration of inorganic nitrogen in soils is generally low, necessitating supplemental nitrogen fertilization to meet crop demands [2]. However, it is estimated that up to 30% to 70% of the applied nitrogen fertilizer may be lost from soils [3,4]. Excessive fertilization contributes to environmental issues, including greenhouse gas emissions that drive ozone depletion and global climate change, as well as nitrate leaching, which can lead to water body eutrophication [5]. The transport and transformation of soil nitrogen in the environment are governed by complex soil nitrogen transformation processes [6]. Microorganism-mediated mineralization plays a crucial role in determining the level of

soil inorganic nitrogen supply, which directly influences an ecosystem's primary productivity. Ammonification and nitrification are critical processes that determine the concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ in soil, which can be directly absorbed and utilized by plants. In autotrophic nitrification, soil microorganisms carrying the *amoA* gene—including ammonia-oxidizing bacteria (AOB), archaea (AOA), and complete ammonia oxidizers (comammox)—mediate the rate-limiting step [7]. However, intensive nitrification elevates soil $\text{NO}_3^-\text{-N}$ levels. If $\text{NO}_3^-\text{-N}$ in the soil is not promptly absorbed by plants, it can easily be leached out, thereby reducing fertilizer efficiency and exacerbating environmental issues such as the nitrate contamination of groundwater and the eutrophication of water bodies [8]. Concurrently, N_2O generated during nitrification is a potent greenhouse gas and a major ozone-depleting substance in the stratosphere, requiring stringent regulation [9]. Therefore, quantifying soil inorganic nitrogen dynamics and net transformation rates not only reflects nitrogen supply capacity but also predicts potential environmental risks, offering a dual indicator for sustainable agricultural management.

Soil net nitrogen transformation rates and N_2O emissions are influenced by factors including soil characteristics and hydrothermal conditions. Specifically, soil pH, soil organic carbon (SOC), total nitrogen (TN), and the carbon-to-nitrogen ratio (C/N) regulate soil mineralization and nitrification processes by influencing nitrogen-fixing bacteria and ammonia-oxidizing microbial communities, thus affecting N_2O emissions [10]. Low pH influences N_2O emissions by activating aluminum ions (Al^{3+}) in soil and reducing microbial activity, thereby inhibiting soil mineralization and nitrification processes [11]. A study by Zhu et al. [12] indicated that although SOC had no significant effect on N_2O emissions, the composition and activity of soil carbon and nitrogen fractions could serve as key drivers regulating N_2O emissions. Hydrothermal conditions further modulate nitrogen dynamics through moisture and temperature interactions [13]. The difference in soil moisture content affects soil nutrient migration and redox conditions, resulting in different processes of microbial-mediated N transformation (N mineralization, nitrification, and denitrification), thereby leading to differences in soil N_2O emissions [14]. For instance, farmland soil exhibits a 1.14-fold increase in primary nitrogen mineralization rates when moisture rises from 75% to 150% water holding capacity (WHC) [15]. The rate of nitrification exhibited a nonlinear trend, initially increasing and subsequently decreasing as soil moisture content increased [16]. However, studies have also reported inconsistent results. For instance, when the soil moisture content varies between 40% and 120% of water-filled pore space (WFPS), the total nitrogen mineralization rate remains largely constant [17]. Primary nitrification rates in upland soils exhibited minimal response to variations in soil moisture content (ranging from 50% to 100% WHC) [18]. Temperature is a critical environmental factor that significantly influences biological processes in terrestrial ecosystems [19]. It alters the soil nitrogen transformation by modulating microbial activity. Elevated soil temperature significantly enhanced the gross nitrogen mineralization rate by stimulating the mineralization of both labile and recalcitrant organic nitrogen fractions [20]. Li et al. [21] discovered that variations in soil temperature can significantly enhance the rates of soil nitrogen mineralization and nitrification, subsequently accelerating denitrification rates. This series of processes ultimately exacerbates soil N_2O emissions [22,23]. Nevertheless, the interplay between soil types and hydrothermal conditions—particularly their relative contributions to net nitrogen transformation and N_2O emissions—remains debated, necessitating context-specific mechanistic studies.

Purple soil, which is characterized by rapid weathering and low organic carbon content, is the dominant soil type in the Sichuan Basin, occupying 51.53% of China's total purple soil area [24]. In croplands of purple soil, nitrogen is a critical yet highly vulnerable nutrient due to the soil's weak retention capacity. Consequently, farmers typically apply

250–380 kg N ha^{−1} to meet crop demands—a rate far exceeding the national average. Excessive nitrogen input, coupled with purple soil’s high permeability, has led to severe environmental challenges, including nitrate leaching and N₂O emissions, which threaten regional water quality and climate stability [25,26]. Therefore, it is necessary to study the nitrogen transformation process in purple soils in order to control surplus inorganic nitrogen in the soil to mitigate environmental risks.

This study investigates the effects of soil moisture and temperature on nitrogen dynamics in three purple soil types (acidic, neutral, and calcareous) through controlled aerobic incubation experiments. By monitoring temporal changes in NH₄⁺-N and NO₃[−]-N concentrations, alongside N₂O emissions, we aim to determine net nitrification and mineralization rates and quantify N₂O fluxes as well as analyze the responses of N₂O emissions to nitrogen transformation rates under varying pH and moisture–temperature conditions. We hypothesize that soil moisture and pH will significantly influence the soil nitrogen transformation process, especially ammonification and nitrification, and may regulate NO₃[−] leaching and N₂O emissions through these processes. These findings could provide a scientific basis for optimizing nitrogen management agroecosystems.

2. Materials and Methods

2.1. Site Description and Soil Sampling

The experimental soil, known as purple soil, is classified as a PupOrthic Entisol or Cambisol according to the Chinese Soil Taxonomy and is classified as a Regosol according to the FAO Soil Taxonomy [24]. Three types of soils with different pH levels were used in this study. The acidic soil (pH4.38 ± 0.13) was collected from Jiangyang District, Luzhou City (105°36′ E, 28°52′ N); the neutral soil (pH6.40 ± 0.51) was collected from Zizhong County, Neijiang City (104°51′ E, 29°44′ N); and the calcareous soil (pH8.16 ± 0.30) was collected from Yanting County, Mianyang City (105°30′ E, 31°15′ N). All soils were collected from croplands with a summer maize and winter wheat rotation. All sites received an annual nitrogen input of 280 kg N ha^{−1}, which is consistent with regional farming practices. Soil samples were collected in October 2022 from the top 0–20 cm layer using a five-point sampling scheme within experimental plots. Following collection, visible stones and roots were removed and the soil was homogenized by passing through a 2 mm sieve to reduce heterogeneity. The homogenized soil was then divided into two equal portions via quartering—one portion was stored at 4 °C for incubation experiments for one week, and the other was air-dried for physicochemical property analysis. The specific physicochemical properties of the tested topsoil are presented in Table 1.

Table 1. Basic physical and chemical properties of soil tested (mean ± standard deviation).

Soil Types	pH	SOC (g kg ^{−1})	TN (g kg ^{−1})	C/N	Clay (%)	Silt (%)	Sand (%)	WHC (%)
Acidic	4.38 ± 0.13 C	9.16 ± 0.08 A	1.11 ± 0.82 A	8.28 ± 0.48 A	41.84 ± 5.14 A	32.65 ± 5.77 A	25.51 ± 3.91 A	51.58 ± 2.26 B
Neutral	6.40 ± 0.51 B	9.32 ± 0.51 A	1.05 ± 0.06 A	8.91 ± 0.12 A	41.84 ± 3.91 A	38.78 ± 9.72 A	19.39 ± 7.73 B	57.83 ± 3.23 A
Calcareous	8.16 ± 0.30 A	5.77 ± 0.40 B	0.82 ± 0.04 B	7.03 ± 0.60 B	32.45 ± 1.00 B	42.44 ± 0.49 A	25.11 ± 0.54 A	54.21 ± 0.40 AB

SOC: soil organic carbon; TN: total nitrogen; C/N: carbon-to-nitrogen ratio; WHC: water holding capacity, measured the moisture after 2 h of saturation and 8 h of free drainage under laboratory conditions. The different capital letters in the table indicate significant differences ($p < 0.05$) in the physicochemical properties of the soils.

2.2. Experimental Setup

For the incubation experiments, three types of purple soil (acidic, neutral, and calcareous) were selected. The detailed experimental setup is provided in Figure 1. There was a total of 24 treatments (3 soil types × 8 moisture or temperature treatments), with each process having 40 samples (4 time points × 10 replicates), resulting in a total of 960 subsam-

ples. A 20 g fresh soil sample (oven-dried basis), which was sieved through a 2 mm sieve, was weighed into a 250 mL conical flask. The conical flask was then sealed with parafilm, which was punctured with five holes using a syringe needle to ensure adequate ventilation. Pre-culturing was subsequently carried out under varying temperature conditions for 48 h in constant-temperature incubators. After pre-incubation, 2 mL of NH_4NO_3 solution (50 mg N kg^{-1} soil) was uniformly applied to the soil surface via concentric pipetting. The samples were then placed back into different temperature incubators for further cultivation in the dark.

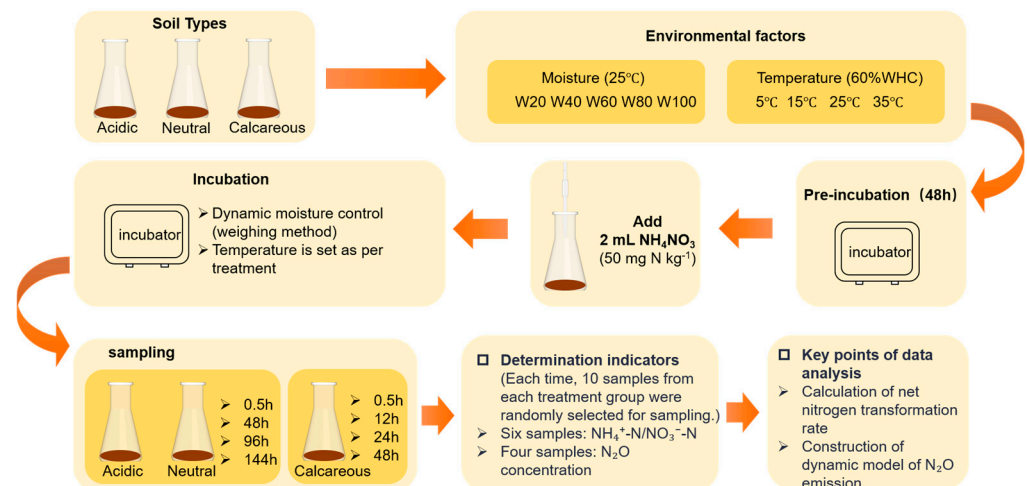


Figure 1. Schematic diagram of the experimental setup and process. Moisture treatments included five levels based on WHC, which was determined using the funnel method (2 h of saturation and 8 h of free drainage under laboratory conditions to record the moisture)—W20 (20% WHC, desiccated state equivalent to wilting coefficient), W40 (40% WHC, typical soil moisture content), W60 (60% WHC, optimal aerobic condition), W80 (80% WHC, transition between aerobic and anaerobic states), and W100 (100% WHC, saturated soil). Temperature regimes comprised the following four gradients: 5 °C (simulating winter cold), 15 °C (spring/autumn average), 25 °C (optimal cultivation temperature), and 35 °C (summer heat). These were based on meteorological data. Notably, the W60 moisture level combined with 25 °C temperature served as the common control condition across experiments.

In acidic and neutral soils, six random samples per treatment were collected at 0.5 h, 48 h, 96 h, and 144 h after inorganic nitrogen addition to measure $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations, while in calcareous soil, sampling occurred at 0.5 h, 12 h, 24 h, and 48 h under the same protocol. For N_2O determination, four replicates per treatment were collected at 6 h, 48 h, 96 h, and 144 h in acidic and neutral soils, as well as at 6 h, 12 h, 24 h, and 48 h in calcareous soils. Before gas sampling, parafilm was replaced with silicone stoppers containing gas ports. Gas was collected at 0 h and 6 h after sealing. Prior to sampling, a 20 mL syringe was used to flush air five times to homogenize the headspace. N_2O concentrations were analyzed within 12 h of collection. Soil moisture was maintained gravimetrically by weight adjustment every 48 h. Due to the rapid nitrification rate in calcareous purple soil [27], data collection was limited to 48 h.

2.3. Analysis of Soil's Physical and Chemical Properties

Soil pH was determined in a 1:2.5 (m/v) soil-to-water ratio using the potentiometric method (Delta 320, Shanghai, China). SOC and TN were analyzed using a C/N elemental analyzer (CNS Elementar vario MAX, Elementar Analysensysteme GmbH, Hanau, Germany). Soil particle composition was determined using the pipette method [28]. The concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ in soils were measured using TU-1810 UV-Visible Spectrophotometer (Persee, Beijing, China) with an extraction solution of 2 mol L^{-1} KCl at

a liquid-to-soil ratio of 5:1 [29]. The WHC was measured using the funnel method [30], in which soil samples were saturated for 2 h, followed by 8 h of free drainage to record the moisture. N_2O concentration was determined using an Agilent 7890 A gas chromatograph (GC, Agilent Technologies Inc., Santa Clara, CA, USA).

2.4. Calculations and Statistical Analysis

The calculation of the net nitrogen transformation rate in the soil is as follows:

$$R_A = \frac{(NH_4^+ - N)_{d_n} - (NH_4^+ - N)_{d_{n-1}}}{d_n - d_{n-1}} \quad (1)$$

$$R_N = \frac{(NO_3^- - N)_{d_n} - (NO_3^- - N)_{d_{n-1}}}{d_n - d_{n-1}} \quad (2)$$

$$R_M = \frac{[(NH_4^+ - N) + (NO_3^- - N)]_{d_n} - [(NH_4^+ - N) + (NO_3^- - N)]_{d_{n-1}}}{d_n - d_{n-1}} \quad (3)$$

where R_A , R_N , and R_M are the net nitrification rate, net ammonification rate, and net nitrogen mineralization rate of soil, respectively ($\text{mg N kg}^{-1} \text{ d}^{-1}$); d_n is the number of cultivation days in the equation.

The calculation of N_2O emission rate is as follows [31]:

$$F = \rho \times \frac{dc}{dt} \times V \times \frac{273/(273 + T)}{W} \quad (4)$$

where F is the emission rate of N_2O ($\text{ng N}_2\text{O-N kg}^{-1} \text{ h}^{-1}$); ρ is the density of N_2O -N at standard conditions, which is 1.25 kg m^{-3} ; dc/dt is the rate of increase in gas concentration per unit time ($\times 10^{-6} \text{ h}^{-1}$); V is the volume of effective gas space in the cultivation flask (m^3); T is the temperature of cultivation; and W is the dry weight of soil (kg). The average N_2O emission rate was calculated using four repeated measurements, which were represented by their mean value.

The N_2O emission ratio during the nitrification process was defined as the ratio of the mean N_2O emission rate to the mean net nitrification rate [32].

The collected data were processed and graphed using Excel 2010 (Microsoft Corp., Redmond, WA, USA) in the experiment. One-way ANOVA and two-way ANOVA were conducted using SPSS Statistics 22.0 (IBM Corp., Armonk, NY, USA), with post hoc multiple comparisons performed using Duncan's method ($p < 0.05$). Structural equation modeling (SEM) was implemented with Smart PLS 4 (SmartPLS GmbH, Boenningstedt, Germany). Graphs were generated utilizing Origin 2021 (OriginLab Corp., Northampton, MA, USA) software.

3. Results

3.1. Soil NH_4^+ -N and NO_3^- -N Concentrations During Incubation

Under 25°C and 60% WHC, acidic soils showed gradual changes in NH_4^+ -N and NO_3^- -N concentrations, while neutral and calcareous soils exhibited a decline in NH_4^+ -N and an increase in NO_3^- -N (Figures 2 and 3). Compared to other moisture levels, NH_4^+ -N and NO_3^- -N concentrations changed minimally at wilting moisture (W20), but most significantly at W60 and W80 (Figure 2a–f). Temperature increases intensified these trends, with more pronounced inorganic nitrogen dynamics being observed under higher temperatures (Figure 3a–f).

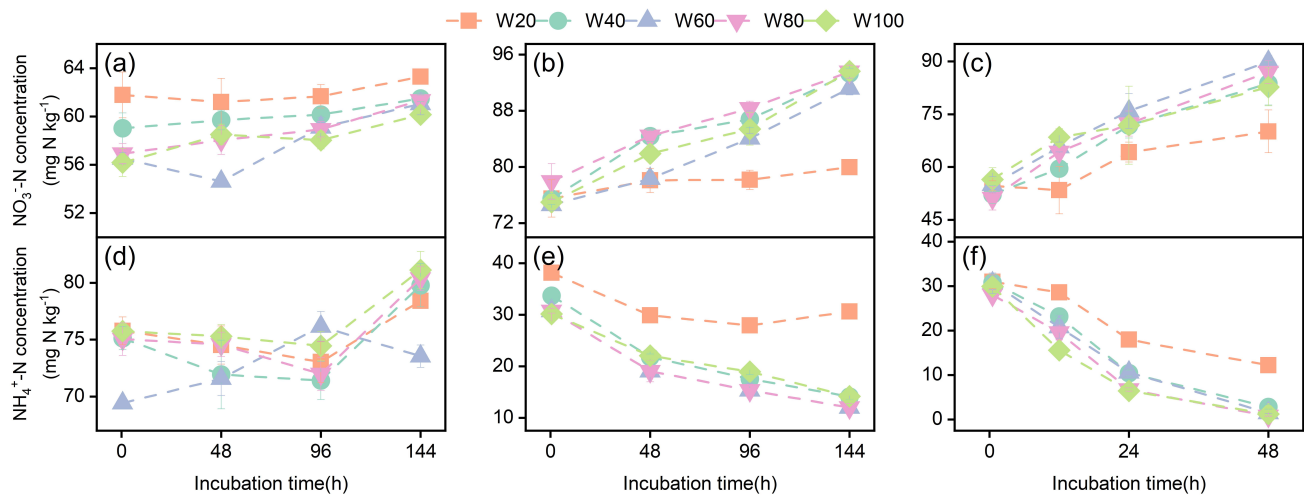


Figure 2. Soil NH_4^+ -N and NO_3^- -N concentrations with different soil moisture. (a,d) Acidic soil; (b,e) neutral soil; and (c,f) calcareous soil. The error bars indicate the standard deviation.

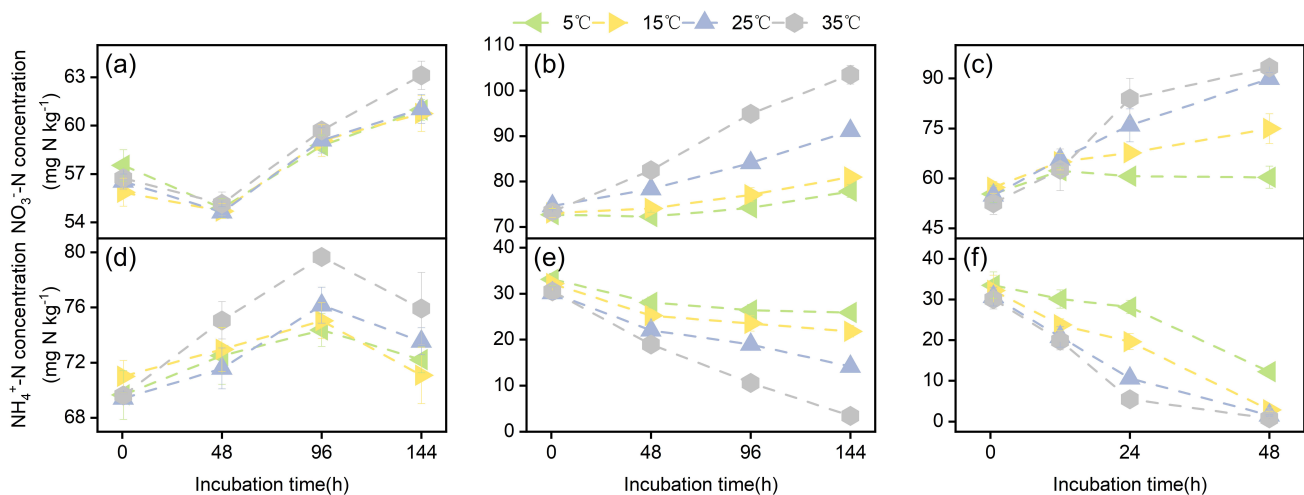


Figure 3. Soil NH_4^+ -N and NO_3^- -N concentrations with different temperature conditions. (a,d) Acidic soil; (b,e) neutral soil; and (c,f) calcareous soil. The error bars indicate the standard deviation.

3.2. Soil Net Nitrogen Transformation Rates

3.2.1. Soil Net Ammonification Rate

At 25 °C and 60% WHC, net ammonification rates differed significantly among soil types ($p < 0.05$). The order of the rate of increase was as follows: acidic soil > neutral soil > calcareous soil, with rates of $0.69 \text{ mg N kg}^{-1} \text{ d}^{-1}$, $-2.67 \text{ mg N kg}^{-1} \text{ d}^{-1}$, and $-14.75 \text{ mg N kg}^{-1} \text{ d}^{-1}$, respectively (Figure 4a,b). Positive ammonification rates in acidic soils are indicative of the conversion of organic nitrogen to inorganic nitrogen within the soil. The absolute ammonification rate of the soil was found to be the lowest at wilting moisture (W20) (Figure 4a). The net ammonification rate of acidic soil exhibited a positive correlation with increasing temperature, reaching a maximum of $1.05 \text{ mg N kg}^{-1} \text{ d}^{-1}$ at 35 °C. In contrast, the net ammonification rate of neutral and calcareous purple soil demonstrated a negative relationship with increasing temperature, reaching a minimum of $-4.51 \text{ mg N kg}^{-1} \text{ d}^{-1}$ and $-14.81 \text{ mg N kg}^{-1} \text{ d}^{-1}$ at 35 °C, respectively (Figure 4b).

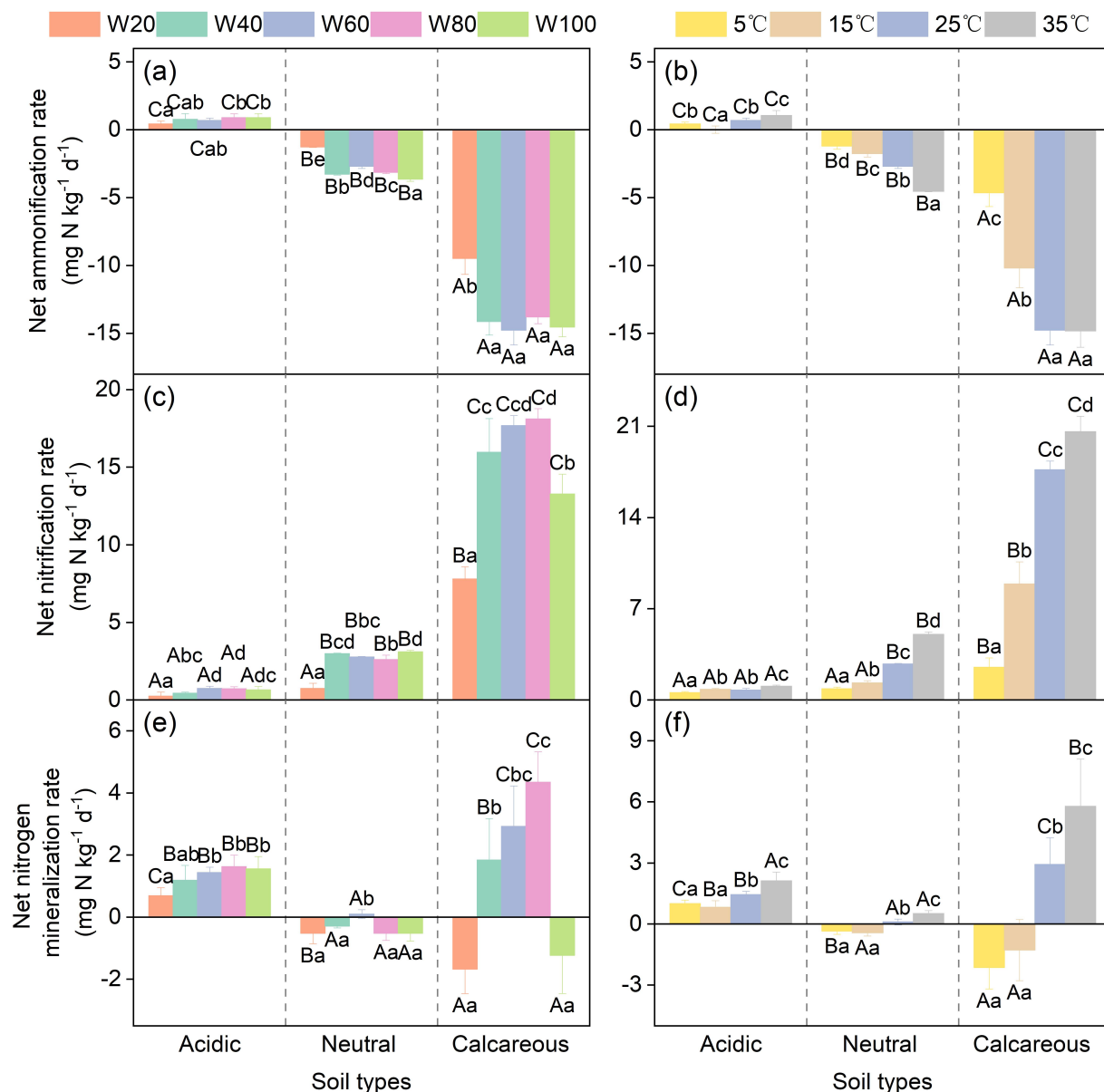


Figure 4. Net nitrogen transformation rate in soil. (a,b) Net ammonification rates under different moisture and temperature conditions, respectively; (c,d) net nitrification rates under different moisture and temperature conditions, respectively; (e,f) net nitrogen mineralization rates under different moisture and temperature conditions, respectively. Error bars indicate standard deviation. Different capital letters indicate significant differences between treatments of different soil types; different lowercase letters indicate significant differences between treatments within the same soil type ($p < 0.05$).

3.2.2. Soil Net Nitrification Rate

At 25 °C and 60% WHC, soil net nitrification rates differed significantly among soil types ($p < 0.05$), in the following order: acidic soil ($0.75 \text{ mg N kg}^{-1} \text{ d}^{-1}$) < neutral soil ($2.77 \text{ mg N kg}^{-1} \text{ d}^{-1}$) < calcareous soil ($17.68 \text{ mg N kg}^{-1} \text{ d}^{-1}$) (Figure 4c,d). Soil pH significantly affected the net nitrification rate of soil ($p < 0.05$). Soil moisture exerted a nonlinear control on nitrification, whereby rates were minimal at wilting moisture (W20), peaked at W60, then declined at W80 (Figure 4c). Temperature further amplified nitrification rates in a soil-specific manner. Linear regression revealed a strong positive temperature response in calcareous soil (slope = 0.63, $p < 0.01$), a moderate response in neutral soil (0.14), and a negligible response in acidic soil (0.014) (Figure 4d). Two-way ANOVA confirmed that

pH, temperature, and their interaction significantly influenced nitrification rates ($p < 0.001$), highlighting the synergistic effects of abiotic drivers.

3.2.3. Soil Net Nitrogen Mineralization Rate

Under 25 °C and 60% WHC, net nitrogen mineralization rates varied significantly among the soil types, with calcareous soils demonstrating the highest rate (2.93 mg N kg⁻¹ d⁻¹), followed by acidic soils (1.44 mg N kg⁻¹ d⁻¹) and neutral soils, which exhibited the lowest rate (0.10 mg N kg⁻¹ d⁻¹) (Figure 4e,f). Soil moisture nonlinearly regulated mineralization rates, which initially increased and then decreased across moisture gradients, with minimal values being reported at wilting moisture (W20) for all soils. However, peak rates varied by soil type—acidic and calcareous soils peaked at W80 (134.6% and 360.5% higher than W20, respectively), while neutral soil peaked at W60 (120.1% increase) (Figure 4e). The net nitrogen mineralization rate of different types of purple soil showed an increasing trend with rising temperature (Figure 4f). The net nitrogen mineralization rates of acidic, neutral, and calcareous soils were highest at 35 °C, reaching 2.12 mg N kg⁻¹ d⁻¹, 0.52 mg N kg⁻¹ d⁻¹, and 5.78 mg N kg⁻¹ d⁻¹, respectively. At 5 °C and 15 °C, the net nitrogen mineralization rates of neutral and calcareous soils were negative, indicating that inorganic nitrogen was transformed into organic nitrogen, which is conducive to the assimilation process of inorganic nitrogen. A two-way ANOVA was conducted separately for the effects of pH and moisture, as well as for pH and temperature, on the net nitrogen mineralization rate. The results showed that pH had no significant effect on the net nitrogen mineralization rate of soil ($p > 0.05$); moisture significantly affected the net nitrogen mineralization rate ($p < 0.05$) and temperature had an extremely significant effect on the soil net nitrogen mineralization rate ($p < 0.001$).

3.3. N₂O Emissions

3.3.1. N₂O Emission Rate

At 25 °C and 60% WHC, soil N₂O emission rates followed the order of purple soil > acidic soil > neutral soil. The neutral soil's emission rate was orders of magnitude lower than the calcareous soil (Figure 5a–f). Moisture regulated emissions nonlinearly, whereby minimal rates occurred at wilting moisture (W20), while peak emissions varied by soil type—acidic soil peaked at W60 (4.95 times higher than W20), neutral soil peaked at 80% WHC (3.00 times higher), and calcareous soil peaked at saturation W100 (5.74 times higher) (Figure 5a–c). A two-way ANOVA confirmed that pH, moisture, and their interaction significantly drove N₂O flux ($p < 0.01$). When the temperature was below 15 °C, the rate of N₂O emission from purple soil changed relatively gradually over time; when the temperature exceeded 25 °C, significant variations in the N₂O emission rate were observed as time progressed. Specifically, at 25 °C, acidic purple soil exhibited a decreasing trend (Figure 5d), while at 35 °C, it showed an initial increase followed by a decrease. Neutral purple soil demonstrated an upward–downward trend (Figure 5e) and calcareous soil showed a consistent downward trend (Figure 5f). The average N₂O emission rate from soil increased with rising temperature. During the incubation period, the average N₂O emission rates for acidic, neutral, and calcareous purple soils were 23.42–269.26 µg N₂O-N kg⁻¹ h⁻¹, 10.24–85.09 µg N₂O-N kg⁻¹ h⁻¹, and 12.07–411.48 µg N₂O-N kg⁻¹ h⁻¹, respectively.

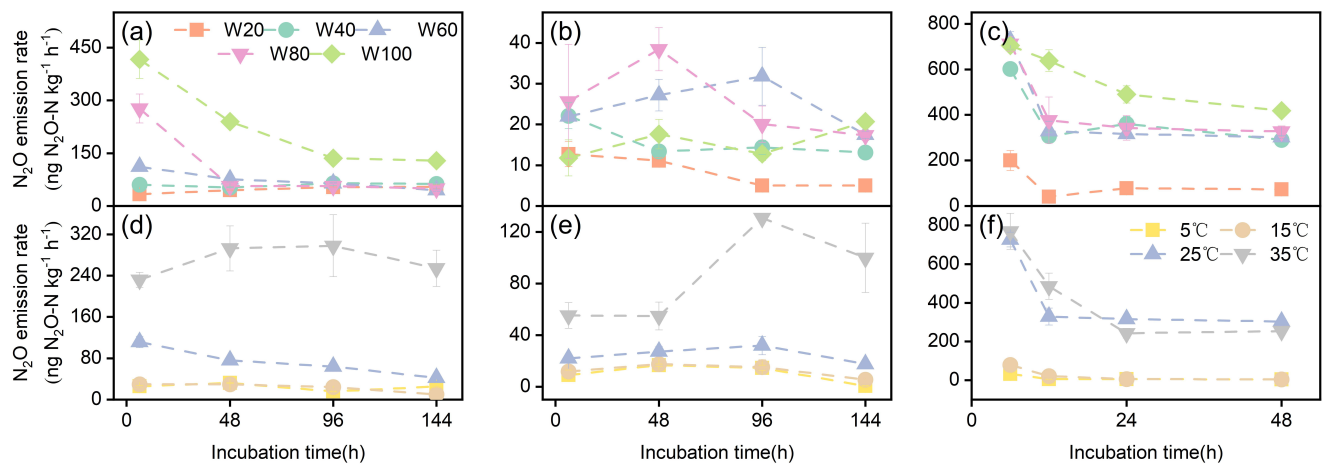


Figure 5. Soil N₂O emission rates. (a–c) Acidic purple soil, neutral purple soil, and alkaline purple soil under moisture cultivation conditions, respectively. Meanwhile, (d–f) represent acidic purple soil, neutral purple soil, and alkaline purple soil under temperature cultivation conditions, respectively. Error bars are used to indicate standard deviation.

3.3.2. N₂O Emission Ratio

Acidic soils exhibited significantly higher N₂O emission ratios than neutral and calcareous soils across all treatments. Notably, under saturated moisture (W100), acidic soils produced the highest emission ratios, contrasting sharply with neutral and calcareous soils, which maintained consistently low ratios regardless of moisture conditions. Extreme values for neutral soils occurred at wilting moisture (W20), while calcareous soils showed peak and minimal ratios at W100 (Figure 6a). Additionally, the N₂O emission ratio in purple soil exhibited an upward trend with increasing temperature. Specifically, the N₂O emission ratio in acidic purple soil at 35 °C was 8.76 times higher than at 15 °C (Figure 6b).

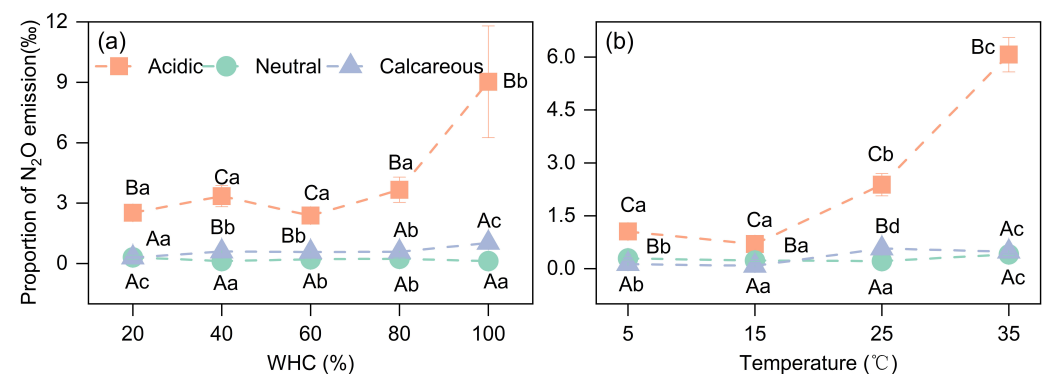


Figure 6. (a) Proportion of N₂O emissions from soils with different soil moisture. (b) Proportion of N₂O emissions from soils with different temperature. The error bars represent the standard deviation. Different capital letters indicate significant differences between treatments across various soil types, while different lowercase letters indicate significant differences between treatments within the same soil type ($p < 0.05$).

3.4. Factors Influencing the Net Nitrogen Transformation Rates and N₂O Emissions in Soil

The correlation analysis indicated significant associations between nitrogen transformation rates and soil variables ($p < 0.05$). The net ammonification rate was negatively correlated with soil moisture, pH, and silt particles, and positively correlated with clay particles. However, the relationship between the net nitrification rate and soil variables was completely opposite to that of the net ammonification rate and soil variables. The net nitrogen mineralization rate had a positive correlation with soil temperature and sand

particles. The average N_2O emission rate and N_2O emission ratio were positively correlated with soil moisture, temperature, and sand particles (Figure 7).

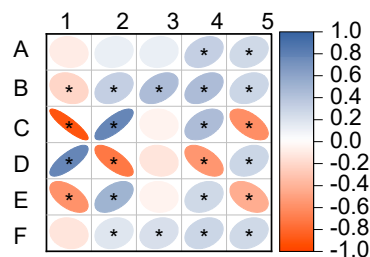


Figure 7. Correlation matrix between soil physicochemical properties, net nitrogen transformation rate, and N_2O emissions. A represents moisture; B represents temperature; C represents pH; D represents clay particles; E represents silt particles; F represents sand particles; 1 represents net ammonification rate; 2 represents net nitrification rate; 3 represents net nitrogen mineralization rate; 4 represents average N_2O emission rate; 5 represents N_2O emission ratio. * indicates significant correlation ($p < 0.05$). The color and bias of the ellipse indicate the correlation between the corresponding row and column; blue indicates the positive correlation, red indicates the negative correlation, chroma indicates the strength of the correlation, and the stronger the color saturation, the stronger the correlation.

Furthermore, the SEM revealed that soil pH and hydrothermal conditions (temperature–moisture interactions) jointly explained 83% ($R^2 = 0.83$; $p < 0.001$) and 93% ($R^2 = 0.93$; $p < 0.001$) of the variance in net ammonification and nitrification rates, respectively. These factors also accounted for 32% ($R^2 = 0.32$) and 77% ($R^2 = 0.77$) of the variance in NO_3^- -N concentration and average N_2O emission rate (Figure 8). Net ammonification, in turn, exerted a significant positive indirect effect on N_2O emissions via its strong stimulation of nitrification (path coefficient = 0.93; $p < 0.001$), which was the most dominant direct contributor to N_2O release (0.98; $p < 0.001$). These results indicate that ammonification mainly affects the nitrification process by providing the substrate (NH_4^+), thereby affecting N_2O emissions.

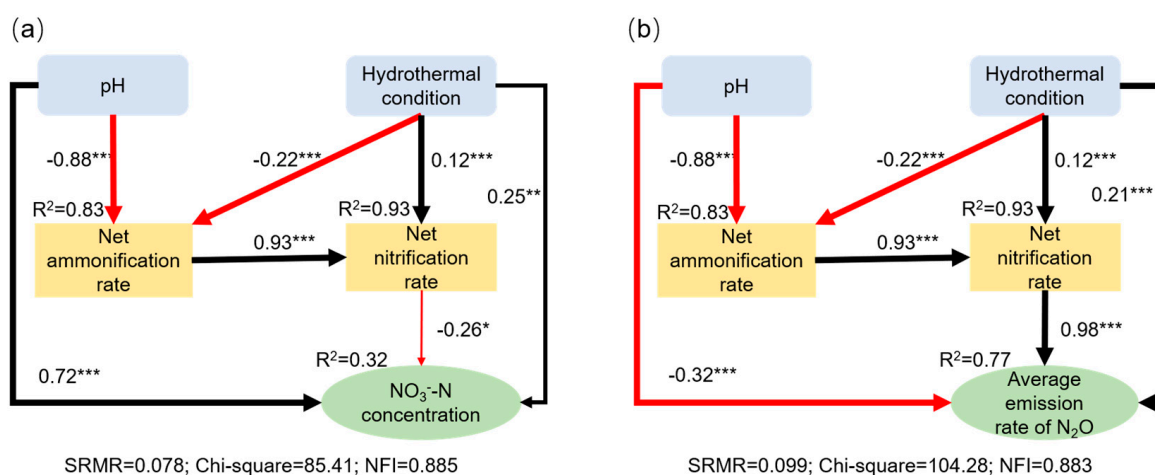


Figure 8. Structural equation model. (a) the hypothesized relationship between soil pH, net nitrogen transformation rate, and NO_3^- -N concentration. (b) the hypothesized relationship between soil pH, net nitrogen transformation rate, and average emission rate of N_2O . The solid lines represent significant path coefficients, with the line width indicating the level of significance. Red and black represent negative correlation and positive correlation, respectively. * represents $p < 0.05$. ** represents $p < 0.01$. *** represents $p < 0.001$. SRMR: standardized root mean square residual.

4. Discussion

4.1. The Influence of Soil Type and Hydrothermal Conditions on the Net Nitrogen Transformation Rates in Soil

4.1.1. The Impact of Soil pH on the Net Nitrogen Transformation Rates in Soil

Soil pH exerted contrasting effects on nitrogen transformation processes. While it significantly influenced net ammonification and nitrification rates ($p < 0.05$), it had no overall effect on net nitrogen mineralization due to opposing trends, i.e., ammonification showed a negative correlation with pH, whereas nitrification exhibited a positive correlation (Figure 7). Acidic soils exhibited a positive net ammonification rate, indicated by NH_4^+ -N accumulation, whereas neutral and calcareous soils displayed negative rates, reflecting NH_4^+ -N depletion, which is driven by microbial uptake for nitrification and assimilation. Li et al. [33] demonstrated that the net NH_4^+ -N accumulation in acidic soils is associated with suppressed nitrification, which is consistent with our findings. During the incubation periods, sustained NH_4^+ -N depletion in neutral and calcareous soils outweighed replenishment, yielding negative net ammonification rates [34]. Conversely, net nitrification rates increased with soil pH, which is consistent with global patterns where neutral–alkaline soils favor autotrophic nitrifiers [35]. Acidic soils inhibit these autotrophs, shifting dominance to heterotrophic nitrifiers (organic carbon-dependent) [36,37], which contributed minimally to total nitrification [38]. Additionally, accumulated NH_4^+ -N in acidic soil further inhibited nitrification [39], collectively explaining their low nitrification capacity.

4.1.2. The Impact of Soil on the Net Nitrogen Transformation Rate in Soil

Soil moisture regulates nitrogen transformation through physicochemical and microbial mechanisms. As moisture decreases, the increased curvature of soil pores elevates water viscosity near particle surfaces, which in turn limits the diffusion of substrates such as NH_4^+ , NO_3^- , and dissolved organic nitrogen to microbial cells, ultimately reducing net nitrogen transformation rates [40,41]. This phenomenon is particularly critical in low-moisture soils, where the discontinuity of the liquid phase can spatially isolate microbial communities from available substrates, leading to declines in both mineralization and nitrification rates. Our results showed that the nitrification rate in purple soil exhibits a parabolic relationship with variations in soil moisture content. The primary reason for this result is that at relatively low moisture levels, microbial activity is restricted due to limited substrate diffusion and cellular desiccation stress. As soil moisture increases, the oxygen content in the soil decreases. Once it is exhausted, the redox potential drops; therefore, NO_3^- is used as an electron acceptor, promoting the reduction of NO_3^- to NH_4^+ , thereby facilitating the process of dissimilatory nitrate reduction to ammonium (DNRA), resulting in a decrease in the net nitrification rate [42]. In this study, peak nitrification occurred at 60% WHC for acidic and calcareous soils versus 40% WHC for neutral soil, indicating soil-specific moisture optima [43]. This is consistent with the results of Wang et al. [17], indicating that the nitrification rate reaches the optimum at a medium moisture level due to the balance between oxygen availability and solute transport.

The net nitrogen mineralization rate of acidic soil did not exhibit a significant increase within the range of 60% to 100% WHC in this study. This suggests that below 60% WHC, soil moisture can influence the net nitrogen mineralization rate by regulating substrate transport, while above 60% WHC, soil moisture does not impose limitations on the net nitrogen mineralization rate of acidic purple soil. However, in neutral and alkaline soils, the net nitrogen mineralization rate declines with increasing soil moisture content beyond 80% WHC, potentially due to the suppression of mineralizing microbial activity caused by excessive water content [44]. These results are consistent with the study by Moyano et al. [45]. These patterns highlight moisture thresholds—governed by substrate

mobility at low moisture and oxygen availability at high moisture—as critical controls on nitrogen cycling, modulated by soil-specific physicochemical properties.

4.1.3. The Impact of Temperature on the Net Nitrogen Transformation Rates in Soil

The net nitrogen mineralization and nitrification rates exhibited a significant positive correlation with temperature ($p < 0.05$), which is consistent with the results of a recent soil-based study by Li et al. [21]. The strengthening of nitrification is attributed to two primary factors. Firstly, the rise in temperature stimulates the activity of ammonia-oxidizing bacteria and archaea that are involved in nitrification [46]. Secondly, within a specific range, an increase in temperature accelerates soil mineralization processes, thereby providing substrate $\text{NH}_4^+\text{-N}$ for nitrification and expediting nitrogen turnover in the soil [47]. The increased mineralization rate can be explained by temperature-driven fluctuations in soil enzyme activity. Enzymes such as urease, protease, and amidase, which catalyze the breakdown of complex organic nitrogen compounds into inorganic forms, exhibit increased catalytic efficiency with rising temperatures up to an optimum range [48]. Enzymes, acting as catalysts for nitrogen transformation, exhibit higher catalytic efficiency under optimal thermal conditions (20–37 °C), which further facilitates nitrogen mineralization. Notably, these enzymes originate from diverse sources, including plant and animal residues, microbial metabolism, and root exudates, collectively regulating the soil nitrogen cycle [49].

These results demonstrate that pH and hydrothermal conditions are dominant drivers of soil nitrogen transformation dynamics. Specifically, hydrothermal conditions likely regulate microbial activity and substrate availability [46,47], while pH modulates enzymatic efficiency and microbial community composition, collectively amplifying their synergistic control over ammonification and nitrification processes.

4.2. The Influence of Soil pH and Hydrothermal Conditions on Soil N_2O Emissions

4.2.1. The Impact of Soil pH on Soil N_2O Emissions

Soil pH is essential for regulating N_2O emissions from soil [50], primarily controlling N_2O emissions by influencing the nitrification and denitrification processes in soil [51,52]. In our analysis of purple soils, the average N_2O emission rate displayed a pH-dependent pattern that was distinct from net nitrification rates in the following order: alkaline purple soil > acidic purple soil > neutral purple soil (Figure 5). This finding contrasts with that of Wu et al. [53], who reported a positive correlation between pH and N_2O emissions in alluvial soils. The observed discrepancy may stem from differences in soil microbial communities or the dominance of heterotrophic nitrification pathways in acidic purple soils. Mechanistically, nitrifying bacteria (e.g., ammonia-oxidizing bacteria—AOB) thrive in soils with $\text{pH} > 5$, where N_2O emissions are predominantly linked to nitrification [54,55]. Elevated pH in alkaline soils (>7.5) further enhances AOB-driven nitrification, amplifying N_2O release [55]. Conversely, in acidic soils ($\text{pH} < 5$), nitrification is suppressed and denitrification becomes the primary N_2O source. Here, low pH inhibits N_2O reductase (N_2OR) activity, blocking the reduction of N_2O to N_2 and leading to its accumulation [56]. Additionally, heterotrophic nitrification—a pH-tolerant pathway mediated by fungi and acidophilic bacteria—may compensate for reduced autotrophic nitrification under acidic conditions, further elevating N_2O production [57].

4.2.2. The Impact of Soil Moisture on Soil N_2O Emissions

Soil moisture plays an important role in regulating N_2O emissions in purple soils by mediating oxygen-driven microbial pathways. Below 60% WHC, aerobic conditions dominate, with nitrification driving N_2O production. Under wilting moisture, limited microbial activity due to water stress sharply reduces emissions [58]. Between 60 and 80% WHC, declining oxygen promotes coupled nitrification–denitrification, amplifying N_2O fluxes [59].

Above 80% WHC, denitrification becomes the primary process, though moderate hypoxia concurrently stimulates nitrogen mineralization, elevating NH_4^+ -N levels, which further fuel nitrification and denitrification [14]. Neutral purple soils, characterized by high clay content, exhibit a unique behavior at saturation (100% WHC), whereby water-filled pores impede gas diffusion, prolonging N_2O retention and enhancing its reduction to N_2 via denitrification, thereby paradoxically lowering net emissions despite high production [60]. This moisture-dependent interplay between microbial processes and gas transport dictates nonlinear N_2O emission patterns across moisture gradients.

4.2.3. The Impact of Temperature on Net N_2O Emissions in Soil

The SEM identified hydrothermal conditions as the primary driver of ammonification processes in purple soils, which indirectly regulate nitrification rates and N_2O emissions by controlling substrate availability (Figure 8). This is consistent with correlation analyses showing strong positive relationships between temperature and both net nitrification and nitrogen mineralization rates (Figure 7). Elevated temperatures amplify N_2O emissions through three synergistic pathways—accelerated nitrogen mineralization increases NH_4^+ -N pools that fuel nitrification and denitrification [61]; enhanced microbial respiration reduces soil oxygen levels, promoting denitrification dominance [62]; and direct thermal stimulation boosts the activity and abundance of AOB and AOA. These thermally driven mechanisms collectively peak within an optimal range (25–35 °C), beyond which enzyme denaturation and microbial stress at extreme temperatures (>40 °C) reverse emission trends, underscoring the nonlinear thermal sensitivity of soil N_2O dynamics.

Field studies indicate that high-temperature, high-rainfall, and alternating dry-wet climate patterns significantly increase the risks of nitrate leaching and N_2O emissions [26,63]. Based on our findings, we propose a mitigation strategy that includes nitrogen transformation management and spatio-temporal nitrogen allocation. For nitrogen transformation management, lime can be applied to acidic soils to enhance AOB-driven nitrification and N_2O reduction, while nitrification inhibitors can be used in calcareous soils to suppress excessive nitrification. For spatio-temporal nitrogen allocation, implementing 60% basal fertilizer combined with 40% split applications (2–3 events), synchronized with precipitation and temperature fluctuations (Figure 8), can align nitrogen supply with crop demand, thereby reducing peak nitrate leaching and N_2O emissions.

5. Conclusions

Under identical cultivation conditions, the net nitrification rate in calcareous purple soil was 4.35 to 36.17 times higher than that in acidic purple soil and 2.90 to 10.47 times higher than that in neutral purple soil. The net nitrification rate exhibited a significant positive correlation with soil N_2O emissions ($p < 0.05$). These results indicate that nitrate accumulation and N_2O emissions are notably severe in calcareous purple soil regions.

Considering the characteristics of purple soil and the high temperature and abundant rainfall in summer that are typical of the subtropical monsoon climate, controlling soil moisture content can effectively mitigate the accumulation of NO_3^- -N and the emission of N_2O resulting from nitrification. The optimal soil moisture contents for acidic, neutral, and calcareous purple soils are 60–100% WHC, 40–100% WHC, and 60–80% WHC, respectively. By implementing these measures, we can ensure maximum nitrogen fertilizer utilization by plants while minimizing nitrate leaching losses and the emissions of reactive nitrogen gasses.

Author Contributions: Conceptualization: Y.F. and B.Z.; methodology: Y.F. and B.Z.; formal analysis: Y.F., X.R. and B.Z.; investigation: Y.F.; writing—original draft: Y.F.; writing—review and editing: Y.F., X.R. and B.Z.; project administration: B.Z.; funding acquisition: B.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Natural Science Foundation of China (U20A20107, 42307329).

Data Availability Statement: The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Vitousek, P.M.; Porder, S.; Houlton, B.Z.; Chadwick, O.A. Terrestrial phosphorus limitation: Mechanisms, implications, and nitrogen-phosphorus interactions. *Ecol. Appl.* **2010**, *20*, 5–15. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Chen, X.; Cui, Z.; Fan, M.; Vitousek, P.; Zhao, M.; Ma, W.; Wang, Z.; Zhang, W.; Yan, X.; Yang, J.; et al. Producing more grain with lower environmental costs. *Nature* **2014**, *514*, 486–489. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Burgeon, V.; Fouche, J.; Garre, S.; Colinet, G.; Cornelis, J.-T.; Dehkordi, R.H. Young and century-old biochars strongly affect nutrient cycling in a temperate agroecosystem. *Agric. Ecosyst. Environ.* **2022**, *328*, 107847. [\[CrossRef\]](#)
4. Gentile, R.M.; Boldingh, H.L.; Campbell, R.E.; Gee, M.; Gould, N.; Lo, P.; McNally, S.; Park, K.C.; Richardson, A.C.; Stringer, L.D.; et al. System nutrient dynamics in orchards: A research roadmap for nutrient management in apple and kiwifruit. A review. *Agron. Sustain. Dev.* **2022**, *42*, 64. [\[CrossRef\]](#)
5. You, L.; Ros, G.H.; Chen, Y.; Zhang, F.; de Vries, W. Optimized agricultural management reduces global cropland nitrogen losses to air and water. *Nat. Food* **2024**, *5*, 995–1004. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Zhang, J.; Zhu, T.; Meng, T.; Zhang, Y.; Yang, J.; Yang, W.; Müller, C.; Cai, Z. Agricultural land use affects nitrate production and conservation in humid subtropical soils in China. *Soil Biol. Biochem.* **2013**, *62*, 107–114. [\[CrossRef\]](#)
7. Gao, N.; Zhang, T.; Li, Z.; Tian, X.; Chen, J.; Zhang, J.; Mueller, C.; Li, S. Long-term effects of film mulching and fertilization regimes on gross N transformations in calcareous dryland soils. *Appl. Soil Ecol.* **2024**, *204*, 105747. [\[CrossRef\]](#)
8. Liu, S.; Chi, Q.; Cheng, Y.; Zhu, B.; Li, W.; Zhang, X.; Huang, Y.; Mueller, C.; Cai, Z.; Zhang, J. Importance of matching soil N transformations, crop N form preference, and climate to enhance crop yield and reducing N loss. *Sci. Total Environ.* **2019**, *657*, 1265–1273. [\[CrossRef\]](#)
9. Yang, L.; Zhu, G.; Ju, X.; Liu, R. How nitrification-related N₂O is associated with soil ammonia oxidizers in two contrasting soils in China? *Sci. Total Environ.* **2021**, *770*, 143212. [\[CrossRef\]](#)
10. Rousk, J.; Brookes, P.C.; Baath, E. Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. *Appl. Environ. Microbiol.* **2009**, *75*, 1589–1596. [\[CrossRef\]](#)
11. Cheng, Y.; Wang, J.; Mary, B.; Zhang, J.; Cai, Z.; Chang, S.X. Soil pH has contrasting effects on gross and net nitrogen mineralizations in adjacent forest and grassland soils in central Alberta, Canada. *Soil Biol. Biochem.* **2013**, *57*, 848–857. [\[CrossRef\]](#)
12. Zhu, Q.; Liu, L.; Wang, C.; Wan, Y.; Yang, R.; Mou, J.; Liu, J.; Wu, Y.; Tang, S.; Zhu, T.; et al. Carbon and nitrogen fractions control soil N₂O emissions and related functional genes under land-use change in the tropics. *Environ. Pollut.* **2023**, *335*, 122370. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Wang, H.; Hou, J.; Zhou, B.; Han, X. Effects of Water Supply Mode on Nitrogen Transformation and Ammonia Oxidation Microorganisms in a Tea Garden. *Agronomy* **2023**, *13*, 1279. [\[CrossRef\]](#)
14. Qin, H.; Xing, X.; Tang, Y.; Zhu, B.; Wei, X.; Chen, X.; Liu, Y. Soil moisture and activity of nitrite- and nitrous oxide-reducing microbes enhanced nitrous oxide emissions in fallow paddy soils. *Biol. Fertil. Soils* **2020**, *56*, 53–67. [\[CrossRef\]](#)
15. Mathieu, O.; Henault, C.; Leveque, J.; Baujard, E.; Milloux, M.J.; Andreux, F. Quantifying the contribution of nitrification and denitrification to the nitrous oxide flux using ¹⁵N tracers. *Environ. Pollut.* **2006**, *144*, 933–940. [\[CrossRef\]](#)
16. Liu, R.; Suter, H.; He, J.; Hayden, H.; Chen, D. Influence of temperature and moisture on the relative contributions of heterotrophic and autotrophic nitrification to gross nitrification in an acid cropping soil. *J. Soils Sediments* **2015**, *15*, 2304–2309. [\[CrossRef\]](#)
17. Wang, H.; Yan, Z.; Chen, Z.; Song, X.; Zhang, J.; Li, S.-L.; Mueller, C.; Ju, X.; Zhu-Barker, X. Microbial ammonium immobilization promoted soil nitrogen retention under high moisture conditions in intensively managed fluvo-aquic soils. *Biol. Fertil. Soils* **2025**, *61*, 641–651. [\[CrossRef\]](#)
18. Osborne, B.B.; Baron, J.S.; Wallenstein, M.D. Moisture and temperature controls on nitrification differ among ammonia oxidizer communities from three alpine soil habitats. *Front. Earth Sci.* **2015**, *10*, 1–12. [\[CrossRef\]](#)

19. Daebeler, A.; Bodelier, P.L.E.; Hefting, M.M.; Rutting, T.; Jia, Z.; Laanbroek, H.J. Soil warming and fertilization altered rates of nitrogen transformation processes and selected for adapted ammonia-oxidizing archaea in sub-arctic grassland soil. *Soil Biol. Biochem.* **2017**, *107*, 114–124. [\[CrossRef\]](#)
20. Li, X.; Xie, J.; Zhang, Q.; Lyu, M.; Xiong, X.; Liu, X.; Lin, T.; Yang, Y. Substrate availability and soil microbes drive temperature sensitivity of soil organic carbon mineralization to warming along an elevation gradient in subtropical Asia. *Geoderma* **2020**, *364*, 114198. [\[CrossRef\]](#)
21. Li, D.; Zhang, J.; Gruda, N.S.; Wang, Z.; Duan, Z.; Müller, C.; Li, X. The regulation of gross nitrogen transformation rates in greenhouse soil cultivated with cucumber plants under elevated atmospheric [CO₂] and increased soil temperature. *Geoderma* **2023**, *439*, 116680. [\[CrossRef\]](#)
22. Li, Z.; Zeng, Z.; Song, Z.; Tian, D.; Huang, X.; Nie, S.; Wang, J.; Jiang, L.; Luo, Y.; Cui, J.; et al. Variance and main drivers of field nitrous oxide emissions: A global synthesis. *J. Clean. Prod.* **2022**, *353*, 131686. [\[CrossRef\]](#)
23. Huang, J.; Liu, R.; Wang, Q.; Gao, X.; Han, Z.; Gao, J.; Gao, H.; Zhang, S.; Wang, J.; Zhang, L.; et al. Climate factors affect N₂O emissions by influencing the migration and transformation of nonpoint source nitrogen in an agricultural watershed. *Water Res.* **2022**, *223*, 119028. [\[CrossRef\]](#)
24. Zhu, B.; Wang, T.; Kuang, F.; Luo, Z.; Tang, J.; Xu, T. Measurements of Nitrate Leaching from a Hillslope Cropland in the Central Sichuan Basin, China. *Soil Sci. Soc. Am. J.* **2009**, *73*, 1419–1426. [\[CrossRef\]](#)
25. Zhou, M.; Wang, X.; Ke, Y.; Zhu, B. Effects of afforestation on soil nitrous oxide emissions in a subtropical montane agricultural landscape: A 3-year field experiment. *Agric. For. Meteorol.* **2019**, *266–267*, 221–230. [\[CrossRef\]](#)
26. Xiao, Q.; Dong, Z.; Han, Y.; Hu, L.; Hu, D.; Zhu, B. Impact of soil thickness on productivity and nitrate leaching from sloping cropland in the upper Yangtze River Basin. *Agric. Ecosyst. Environ.* **2021**, *311*, 107266. [\[CrossRef\]](#)
27. He, X.; Dai, S.; Meng, L.; He, M.; Wang, X.; Cai, Z.; Zhu, B.; Zhang, J.; Nardi, P.; Mueller, C. Effects of 18 years repeated N fertilizer applications on gross N transformation rates in a subtropical rain-fed purple soil. *Appl. Soil Ecol.* **2023**, *189*, 104952. [\[CrossRef\]](#)
28. Liu, G. *Protocols for Soil Physicochemical Analysis and Profile Description*; China Standards Press: Beijing, China, 1996.
29. Bao, S. *Soil Agrochemical Analysis*; China Agriculture Press: Beijing, China, 2000.
30. Fierer, N.; Schimel, J.P. Effects of drying-rewetting frequency on soil carbon and nitrogen transformations. *Soil Biol. Biochem.* **2002**, *34*, 777–787. [\[CrossRef\]](#)
31. Li, P.; Lang, M.; Li, M.; Wei, W.; Li, K.-K. Short-Term Effects of Different Fertilization Treatments on Greenhouse Gas Emissions from Northeast Black Soil. *Environ. Sci.* **2018**, *39*, 2360–2367. [\[CrossRef\]](#)
32. Lang, M.; Li, P.; Wei, W. Regularity of net nitrogen transformation rates and greenhouse gas emissions in black soil of different textures. *J. Agro-Environ. Sci.* **2020**, *39*, 429–436.
33. Li, Y.; Chapman, S.J.; Nicol, G.W.; Yao, H. Nitrification and nitrifiers in acidic soils. *Soil Biol. Biochem.* **2018**, *116*, 290–301. [\[CrossRef\]](#)
34. Chen, T.; Cheng, R.; Xiao, W.; Zeng, L.; Shen, Y.; Wang, L.; Sun, P.; Zhang, M.; Li, J. Response of Nitrogen Mineralization in Soil Aggregates to Changes in Soil Moisture and Temperature in the Three Gorges Reservoir Area's Typical Plantation. *For. Res.* **2024**, *37*, 27–38.
35. Li, Z.; Zeng, Z.; Tian, D.; Wang, J.; Fu, Z.; Zhang, F.; Zhang, R.; Chen, W.; Luo, Y.; Niu, S. Global patterns and controlling factors of soil nitrification rate. *Glob. Change Biol.* **2020**, *26*, 4147–4157. [\[CrossRef\]](#)
36. Islam, A.; Chen, D.; White, R.E. Heterotrophic and autotrophic nitrification in two acid pasture soils. *Soil Biol. Biochem.* **2007**, *39*, 972–975. [\[CrossRef\]](#)
37. Qian, X.; Li, Q.; Chen, H.; Zhao, L.; Wang, F.; Zhang, Y.; Zhang, J.; Mueller, C.; Yi, Z.; Antoniadis, V.; et al. Enhancing Soil Nitrogen Retention Capacity by Biochar Incorporation in the Acidic Soil of Pomelo Orchards: The Crucial Role of pH. *Agronomy* **2023**, *13*, 2110. [\[CrossRef\]](#)
38. Booth, M.S.; Stark, J.M.; Rastetter, E. Controls on Nitrogen Cycling in Terrestrial Ecosystems: A Synthetic Analysis of Literature Data. *Ecol. Monogr.* **2005**, *75*, 139–157. [\[CrossRef\]](#)
39. Malhi, S.S.; McGill, W.B.; Nyborg, M. Effect of temperature, moisture, and substrate concentration on the rate of nitrification. *Soil Biol. Biochem.* **1990**, *22*, 733–737. [\[CrossRef\]](#)
40. Burton, J.; Chen, C.; Xu, Z.; Ghadiri, H. Gross nitrogen transformations in adjacent native and plantation forests of subtropical Australia. *Soil Biol. Biochem.* **2007**, *39*, 426–433. [\[CrossRef\]](#)
41. Butcher, K.R.; Nasto, M.K.; Norton, J.M.; Stark, J.M. Physical mechanisms for soil moisture effects on microbial carbon-use efficiency in a sandy loam soil in the western United States. *Soil Biol. Biochem.* **2020**, *150*, 107969. [\[CrossRef\]](#)
42. Pandey, C.B.; Kumar, U.; Kaviraj, M.; Minick, K.J.; Mishra, A.K.; Singh, J.S. DNRA: A short-circuit in biological N-cycling to conserve nitrogen in terrestrial ecosystems. *Sci. Total Environ.* **2020**, *738*, 139710. [\[CrossRef\]](#)
43. Kiese, R.; Hewett, B.; Butterbach-Bahl, K. Seasonal dynamic of gross nitrification and N₂O emission at two tropical rainforest sites in Queensland, Australia. *Plant Soil* **2007**, *309*, 105–117. [\[CrossRef\]](#)

44. Yu, S.; Zhang, L.; Xie, X.; Han, X. Effects of Water Regimes on Soil Nitrogen Dynamics in Tea Garden in Shandong Province. *J. Soil Water Conserv.* **2021**, *35*, 289–298.
45. Moyano, F.E.; Manzoni, S.; Chenu, C. Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. *Soil Biol. Biochem.* **2013**, *59*, 72–85. [[CrossRef](#)]
46. Nguyen, L.T.T.; Broughton, K.; Osanai, Y.; Anderson, I.C.; Bange, M.P.; Tissue, D.T.; Singh, B.K. Effects of elevated temperature and elevated CO₂ on soil nitrification and ammonia-oxidizing microbial communities in field-grown crop. *Sci. Total Environ.* **2019**, *675*, 81–89. [[CrossRef](#)]
47. Liang, Y.; Wu, C.; Wei, X.; Liu, Y.; Chen, X.; Qin, H.; Wu, J.; Su, Y.; Ge, T.; Hu, Y. Characterization of *nirS*- and *nirK*-containing communities and potential denitrification activity in paddy soil from eastern China. *Agric. Ecosyst. Environ.* **2021**, *319*, 107561. [[CrossRef](#)]
48. Kumar, N.; Shambhavi, S.; Das, A.; Yasmeen, S.; Ganguly, P.; Kumar, S.; Rakshit, R. Soil biological indicators associated with nitrogen mineralization patterns in rice soils under long-term integrated nutrient management. *Soil Use Manag.* **2024**, *40*, e12963. [[CrossRef](#)]
49. Zhang, X.; Li, Q.; Gao, J.; Hu, Y.; Song, M.; Yue, Y. Effects of rainfall amount and frequency on soil nitrogen mineralization in Zoige alpine wetland. *Eur. J. Soil Biol.* **2020**, *97*, 103170. [[CrossRef](#)]
50. Wang, J.; Cui, W.; Che, Z.; Liang, F.; Wen, Y.; Zhan, M.; Dong, X.; Jin, W.; Dong, Z.; Song, H. Effects of synthetic nitrogen fertilizer and manure on fungal and bacterial contributions to N₂O production along a soil acidity gradient. *Sci. Total Environ.* **2021**, *753*, 142011. [[CrossRef](#)]
51. Qiu, Y.; Zhang, Y.; Zhang, K.; Xu, X.; Zhao, Y.; Bai, T.; Zhao, Y.; Wang, H.; Sheng, X.; Bloszies, S.; et al. Intermediate soil acidification induces highest nitrous oxide emissions. *Nat. Commun.* **2024**, *15*, 2695. [[CrossRef](#)]
52. Tzanakakis, V.A.; Taylor, A.E.; Bakken, L.R.; Bottomley, P.J.; Myrold, D.D.; Dörsch, P. Relative activity of ammonia oxidizing archaea and bacteria determine nitrification-dependent N₂O emissions in Oregon forest soils. *Soil Biol. Biochem.* **2019**, *139*, 107612. [[CrossRef](#)]
53. Wu, G.; Liang, F.; Wu, Q.; Feng, X.; Shang, W.; Li, H.; Li, X.; Che, Z.; Dong, Z.; Song, H. Soil pH differently affects N₂O emissions from soils amended with chemical fertilizer and manure by modifying nitrification and denitrification in wheat-maize rotation system. *Biol. Fertil. Soils* **2023**, *60*, 101–113. [[CrossRef](#)]
54. Cheng, Y.; Zhang, J.; Wang, J.; Cai, Z.; Wang, S. Soil pH is a good predictor of the dominating N₂O production processes under aerobic conditions. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 370–373. [[CrossRef](#)]
55. Deng, N.; Gubry-Rangin, C.; Song, X.-T.; Ju, X.-T.; Liu, S.-Y.; Shen, J.-P.; Di, H.-J.; Han, L.-L.; Zhang, L.-M. AOB Nitrosospira cluster 3a.2 (D11) dominates N₂O emissions in fertilised agricultural soils. *J. Environ. Manag.* **2024**, *355*, 120504. [[CrossRef](#)] [[PubMed](#)]
56. Zheng, X.; Guo, B.; Liu, H.; Wu, Y.; Yu, J.; Ding, H.; Jiang, X.; Luo, Q.; Zhang, Y. Low pH inhibits soil nosZ without affecting N₂O uptake. *J. Soils Sediments* **2022**, *23*, 422–430. [[CrossRef](#)]
57. Zhang, Y.; Zhao, W.; Cai, Z.; Müller, C.; Zhang, J. Heterotrophic nitrification is responsible for large rates of N₂O emission from subtropical acid forest soil in China. *Eur. J. Soil Sci.* **2018**, *69*, 646–654. [[CrossRef](#)]
58. Xu, H.; Liu, S.; Ding, J.; Liu, L. Mapping crop-specific emission factors highlights hotspots of ammonia mitigation in China. *Sci. Total Environ.* **2024**, *908*, 168157. [[CrossRef](#)] [[PubMed](#)]
59. Wei, X.; Zhu, Z.; Wei, L.; Wu, J.; Ge, T. Biogeochemical cycles of key elements in the paddy-rice rhizosphere: Microbial mechanisms and coupling processes. *Rhizosphere* **2019**, *10*, 100145. [[CrossRef](#)]
60. Jayarathne, J.R.R.N.; Chamindu Deepagoda, T.K.K.; Clough, T.J.; Thomas, S.; Elberling, B.; Smits, K.M. Effect of aggregate size distribution on soil moisture, soil-gas diffusivity, and N₂O emissions from a pasture soil. *Geoderma* **2021**, *383*, 114737. [[CrossRef](#)]
61. Chen, X.; Wang, G.; Zhang, T.; Mao, T.; Wei, D.; Hu, Z.; Song, C. Effects of warming and nitrogen fertilization on GHG flux in the permafrost region of an alpine meadow. *Atmos. Environ.* **2017**, *157*, 111–124. [[CrossRef](#)]
62. Tan, S.; Ni, X.; Yue, K.; Liao, S.; Wu, F. Increased precipitation differentially changed soil CO₂ efflux in arid and humid areas. *Geoderma* **2021**, *388*, 114946. [[CrossRef](#)]
63. Wang, J.; Liu, Q.; Zhao, S.; He, S.; Yang, B.; Wang, N.; Hou, P.; Xue, L.; Yang, L. Heavy rainfall stimulates more N₂O emissions from wheat fields during basal and overwintering fertilization phases. *Agric. Ecosyst. Environ.* **2024**, *376*, 109227. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.