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Soil Biogeochemical Feedback to Fire in the Tropics: Increased Nitrification and Denitrification Rates and N_2O Emissions Linked to Labile Carbon and Nitrogen Fractions

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Abstract: Although tropical ecosystems have become increasingly vulnerable to fire over the past century, the mechanisms by which fire disturbance influences N_2O emissions in these regions remain poorly understood. This study investigated the effects of fire on nitrous oxide (N_2O) emissions, the gross nitrification rate (GN), denitrification genes, and carbon (C) and nitrogen (N) fractions in a tropical forest. The results showed that fire increased the GN by 41.5%. The abundance of the *nirK* and *nirS* genes encoding nitrite reductase increased by 16.3% and 27.5%, respectively, while the abundance of the *nosZI* gene encoding N_2O reductase increased by 28%, suggesting a potentially enhanced denitrification capacity. This enhancement in nitrification and denitrification was mainly due to increased easily oxidizable organic C (EOC, +35%), light fraction organic C (LFOC, +32%), hydrolyzable ammonium N (HAN, +13%), and amino sugar N (ASN, +11%), which provided additional substrates for nitrification and denitrification. As a result, soil N_2O emissions increased by 18% in response to fire. Soil N_2O emissions showed a significant and positive linear correlation with GN, EOC, LFOC, HAN, *nirK*, *nirS*, and *nosZI*. Thus, the post-fire increase in N_2O emissions is likely driven by enhanced nitrification and denitrification processes, facilitated by the elevated availability of labile C and N fractions. Our findings provide new evidence for the role of soil C and N fractions in controlling N_2O emission and nitrification–denitrification under fire disturbances in tropical soils.

Keywords: soil N_2O emission; N cycle pattern; gross nitrification rate; tropical region; soil C and N fractions

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1. Introduction

Globally, approximately 500 million hectares of terrestrial ecosystems are burned each year [1], altering ecosystem dynamics in both the short and long term [2,3]. Fire is more prevalent in tropical and subtropical ecosystems than in any other region on Earth [4]. As a strong and direct environmental factor, fire can have a significant impact on long-term soil nutrient transformations by affecting the microbial abundance, soil biochemistry, and vegetation cover [5]. Due to climate change, the length of the wildfire season, as well as the

frequency and scale of severe fires have increased [6], which will have profound impacts on the physical, chemical, and biological properties of forest soils [7].

Nitrous oxide (N_2O), a potent greenhouse gas (GHG), is produced and emitted in the soil in close association with soil nutrient cycling processes [8]. Soil is a major source of N_2O [9,10], and has a global warming potential nearly 300 times greater than that of carbon dioxide (CO_2) over a 100-year period [11]. Although an increasing number of studies have explored the effects of fire on soil GHG emissions, most of them have focused mainly on CO_2 emissions [12–14], and there are fewer studies on the feedback of soil N_2O to fire perturbations. Some studies have indicated that soil N_2O emissions may increase significantly in the short term after fire [15]. This may be because fire raises the concentration of inorganic nitrogen (N) in the soil, which provides an energy source for the microbial consumption process of N_2O production [16]. At the same time, the change in the soil properties by fire may also affect the activity of nitrifying and denitrifying bacteria in the soil, which may influence the production and emission of N_2O [17].

Nitrification (the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-)) and denitrification (the reduction of NO_3^- to N_2 or N oxides) are important factors in the production of N_2O in soil [18,19]. Studies have shown that fire can stimulate nitrification [20]. However, in another study, a fire reduced the transcriptional activity and nitrifying enzyme activity of archaeal nitrifying bacteria [21]. The denitrification process is regulated by specific genes, primarily involving nitrite reductase encoded by the *nirK* and *nirS* genes and N_2O reductase encoded by the *nosZI* gene, and dynamic changes in these microbial communities regulate N_2O emissions [18,22]. According to Yang et al. [23], fire disrupts the structure of soil microbial communities, which in turn affects the abundance and activity of denitrifying bacteria, and post-fire soil restoration leads to changes in the composition of denitrifying microbial populations, which potentially affect the rate and efficiency of denitrification. Huang et al. [24] on forest ecosystems provide further evidence that fire may lead to increased soil N concentrations and N-transforming enzyme activities. This leads to an increase in the abundance of microbially mediated functional genes (nitrification and denitrification) associated with soil N loss. Although tropical ecosystems have become increasingly vulnerable to fire over the past century, the effect of fire disturbance on N_2O emissions in these regions is unclear [25]. In particular, how post-fire changes in the soil biochemistry and related functional genes influence soil N_2O emissions in the tropical soils is still unknown.

Previous studies have shown that the patterns of influence of organic carbon (C) and total N on soil N_2O emissions and their associated functional genes are not consistent [26,27]. These conflicting results make it difficult to draw firm conclusions about how the response of the soil C and N content to fire affects N_2O emissions, probably because previous studies have neglected the response of soil C and N fractions to fire. Soil C and N fractions can indirectly affect soil N_2O emissions by affecting soil nitrification and denitrification genes [10]. For instance, Wang et al. [28] reported that easily oxidizable organic C (EOC) is a key factor in perturbing the community composition of denitrifying bacteria. This is because EOC can directly participate in denitrification [29] due to its high turnover rate and ability to be absorbed and utilized by microorganisms [30,31]. Hydrolyzable NH_4^+-N (HAN) is derived from acid-resistant organic components [32], which facilitates microbial uptake and assimilation [32,33]. HAN can significantly contribute to soil N_2O emissions by increasing the abundance of denitrification genes [29]. Understanding the mechanisms by which fire contributes to the production and emission of N_2O in tropical forest soils and ultimately to the mitigation of global warming is critical [15]. Yet, it remains unclear how the response of soil C and N fractions to fire affects N_2O emissions in tropical forests. We hypothesized that fire would stimulate nitrification and denitrification genes

and ultimately N_2O emissions from tropical forest soils by increasing the concentrations of C and N fractions (e.g., EOC, HAN).

To fill this research gap and validate the research hypothesis, we selected a suburban forest in tropical China as the study area (which experienced wildfire disturbance in April 2024) and analyzed soil samples from both the fire-affected area and an adjacent unburned control site. The main objective of this study was to investigate how and why fire disturbance affects soil N_2O emission in tropical ecosystems. Understanding these changes is important to predict post-fire GHG emissions and their implications for ecosystem nutrient dynamics.

2. Materials and Methods

2.1. Site Description and Sample Collection

The study site is located in Danzhou City, Hainan Province, China (19°29′ N, 109°40′ E). The area has a typical tropical island monsoon climate with mean annual temperatures ranging from 23.5 °C to 24.1 °C and mean annual precipitation of about 1600 mm. The soil type is sandy loam (USDA classification), with forest vegetation dominated by native species. Dominant tree species include Hainan green plum (*Vatica mangachapoi*) and thick-barked tree (*Lannea coromandelica*), among others. The shrub layer includes mountain sesame (*Helicteres angustifolia*) and nine-section wood (*Psychotria rubra*), with occasional eucalyptus or rubber trees. Land use history is primarily natural succession, managed through natural growth. The region experienced its recent forest wildfire in April 2024, resulting in the complete destruction of lowland vegetation, charred tree roots, and a 0 to 1 cm thick layer of white and black ash and charred plant debris covering the soil surface. Samples were collected from a 45-hectare burned area and an adjacent 45-hectare unburned area. The unburned plots were sampled based on the absence of ash or charcoal in the organic layer, ensuring no recent fire disturbance. The distance between the burned and unburned sites was approximately 250 m, and the minimum distance between plots was 100 m. Soil samples were collected from three 50 × 50 m plots at each site (unburned and burned areas). Five points were randomly selected from each plot and mixed to form a composite soil sample. All sub-sample plots were selected following uniform criteria, including similar vegetation and terrain with slopes < 25°. Soil samples were kept in sterile plastic bags, transported quickly to the laboratory, and sieved (2 mm) for further processing. Subsamples were stored at 4 °C for physicochemical analysis and at −80 °C for DNA extraction.

2.2. Soil Properties

Soil pH was analyzed using the potentiometric method with a water–soil ratio of 1:2.5. Soil NH_4^+ and NO_3^- were extracted with 2 M KCl solution at a ratio of 1:5 (soil:water) and determined by spectrophotometer. Soil organic C (SOC) was determined through potassium dichromate–sulfate digestion, and total N was measured using the semi-micro Kjeldahl method. Dissolved organic C (DOC) was determined using deionized water extraction and a TOC analyzer [34]. Potassium permanganate oxidation–UV spectrophotometry was used to determine the concentration of EOC. Sodium hexametaphosphate extraction and potassium dichromate external heating method were used to determine the concentration of particulate organic C (POC) [35]. The potassium dichromate oxidation–external heating method was used to determine the concentration of recalcified organic C in soil, and the difference method was used to obtain the concentration of light fraction organic C (LFOC) [36]. Soil N fractions were determined following the methodology of Lin et al. [37]. The Kjeldahl microtitration method was used to determine acid-hydrolyzable N (AHN). Soil HAN was determined using the magnesium oxide steam distillation method, while the concentration

of amino sugar N (ASN) was calculated as follows: the hydrolyzed material was subjected to steam distillation using a phosphate–borate buffer solution, and the difference between the resulting value and HAN was taken as ASN. Amino acid N (AAN) was determined using the indophenol colorimetric method. The concentration of hydrolyzed non-ammonium N (HUN) was calculated using the formula: HUN = AHN − (ASN + AAN + HAN). Non-hydrolyzable N (NHN) was estimated by subtracting AHN from total N. Gross nitrification rate (GN) was measured by the ^{15}N isotope technique and using a Sercon Integra 2 isotope ratio mass spectrometer (Sercon Ltd., Crewe, UK).

2.3. DNA Extraction and Quantitative PCR Analyses

Total nucleic acids were extracted from 0.5 g of soil aggregate components. Following the manufacturer's instructions, soil DNA extraction was performed using the Fast DNA® Soil Spin Kit (MP Biomedicals, Solon, OH, USA). The extracted DNA was stored at −20 °C for subsequent use. The quality and concentration of soil DNA were determined using a NanoDrop 2000 spectrophotometer (Thermo Fisher Scientific, Wilmington, DE, USA). To explore the response of soil N_2O emissions related to functional microorganisms, real-time quantitative PCR analysis was employed to measure the abundance of multiple genes. These genes include those of ammonia-oxidizing archaea (AOA), ammonia-oxidizing bacteria (AOB), nitrite-reducing bacteria and fungi (*nirK*, *nirS*, and fungal *nirK*), as well as N_2O-reducing bacteria (*nosZI*). Gene abundance was evaluated through real-time quantitative PCR conducted on a CFX-96 thermal cycler (Bollinger Laboratories, Hercules, CA, USA). The analysis included three biological replicates, with three technical replicates set up for each biological replicate. The qPCR reaction mixture contained 10 μL SYBR Premix Ex Taq (Dalian Bao Bio Company, Dalian, China), 0.5 μM of each primer, and 1 μL of DNA template (7.0–23.5 ng). The amplification program was as follows: 95 °C for 1 min × 1 cycle; 95 °C for 15 s, 60 °C for 15 s, and 72 °C for 30 s × 40 cycles; and 95 °C for 5 s, 60 °C for 1 min, and 95 °C and 50 °C for 30 s × 1 cycles.

2.4. Soil N_2O Measurements

Gas samples was collected after 1, 2, 4, 7, 14, 21, and 28 days of incubation at 60% water holding capacity. Before gas collection, a substantial amount of air was introduced into the serum vials to displace the gas within them. The vials were then sealed with adhesive plugs and aluminum caps. Approximately 15 mL of gas was extracted from the vials using a 25 mL syringe at both 0 and 45 min after sealing. During the collection process, the syringe was moved back and forth to ensure thorough mixing of the gas inside the vials. The gas was analyzed using a gas chromatograph (Shimadzu GC-2014, Shimadzu Corporation, Suzhou, China) to determine the concentrations of N_2O.

2.5. Statistical Analyses

The experimental data were organized using Excel 2019. Analysis of variance (ANOVA) was used to further analyze intergroup differences using Duncan's multiple comparison method, with ($p < 0.05$) as the criterion for statistical significance. Corresponding graphs were drawn using Origin 2021. Principal component analysis was applied to explore the relationships among variables. Statistical analyses were performed using IBM SPSS Version 24. Bivariate correlation analysis and linear fitting methods were used to analyze the correlations between soil physicochemical properties, genes, and GN, and the linear correlation between quantitative variables was quantified using Pearson's correlation coefficient ($p < 0.05$).

3. Results

3.1. Soil Physicochemical Properties

Our results indicated that forest fires induced significant changes in soil chemical properties (Table 1). Forest fires increased the soil pH (+5.02%, $p = 0.001$) and the concentrations of SOC (+27.9%, $p = 0.002$), NH_4^+-N (+33.3%, $p = 0.047$), EOC (+35.0%, $p = 0.01$), LFOC (+31.9%, $p = 0.02$), HAN (+13.1%, $p = 0.003$), ASN (+11.4%, $p = 0.023$), and HUN (+84.6%, $p = 0.006$). In contrast, forest fires reduced the soil concentrations of NO_3^--N (−7.41%, $p = 0.001$), POC (−34.8%, $p = 0.001$), DOC (−8.92%, $p < 0.0001$), and NHN (−30.1%, $p = 0.006$). However, forest fires exerted no significant influence on the concentrations of total N and AAN.

Table 1. The impact of fire on soil physicochemical properties.

Parameter	Unburned Soil	Burned Soil
pH	4.99 ± 0.05 b	5.24 ± 0.03 a
TN (g kg^{-1})	1.26 ± 0.00 a	1.29 ± 0.03 a
NH_4^+ (mg kg^{-1})	0.85 ± 0.12 b	1.13 ± 0.13 a
NO_3^- (mg kg^{-1})	6.87 ± 0.07 a	6.36 ± 0.05 b
SOC (g kg^{-1})	16.9 ± 0.48 b	21.6 ± 1.04 a
EOC (g kg^{-1})	5.01 ± 0.19 b	6.76 ± 0.25 a
DOC (g kg^{-1})	0.15 ± 0.00 a	0.14 ± 0.00 b
LFOC (g kg^{-1})	4.77 ± 0.04 b	6.29 ± 0.35 a
POC (g kg^{-1})	1.42 ± 0.04 a	0.93 ± 0.09 b
ASN (mg kg^{-1})	284 ± 2.14 b	316 ± 15.5 a
HUN (mg kg^{-1})	63.5 ± 16.7 b	117 ± 4.92 a
AAN (mg kg^{-1})	182 ± 21.0 a	215 ± 17.6 a
HAN (mg kg^{-1})	306 ± 4.50 b	346 ± 10.1 a
NHN (mg kg^{-1})	425 ± 33.1 a	297 ± 25.6 b

TN, total N; NH_4^+, ammonium; NO_3^-, nitrate; SOC, soil organic C; EOC, easily oxidizable organic C; DOC, dissolved organic C; LFOC, light fraction organic C; POC, particulate organic C; ASN, amino sugar N; HUN, hydrolyzable unknown N; AAN, amino acid N; HAN, hydrolyzable ammonium N; NHN, non hydrolyzable N. Different lowercase letters in the data indicate significant differences between groups ($p < 0.05$, n = 3).

3.2. N-Cycling Functional Gene Abundances

Forest fires significantly reduced the abundances of AOA (−37.5%, $p = 0.002$) and AOB (−71.0%, $p < 0.0001$; Figure 1a,b). In contrast, forest fires significantly increased the abundances of *nirK* (+16.3%, $p = 0.043$), *nirS* (+27.5%, $p = 0.007$), and *nosZI* (+28.0%, $p = 0.001$; Figure 1c–e). However, fire had no significant effect on the abundance of fungi-*nirK* (Figure 1f).

3.3. Soil N_2O Fluxes and Gross Nitrification Rate

As shown in Figure 2, forest fires continuously augmented soil N_2O fluxes. The statistical analysis indicated that the treatment effects were significant ($p < 0.05$). Peak N_2O emissions from both unburned and burned soils occurred on day 4. After 28 days of incubation, the cumulative N_2O emission from the burned soil was significantly higher than that from the unburned soil ($p < 0.05$). Forest fires significantly increased GN by 41.5% compared to unburned soils (Figure 3).

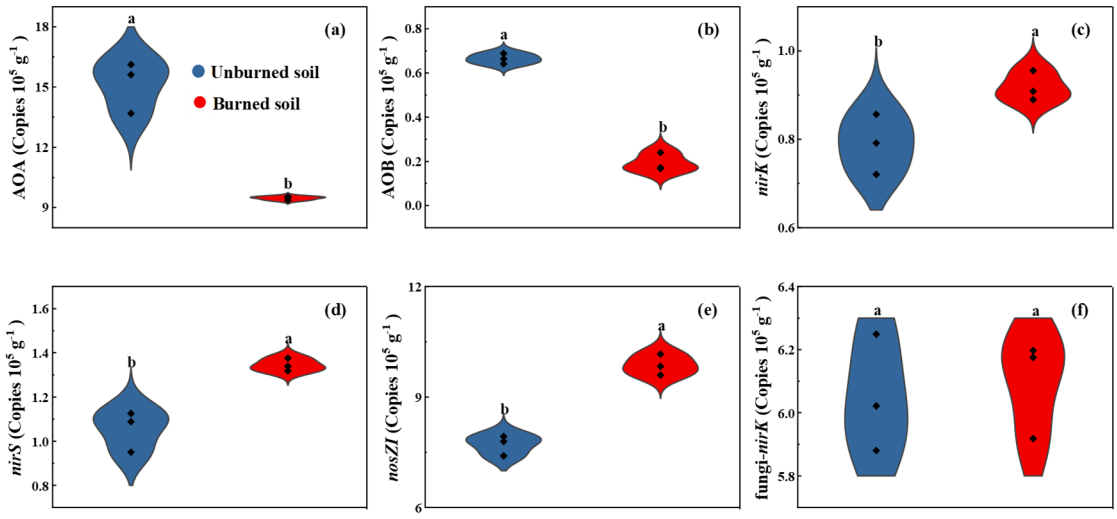


Figure 1. The abundance of ammonia-oxidizing archaea (AOA–*amoA*, (**a**)), ammonia-oxidizing bacteria (AOB–*amoA*, (**b**)), nitrite-reducing bacteria (*nirK*, (**c**)), nitrite-reducing bacteria (*nirS*, (**d**)), N_2O-reducing bacteria (*nosZI*, (**e**)), and nitrite-reducing fungi (fungi-*nirK*, (**f**)). Different lowercase letters in the data indicate significant differences between groups ($p < 0.05$, n = 3).

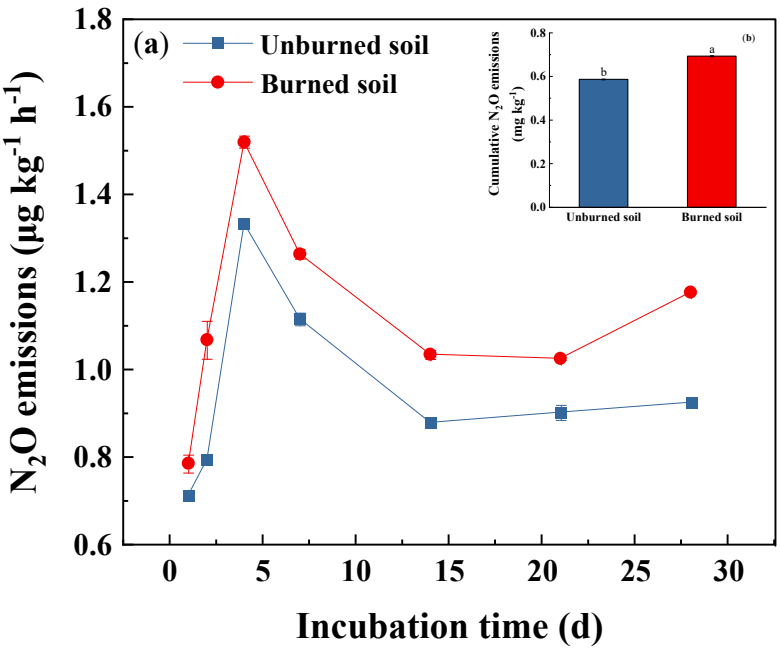


Figure 2. Soil N_2O emissions over a one-month period: (**a**) represents soil N_2O emission flux and (**b**) represents cumulative soil N_2O emissions. Values are expressed as mean ± standard error (n = 3). Different lowercase letters in (**b**) indicate significant differences between treatment groups ($p < 0.05$).

3.4. Relationships Among Studied Variables

The fitted relationships showed that soil N_2O emissions were significantly and positively linearly correlated with the soil pH, NH_4^+, SOC, GN, EOC, LFOC, HAN, *nirS*, *nirK*, and *nosZI* (Figure 4a–j). The abundance of *nirS* increased significantly with the increasing soil pH, SOC, EOC, LFOC, and HAN (Figure 4k,l and Figure 5a–c). EOC and HAN were positively and linearly correlated with *nirK* (Figure 5d,e). The abundance of *nosZI* significantly increased with the increasing EOC, ASN, and HAN (Figure 5f–h). The GN rate had a significant and positive correlation with EOC, LFOC, HAN, and ASN (Figure 5i–l).

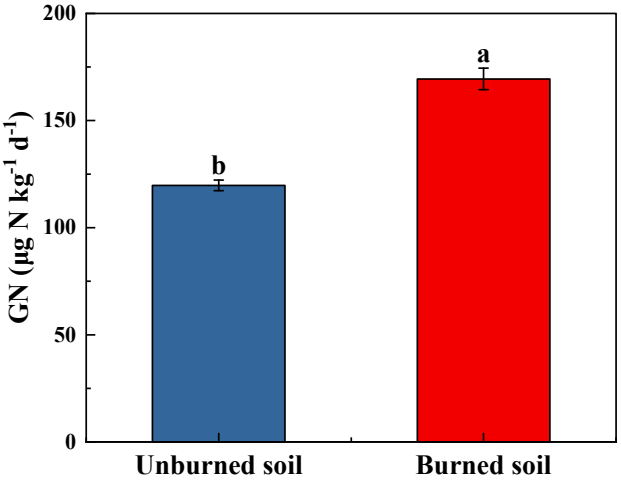


Figure 3. Soil gross nitrification rate under unburned and burned soil. Different lowercase letters in the data indicate significant differences between groups ($p < 0.05$, n = 3).

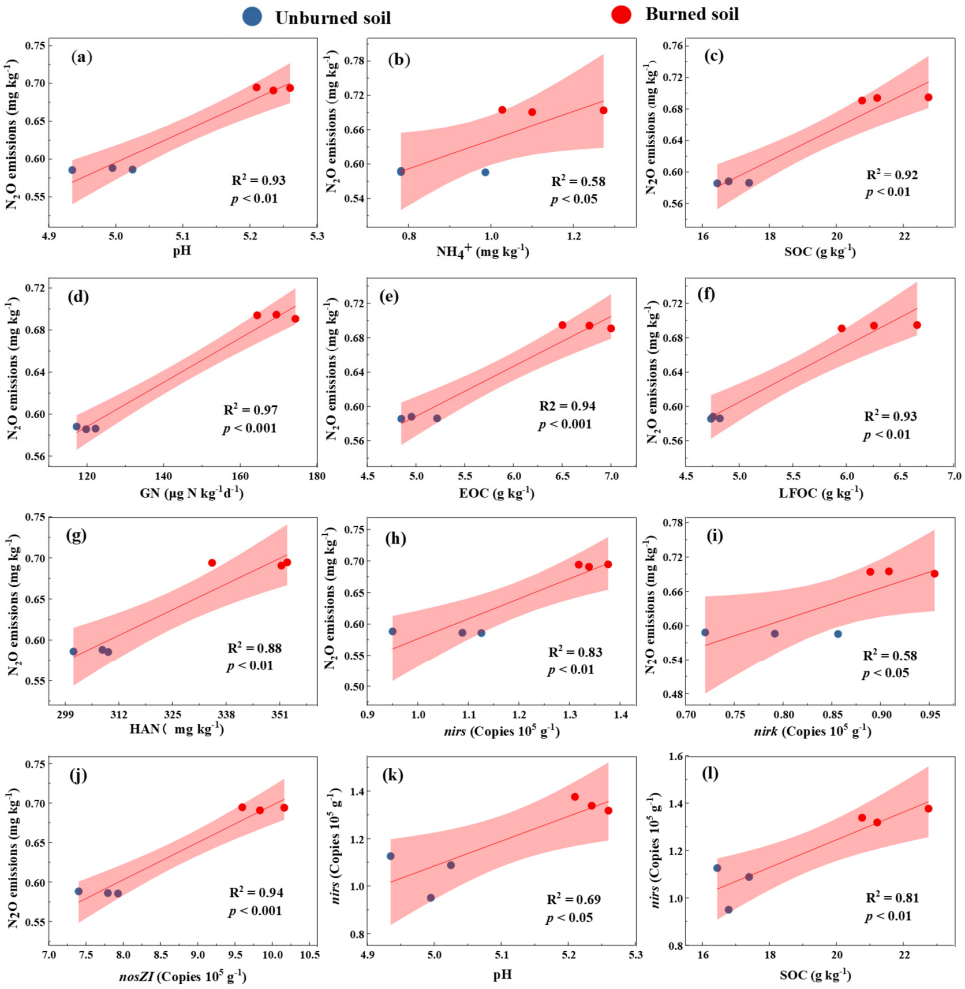


Figure 4. The relationship between soil chemical properties, gross nitrification rate, nitrogen cycle gene abundance, and soil N_2O emissions across ecosystems. Red fitted line denotes trend fitting of scatter data using a linear model and red area denotes confidence interval. The correlation between N_2O emissions and pH (**a**), NH_4^+ (**b**), SOC (**c**), GN (**d**), EOC (**e**) LFOC (**f**), HAN (**g**), *nirS* (**h**), *nirK* (**i**), and *nosZI* (**j**). The correlation between *nirS* and pH (**k**) and SOC (**l**). NH_4^+, ammonium nitrogen; SOC, soil organic carbon; GN, gross nitrification rate; LFOC, light fraction organic carbon; EOC, easily oxidizable organic carbon; HAN, hydrolyzable ammonium nitrogen; *nirK* and *nirS* denote genes associated with nitrite-reducing bacteria; and *nosZI* denotes genes associated with N_2O-reducing bacteria.

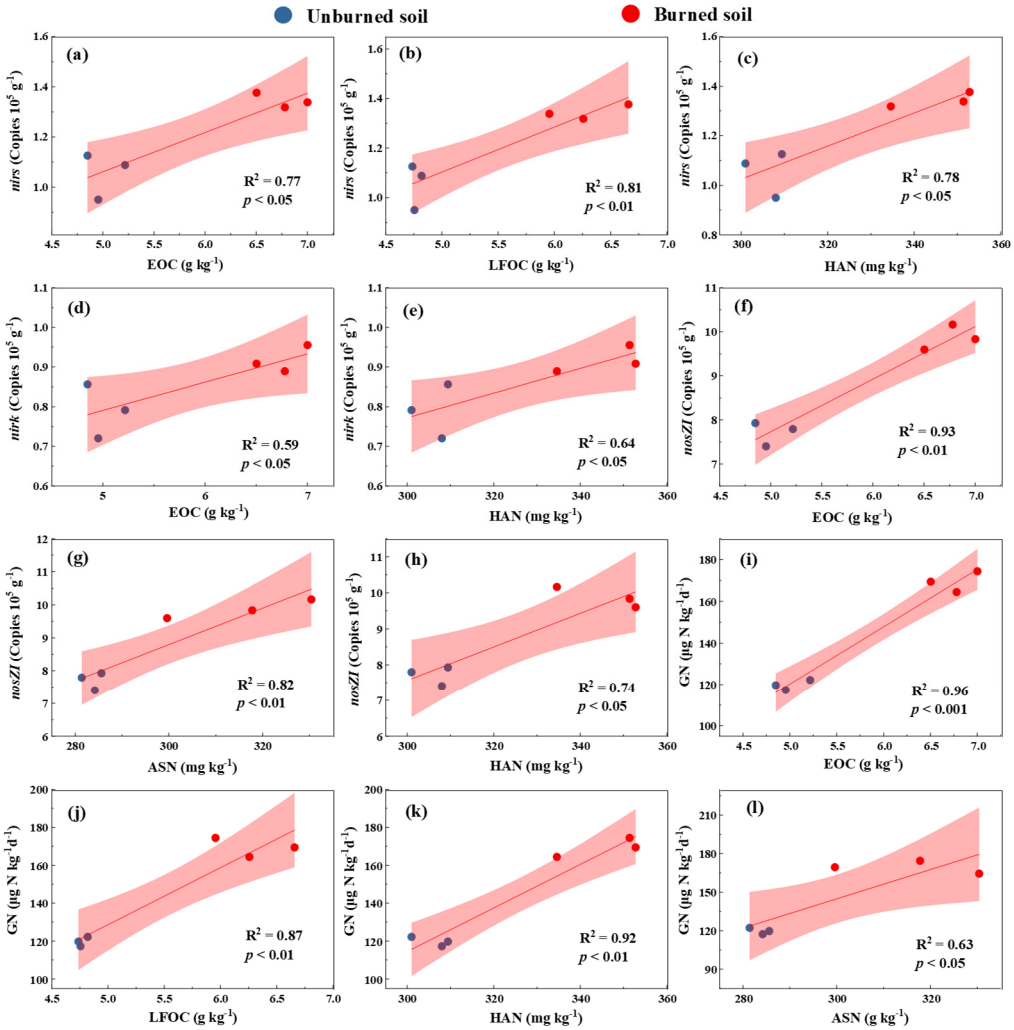


Figure 5. The relationship between soil carbon and nitrogen fractions, gross nitrification rate, and nitrogen cycle gene abundance across ecosystems. Red fitted line denotes trend fitting of scatter data using a linear model and red area denotes confidence interval. (**a**) the correlation between *nirS* and EOC; (**b**) the correlation between *nirS* and LFOC; (**c**) the correlation between *nirS* and HAN; (**d**) the correlation between *nirK* and EOC; (**e**) the correlation between *nirK* and HAN; (**f**) the correlation between *nosZI* and EOC; (**g**) the correlation between *nosZI* and ASN; (**h**) the correlation between *nosZI* and HAN; (**i**) the correlation between GN and EOC; (**j**) the correlation between GN and LFOC; (**k**) the correlation between GN and HAN; (**l**) the correlation between GN and ASN. GN, the gross nitrification rate; LFOC, light fraction organic carbon; EOC, easily oxidizable organic carbon; HAN, hydrolyzable ammonium nitrogen; ASN, amino sugar nitrogen; *nirK* and *nirS* denote genes associated with nitrite-reducing bacteria; and *nosZI* denotes genes associated with N_2O-reducing bacteria.

The principal component analysis results revealed strong relationships among the studied variables (Figure 6). PC1 and PC2 explained 83.3% and 7.8% of the total variance, respectively, with a cumulative contribution rate of 91.1%. Burned soil and unburned soil exhibited a clear separation trend in the PC1–PC2 space, which intuitively reflects significant differences between the two soil types in the combination of variables analyzed. GN, total N, HUN, pH, EOC, N_2O emissions, ASN, SOC, LFOC, HAN, NH_4^+, and denitrification-related genes *nirS*, *nirK*, and *nosZI* showed high correlations in the PC1 region.

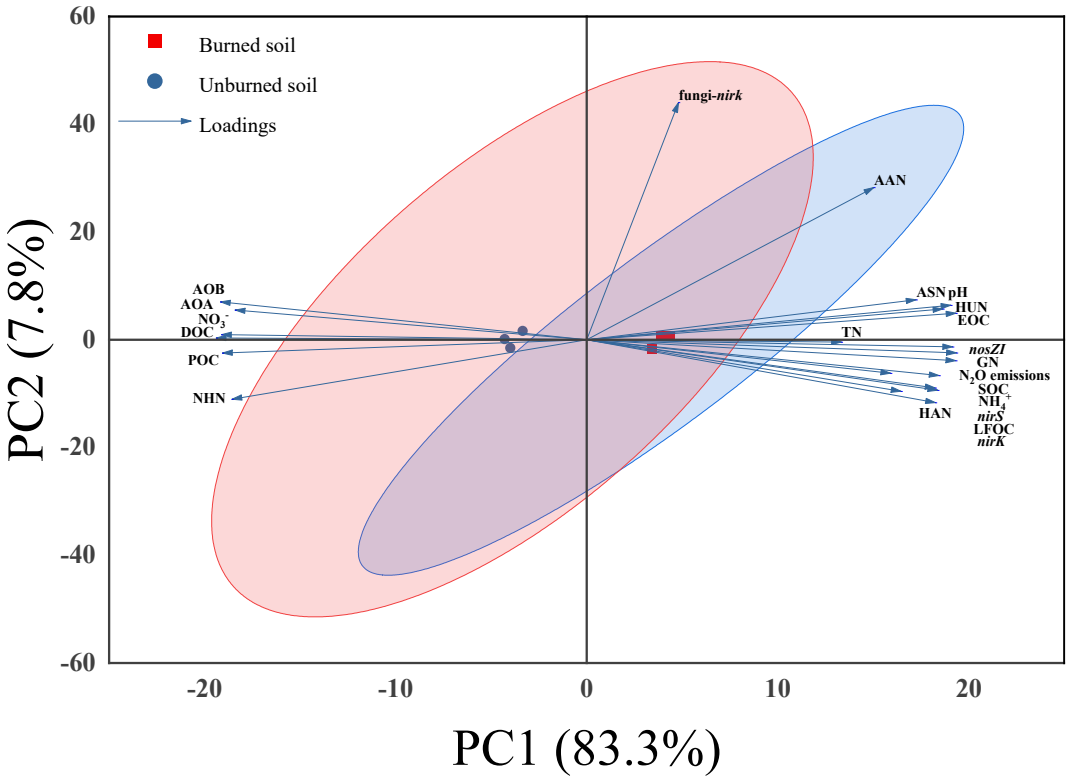


Figure 6. Principal component bivariate analysis: blue arrows indicate the contribution of each soil nutrient indicator to principal component 1 (PC1) and principal component 2 (PC2). The direction of the arrows represents their correlation with principal components 1 and 2, while the length of the arrows indicates the degree of correlation with principal components 1 and 2. Consistent arrows indicate a positive correlation between properties, while perpendicular arrows indicate no correlation. TN, total N; NH_4^+, ammonium; NO_3^-, nitrate; SOC, soil organic C; EOC, easily oxidizable organic C; DOC, dissolved organic C; LFOC, light fraction organic C; POC, particulate organic C; ASN, amino sugar N; HUN, hydrolyzable unknown N; AAN, amino acid N; HAN, hydrolyzable ammonium N; NHN, non-hydrolyzable N; N_2O emissions, cumulative nitrous oxide emissions; GN, gross nitrification rate; AOA, ammonia-oxidizing archaea; AOB, ammonia-oxidizing bacteria; fungi-*nirK*, nitrite-reducing fungi; *nirK*, *nirS*, nitrite-reducing bacteria, *nosZI*, and N_2O reducing bacteria.

4. Discussion

4.1. Fire Increased Soil NO_3^- Production

At the ecosystem scale, the effects of fire on GN are extremely complex, with processes intertwined with changes in soil physicochemical properties, changes in the microbial community structure and function, and the feedback regulation of the ecosystem [21]. Zhu et al. [15] showed that fire significantly increased the gross N mineralization rate by 37.8%, which may have provided a richer inorganic N substrate for nitrification, thus driving up the GN. This is consistent with our findings that fire disturbance led to a significant increase in the NH_4^+ concentration in tropical forest soils (Table 1), providing substrate support for the nitrification process. However, fire led to a substantial reduction in the microbial assimilation of NO_3^- [15], increasing the risk of NO_3^- loss (Table 1). Alterations in the microbial community structure and function play a central role in how fire affects GN. AOB and AOA are the main microbial taxa driving nitrification, and changes in their abundance, activity, and community composition directly affect nitrification rates [38]. Srikanthasamy et al. [21] found a decreasing trend in the archaeal nitrifying transcriptional activity and nitrifying enzyme activity after a fire in a study in a humid savanna. Consistent with their findings, the abundance of AOA and AOB significantly decreased in our study (Figure 1a,b).

Fire significantly increased the pH of tropical forest soils [15]. For AOA and AOB, the soil pH is a key factor in their ecological niche isolation [39]. The increase in the soil pH after fire may disrupt the original ecological balance of AOA and AOB, leading to a decrease in their abundance. However, the soil microbial population killed by high temperatures can act as a substrate for the N cycling process [15,40], thus maintaining or increasing GN. The scientific community is still divided on the effects of fire on C and N in soil [41]. Our results showed that the effect of fire on the soil's total N was not significant (Table 1). However, the reasons for the inconsistent results of C and N changes may be multifaceted. As suggested by Meng et al. [42], previous studies have tended to focus on the overall change in the C or N concentration or the size of the C or N pool, while neglecting the C and N fractions [29].

The principal component analysis revealed that GN had a significant correlation with HUN, ASN, HAN, LFOC, and EOC in the PC1 (Figure 6), indicating the key role of soil C and N fractions in controlling the nitrification process. The GN is closely associated with HUN, and the hydrolysis products of HUN may provide a N source for nitrifying microorganisms or influence the metabolic environment of microorganisms [43,44], thereby influencing the rate of GN. Amino sugars in soil, as an important component of microbial-derived organic N, participate in soil N transformation and storage [45], thereby promoting an increase in GN (Figure 5l). HAN originates from acid-resistant organic components and serves as a temporary reservoir for rapidly retaining N, contributing approximately 20%–35% of soil N [32] and influencing soil N transformation [29]. LFOC, as a highly active organic C component in soil, provides microorganisms with rapidly available C sources, promoting microbial growth and metabolism [46]. Changes in the EOC content may affect microbial C source utilization and alter the soil microenvironment [28], indirectly regulating GN. An adequate C source supply maintains microbial activity, enhances their N transformation capacity, and thereby increases the rate of GN.

4.2. Fire Stimulated N_2O Emissions by Increasing GN and Affecting C and N Fractions

N_2O emissions from soils are regulated by a combination of biotic and abiotic factors. Nitrification is the process of ammonia oxidation to NO_3^-, which is the main source of N_2O emissions in soil [47]. In this study, we investigated the relationship between GN and N_2O emissions in soil under fire disturbances. Our results showed a significant and positive correlation between GN and N_2O emissions (Figure 4d). The ammonia monooxygenase *amoA* gene, encoded by AOA and AOB, plays a key stimulatory role in the nitrification process [48]. NH_4^+ is a substrate for ammonia oxidation by AOA and AOB, and an increase in the substrate concentration can promote ammonia oxidation to some extent [49,50]. Even if fire reduces the abundance of AOA and AOB (Figure 1a,b), the remaining AOA and AOB can still utilize the abundant substrate for ammonia oxidation, thus maintaining or increasing GN. However, the relationship between GN and N_2O emissions is not always straightforward. Other factors, such as C and N concentration, and the presence of functional genes for denitrification, also affect the production of N_2O [29]. Our results also confirm this, as N_2O emissions show a high correlation with HUN, EOC, ASN, SOC, LFOC, HAN, LFOC, NH_4^+, *nirS*, *nirK*, and *nosZI* (Figure 6). Denitrification is regulated by specific genes, and in this process, nitrite reductase (encoded by the *nirK* and *nirS* genes) and N_2O reductase (encoded by the *nosZI* gene) play key roles [51,52]. Soil microbial activities are vigorous in tropical humid regions, and the reduced soil permeability after fire creates an anaerobic microenvironment that provides a suitable growth environment for denitrifying microorganisms and ultimately increases soil N_2O emissions [53]. Our results support this hypothesis as fire occurrences led to the positive feedback of denitrifying N cycle genes (*nirK, nirS,* and *nosZI*; Figure 1c–e). The results of previous studies on the effects of SOC and total N on N_2O emissions have been inconsistent [54,55]. For example, the study by

Garcia-Ruiz et al. [56] showed that there was no correlation between SOC and the total N and soil N_2O emissions. However, some studies also reported that soil N_2O emissions were positively correlated with SOC and total N [26,57]. Soil total N did not correlate with N_2O emissions, but soil C and N fractions may have potentially influenced the N_2O emissions (Figure 6). The significant increase in EOC concentrations after the fire may be due to the relative stability of aggregates in forest soils in the tropics and the increase in EOC concentrations with the increasing temperature [58,59] (Table 1). The results showed that the denitrification genes (*nirS, nirK,* and *nosZI*) were significantly and positively correlated with EOC (Figure 5a,d,f), which was consistent with the findings of Wang et al. [28] indicating that EOC was the main reason triggering the community structure of denitrifying bacteria. The significant increase in the concentration of LFOC in our results (Table 1) is consistent with the findings of Wang et al. [60], who showed that the concentration of LFOC in the soil of fire-prone plant communities in Poyang Lake increased significantly from 14.8 g kg^{-1} to 20.6 g kg^{-1} after the fire. The increase in LFOC in the burned soil may be attributed to the post-fire root growth and activity enhancement [61]. Both EOC and LFOC are important energy sources for denitrifiers, increasing the expression of *nirk* and *nirS*, crucial genes involved in nitrite reduction in the denitrification pathway.

The experimental results of Zhu et al. [29] showed that HAN could significantly contribute to soil N_2O emission by increasing denitrifying gene abundance. This is consistent with our results (Figures 4g and 6). HAN originates from acid-tolerant organic constituents and is a temporary reservoir for rapid N fixation. It includes partially exchangeable NH_4^+, and the unique rapid-release characteristics of its inorganic nitrogen may represent a critical factor in the enhancement of soil N_2O emissions [32]. A higher HAN concentration adsorbs soil NH_4^+, the substrate for the nitrification process [62]. Fire increases soil NH_4^+ dramatically, providing energy support for nitrification and denitrification (Figure 6). Interestingly, HAN and ASN showed a significant positive correlation with *nosZI* after tropical forest fires, demonstrating that N fractions can indirectly affect N_2O emissions by influencing denitrification genes (Figure 5g,h). On the one hand, this might stem from the high turnover rate of EOC and its capacity to be directly absorbed and utilized by microorganisms [30,31], which allows it to participate directly in the nitrification process [29]. LFOC exhibits a significant positive correlation with soil respiration and plays a role in organic matter mineralization [63], thus providing substrate support for the nitrification process. On the other hand, fires lead to higher concentrations of HAN and ASN (Table 1), which can adsorb soil NH_4^+, and NH_4^+ is the substrate for the nitrification process [62].

Consistent with previous research findings, this study confirms that fire significantly increases N_2O emissions [15,16]. Building on this, this study further reveals that labile C and N play a key driving role in N_2O emissions triggered by fire disturbances. This paper is the first to explore the impact of C and N fractions on N_2O emissions under fire disturbances in Hainan Province, and it provides an in-depth analysis of the mechanisms by which C and N fractions influence N_2O emissions. These findings provide important indicators for assessing N_2O emissions from soils in tropical regions. As an important ecological disturbance factor, wildfires not only significantly impact the soil, but also reshape the vegetation composition and structure. Many fire-sensitive plant species die due to the high temperatures caused by wildfires [64]. Frequent wildfires drive changes in the species composition, dominance, and spatial distribution patterns [65]. These changes in the vegetation composition and structure may directly or indirectly influence nitrification, denitrification processes, and soil physical and chemical properties [66], ultimately altering N_2O emission patterns. However, due to limitations in the study duration, sampling scope, and analytical methods, systematic research on changes in the vegetation composition and structure has not yet been conducted. This limitation may result in an incomplete

understanding of post-fire ecosystem evolution and an inability to fully elucidate the complex feedback mechanisms between the vegetation and soil. Future research plans could incorporate dimensions such as the species composition and community structure into existing research sites to further explore the co-evolutionary mechanisms between the two under fire disturbances.

5. Conclusions

In this study, we investigated the impact of changes in C and N fractions caused by tropical forest fires in Hainan Province on soil N_2O emissions. We examined the intricate relationship between fire events and soil N_2O emission fluxes, as well as associated changes in genes related to N cycling. The study results showed that N_2O emissions were significantly increased under fire disturbances and that fire had a significant effect on C and N fractions in forests. Fire induced positive feedback of GN and denitrification genes (*nirK*, *nirS*, and *nosZI*), which led to a significant increase in soil N_2O emissions by 18.2%. These findings emphasize that the C and N fractions (EOC, LFOC, HAN, and ASN) are key regulators of N_2O emissions, influencing the relative abundance of functional denitrification genes. We suggest that future studies on soil N_2O emissions should not only focus on total soil C and N, but should also consider the roles of the C and N fractions in regulating GN and denitrification genes and soil N_2O emissions.

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