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Original Research

Salinity Levels Alter Soil Nitrous Oxide Emission, Ammonia Volatilization, and Nitrogen Leaching

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Abstract

Soil nitrogen (N) turnover in saline soils is largely unknown, and investigations of N losses from such soils have yielded conflicting findings. A meta-analysis was thus employed to explore the influence of salinity on soil N_2O and NH_3 emissions, and N leaching potential (P_{Nr}, the proportion of NO_3^- to total inorganic N). Results indicated that increasing salinity significantly increased soil NH_3 emissions, except during experiments longer than 14 d under low salinity (ECe<4-12 dS m^{-1}). Salinity effects on soil N_2O emissions decreased by 30-82% at medium salinity (ECe = 12-16 dS m^{-1}) over periods shorter than 14 d, and increased by 90-177% at high salinity (ECe>16 dS m^{-1}). P_{Nr} decreased by 36-68% at high salinity. Soil pH, organic carbon, total and inorganic N also had significant influences on N_2O and NH_3 emissions, and P_{Nr}. Hence, salinity levels have significant direct effects on N losses, simultaneously, indirectly influencing N turnover by altering soil properties. In brief, N losses from saline soils mainly derive from N_2O and NH_3 emissions, and more attention should be given to understanding the transformation of N forms and the involved mechanisms for better N management in saline soils.

Keywords: soil salinity, N leaching, NH_3 volatilization, N_2O emission, N transformation

Introduction

Salinization affects soil physicochemical and microbial properties, thus decreasing soil productivity [1]. More than 100 countries are currently facing the environmental problem of soil salinization, and about 10^9 ha of extremely salt-affected soil is widely distributed in arid and semiarid regions [2, 3]. Nevertheless, 86% of saline lands provide 11% of the total biomass production on Earth [4], and saline lands possess great potential for grain production, greenhouse gas mitigation, and biodiversity conservation. Therefore, the utilization of saline land has recently received increasing attention as a method of addressing global challenges such as world food security.

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Nitrogen (N) is one of the most important nutrients for plant growth and soil productivity. Soil N turnover and fertilization are closely related to agricultural, ecological, and environmental management. In order to enhance crop yield, excessive amounts of N fertilizers are often applied, which has already caused N loss to become a major environmental problem [5]. N losses mainly occur through leaching and runoff of aqueous N, and emissions of gaseous N forms, i.e., ammonia (NH_3), nitrous oxide (N_2O), NO_x, and N_2 [6]. N transformation in non-saline soil types has been extensively investigated, and many efforts have been made to improve N use efficiency and decrease N losses, such as supplying N in combination with organic additives or nitrification inhibitors [7-9]. However, the effects of soil salinity levels on N transformation and loss have received less attention, and the characteristics and main factors controlling N loss in saline soils are largely unknown [10, 11].

With increasing soil salinity, plant growth becomes increasingly limited and ultimately stops, which causes decreases in soil organic carbon (SOC) content as well as microbial biomass and diversity [12, 13]. The critical soil processes involved in carbon (C) and N turnover, such as decomposition, ammonification, and nitrification, are then disturbed [11, 14]. In particular, nitrification and denitrification are the main processes leading to the production and emission of N_2O, a strong greenhouse gas, from soils [10, 15]. The cumulative N_2O emissions from saline soils seem to increase with increasing salinity [14], although a reduction of N_2O emissions has also been observed in soil with relatively high salt content [16]. These inconsistent results indicate there is much uncertainty about N_2O emissions from saline soils. Nitrification also affects the substrate concentration for NH_3 volatilization. NH_3 volatilization is significantly increased with increasing soil salinity, with a wider stimulating span at higher salinity levels [17, 18]. Nitrate adsorption to negatively charged soil particles is limited, and the nitrate thus easily leaches away, accounting for 78% of water-borne N losses [6]. The abundance of NO_3^- and NH_4^+ in soil solution mainly depends on the processes of nitrification and N mineralization. Nitrification is more sensitive to soil salinization than the mineralization of organic compounds [19]. Therefore, with increasing soil salinity level, less NH_4^+ is transferred to NO_3^-, which leads to NH_4^+ accumulation in the soil solution and increased NH_3 volatilization, while decreasing nitrate leaching. Besides salinity, other soil properties, especially SOC content and the C/N ratio, are important factors controlling N losses in saline soils. SOC and C/N ratio significantly affect N mineralization and nitrification [11]. The nitrification and mineralization processes in saline soils are mostly shifted from stimulation to inhibition with increasing pH [11]. NH_3 volatilization, in particular, is closely related to soil pH and SOC [5], which are both affected by soil salinization [6, 11].

In short, the characteristics of N losses in saline soils are still unclear, and the main regulators of N turnover need to be elucidated. In order to reduce N losses and optimize N management in saline fields, the study aimed to explore the impacts of soil salinization on N losses and to determine the main controlling factors at different salinity levels. Specifically, we compiled 167 observations from 39 published articles to address the following goals: 1) determining the patterns and sources of N losses in soils with contrasting salinity levels; and 2) assessing the relationships between N losses and other properties of saline soils that intensify the effects of salinity on N losses.

Materials and Methods

Data Compilation

The terms "saline soil", "soil salinity", and "nitrogen" were searched in publications available before Sep. 2024 on the Web of Science (WOS), Google Scholar, and China National Knowledge Infrastructure (CNKI) databases, where a total of 162 papers were retrieved. Appropriate studies were selected based on the following criteria: 1) saline and non-saline treatments were included in the study; and 2) NH_3 volatilization and/or N_2O emissions were estimated in the study; and/or 3) soil NO_3^- and NH_4^+ concentrations were determined after addition of inorganic N as a substrate in studied soils. Soils with a measured electrical conductivity of saturated paste extract (ECe) <4 dS m^{-1}, or salt contents <1 g kg^{-1}, were considered non-saline soils. In accordance with the above criteria, 39 papers, including 167 observations, were screened from the initial 162 publications. Apart from ECe, the variables in the compiled database included the following soil properties: pH values; the contents of SOC, total N (TN), NH_4^+, NO_3^-, and clay; C/N ratio; and N_2O and NH_3 emission rates. The N_2O and NH_3 emission rates were recalculated for time scales <3 d, 3-7 d, 7-14 d, and >14 d based on the given data in the selected studies. To evaluate the influence of salinity on soil N leaching, the proportion of NO_3^- to total mineral N was calculated as N leaching potential (P_{Nr}) using Eq. (1):

$$P_{Nr}(\%) = 100 \times cNO_3^- / (cNO_3^- + cNH_4^+) \quad (1)$$

where cNO_3^- and cNH_4^+ are soil NO_3^- and NH_4^+ contents at the mentioned time scales.

Multiple salinity levels were usually addressed in the analyzed studies, which were defined as individual treatments in this meta-analysis, and all comparisons were recorded as independent observations [20]. For each study, information on soil properties, NH_3 volatilization, and N_2O emission was extracted. If the data were reported as figures, GetData Graph Digitizer (version 2.24) was employed to extract the data. Soil salinity data were assigned into three salinization categories based on the reports of Wicke et al. (2011) and Bao (2000): 4-12 dS m^{-1} (low-level), 12-16 dS m^{-1} (medium-level), and >16 dS m^{-1} (high-level) [4, 21]. Soil salinity EC1:5 data (electrical conductivity of a 1:5 mixture of soil: water) were converted into ECe values [22]. Based on our pilot experiment, salt contents were converted into ECe values through an experimental equation presented in Tao et al. (2024) [11]. Clay contents in sandy loam and clay loam soils were assigned as 10% and 20%, respectively, if the clay content was not provided in the papers.

Data Analysis

The normality of the data was checked using the Shapiro-Wilk test, and all initial soil variables were natural-logarithm (ln) transformed before analyses. To investigate the influences of soil salinity on N losses, the response ratio (*R*) was used as a metric of effect size. For a given variable, the natural logarithm of R (*RR*) was calculated as the ratio of the value in saline treatment (*X*t) to that in the control (non-saline) treatment (*X*c) in each study (Eq. (2)):

$$RR = \ln{(X_t/X_c)} \tag{2}$$

The weighted effect size (*RR*+) for all observations was calculated using Eq. (3):

$$RR_{+} = \sum_{i=1}^{n}(lnR_i \times W_i)/\sum_{i=1}^{n}W_i \tag{3}$$

where *n* is the number of observations and *Wi* is the weighting factor of the *i*-th study in the group, which was calculated using Eq. (4) (Van Groenigen et al., 2014):

$$W_i = (N_t \times N_c)/(N_t + N_c) \tag{4}$$

where *N*t and *N*c are the sample sizes for the saline and control treatment groups, respectively.

The effects of soil salinity and experiment duration were considered significant at $p<0.05$ if the 95% confidence intervals (CIs) did not overlap with zero. In particular, the weighted *RR*+ is considered to have a positive effect when greater than zero, but a negative effect when lower than zero. To better explain the responses of the selected variables to the soil salinity levels and the experiment duration, *RR*+ was converted into percentage change, calculated using Eq. (5):

$$\text{Percentage change (\%)} = (e^{RR+} - 1) \times 100 \tag{5}$$

The weighted effect size (*RR*+) and 95% CIs were calculated using the R package "Metafor". The relationships between the response ratios of the selected variables (e.g., soil N_2O and NH_3 emissions) to salinity levels, experiment duration, and initial soil properties were estimated using linear or non-linear regression analysis. All statistical analyses and generating figures were performed using R software (version 4.2.1).

Results

Responses of Soil N_2O, NH_3, and P_{Nr} to Salinity Levels and Experiment Duration

Soil N_2O emissions exhibited no significant response to experiment duration under low salinity. Medium salinity decreased N_2O emissions by 62-66% (95% CI, -82% to -26%) when the experiment duration was less than 14 d, whereas high salinity increased N_2O emissions by 90-177% regardless of experiment duration (Fig. 1(a-c)). Across salinity levels, N_2O emissions increased significantly, only when the experiment duration was more than 14 d (Fig. 2a)).

NH_3 emissions significantly increased by 107-940% regardless of experiment duration and salinity levels, except when the experiment duration was longer than 14 d under low salinity (Fig. 1(d-f)). Across each salinity level, the positive response of NH_3 emissions showed a negative trend with the experiment duration (Fig. 2b)).

The P_{Nr} showed no significant changes (-15% to 12%) under low- and medium salinity, whereas it decreased significantly by 36-68% under high salinity, regardless of the experiment duration (Fig. 1(g-i)). Across salinity levels, the P_{Nr} responded negatively (-30% to -53%) to the experiment duration, especially to those over 3 d (Fig. 2c)).

Regulating Effects of Initial Soil Properties on Soil N_2O, NH_3, and P_{Nr}

Regression analysis showed that the response ratios of soil N_2O fluxes to experiment duration and salinity level were positively linearly correlated with the initial soil ECe and pH (Fig. 3a) and b)), while being negatively linearly correlated with soil C/N ratio and NO_3^- contents (Fig. 3e) and h)). There was a positive linear correlation between the response ratios of NH_3 volatilization with initial soil ECe, NO_3^-, and NH_4^+ contents (Fig. 4(a, g, h)), while there was a negative linear correlation with SOC and TN contents (Fig. 4c)) and d)). However, the response ratios of NH_3 volatilization were non-linearly correlated with soil pH, with a maximum response ratio observed at a soil pH of approximately 8.4 (Fig. 4b)). The response ratios of P_{Nr} were positively linearly correlated with initial soil SOC, TN, and clay contents (Fig. 5(c, d, f)), while being negatively linearly correlated with ECe (Fig. 5a)).

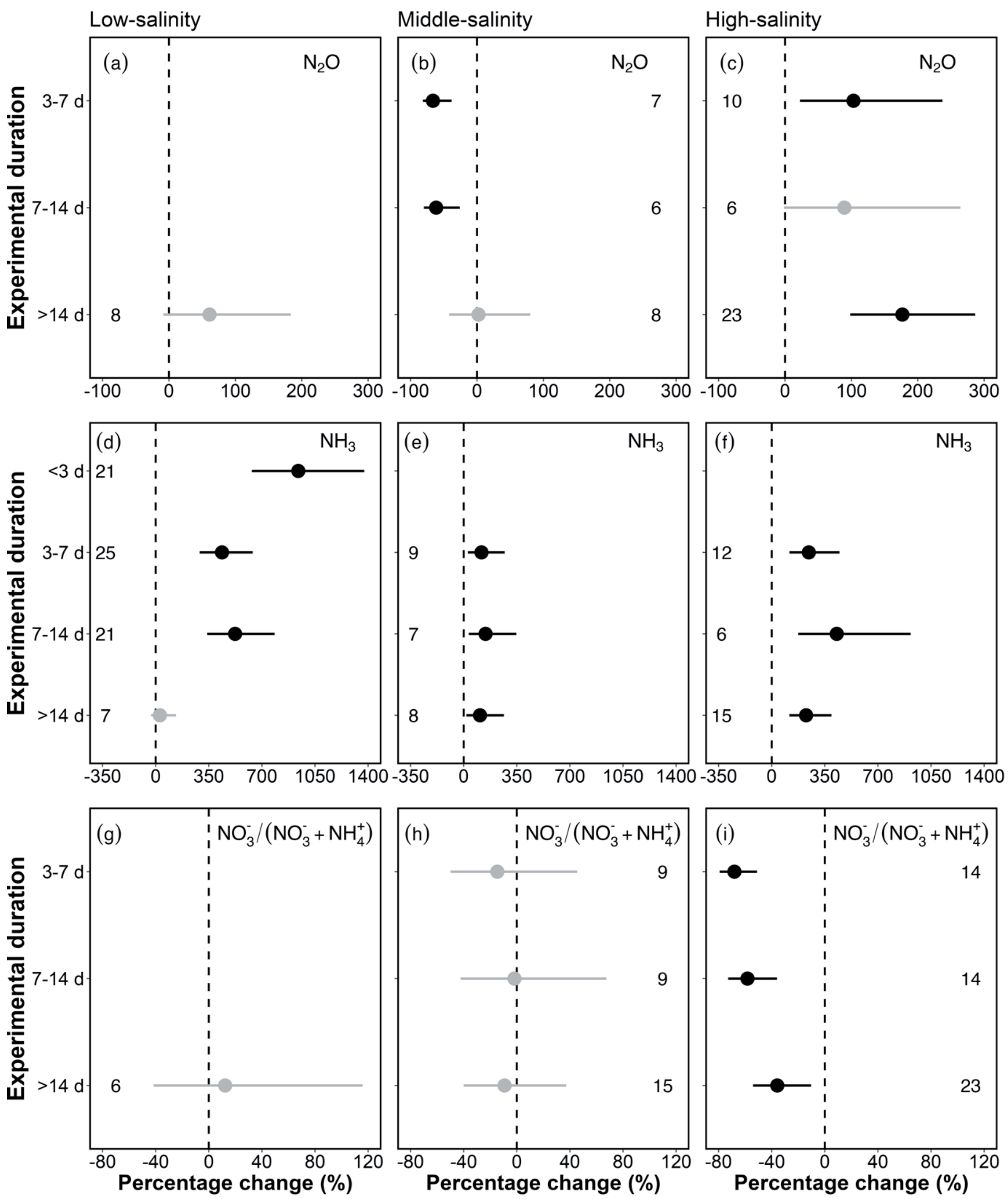

Fig. 1. Effects of salinity levels on soil N_2O and NH_3 emissions, and NO_3^- / (NO_3^- + NH_4^+) ratios (P_{Nr}) related to the experiment duration. The numbers inside the sub-figure are the sample sizes, i.e., observations for corresponding experiment durations. The error bars represent 95% confidence intervals (CI). The effect is significant if the 95% CI does not overlap with zero (p<0.05).

Discussion

Salinization is a key factor driving N transformation pathways in soils, and inevitably influences gaseous N emissions, i.e., those of N_2O, NH_3, and N_2 [16, 17, 20]. A better understanding of the response of soil N cycles to salinity can facilitate the enhancement of N use efficiency in saline soils and reduce the adverse environmental impacts of hydrological and gaseous N losses. We investigated the effects of various soil salinity levels together with time on N_2O and NH_3 fluxes and P_{Nr}, based on a quantitative synthesis of 167 observations from 39 studies worldwide.

Effects of Soil Salinity on N_2O Emissions

N_2O emissions mainly result from soil nitrification and denitrification processes [20], and predominantly from nitrification in saline soils [10]. In this study, soil N_2O emissions were significantly influenced by salinity level and experiment duration. The strong decrease in soil N_2O emissions by 62-66% under medium salinity, i.e., ECe = 12-16 dS m^{-1}, when experiment duration was ≤14 d (Fig. 1b)) was due to the increasing restriction of N mineralization and microbial activity, as well as decreasing substrate availability, e.g., of ammonium for nitrification [11]. However, the significant increase

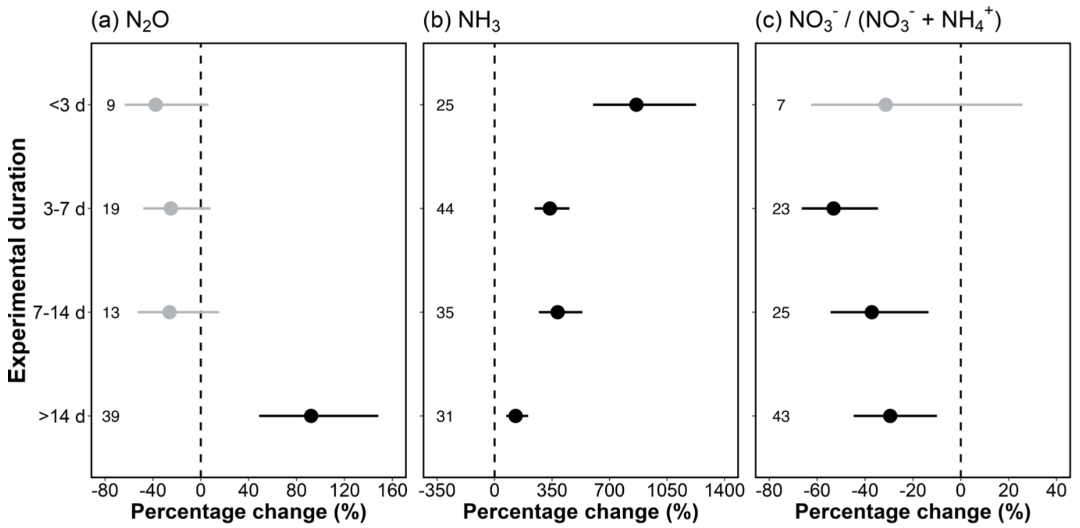

Fig. 2. The relations between experiment duration and soil N_2O and NH_3 emissions, and NO_3^- / (NO_3^- + NH_4^+) ratios (P_{Nr}) in saline soils. The numbers inside the sub-figure are the sample sizes, i.e., observations for corresponding experiment durations. The error bars represent 95% confidence intervals (CI). The effect is significant if the 95% CI does not overlap with zero (p<0.05).

in N_2O emissions by 90-177% at the highest salinity level, ECe>16 dS m^{-1} (Fig. 1c)), may be due to the increased inhibition of the activity of nitrite oxidizers relative to ammonia oxidizers [20], which leads to accumulation of NO_2 produced from ammonium oxidation and an increase of N_2O production through nitrifier denitrification [16]. Because N_2O reductase is more sensitive to environmental conditions, the other possible reason for increased N_2O emission under high salinity is the reduced suppression of N_2O to N_2 [20]. Across all salinity levels, N_2O emission significantly increased with rising ECe (Fig. 3a)). Taken together, N_2O emission in saline soils should receive more attention in terms of its potential to enhance greenhouse gas emissions.

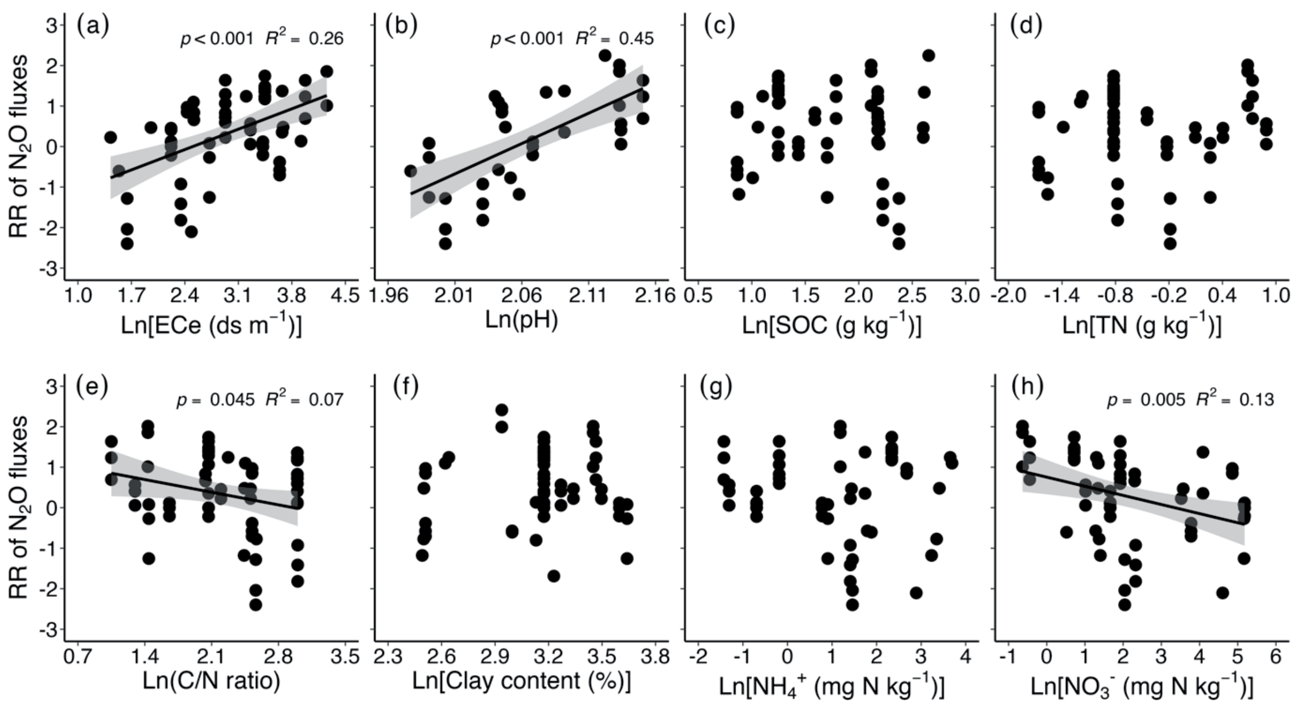

Fig. 3. Relationships between the response ratios (RR) of soil N_2O emission and soil ECe a), pH b), contents of SOC c), and TN d), C/N ratio e), clay content f), and concentration of NH_4^+ g) and NO_3^- contents h). The plots with a black solid regression line indicate significant correlation between N_2O emission and the corresponding soil property at p<0.05. The shaded areas represent 95% confidence intervals (CI) for the regression lines. The plot without a dashed line represents no significance. Ece: soil electrical conductivity; SOC: soil organic carbon; TN: total nitrogen; NH_4^+: ammonium; NO_3^-: nitrate.

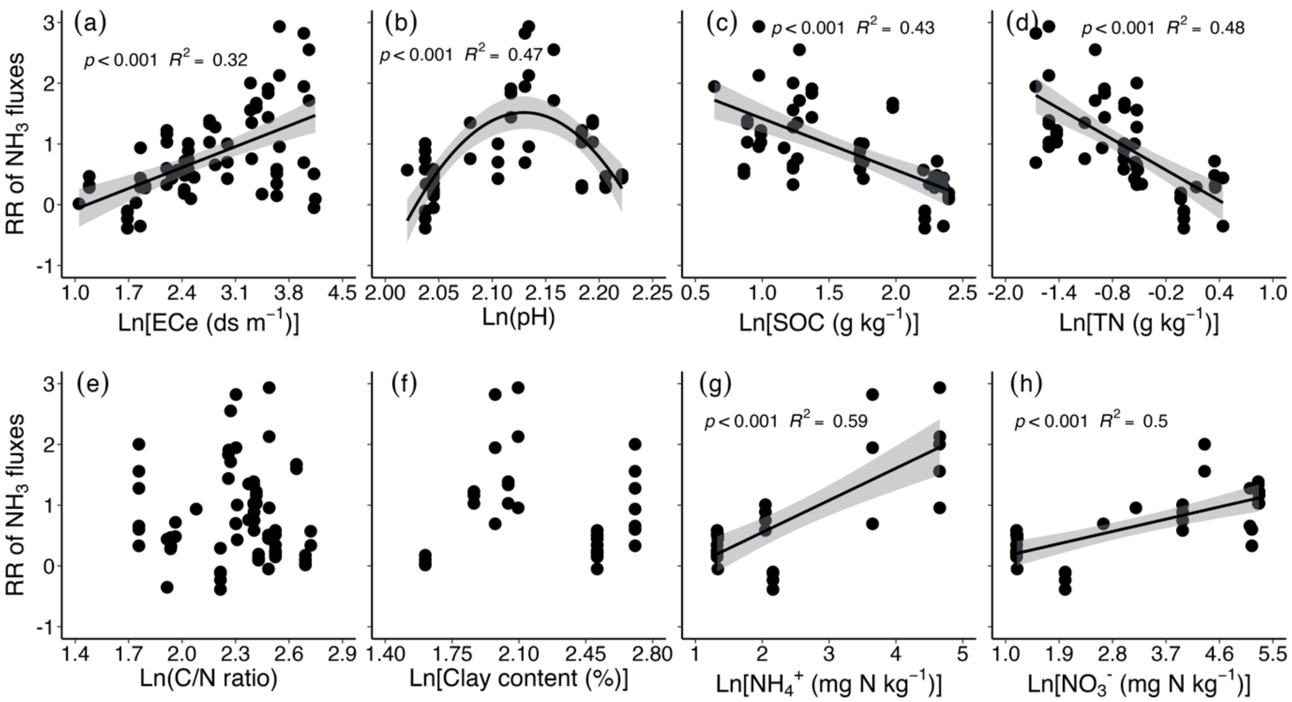

Fig. 4. Relationships between the response ratios (RR) of soil NH_3 emission and soil ECe a), pH b), contents of SOC c), and TN d), C/N ratio e), clay content f), and concentration of NH_4^+ g) and NO_3^- contents h). The plots with a black solid regression line indicate significant correlation between N_2O emission and the corresponding soil property at p<0.05. The shaded areas represent 95% confidence intervals (CI) for the regression lines. The plot without a dashed line represents no significance. Ece: soil electrical conductivity; SOC: soil organic carbon; TN: total nitrogen; NH_4^+: ammonium; NO_3^-: nitrate.

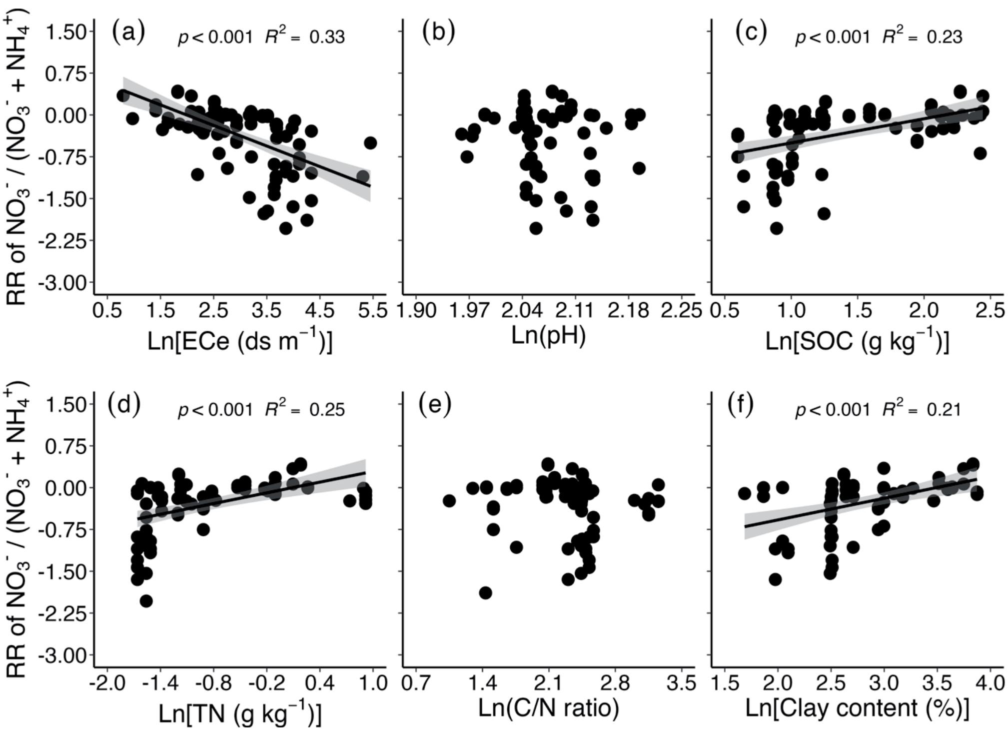

Fig. 5. Relationships between the response ratios (RR) of NO_3^- / (NO_3^- + NH_4^+) ratios (P_{Nr}) and soil ECe a), pH b), contents of SOC c) and TN d), C/N ratio e), and clay content f). The plots with a black solid regression line indicate significant correlation between N_2O emission and the corresponding soil property at p<0.05. The shaded areas represent 95% confidence intervals (CI) for the regression lines. The plot without a dashed line represents no significance. ECe: soil electrical conductivity; SOC: soil organic carbon; TN: total nitrogen; NH_4^+: ammonium; NO_3^-: nitrate.

Besides ECe, the regression analysis indicated that N_2O fluxes are positively and significantly correlated with pH in saline soils (Fig. 3a) and b)). This finding contrasts with the prevailing view that N_2O emissions decrease with increasing soil pH [23]. The pH of saline soils often significantly increases with increasing salinity [11]. Thus, N_2O emission increases with rising pH might occur via the reduction inhibition from N_2O to N_2 under high saline conditions [16]. Soil C/N ratio plays a vital role in N transformation regulation [24]. We found that N_2O emissions are significantly negatively correlated with C/N ratio in saline soils (Fig. 3e)). With increasing C/N ratio, more N immobilization than mineralization occurs to support soil microbial growth [25], which results in the inhibition of nitrification due to the decrease in substrate availability, and a corresponding drop in N_2O production [26]. The significant decrease in N_2O emission with increasing soil NO_3^- concentration (Fig. 3h)) might be due to inhibition of NO_3^- reduction to NO_2^- as a result of a decrease in easily available C sources in saline soils [27]. This causes NO_3^- accumulation and further reduction of N_2O emissions.

Effects of Soil Salinity on Ammonium N Loss

Ammonia volatilization is mainly regulated by non-biological factors such as soil pH, texture, and NH_4^+ concentration, but is also indirectly regulated by soil microbial factors that affect N bio-mineralization and nitrification [28, 29]. The N losses from NH_3 volatilization account for 16% of the average N applied worldwide [30]; thus, the reduction of NH_3 loss from soils is crucial for improving N use efficiency. In this study, the significant increase in NH_3 volatilization by 107-940% (Fig. 1(d-f)) was observed, and soil NH_3 volatilization was positively correlated with ECe values (Fig. 4a)). Hence, increased NH_3 volatilization in saline soils is partly caused by the elevated pH by increasing ECe, because high pH can favor NH_4^+ transformation to NH_3 [11, 27]. This is supported by the observation that NH_3 volatilization significantly increased with rising soil pH with values less than 8.4 (Fig. 4b)). Decreasing NH_3 emission at high pH values (>8.4) was also recorded, indicating that N mineralization may be significantly inhibited by pH>8.0 [31] because of the reduction of enzymatic activities directly regulating N mineralization, such as urease [32]. On the other hand, soil NH_4^+ concentration significantly increased with rising ECe values, and NH_3 volatilization rises with increasing substrate availability [16, 33]. The increase in soil NH_4^+ concentration could be explained as follows: 1) nitrification is inhibited by increasing soil salinity, and leads to more NH_4^+ accumulation in soils [11]; and 2) the competition of adsorption to soil particles between NH_4^+ and sodium or other cations rises with increasing salinity levels, causing more NH_4^+ desorption into soil solutions [34]. Therefore, the influence of soil salinity on NH_3 volatilization mainly occurs through soil NH_4^+ desorption, pH increase, and N mineralization and nitrification inhibition.

Our regression analysis indicated that SOC and TN are significantly negatively correlated with NH_3 volatilization (Fig. 4c) and d)). Soils with high SOC and TN contents usually have comparatively high microbial activity [31], and NH_4^+ can be preferentially immobilized into microbial biomass [24], resulting in the reduction of soil NH_4^+ concentration. Simultaneously, soil organic matter plays an important role in NH_4^+ adsorption, and the adsorption capability increases with increasing SOC [35]. The reduction of soil NH_4^+ concentration and increase in NH_4^+ adsorption both decrease substrate availability for NH_3 volatilization [36], thus decreasing NH_3 volatilization in saline soil.

Effects of Soil Salinity on N Leaching

The leaching of NH_4^+ is impeded due to its adsorption to soil particles, and a previous study had reported that more than 90% of the total N leaching is in the form of nitrate [37]. Nitrate leaching not only decreases N use efficiency, but also causes environmental and health risks, such as contamination of underground, surface, and drinking water [38]. As the knowledge about the significance of N leaching in saline soils is limited, the proportion of NO_3^- to total mineral N, i.e., P_{Nr}, was used for the first time to explore the potential of N leaching from soils with different salinity levels. The significant negative effect of salinity on P_{Nr} was observed in this study (Fig. 5a)), which was supported by the significant decrease in P_{Nr} (36-68%) at high salinity (Fig. 1i)). With rising soil salinity, nitrification is suppressed more than N mineralization [19], which could lead to soil NO_3^- reduction and NH_4^+ accumulation. Therefore, P_{Nr} significantly decreased with increasing soil ECe. Notably, we found N leaching to decline along with increasing nitrous oxide emissions in saline soils (Fig. 3a), Fig. 4a), Fig. 5a)).

SOC, TN, and clay content are significantly positively correlated with P_{Nr} (Fig. 5(c, d, f)). Increasing SOC and TN can improve microbial activity, which facilitates the oxidation of NH_4^+ to NO_3^-, thus causing an increase in P_{Nr}. It is generally known that soil clay plays a vital role in organic C sequestration, and soils' capacity for organic C sequestration can increase greatly with increasing clay content [39]. Hence, the positive effect of clay content on P_{Nr} might occur via increasing the bioavailability of C sources and the microbial activity in saline soils.

Responses of N Losses to Saline Soil Environments

We demonstrated that soil salinization increases N_2O emissions (Fig. 3a)) and NH_3 volatilization (Fig. 4a)), while decreasing N leaching potential (Fig. 5a)). Nevertheless, to explore N losses from saline soils accurately, the relationships between soil properties and N loss ought to be determined (Fig. 6).

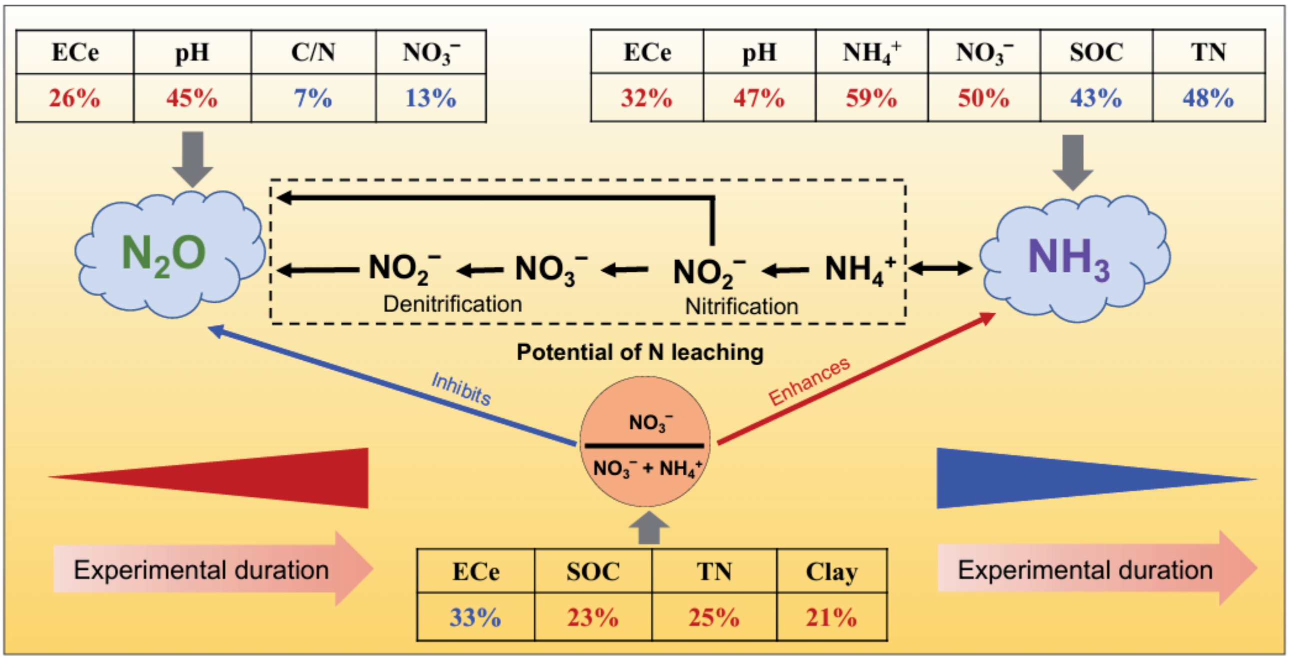

Fig. 6. Graphical summary explaining the relations between experiment duration and initial soil properties with soil N_2O and NH_3 emissions, and NO_3^- / (NO_3^- + NH_4^+) ratios (P_{Nr}). The red arrows indicate positive effects, and the blue ones indicate negative effects. The red and blue numbers in the upper table indicate the variations of the positive and negative response ratios of N_2O emission and NH_3 volatilization, respectively. ECe: soil electrical conductivity of saturated paste extract; SOC: soil organic carbon; TN: total nitrogen; NH_4^+: ammonium; NO_3^-: nitrate.

Besides the direct effects of salinity, increasing SOC and TN contents efficiently boost the oxidation and adsorption of NH_4^+ [35], which significantly decreases NH_3 volatilization while increasing P_{Nr}. With rising salinity, P_{Nr} is significantly reduced along with the increase of N_2O and NH_3 fluxes, suggesting that N losses in saline soils occur mainly through gaseous N emissions. In contrast to non-saline soils, C limitation caused by the shortage of SOC in saline soils might restrict the reduction of NO_3^- to NO_2^- (Fig. 3h)), which directly decreases the availability of substrate for N_2O emissions [16, 40]. In order to precisely predict and evaluate N losses from saline soils, the mechanisms for each pathway of N loss should be explored in future studies.

Conclusions

This meta-analysis found that gaseous N emissions, including N_2O and NH_3, strongly contribute to N losses from saline soils due to the substantial decrease in P_{Nr} with increasing ECe. Besides soil ECe, SOC, TN, C/N, and pH were closely correlated with N_2O and NH_3 emissions, and P_{Nr}, in saline soils. Hence, the relations between salinity level and soil properties should be considered when developing N management plans or evaluating N losses from saline soils. Limitation of C sources seems to have a great influence on N turnover in saline soils, supported by the negative correlation between N_2O emission and NO_3^- concentration. Thus, the transformation of N forms and the mechanisms controlling their transformation rates should be the core focus of future research better to understand the dynamics of N in saline soils.

Author Contributions

Wenjun Xie and Guodong Shao: Conceptualization, Data analysis, Writing and Editing; Shaowen Liu and Jingru Xu: Data analysis and Writing; Kazem Zamanian and Weiming Li: Writing-Reviewing and Editing; Lei Xu and Yue Wu: Data collection and analysis. All authors read and approved the final manuscript.

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

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