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The characteristics of soil salinization effects on nitrogen mineralization and nitrification in upland fields

Yinglu Tao[1], Wenjun Xie[1]*, Lei Xu[1], Lichang Zhang[1], Guangmei Wang[2], Xiaoning Wang[1] and Cailing Shi[1]

[1]School of Environmental and Municipal Engineering, Qingdao University of Technology, Qingdao, China, [2]Shandong Key Laboratory of Coastal Environmental Processes, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai, China

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Shihong Yang,
Hohai University, China

*CORRESPONDENCE
Wenjun Xie,
xiewenjun@qut.edu.cn,
xwjeric@163.com

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The influence of soil salinization on nitrogen (N) transformation is largely unknown, which impedes the reasonable management of N in saline fields. A comprehensive meta-analysis was thus conducted to evaluate the effects of salinity and relative soil physicochemical properties on net N mineralization and nitrification in upland soils. Results showed that effects of salinity on the net-N mineralization rate (Min) and nitrification rate (Nit) changed with the salinity level and incubation time. Generally, the inhibitory effect of salt on Min and Nit decreased gradually with incubation time. At 14–16 days of soil incubation, significant stimulatory effects on Min were observed in middle-level (ECe: 12–16 dS m^{-1}) and high-level (ECe >16 dS m^{-1}) saline soils, and on Nit in low-level (ECe: 4–12 dS m^{-1}) saline soils. Regression analysis revealed that the effects of soil organic carbon (SOC), total N (TN), C/N, pH, and clay content on Min and Nit were closely related to salinity levels. Nit at 5–7 days of soil incubation first enhanced and then decreased with C/N increase, and the threshold value was 34.7. The effect of pH on Nit changed with salinity levels, and shifted from stimulation to inhibition with increasing pH. Min at 5–7 days of soil incubation in middle-level group first increased with increasing pH, and decreased when pH was higher than 8.1. Salinization deeply affected soil properties, which further influenced N turnover via alteration of the availability of substrates and microbial biomass and activities. Our findings suggest that the influence of salinity on soil N turnover closely related with salinity level, and salinity level should be considered fully when optimizing N management in saline upland fields.

KEYWORDS

salinity level, N turnover, soil properties, N management, meta-analysis

1 Introduction

Soil nitrogen (N) transformation involves a series of microbial processes that control soil N availability and thus ecosystem productivity. Among these, N mineralization and nitrification, which involve the release of active N from organic N and oxidation of ammonium to nitrate, respectively, are associated with the two largest terrestrial N fluxes on Earth (Kuypers et al., 2018). Ammonium and nitrate in soils are the most important forms of the available N for plant and microbial growth, and are thus important for terrestrial net primary production (Wieder et al., 2015). From regional to global scales, the patterns and controlling factors of N mineralization and nitrification in soils have received much attention, and the drivers of both processes vary with ecosystem type (Elrys et al., 2021a; b). However, little information about the characteristics of N mineralization and nitrification in saline soils has been available to date. More than 6% of agricultural land worldwide is affected by salt, and soil salinization is still on the rise (Zhang et al., 2010; Yang et al., 2022). The current security of the world's food supply is severely challenged by its increasing population. Globally, 86% of saline land provides 11% of the total biomass production on Earth (Wicke et al., 2011), and saline lands thus possess great potential for grain production. N supply plays an irreplaceable role in increasing crop yields; however, excess N easily leads to numerous environmental problems, such as nitrous oxide and NH_3 emissions (Ichihashi et al., 2020). Therefore, it is imperative to reveal the features of N mineralization and nitrification, and of their controlling factors, in saline soils.

In soils, N mineralization and nitrification can be influenced by soil properties, microbial characteristics, and climate factors. The rates of N mineralization and nitrification significantly increase with microbial biomass and diversity (Zeng et al., 2014; Li et al., 2020). Bacteria and fungi participate in N mineralization in soil, and ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) are participants in autotrophic nitrification (Lang and Jagnow, 1986; Brierley and Wood, 2001; Martens-Habbena et al., 2009). N mineralization and nitrification usually increase with increasing soil organic carbon (SOC) and total N (TN), but decrease with increasing SOC to TN ratio (C/N) (Wang et al., 2016; Cheng et al., 2019; Li et al., 2020). An increase in soil pH can stimulate nitrifying activity and increase N mineralization rates (Nugroho et al., 2007; Wang et al., 2016). Soil physical properties such as soil bulk density are correlated with microbial biomass, activity, and oxygen supply, and ultimately affect N mineralization and nitrification (Elrys et al., 2021a; b).

However, the above findings were mostly observed in non-saline soils. Some studies have reported that the rate of N mineralization increases with increasing soil salinity level (Zhou et al., 2017), whereas other studies have found that N mineralization decreases with salinity levels (Duan et al., 2018), or that salinity has little effect on N mineralization (Laura, 1974). Nitrification has been found to be more sensitive to soil salinization relative to mineralization, as the former can be inhibited completely if soil saturation extract electrical conductivity (ECe) exceeds 26 dS m^{-1} (McCormick and Wolf, 1980; Pathak and Rao, 1998). However, Magalhaes et al. (2005) revealed that nitrification rates are stimulated when the soil salinity increases from 0 to 15 parts per thousand. Thus, the currently available information about the effect of salinity on N turnover is not consistent. Moreover, the roles of relevant saline soil properties such as SOC, TN, and pH in N transformation were previously ignored, and remain unclear. Therefore, it is essential to discover the general trend of soil salinization and relevant soil properties' effects on N mineralization and nitrification by synthesizing the available results.

Increases in soil salinity have been found to inhibit plant growth and decrease biomass production significantly (Erickson et al., 2007), further resulting in the reduction of soil organic inputs and SOC (Kamble et al., 2014). SOC is positively correlated with microbial biomass and diversity (Zhang et al., 2019). C/N is an important variable in regulating the balance between N mineralization and immobilization, and mineralization is suppressed with C/N > 18 (Cheng et al., 2017). Thus, we hypothesize that N mineralization and nitrification will be inhibited by soil salinization (hypothesis 1), and that SOC and C/N are important controlling factors under saline conditions (hypothesis 2). With salinization, $Ca^{2+}$and Mg^{2+} in soil colloids are replaced by Na^{+}, which causes soil structure destruction, soil compaction, and aeration reduction (Wong et al., 2010). Oxygen supply directly and indirectly affects mineralization and nitrification (Zhou et al., 2017; Elrys et al., 2021b). We thus hypothesize that N mineralization and nitrification will be regulated by the status of soil aeration (hypothesis 3).

Unlike a previous report that studied soil salinization's effects on N cycling in coastal ecosystems (Zhou et al., 2017), a meta-analysis was conducted to examine the responses of N mineralization and nitrification to soil salinization in upland fields. To the best of our knowledge, this is the first meta-analysis that considers soil salinity and the relevant soil properties' effects on N mineralization and nitrification in upland soils. The questions examined in this analysis were as follows: i) What are the main features of N mineralization and nitrification in saline upland soils? ii) Are SOC and C/N the key controlling factors of mineralization and nitrification under saline conditions? And iii) Do the effects of salinity on mineralization and nitrification vary with soil texture (clay content)?

2 Materials and methods

2.1 Data compilation

The following terms: "saline soil" or "salinity," and "nitrogen," were used in publication searches in the Web of Science and China National Knowledge Infrastructure (CNKI) databases before May 2023. In total, 132 papers were retrieved. Appropriate studies were selected based on the following criteria: 1) net nitrification or mineralization was estimated in the studies; 2) salinization treatments in addition to non-salinization treatments in which soil ECe <4 dS m^{-1}, or salt contents <1 g kg^{-1}, were included in the studies; and 3) surface soils (0–20 cm or 0–10 cm) were used in the studies, and not flooded during experiments. In accordance with the above criteria, 14 papers including 61 observations were screened from the initial 132 publications (Table 1). The variables in the compiled database included the following soil properties: soil salinity, pH, SOC, TN, C/N, clay content, inorganic N content (TIN), net N mineralization rate (Min) and net nitrification rate (Nit). To determine Min or Nit, organic manure or inorganic N were added as a substrate in the studied soils. After substrate addition, Min was calculated at 2–3 days, 5–7 days, 14–16 days, and >21 days in the selected studies, using Eq. 1 (Duan et al., 2018):

$$Min\ (mg\,N\,kg^{-1}\,\mathrm{soil}\,d^{-1}) = (C_{t2} - C_{t1}) / (t_2 - t_1) \qquad (1)$$

where C_{t2} and$C_{t1}$are the sums of the exchangeable NH_4^+–N and NO_3^-–N concentrations (mg N kg^{-1} soil) at incubation time t_2 and t_1, respectively, andt_2 and t_1 are the incubation times (d).

Similarly, *Nit* was determined using Eq. 2:

$$Nit\ (mg\,N\,kg^{-1}\,\mathrm{soil}\,d^{-1}) = (D_{t2} - D_{t1}) / (t_2 - t_1) \qquad (2)$$

where D_{t2} and D_{t1} are the exchangeable NO_3^-–N concentrations (mg N kg^{-1} soil) at incubation time t_2 and t_1, respectively, and t_2 and t_1 are the incubation times (d).

In each paper, more than one salinity level was used. Subsequently, one salinity level was defined as one treatment in

TABLE 1 Soil salinity levels, soil clay contents, experimental type, duration time, and effects in this study.

Number	Salinity level	Clay content	Experimental type	Duration time (d)	Number of treatments	Effects	References
1	0.8–15.1 g kg^{-1}	12.1%–14.6%	Incubation experiment	42	4	Net nitrification rate decreased with increasing soil salinity and incubation time; Net mineralization rate first decreased and then increased with incubation time	Li et al. (2018)
2	2.3–13.2 dS m^{-1}[a]	8.9%–48.1%	Incubation experiment	75	6	Net nitrification rate first increased and then decreased with soil salinity and incubation time; Net mineralization rate decreased with increasing soil salinity and changed irregularly with incubation time	Al-Rashidi and Al-Jabri (1990)
3	1.9–54.3 dS m^{-1}	6.5%–8.1%	Incubation experiment	56	5	Net nitrification rate decreased with increasing salinity, and varied differently with incubation time in different saline treatments. Net mineralization rate first decreased then increased with increasing soil salinity, and decreased with incubation time	Zhu et al. (2020)
4	3.0–64.9 dS m^{-1}	12.3%–14.5%	Field experiment	56	3	Net nitrification rate first increased then decreased with incubation time, and changed with soil salinity inversely. Net mineralization rate first decreased and then increased with increasing soil salinity and incubation time	Li et al. (2020c)
5	1.3–15.0 dS m^{-1}	20.0%	Incubation experiment	90	3	Net nitrification rate decreased with increasing incubation time and soil salinity; Net mineralization rate decreased with increasing soil salinity	Raiesi et al. (2018)
6	0.2–8.8 g kg^{-1}	10.0%	Incubation experiment	102	4	Net nitrification rate first decreased and then increased with incubation time, and decreased with increasing soil salinity. Net mineralization rate decreased with increasing soil salinity	Laura (1977)
7	0.3–44.0 dS m^{-1}	—	Incubation experiment	100	12	Net nitrification rate decreased with increasing soil salinity. Net mineralization rate first increased and then decreased with incubation time, and decreased with increasing soil salinity	Mcclung and Frankenberger (1987)
8	1.0–12.4 dS m^{-1}	2.0%–3.0%	Incubation experiment	56	2	Net nitrification rate first increased and then decreased with incubation time, and changed with soil salinity inversely. Net mineralization rate first increased and then decreased with incubation time, and decreased with increasing soil salinity	López-Valdez et al. (2010)
9	0.2–11.4 dS m^{-1}	10.0%	Incubation experiment	56	3	Net nitrification and mineralization rates decreased with increasing soil salinity and incubation time	Irshad et al. (2005)

(Continued on following page)

TABLE 1 (*Continued*) Soil salinity levels, soil clay contents, experimental type, duration time, and effects in this study.

Number	Salinity level	Clay content	Experimental type	Duration time (d)	Number of treatments	Effects	References
10	1.9–39.5 dS m^{-1}	6.5%–8.1%	Incubation experiment	56	4	Net nitrification rate first decreased and then increased with increasing soil salinity and incubation time	Zhu et al. (2022)
11	2.4–28.2 dS m^{-1}	25.0%	Incubation experiment	35	4	Net nitrification rate first increased and then decreased with incubation time, and changed with soil salinity inversely	Yao et al. (2021)
12	3.0–64.9 dS m^{-1}	12.3%–14.5%	Field experiment	50	3	Net mineralization rate decreased with increased soil salinity and incubation time	Li et al. (2020d)
13	1.1–96.7 dS m^{-1}	10.0%	Incubation experiment	90	5	Net mineralization rate decreased with increasing soil salinity	Pathak and Rao (1998)
14	2.6–21.3 dS m^{-1}	10.0%	Incubation experiment	98	3	Net mineralization rate increased with incubation time, and decreased with increasing soil salinity	Al-Ismaily and Walworth (2008)

[a]Note:, ECe, values; "/" means no available information.

this meta-analysis, and all comparisons were recorded as independent observations (Zhou et al., 2017). For each study, information on soil properties, net N mineralization, and nitrification were extracted. If the data were reported as figures in the original publications, these data were extracted by GetData Graph Digitizer (version 2.24). Soil salinity (ECe level) 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} (middle-level), and >16 dS m^{-1} (high-level). Soil salinity $EC_{1:5}$ data (electrical conductivity of a 1:5 mixture of soil: water) were converted into ECe values (Rengasamy, 2006). Salt contents were converted into ECe values through an experimental equation (Eq. 3), which was developed in our pilot experiment:

$$ECe\ (dS\,m^{-1}) = 3.17 \times S - 0.31 \quad (3)$$

where S is the value of soil soluble salt contents (g kg^{-1}).

Clay contents in sandy loam and clay loam soils were assigned as 10% and 20%, respectively, if clay content was not provided in the papers.

2.2 Data analyses

The normality of the data was checked using the Kolmogorov–Smirnov test, and natural logarithm (ln) transformation was used when the data did not exhibit normal distribution, with the exception of the value of pH. To investigate the influences of soil salinity on N mineralization and nitrification, the response ratio (R) was used as a metric of effect size in this study. For a given variable, the natural logarithm of R (ln$R$) was calculated as the ratio of the value in saline treatment (Xt) to that in the control (non-saline) treatment (Xc) in each study (Eq. 4):

$$\ln R = \ln(Xt/Xc) \quad (4)$$

The mean effect size for all observations (ln$R$+) was calculated using Eq. 5:

$$\ln R+ = \sum_{i=1}^{i} (\ln Ri \times Wi) \Big/ \sum_{i=1}^{i} Wi \quad (5)$$

where i is the number of observations. Wi is the weight factor in each study, which was calculated using Eq. 6 (Van Groenigen et al., 2014):

$$Wi = (Nt \times Nc) / (Nt + Nc) \quad (6)$$

where Nt and Nc are the sample sizes for the saline and control treatment groups, respectively.

Bootstrapping procedures within METAWIN 2.1 software (Arizona State University, Tempe, AZ, USA) were used to generate 95% confidence intervals (95%CI) for the weighted effect sizes using 4999 iterations (Rosenberg et al., 2000). The effects of soil salinity were considered significant if the 95%CI values did not overlap with zero. To compare the effects of salinity directly, ln$R$+ was converted into the mean response ratio (R_Y), calculated using Eq. 7:

$$R_Y\ (\%) = \left(e^{lnR+} - 1\right) \times 100 \quad (7)$$

Using SPSS software (12.0), Pearson correlation was conducted to investigate the influence of salinity on soil physicochemical properties. Curvilinear regression analysis was employed to test the relationships between the following soil properties: salinity, pH, SOC, TN, C/N, clay content, and the response ratios (ln$R$) for N mineralization or nitrification in soils with different salinity levels. If the number of observations was less than five (n < 5), meta and curvilinear regression analysis were negligible.

3 Results

3.1 Soil properties

Soil salinization significantly increased TN, and the values of R_Y for the total observations and low-level group were 53.5% and 142.7%,

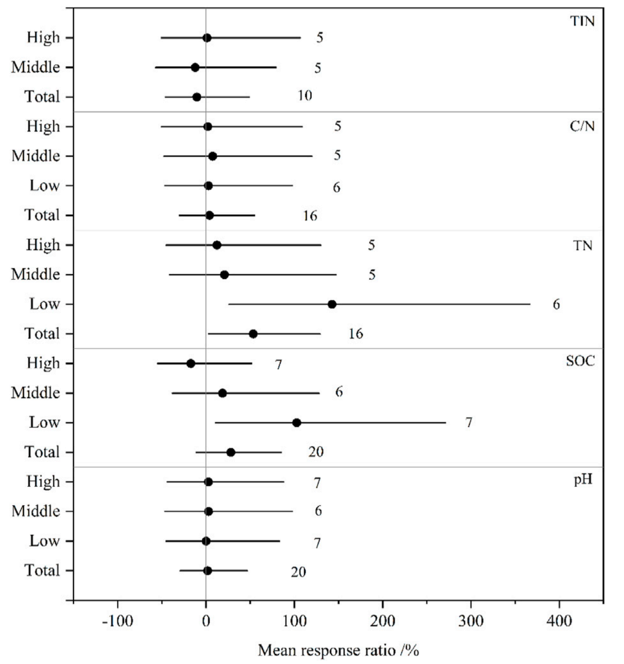

FIGURE 1
The mean effect sizes of salinization on soil properties from the total, low-, middle-, and high-level groups. Error bars represent 95% bootstrapped confidence intervals (CIs). The number of observations for each variable is shown next to the error bars. The effect of salinization was considered significant if the 95% CI of the effect size did not overlap with zero. TIN, soil total inorganic N; C/N, ratio of soil organic C to total N; TN, soil total N; SOC, soil organic C.

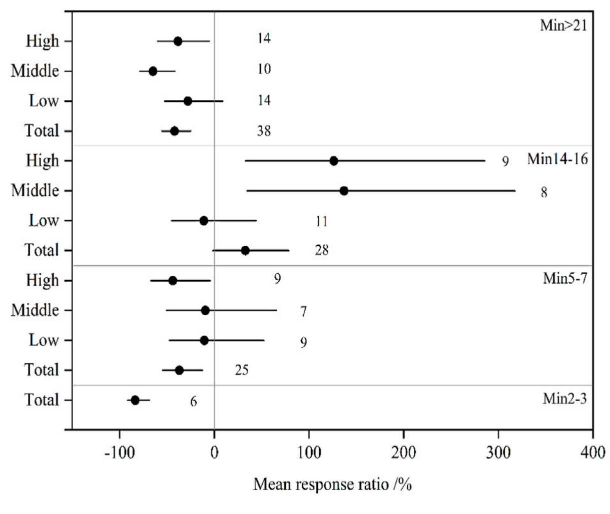

FIGURE 2
The mean effect sizes of salinization on net nitrogen mineralization in the total, low-, middle-, and high-level soils. Error barsrepresent 95% bootstrapped confidence intervals (CIs). The number of observations for each variable is shown next to the error bars. The effect of salinization was considered significant if the 95% CI of the effect size did not overlap with zero. Min2-3, Min5-7, Min14-16, and Min>21 mean the rate of net soil nitrogen mineralization at 2–3 days, 5–7 days, 14–16 days, and after 21 days incubation, respectively.

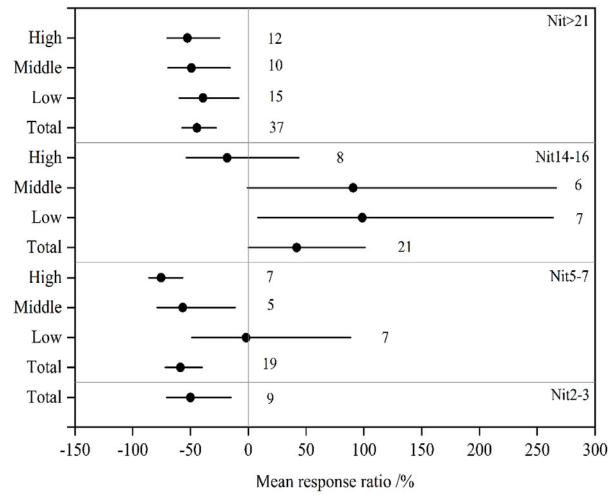

FIGURE 3
The mean effect sizes of salinization on net nitrification in the total, low-, middle-, and high-level soils. Error barsrepresent 95% bootstrapped confidence intervals (CIs). The number of observations for each variable is shown next to the error bars. The effect of salinization was considered significant if the 95% CI of the effect size did not overlap with zero. Nit2-3, Nit5-7, Nit14-16, and Nit>21 mean the rate of net soil nitrification at 2–3 days, 5–7 days, 14–16 days, and after 21 days incubation, respectively.

respectively (Figure 1). SOC was also significantly improved in low-level saline soils (95%CI of R_Y: 10.7%–271%). However, the effects of salinity on SOC in middle- and high-level saline soils were non-significant. Soil pH, C/N, and TIN did not vary significantly within the total observation, the low-, middle-, and high-level groups.

3.2 Nitrogen mineralization

The effect of soil salinity on Min changed with incubation time and salinity levels (Figure 2). The effects on Min in total soils significantly decreased by 83.6% at 2–3 days (Min2-3), 37.0% at 5–7 days (Min5-7), and 42.0% after 21 days (Min>21). Inhibitory influences reduced with incubation time, and a significant inhibitory effect was observed in middle- and high-level saline soils after 21 days. A small influence of salinity on Min was observed in low-level saline soils throughout the incubation. Significantly negative effects on Min5-7 were observed in high-level saline soils, and similar inhibitory effects on Min>21 were observed in middle- and high-level saline soils. However, Min at 14–16 days (Min14-16) increased significantly in middle- and high-level saline soils, with R_Y 95%CI of 34.6%–317.5% and 32.7%–285.7%, respectively.

3.3 Nitrification

Soil salinization effects on Nit are shown in Figure 3. With the exception of Nit at 14–16 days (Nit14-16), Nit significantly decreased by 50.1% at 2–3 days (Nit2-3), 58.8% at 5–7 days (Nit5-7), and 44.5% after 21 days incubation (Nit>21) in the total observations. Thus, the

TABLE 2 Curvilinear regression analysis between the net nitrification and saline soil properties.

Group	Regression equation	*Y*	*X*	R^2	*p*-Value
Low-level					
	$Y = 2.95 + 2.08X$	ln (TN)	lnR of Nit5-7	0.969	0.002
	$Y = 28.21–20.03X+3.51X^2$	ln (C/N)	lnR of Nit5-7	0.987	0.013
	$Y = −12.95 + 1.63X$	pH	lnR of Nit14-16	0.612	0.022
	$Y = −0.10–0.93X$	ln (TN)	lnR of Nit14-16	0.594	0.043
	$Y = −2.98–0.79X$	ln (Clay)	lnR of Nit14-16	0.515	0.045
	$Y = −1.54 + 0.43X$	ln (Clay)	lnR of Nit>21	0.425	0.022
Middle-level					
	$Y = −22.74 + 13.12X–1.85X^2$	ln (C/N)	lnR of Nit5-7	0.997	0.003
	$Y = −104.81 + 23.59X–1.30X^2$	pH	lnR of Nit14-16	0.933	0.017
High-level					
	$Y = 6.04–0.21X$	ln (Salinity)	lnR of Nit5-7	0.563	0.032
	$Y = 31.799–4.056X$	pH	lnR of Nit5-7	0.869	0.002
	$Y = −3.31 + 1.43X$	ln (SOC)	lnR of Nit5-7	0.564	0.032
	$Y = −6.12 + 1.86X$	ln (Clay)	lnR of Nit5-7	0.517	0.044
	$Y = −2.49 + 1.71X$	ln (SOC)	lnR of Nit14-16	0.683	0.011
	$Y = 23.71–20.75X+4.33X^2$	ln (Clay)	lnR of Nit14-16	0.803	0.017
Total soils					
	$Y = 1.91–0.97X$	ln (Salinity)	lnR of Nit5-7	0.473	0.002
	$Y = −3.71 + 3.25X–0.68X^2$	ln (SOC)	lnR of Nit5-7	0.428	0.015
	$Y = −25.32 + 14.49X–2.03X^2$	ln (C/N)	lnR of Nit5-7	0.402	0.046
	$Y = −2.61 + 3.0X–0.64X^2$	ln (Salinity)	lnR of Nit14-16	0.334	0.026

Note: SOC, soil organic C; TN, soil total N; C/N, ratio of soil organic C to total N; clay, soil clay content; Nit5-7, Nit14-16, and Nit>21 mean soil nitrification rate at 5–7 days, 14–16 days, and after 21 days soil incubation, respectively.

inhibitory effect decreased with incubation time. In middle- and high-level saline soils, Nit5-7 significantly decreased by 56.7% and 75.5%, respectively. Nit>21 in low-, middle-, and high-level saline soils significantly decreased by 39.2%, 49.3%, and 52.7%, respectively. The effects of salinity on Nit14-16 significantly increased by 98.6% in low-level soils, and changed non-significantly by 90.6% and −18.4% in middle- and high-level saline soils. Thereby, the inhibitory effect of salinity on Nit increased with increasing salinity level.

4 Discussion

4.1 Salinity levels

Overall, the influencing degree of salinity on N mineralization and nitrification depended on salinity level, and the response of mineralization to salinity was different from that of nitrification. The inhibitory effect of salinity on Nit and Min may be explained by the soil microbial biomass, activity, and abundance significantly decreasing with increasing salinity levels (Sun et al., 2016; Xie et al., 2017; Zhu et al., 2022). In the low-level group, Min was little affected by soil salinization throughout the incubation (Figure 2), whereas significant negative influences on Nit>21 were observed (Figure 3). In the middle- and high-level groups, except Min>21, the inhibitory effect of salinity on Min was markedly lower than that on Nit. This suggested that nitrification was more easily affected by salinity than mineralization, which may be due to the higher salt tolerance of the enzymes involved in N mineralization relative to those that catalyze nitrification (Pathak and Rao, 1998; Dendooven et al., 2010). Our results were in accordance with the report of Li et al. (2020), which indicated that N mineralization was little affected by soil salinization if salt content was less than 3.0 g kg^{-1} (equivalently, ECe <9.2). Furthermore, our results differed from those of previous studies in which nitrification increased in low-level saline soils (salt content <3.0–3.5 g kg^{-1}), or showed no inhibition when salinity was below a threshold (Zeng et al., 2013; Cortes-Lorenzo et al., 2015; Li et al., 2020). In our study, the responses of Nit to salinization varied with salinity level and incubation time, and Nit>21 significantly decreased in total, low-, middle-, and high-level saline soils. The inconsistent conclusions might be caused by the different incubation times in different studies.

Regression analysis indicated that the ln*R* of Nit5-7 was significantly negatively correlated with salinity in the total ($p < 0.01$) and high-level ($p < 0.05$) groups (Table 2), indicating that after 5–7 days of substrate addition, Nit significantly decreased with increasing salinity level. This was consistent with the results of Dendooven et al. (2010), which showed that concentrations of NO_3^- or Nit decreased with salinity level increases. The relation between the ln*R* of Nit14-16 and salinity in the total soils fitted the quadratic equation well ($p < 0.05$), and the ln*R* of Nit14-16 increased when ECe <10.4 dS m^{-1}, and decreased when ECe >10.4 dS m^{-1}. This could be explained by the high substrate (NH_4^+) accumulation due to nitrification inhibition by salinity at 14–16 days, which in turn increased Nit. However, excessively high salinity can increase NH_3 loss and decrease microbial activities in soil (Mandal et al., 2016; Zhu et al., 2020), and leads to Nit decrease. An ECe value of 10.4 dS m^{-1} can be used as a threshold value to estimate the nitrifying process after 14–16 days of N addition in saline soils. In contrast to the observed stimulatory effect on Min by increasing salinity in coastal ecosystems (Zhou et al., 2017), no significant relation was observed between Min and salinity in the present study. This is probably due to the complex mechanisms of N mineralization in soils, which is regulated by microbial N immobilization (Kooijman et al., 2009), microbial community composition (Wong et al., 2008), and ecosystem type (Bai et al., 2012).

4.2 Incubation time

The total inhibitory effect of salinity on N mineralization and nitrification reduced with time in general, and the stimulatory effect of salinity on Nit14-16/Min14-16 was recorded (Figure 2; Figure 3). The stimulatory effect of salinity on N transformation, especially at 14–16 days after substrate addition, was mostly caused by the residence time of substrates (organic nitrogen and NH_4^+) increase. Awadelkarim et al. (1995) found that urea hydrolysis significantly decreased when salt concentration rose from 40 meq L^{-1}–200 meq L^{-1}. Under high saline conditions, NH_4^+ transformation was found to be delayed by approximately 2 days (Tao et al., 2020), and Nit14-16 still remained at a relatively high level, compared with that in low- and mid-level soils. The accumulation of substrates in saline soils increased Min and Nitto a different extent. Therefore, to discover the influence of salinity on N transformation in soil, the incubation time must be considered carefully.

4.3 Saline soil physicochemical properties

4.3.1 SOC, TN, and C/N

SOC, TN, and C/N significantly influenced N mineralization and nitrification in saline soils (Table 2; Table 3). Soil microbial activity and biomass increase with increasing SOC (Elrys et al., 2021a), and soil nitrifying enzyme activity is positively correlated with SOC (Silva et al., 2012). Thus, the ln*R* of Nit5-7 and Nit14-16 in the high-level group was significantly positively correlated with SOC ($p < 0.05$). However, the relation between the ln*R* of Nit5-7 and SOC in the total group fitted the quadratic equation ($p < 0.05$), and Nit5-7 first increased and then decreased with increasing SOC. This could be because more ammonium was preferentially immobilized by the microbial community under high SOC conditions (Cheng et al., 2017), further causing the decrease of substrate for nitrifiers. This was supported by the relation between the ln*R* ofNit5-7 and C/N fitting well with the curves of the second-order equation in the total ($p < 0.05$) and mid-level groups ($p < 0.01$). The threshold values of C/N were 34.7 and 35.5, which were much higher than the 18 reported by Cheng et al. (2017) in non-saline soils, suggesting microbes require more C source to produce energy and osmoregulatory compounds to withstand the low osmotic potential stress (Elmajdoub and Marschner, 2013). The relation between TN and Nit in low-level saline soils changed with incubation time, showing a positive correlation with the ln*R* ofNit5-7 ($p < 0.01$) and a negative correlation with the ln*R* of Nit14-16 ($p < 0.05$). Soil TN, which is mostly constituted of organic N, can be directly or indirectly used as a substrate for nitrification (Corre et al., 2010). Simultaneously, soils with a higher TN usually have high microbial biomass and abundance (Elrys et al., 2021b; Cai et al., 2021). Thus, the ln*R* of Nit5-7significantly increased with increasing TN. The decrease of Nit14-16 with increasing TN maybe caused by the faster consumption of substrates during 0–14/16 days incubation in soils with high TN, and substrate concentrations thereby decreasing with increasing TN, ultimately leading to the decrease of Nit14-16.

The net N mineralization resulted from two concurrent and opposite microbial processes: gross N mineralization and microbial immobilization. Significantly negative correlations were found between the ln*R* of Min2-3 and SOC or TN ($p < 0.01$), and between the ln*R* of Min14-16 and TN ($p < 0.05$) in the total group (Table 3), indicating that N immobilization was greater than N mineralization, and rose with increasing SOC and TN. Due to the reduction of exogenous organic matter input, soil salinization is usually coupled with low SOC and TN contents, and the shortage of C and N sources are key factors limited microbial growth (Kamble et al., 2014). Therefore, microbial growth and reproduction can be boosted when the available C and N increase, ultimately reducing Min. The ln*R* of Min2-3 in the total group and the ln*R* of Min5-7 in the low-level, mid-level, and total groups were significantly negatively correlated with C/N. Similarly to the nitrification discussed above, more N would have been immobilized with increasing C/N to meet microbial requirements (Wang et al., 2016; Cheng et al., 2019). This also could be confirmed by the relation of the quadratic equation between the ln*R* of Min5-7and SOC in the mid-level group ($p < 0.05$), with Min showing an initial increase and then decreasing with increasing SOC.

4.3.2 pH

Interestingly, the effect of pH on nitrification changed with salinity levels (Table 2). In the low-level group, the ln*R* of Nit14-16 was significantly positively correlated with pH ($p < 0.05$). In the middle-level group, the relation between the ln*R* of Nit14–16 and pH showed aparabolic trend ($p < 0.05$), and the threshold value was 9.1. In the high-level group, the ln*R* of Nit5-7 was significantly negatively correlated with pH ($p < 0.01$). Thereby, the effect of pH on nitrification generally shifted from stimulation to inhibition with increasing pH. The positive effect was in line with the finding of Elrys et al. (2021a) in non-saline soils, and might be due to the positive effect of pH on ammonia-oxidizing bacterial abundance and

TABLE 3 Curvilinear regression analysis between the net nitrogen mineralization and saline soil properties.

Group	Regression equation	*Y*	*X*	R^2	*p*-Value
Low-level					
	$Y = 12.77–4.61X$	ln (C/N)	lnR of Min5-7	0.801	0.001
Middle-level					
	$Y = −56.42 + 13.73X–0.83X^2$	pH	lnR of Min5-7	0.998	0.05
	$Y = −2.08 + 3.19X–0.89X^2$	ln (SOC)	lnR of Min5-7	0.800	0.04
	$Y = 5.76–1.96X$	ln (C/N)	lnR of Min5-7	0.834	0.004
High-level					
	$Y = 11.46–5.14X$	ln (Clay)	lnR of Min >21	0.669	0.002
Total soils					
	$Y = 2.02–2.18X$	ln (SOC)	lnR of Min2-3	0.855	0.008
	$Y = −8.83–5.52X$	ln (TN)	lnR of Min2-3	0.850	0.009
	$Y = 9.57–3.57X$	ln (C/N)	lnR of Min2-3	0.852	0.009
	$Y = −8.87 + 3.15X$	ln (Clay)	lnR of Min2-3	0.734	0.029
	$Y = 4.61–1.78X$	ln (C/N)	lnR of Min5-7	0.209	0.025
	$Y = −0.27–0.83X$	ln (TN)	lnR of Min14-16	0.160	0.039

Note: SOC, soil organic C; TN, soil total N; C/N, ratio of soil organic C to total N; clay, soil clay content; Min2-3, Min5-7, Min14-16, and Min>21 mean soil N mineralization rate at 2–3 days, 5–7 days, 14–16 days, and after 21 days soil incubation, respectively.

potential nitrification (Zhang et al., 2017). However, a threshold effect was observed in the relation between pH and nitrification, whereby nitrification suppression occurred if the pH exceeded a threshold value, such as 9.1. The potential reasons for nitrification suppression under high pH conditions are: i) higher pH reduced the relative abundance of bacterial genes related to the process of nitrification (Li et al., 2022); ii) soil pH was significantly positively correlated with salinity (r = 0.473, $p = 0.013$), and salinity increase led to the accumulation of ammonium and high pH, which resulted in a significant increase in NH_3 volatilization (Mandal et al., 2016; Zhu et al., 2020), ultimately reducing substrate concentration and Nit.

A threshold effect may also exist in the relationship between N mineralization and soil pH, as supported by the relation of the quadratic equation between the ln*R* of Min5-7 and pH in the middle-level group ($p = 0.05$; Table 3). With increasing pH, Min5-7 first increased, and decreased thereafter. The threshold value was 8.1, which was highly similar to the results of Elrys et al. (2021b), where gross N mineralization significantly decreased when pH was higher than 8.0. Under conditions of pH < 8.1, the positive effect of pH on Min might be caused by an increase in the availability of microbial C source (Curtin et al., 1998). The negative effect of high pH on Min may be due to high pH decreasing the enzymatic activities that directly regulate N mineralization, as observed urease activity was negatively influenced by pH in saline soils (Zhang et al., 2014).

4.3.3 Clay

Clay contents in saline soils could influence nitrification mainly related to NH_4^+ adsorption, and microbial activity and diversity. In the low-level group, the ln*R* of Nit14-16 was significantly negatively correlated with soil clay content ($p < 0.05$; Table 2), because fine-textured soils (i.e., those with high clay content) possessed a high cation exchange capacity and adsorbed more NH_4^+ (Jarecki et al., 2008), leading to the reduction of substrate availability for nitrification. However, the ln*R* of Nit>21 was significantly positively correlated with soil clay content ($p < 0.05$). This was likely due to more NH_4^+being released into soil solution when the substrate concentration decreased, further increasing Nit>21. In addition, the fine-textured saline soil resulted in high microbial biomass and diversity (Zhu et al., 2021), which in turn increased N mineralization and increased the availability of NH_4^+ (Elrys et al., 2021b). In the high-level group, the ln*R* of Nit5-7 was significantly positively correlated with soil clay content, suggesting that low microbial activity was the key factor constraining nitrification in severely saline soils.

Soil microbial biomass and compaction play significant roles in controlling N mineralization (Elrys et al., 2021b). In this study, the ln*R* of Min2-3 in the total group was significantly positively correlated with soil clay content ($p < 0.05$, Table 3), mainly due to the high microbial biomass and activity in fine-textured saline soils (Zhu et al., 2021). Nevertheless, in the high-level group, a significant negative relationship was observed between clay content and the ln*R* of Min>21 ($p < 0.01$). Soil oxygen availability can be reduced with increasing salinity level (Noe et al., 2013), and this would be even more pronounced in soils with high clay content. Ishak et al. (2016) reported that soil microbial activity was reduced by 50%–60% with decreasing soil oxygen and increasing compaction. Meanwhile, soil enzymatic activity, e.g., mineralization-related protease levels, also decreased with increasing compaction (Mishra et al., 2005). Therefore, coarse soil texture was conducive to N mineralization by improving soil aeration in severely saline conditions.

4.4 Limitations and future perspectives

N mineralization and nitrification are vital transformative processes in agricultural soil ecosystems. There is far less information available about N transformation in the context of saline soils compared to non-saline soils, and the gross N turnover (i.e., mineralization, nitrification, denitrification, and immobilization) in saline soils has not been reported thus far. Net mineralization and nitrification involve production and consumption of NO_3^- and NH_4^+ concurrently. Thus, this study contained some limitations that impeded elucidation of the direct mechanisms of salinity's effects on N turnover. Even so, our findings clearly indicated that the effects of salinity on the availability of NO_3^- (nitrification) and NH_4^+ (mineralization) changed with incubation time and salinity levels. Such knowledge is greatly important for optimizing N management in saline fields.

According to our results, the residence time of substrates for N mineralization and nitrification clearly increased under saline conditions. Except for the negative influences, stimulatory effects on Min and Nit were found 14–16 days after substrate addition. The differences in N turnover from non-saline soils can guide us to optimize fertilization times for saline soils. In effect, N management plans for saline soils are rare at present, mainly due to the knowledge gap regarding the responses of N transformation to salinization. Besides salinity, C/N, pH, and clay content are also important factors controlling N mineralization and nitrification in saline soils. These factors work by influencing microbial activities and/or substrate availability. Nevertheless, due to lack of sufficient data, soil microbial biomass, diversity, and community composition were not included in this study. Thus, the direct relationships between saline soil biological properties and N turnover remain unclear. Further research is needed on gross N transformation as well as its biomechanisms under different salinity level conditions.

5 Conclusion

This study provides a comprehensive evaluation of salinity and relevant soil variables' effects on N mineralization and nitrification in upland fields. The findings revealed that the influences of salinity on N turnover changed with salinity level and incubation time. Soil salinization and other easily available variables, such as SOC, TN, C/N, pH, and clay content, might have affected N mineralization and nitrification via directly or indirectly altering microbial activity and substrate availability. The residence time of substrates for N transformation in saline soils significantly increased relative to non-saline soils, and transformation rates changed with salinity level and time, suggesting that N-fertilization time, supply rate, and fertilizer type must be considered seriously when developing N management plans. Further research on gross N transformation and its mechanisms in saline soils should be conducted in future. Such knowledge can help us implement sustainable agricultural production while minimizing N loss in saline fields.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YT: Data curation, Writing–original draft. WX: Conceptualization, Data curation, Writing–review and editing. LX: Data curation, Writing–review and editing. LZ: Data curation, Writing–review and editing. GW: Data curation, Writing–review and editing. XW: Writing–review and editing. CS: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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