Received: 26 July 2024 | Accepted: 14 August 2024

DOI: 10.1002/ecs2.70097

ARTICLE

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

Accumulation of sodium and manganese during litter decomposition of Qinghai spruce (*Picea crassifolia*) forest in China

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Funding information
"Innovation Star" project of Gansu Province's outstanding graduate students, Grant/Award Number: 2022CXZX-094; National Natural Science Foundation of China, Grant/Award Number: 32271710

Handling Editor: Kristofer D. Johnson

Abstract

Litter decomposition is a key ecological process as a control on nutrient cycling in forest ecosystems. Forest litter is an important carrier of element cycles in forest ecosystems. The biogeochemical cycle of elements is of great significance to plant communities and ecosystem functions. At present, most of the studies on the litter major elements have focused only on C, N, and P, and there are few studies on the biogeochemical cycle of sodium (Na) and manganese (Mn) of forest litter. In this study, we investigated the concentrations and fluxes of Na and Mn in needle litter of Qinghai spruce over a 12-month period. We measured the release and accumulation dynamics of litter Na and Mn during litter decomposition at different canopy coverage and elevations over 3.9 years. The results show that the annual Na and Mn concentrations were 312.34 and 621.19 mg kg^{-1}, and the annual fluxes of Na and Mn were 236.67 and 343.16 g ha^{-1} in needle litter, respectively. After 3.9 years of litter decomposition, Na released 15.6% and Mn accumulated 93.4% compared to the initial concentration. The concentration of Na and Mn in needle litter both accumulated fastest at low canopy coverage. The concentrations of Na and Mn were different at various elevations, but there was no obvious regularity. These results illustrate the seasonal characteristics of litter element return and nutrient cycling during litter decomposition in typical coniferous forests in the Qilian Mountains and could provide basic data and theoretical basis for ecological protection in the Qilian Mountains.

KEYWORDS
canopy coverage, conifer, element return, elevation, litter decomposition, needle litter, nutrient cycling, Qilian Mountains

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INTRODUCTION

Litter decomposition is the second most important ecosystem function after primary production (Wilkinson, 1998), which plays a major role in biogeochemical cycling in ecosystems (Yue et al., 2021). Forest litter decomposition is strongly associated with energy flow and nutrient cycling, and it is the main way for organic matter to transfer from vegetation to the soil surface (Hobbie, 2015; Villar et al., 2001). Scientists' interest in litter has been focused on litter decomposition rate and factors affecting litter decomposition (Liu et al., 2016; Lu et al., 2017; Perez et al., 2013) and has addressed nutrient cycling during the litter decomposition process (Guo & Sims, 1999; Rahman et al., 2013). In the past decades, considerable studies have been devoted to understanding the key elements affecting decomposition litter such as C, N, and P (Bo et al., 2020); only a few studies have focused on the dynamics of Na and Mn during litter decomposition (De Marco et al., 2023; Xu et al., 2019).

Nutrient elements are essential for plant growth. The nutrient content in plants not only reflects the ability of plants to absorb and accumulate mineral nutrients, but also reflects the nutrients contained in individual plants in terrestrial ecosystems (Shao et al., 2012). Sodium and manganese have been recognized as important nutrients in forest ecosystems and are involved in plant photosynthesis and residues degradation (Kaspari et al., 2008; Pang et al., 2022), which play a crucial role in soil fertility and plant physiology (Bai et al., 2022). Sodium is generally not essential for plants tissues (Wu, 2018), but critical to the metabolism of plant consumers and decomposers (Kaspari et al., 2009). A previous study indicated that Na content indirectly affected litter decomposition by regulating the decomposer community and activity (Li et al., 2020). Na^+ is involved in the formation of chlorophyll in many C_4 plants and can stimulate plant growth, but it is easily lost due to the leaching effect (Wang et al., 2023). Ji et al. (2020) also proposed that Na amendment enhances soil extracellular enzyme activity and soil faunal abundance to promote litter decomposition. As the main component of litter, the decomposition of lignin is a complex process that requires the cooperation of several extracellular enzymes (Hemati et al., 2022). Certain litter decomposing fungi secrete manganese peroxidase (MnP), mostly into their microenvironments, and MnP is thought to play a vital role in lignin degradation (Berg et al., 2013; Martin, 2002). As a necessary component of MnP (Perez & Jeffries, 1992; Wu et al., 2022), the importance of Mn in affecting litter decomposition has been observed. Sun et al. (2019) found that Mn addition promoted later stage of litter decomposition. And initial root Mn concentration and Mn supply capacity of the decomposition environment jointly control root decomposition rates throughout the decomposition process (Chen, Sun, et al., 2023). Litter decomposition also regulates the transfer and cycling of nutrient elements such as Na and Mn across terrestrial ecosystems (Peng et al., 2023). Litter Na and Mn are critical elements in the energy metabolism of forest ecosystems, which are important for biogeochemical cycling (De Marco et al., 2023; Jia et al., 2015). However, they can affect microbial communities and litter decomposition process when they exceed certain levels, and thereby impact soil health (Peng et al., 2023). Understanding the dynamics of Na and Mn in litter during decomposition is important to resolve the source and sink terms of Na and Mn in the forest floor.

Litter decomposition is a complex process, and its main controlling factors are climate, litter quality, and decomposers (Bradford et al., 2016; Cornwell et al., 2008; Yu & Zhou, 2016). Canopy coverage can also increase the leaching effect of precipitation on litter surface and regulate the processes of nutrient release during litter decomposition (Chen, Zhu, et al., 2023). Previous studies have shown that there is more snow cover in the gap in winter, which makes the microorganisms maintain higher activity, while stronger precipitation and radiation in the growing season increase the leaching of litter, thus promoting the loss of litter quality (Li, Du, et al., 2022; Li, Lv, et al., 2022). Wu et al. (2014) showed litter N release rates were higher in the center of canopy gaps than under closed canopy. Elevation changes the light, temperature, and humidity, making the hydrothermal conditions and the characteristics of the forest microenvironment significantly different, thus affecting the nutrient cycling process of litter (Yang et al., 2006). Temperature decreases with the increase of elevation, and the microbial activity decreases accordingly, which may directly affect litter decomposition (Li et al., 2021). Lu and Liu (2012) found that litter N content increased with increasing elevation.

The Qilian Mountains are the important ecological security barrier in northwest China (Ba et al., 2022). Qinghai spruce is the main constructive species of the mountain forests in the Qilian Mountains, which play a vital role in water conservation, soil maintenance, air purification, biodiversity protection, and regional ecological balance (Ta et al., 2021). Previous studies mainly focused on litter yield (Li, 2021), decomposition rate (Li et al., 2021), hydrological effects (Liu & Che, 2004; Meng et al., 2013), and effect of litter on soil respiration (Xie et al., 2017; Yang et al., 2022) of Qinghai spruce forest in the Qilian Mountains. The circulation mechanism of Na and Mn in forest litter during the decomposition period has not been reported. This study aims to improve our understanding of nutrient cycling, productivity and stability of the Qilian Mountain ecosystems.

Taken together, we investigated the seasonal pattern of Na and Mn in needle litter, and explored the dynamics of Na and Mn during needle litter decomposition in the Qilian Mountains. To improve the understanding of Na and Mn release from forest litter, we performed two separate experiments: a 1-year litter collection experiment and a litter bag decomposition experiment over approximately 4 years. Our research objectives were to (1) investigate the concentration and flux of Na and Mn in the needle litter of Qinghai spruce and (2) reveal the accumulation and release pattern of Na and Mn during needle litter decomposition at different elevations and canopy coverage. Our study provides basic data for the plant input of Na and Mn in forest soil, and will promote the study of the biogeochemical cycle in the forest ecosystem in the Qilian Mountain. Our study tested two hypotheses: (1) needle litter Na and Mn show obvious significant temporal and spatial patterns; (2) litter Na and Mn concentrations are significantly regulated by litter decomposition time and litter mass.

MATERIALS AND METHODS

Study site

This study was conducted at the Tianlaochi catchment (38°23′56″–38°26′47″ N, 99°53′57″–99°57′10″ E) in the Qilian Mountains, northwest China. It has an area of approximately 12.8 km^2 and an elevation range of 2600–4450 m (Zang et al., 2021). This region has an alpine climate, with the mean annual temperature of approximately 0.6°C. The rainy season is from May to September and the mean annual precipitation is 535.9 mm from 2014 to 2019 (Wang et al., 2022). The main vegetation types in the catchment include steppe, alpine meadow, shrubs, bare rock, and forest. The dominant tree species in the catchment are Qinghai spruce (*Picea crassifolia* Kom.) and Qilian juniper (*Sabina przewalskii* Kom.). The soil in the study region primarily consists of mountain gray cinnamon soil. According to its characteristics, it can be divided into three sub-categories: mountain leaching gray-brown forest soil, mountain carbonate gray-brown forest soil, and typical brown forest soil (Zang, Wu et al., 2024).

Experiment design and field sampling

A litter collection experiment was established at four elevations (2800, 2850, 3050, and 3200 m) of the Qinghai spruce forest. We randomly selected six replicate frames (70 cm × 70 cm) in each plot (30 m × 30 m), and there were 24 litter samples in each month. Fresh litter samples were collected in the abovementioned plots in the middle of each month during September 2020 and August 2021. The collected litter was transported to the lab and then sorted into four parts: needle, branch and bark, cone, and impurity. All litter samples were oven-dried at 65°C to a constant mass. All needle litter samples were crushed, screened and then used for the determination of Na and Mn concentrations.

The litter decomposition experiment was set at four elevations (2850, 3050, 3250, and 3450 m) and three canopy coverages (high [80%], middle [73%], and low [67%] canopy coverage) using a litter decomposition bag method. The litter decomposition experiment at different canopy coverages was only at 2850 m (30 m × 30 m). The specific sample information is shown in Appendix S1: Tables S1–S3. Litter bags (10 cm × 8 cm) were made of nylon mesh (mesh size 1 mm^2) and filled with 5 g needle litter samples. Litter from the Qinghai spruce forest was collected every 2–3 months from April 2016 to August 2020. The collected samples were transported to the lab and then cleaned to remove impurities. All litter samples were oven-dried at 65°C to a constant mass.

Measurement of element concentration

Litter Na and Mn were analyzed as follows: a 0.2000-g litter sample was placed in a microwave digestion tank and 8 mL HNO_3 and 2 mL H_2O_2 were added. The mixtures were digested with a microwave digestion instrument (Multiwave PRO, Anton Paar, Austria). The concentrations of Na and Mn in the digested solution were determined by inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7800, United States). For quality control and assurance, the digestion blank, duplicates and standard reference material (GBW10023 [GSB-14]) were used. The digestion blanks were lower than the detection limits of the instrument. The SD of the duplicates was <5%. The mean recoveries of Na and Mn in standard reference material were 97.6% and 96.2%, respectively, and the relative SD was below 5%.

Calculations and data analysis

The fluxes (F) of litter Na and Mn were calculated using the following formula:

$$F = C_{Na/Mn} \times P,$$

where C (in milligrams per kilogram) is the concentration of litter and P (in kilograms per hectare) is the needle litter production.

The mass loss (M) during litter decomposition was calculated using the following formula:

$$M = \left(1 - \frac{M_t}{M_0}\right) \times 100\%,$$

where M_0 (in grams) is the mass of the initial litter and M_t (in grams) is the residual mass of litter after decomposition time t (in days).

The element release rate (R) during litter decomposition was calculated using the following formula:

$$R = \left(1 - \frac{M_t X_t}{M_0 X_0}\right) \times 100\%,$$

where X_0 (in milligrams per kilogram) is the initial element concentration in litter and X_t (in milligrams per kilogram) is the element concentration in litter at decomposition time t (in days).

The temperature and humidity were obtained using a temperature and humidity meter, and the recording interval was 30 min. The daily temperature and humidity data were obtained by calculating the average value, and then the monthly average value was obtained. A one-way analysis of variance was used to test the differences in element concentrations and fluxes in the needle litter. Duncan's test was used to compare differences between elevations and canopy coverages at each sampling date ($p < 0.05$). Linear regression was used to determine the relationship between element concentration and litter decomposition ($p < 0.001$). The data were analyzed using SPSS version 25, and all the charts were drawn using Origin 2021 and R (version 4.2.2).

RESULTS

Na and Mn concentrations and fluxes of needle litter

Figure 1 shows the difference of Na and Mn concentrations in needle litter among four elevation gradients. During the entire sampling year, the highest Na (380.78 mg kg^{-1}) and Mn (1049.12 mg kg^{-1}) concentrations appeared at 3050 m, while the lowest Na (235.67 mg kg^{-1}) and Mn (366.63 mg kg^{-1}) concentrations in needle litter were found at 2800 m. The Na concentrations of needle litter showed significant seasonal variation at four elevations, while there was no significant difference between Mn concentrations in needle litter and elevations among various months. The highest value of Na concentrations in needle litter usually appeared from April to June 2021. The Na concentrations in needle litter at 2800 m were significantly lower than other elevations except in April 2021. During each month, Mn concentrations in needle litter at 3050 m were much higher than that of 2800 m.

There were significant differences of Na and Mn fluxes in needle litter among different elevations (Figure 2). The highest Na flux (322.53 g ha^{-1}) in needle litter appeared at 3200 m, and the highest Mn flux (527.79 g ha^{-1}) in needle litter appeared at 3050 m. The lowest Na (196.63 g ha^{-1}) and Mn (194.48 g ha^{-1}) fluxes in needle litter were found at 2800 m. The Na and Mn fluxes in needle litter were significantly highest in October 2020 to April 2021 at 2800, 2850, and 3050 m, and reached the maximum value in October 2020–May 2021 at 3200 m. The fluxes of Na and Mn in needle litter were generally lower in July–September.

Concentration and release rate of Na and Mn during litter decomposition

Na and Mn dynamics at different canopy coverages

The Na and Mn concentrations in needle litter increased significantly with decomposition time at the high, middle, and low canopy coverages (Figure 3). The concentrations of Mn and Na were significantly positively correlated with decomposition time ($p < 0.001$). The concentration of Na in needle litter increased at 0–321 days and then decreased slightly at 415–710 days, following a remarkable increase at 1053–1410 days. After 3.9 years of litter decomposition, the average Na concentration was 44.57 mg kg^{-1}, which was higher than the initial concentration (76.84 mg kg^{-1}). Likewise, the concentration of Mn showed a general increase pattern in decomposing litter at all canopy coverage during different decomposition time. And the average concentration of Mn in needle litter was higher than the initial value (120.69 mg kg^{-1}) at 1410 days. Litter Na showed an accumulation pattern at low and high canopy coverages during the 3.9-year decomposition period (Appendix S1: Figure S1). Although with some fluctuations, Mn generally showed an accumulation pattern at the three canopy coverages. Litter Mn accumulated most at 1318 days, which were 1.96, 1.67, and 1.65 times higher than the initial value at high, middle, and low canopy coverage, respectively. They accumulated the least at 620 days, which were 0.06, 0.24, and 0.27 times higher than the initial value, respectively.

Na and Mn dynamics along different elevations

The concentration of Na increased with decomposition time (Figure 4). The initial Na concentration was 76.84 mg kg^{-1}. After the 3.9-year decomposition, litter Na lost 0.34 mg kg^{-1}

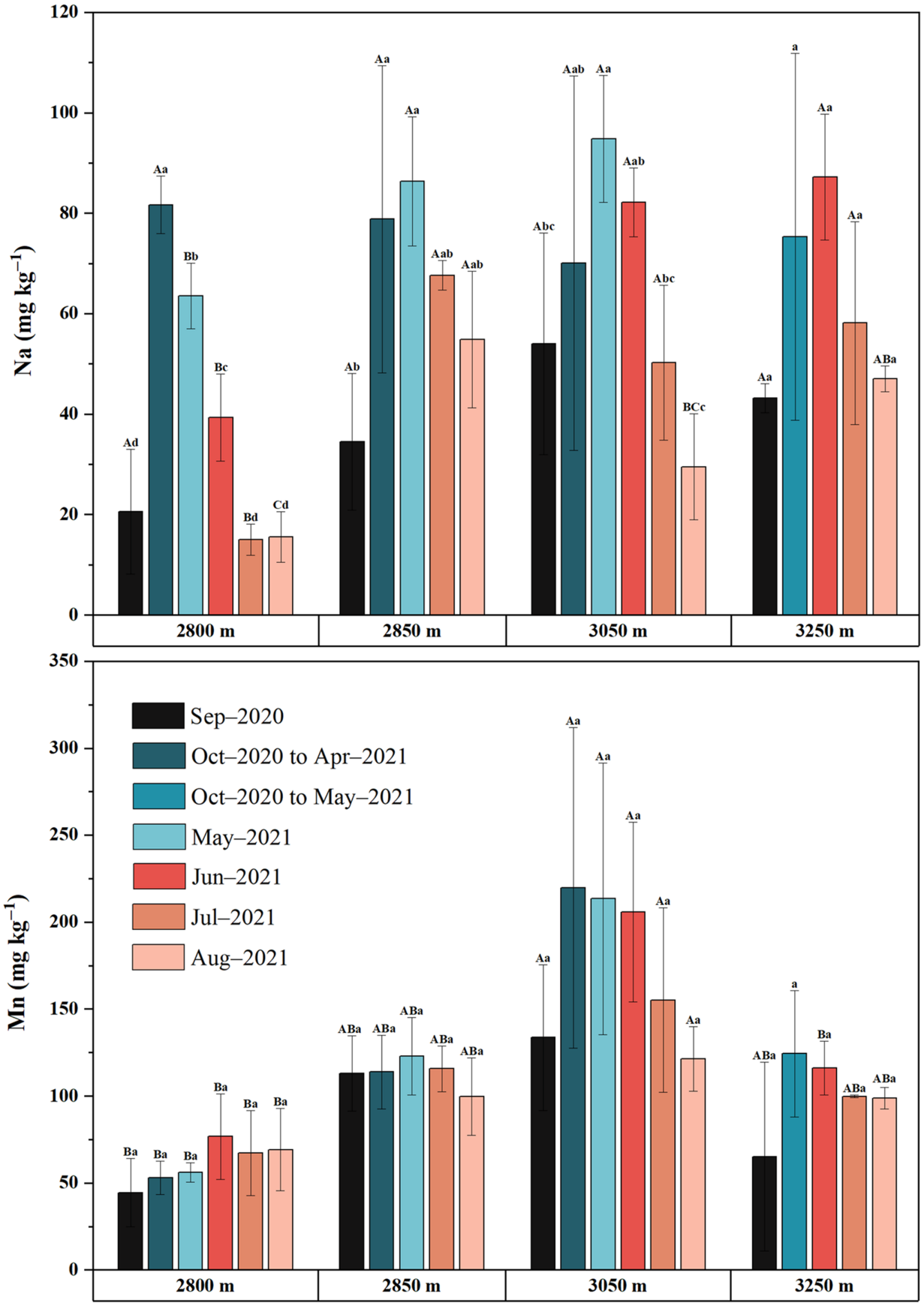


FIGURE 1 Legend on next page.

at 3250 m and accumulated 9.03–22.06 mg kg^{-1} at other elevations compared with its initial concentration. The Na concentration in decomposing litter increased fastest at 3450 m, and increased most slowly at 3050 m. After the 3.9-year decomposition, Na lost 14%–31% of its initial concentration. Although Na generally showed an accumulation pattern, the accumulation occurred at 213, 259, and 1053 days of decomposition. Na released fastest at 710 days at elevations of 3050, 3250, and 3450 m. The concentration of Mn was increased with decomposition time. The initial Mn concentration was 49.56 mg kg^{-1}, respectively. After the 3.9-year decomposition, Mn accumulation was 39%–99% higher than initial Mn concentrations at all elevations. The Mn concentration increased fastest at 3050 m and increased most slowly at 3450 m. Litter Mn always accumulated and the accumulation rates at 2850, 3250, and 3450 m were the fastest at 1053 days, which were 149%, 146%, and 111% higher than initial concentration values, respectively.

Effects of decomposition time and litter quality on Na and Mn release rates

The concentration of Na and Mn in needle litter increased with increasing decomposition time (Appendix S1: Figure S2). The Na and Mn concentrations were significantly correlated with decomposition time ($p < 0.001$). Here we found that Na was accumulated during the first 259 days, and then released in 321–710 days of litter decomposition (Figure 5). Na accumulated at 1053 and 1318 days and accumulated 11% and 47%, respectively. Compared with the initial value of the element, 15.5% was released in 1410 days. In contrast, Mn accumulated obviously throughout the decomposition process, increasing by 93.4% compared to the initial value of the element at 1410 days. There was a positive correlation between Na release rate and litter mass loss (Figure 6). The release rate of Mn was significantly negative corrected with litter mass loss ($p < 0.001$), which indicated that Mn was accumulated with litter mass loss.

DISCUSSION

The concentrations and fluxes of Na and Mn in needle litter

Our results revealed that the annual concentrations of Na and Mn were 312.34 and 621.19 mg kg^{-1}, respectively. The content of Mn in needle litter was relatively high, which was similar to the results of Liu (2007), indicating that there was no significant transfer of Mn before litterfall. Moreover, as the main element involved in photosynthesis, Mn concentration was higher in leaves (Berg et al., 2013). The highest Na concentration appeared in April–June 2021. The maximum values of the litter Na return dynamics in a primary dark coniferous forest occurred in May and October (Zeng et al., 2020). This may be due to seasonal leaching, such as bulk precipitation, dry deposition, throughfall, and stemflow (Pereira et al., 2022; Tonello et al., 2022). The annual fluxes of Na and Mn were 0.23 and 0.34 kg ha^{-1}, which were similar to the annual return of litter Na (0.13–0.58 kg ha^{-1}) and Mn (0.16–0.48 kg ha^{-1}) in alpine forest ecosystems (Wu et al., 2021). According to previous studies, the nutrient return from litter is jointly controlled by litter production and its element concentration, with factors affecting litter production also influencing the amount of nutrients returned in the litter (Fu, 2020; Yang et al., 2006). The highest Na and Mn fluxes appeared in April 2021, which may be due to higher litter production during this period. Annual litter production was the main factor governing the annual return of nutrients (Zeng et al., 2020), and seasonality also affected the litter nutrients return (Tonello et al., 2022). The seasonal pattern of litter may be attributed to temperature and rainfall (Pereira et al., 2022). The fluxes of both Na and Mn increased with higher elevations, reaching the maximum at 3050 m, which is consistent with the altitude difference of needle litter production (Zhao et al., 2024). There were correlations between some forest stand characteristics (e.g., stand age, litter mass) and element concentrations (Radwan et al., 1984). More research is needed to explore how environmental and internal factors regulate litter Na and Mn return.

The dynamics of Na and Mn during litter decomposition

In the current study, we found that the release rate of Mn was significantly correlated with the decomposition time ($p < 0.001$), and Na release rate gradually decreased with the decomposition time ($p = 0.239$; Appendix S1: Figure S3). Litter Na has been reported to be accumulated in a broad range of forest ecosystems (Bai et al., 2022; He et al., 2014; Qu et al., 2010). The enrichment of Na and Mn indicated that leaf litter may have acted as an efficient nutrient storage pool on the ground in decomposing litter.

FIGURE 1 Variation of Na and Mn concentrations in needle litter at different elevations from September 2020 to August 2021. Bars represent mean ± SD. Lowercase letters indicate significant differences among different months; uppercase letters indicate significant differences among different elevations ($p < 0.05$).

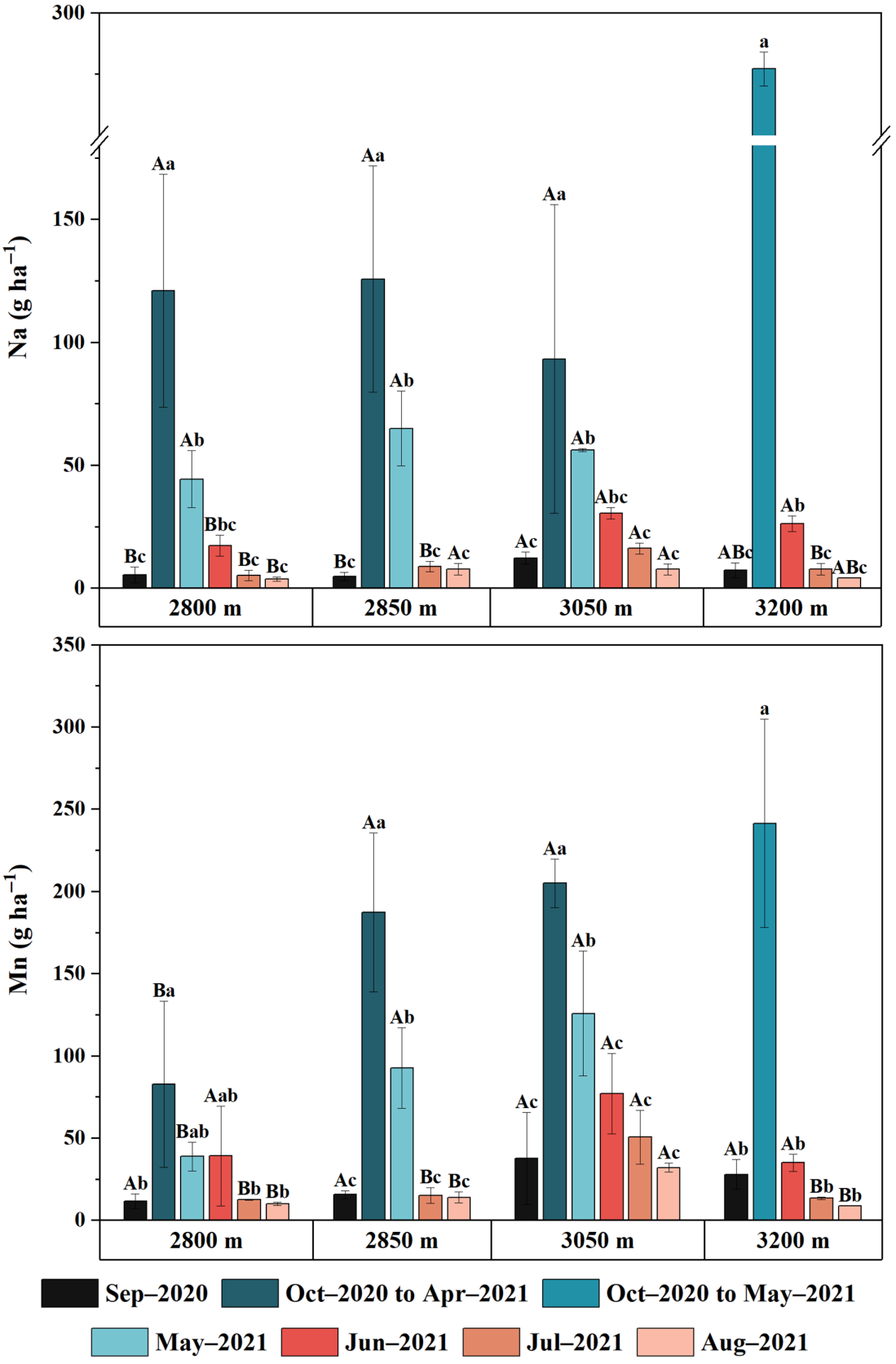


FIGURE 2 Variation of Na and Mn fluxes in needle litter at various elevations from September 2020 to August 2021. Bars represent mean ± SD. Lowercase letters indicate significant differences among different months; uppercase letters indicate significant differences among different elevations ($p < 0.05$).

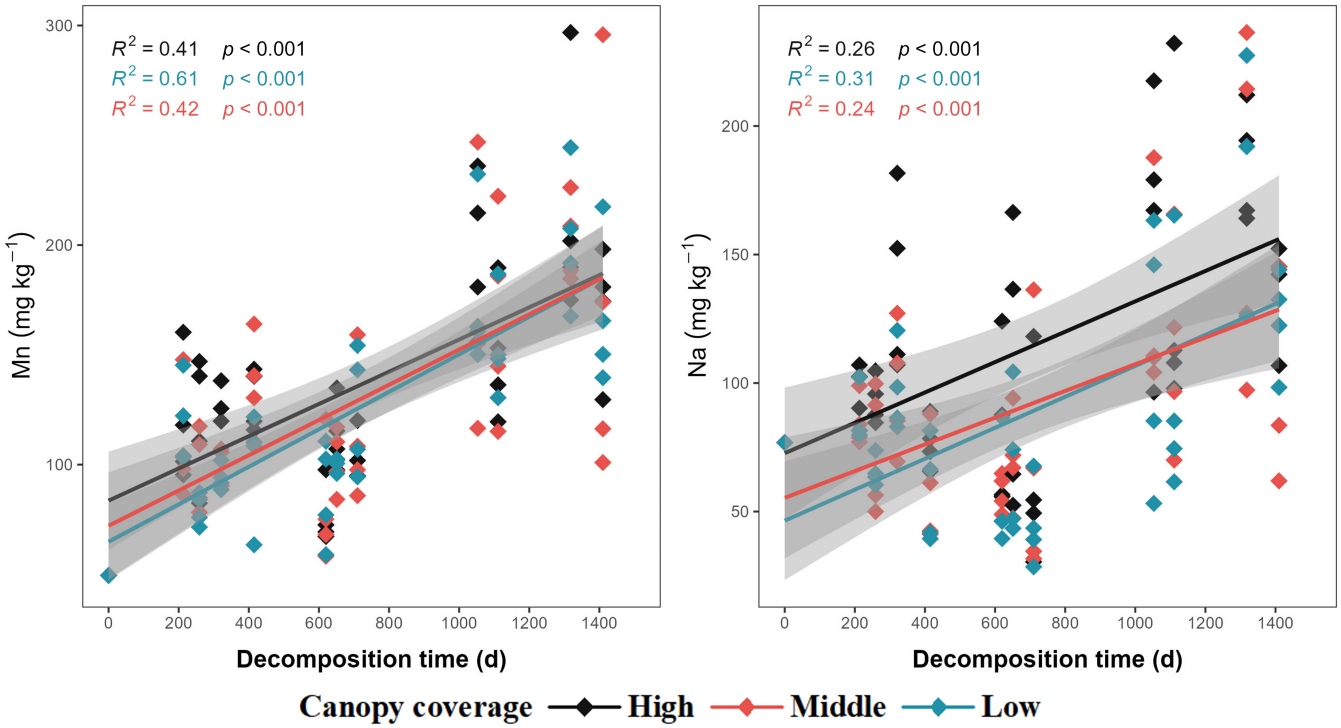


FIGURE 3 Variations of Na and Mn concentrations among different canopy coverages during litter decomposition ($p < 0.001$).

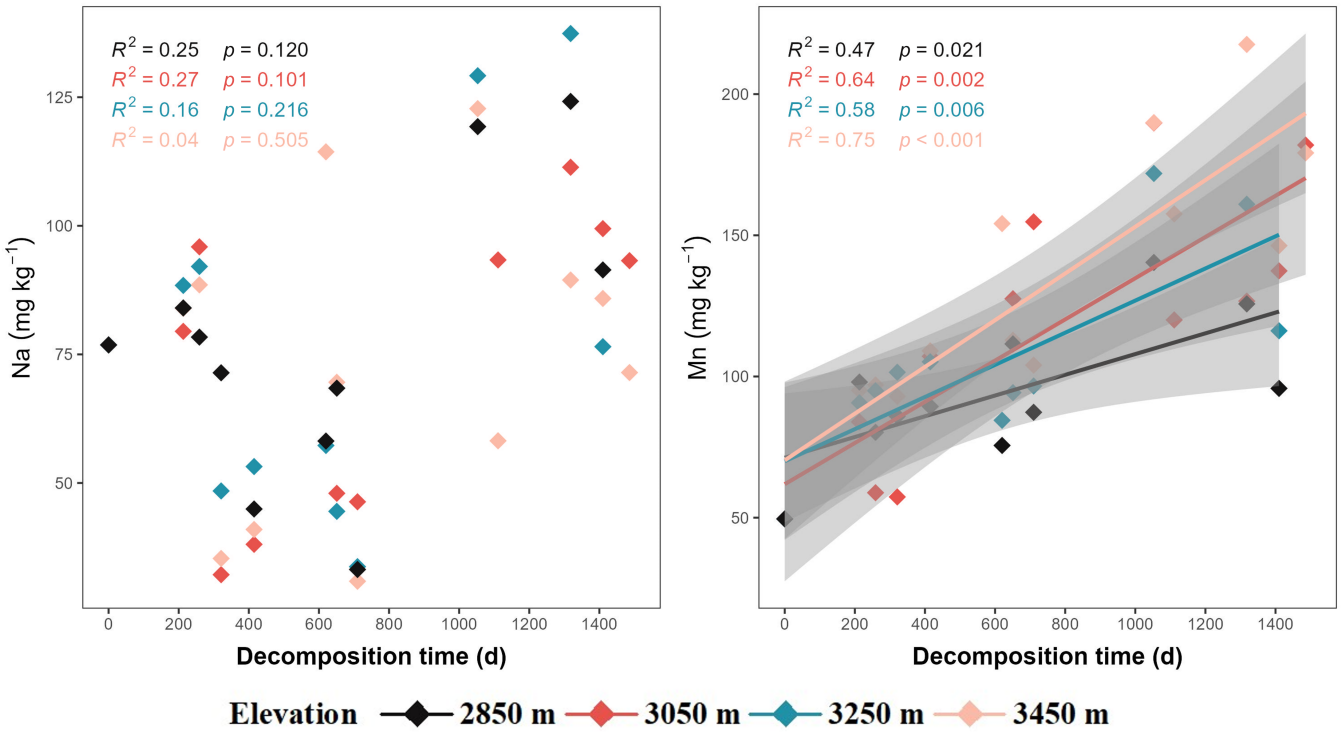


FIGURE 4 Variations of Na and Mn concentrations among different elevations during litter decomposition ($p < 0.001$).

Since no measurement of the concentration of Na and Mn elements was conducted in the soil around litter decomposition bags, we can only speculate the source of Mn enrichment in litter decomposition. This may be attributed to the fact that Na is easily transferred and reused in plants. And it is transferred to other parts of the plant before defoliation, resulting in low concentrations in litter and obvious accumulation during decomposition

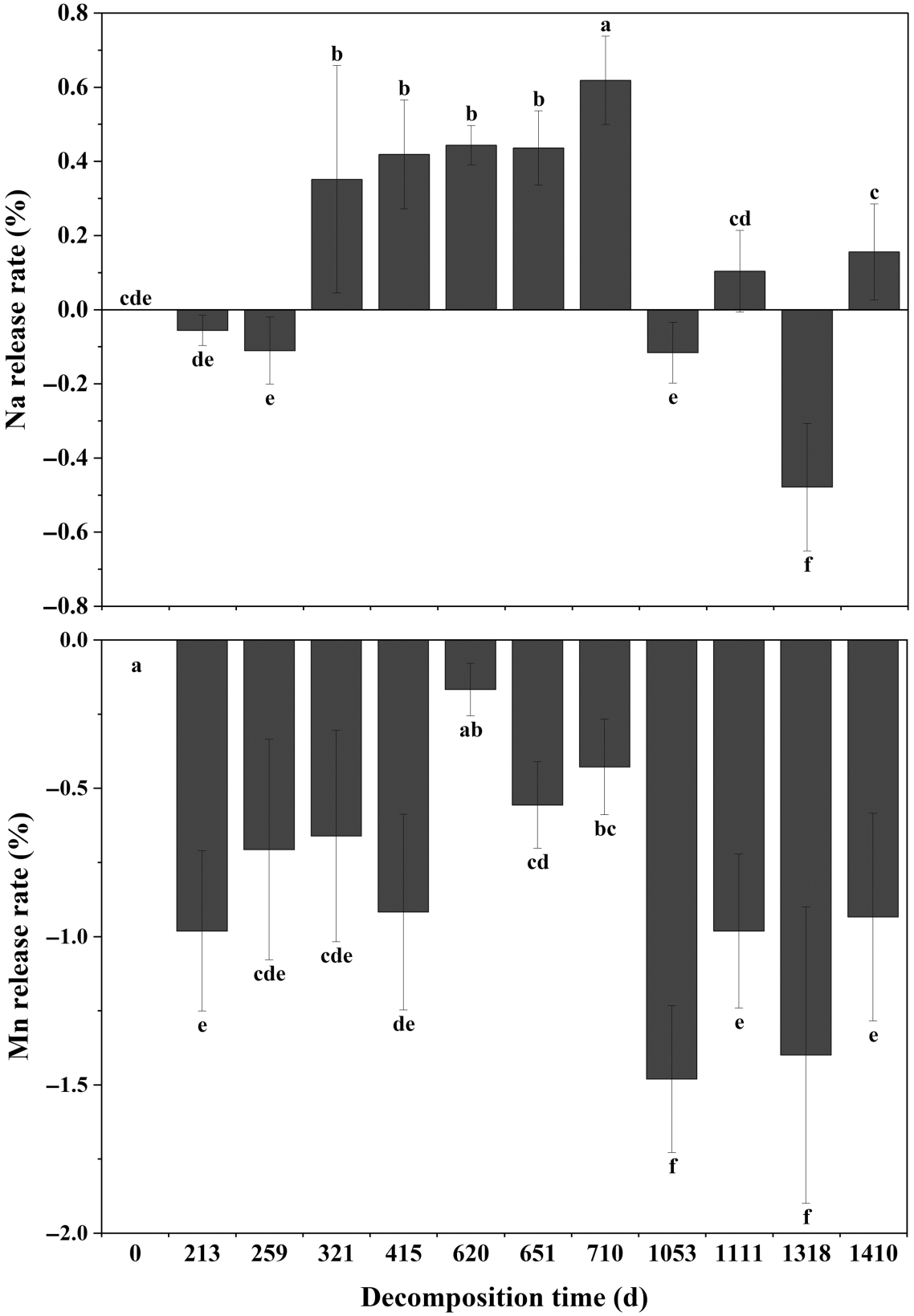


FIGURE 5 Release rates of Na and Mn in decomposing litter. Different lowercase letters indicate significant ($p < 0.05$) differences among decomposition stages.

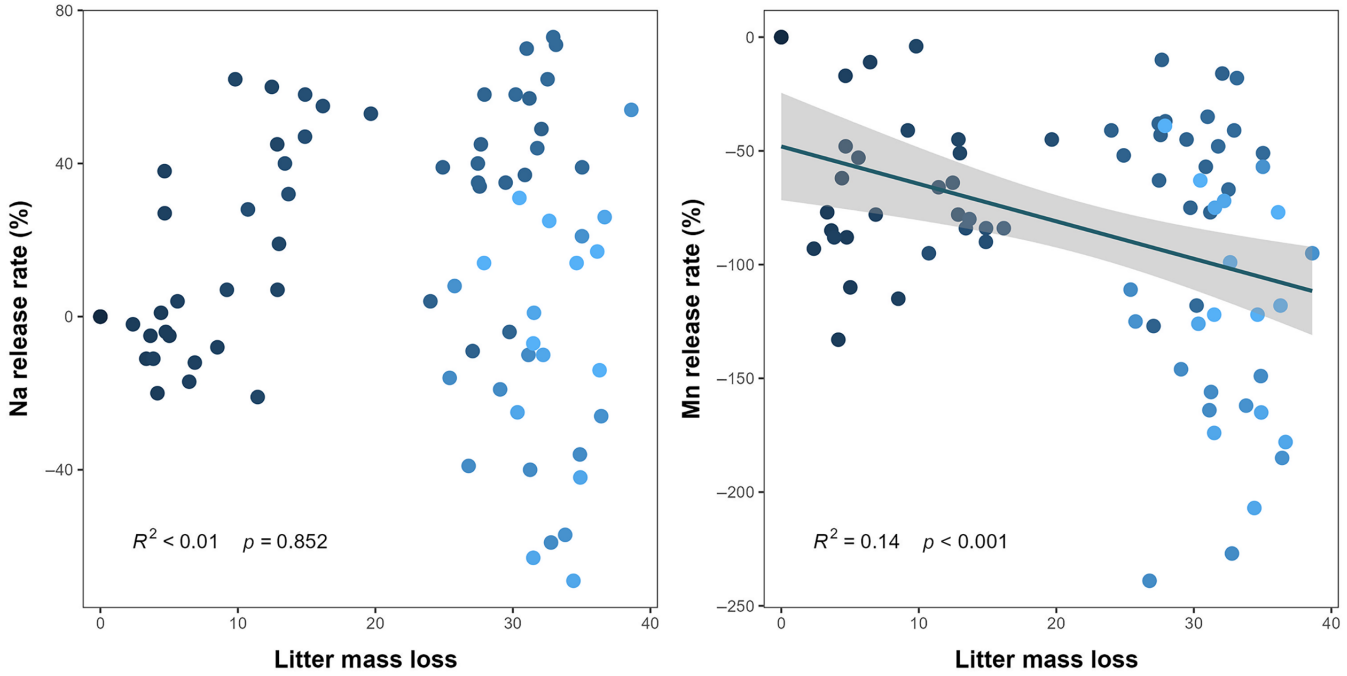


FIGURE 6 The correlation between litter mass loss (%) and element release rate during litter decomposition. The gray bands represent the 95% CI.

(Qu et al., 2010). Pandey et al. (1993) also suggested the possibility of redistribution of elements in plants. However, a recent study indicated that Na was released as decomposition proceeded, possibly because it was subjected to intense physical leaching (Xu et al., 2006). Nickmans et al. (2019) also found that the accompanying tree species had positive effects on local return of Mn. The accumulation of Mn during litter decomposition may be caused by the microbial immobilization and perhaps even the transport of fungal hyphae from soil (Berg et al., 1991). Studies have also shown that cellulose and hemicellulose in plant litter began to decompose and form a large number of large molecular mass organic matter (Peng et al., 2023; Xu et al., 2019). High-molecular mass components are more likely to form insoluble complexes or coprecipitation with heavy metals, thus promoting the adsorption of heavy metals by sediments (Guven & Akinci, 2008; Kaiser & Zech, 1998). In addition, as the critical component of MnP, the accumulation of Mn can be attributed to the adsorption of Mn from the ambient environment during microbial community degradation (Sun et al., 2019; Yue et al., 2021). However, Mn content was released in the coniferous forest of the Changbai Mountains (Wang, 2016), which was different from our results. Litter Mn relative release rate is related to initial Mn concentration (Berg et al., 2013).

The dynamics of litter nutrients in decomposition process may be controlled by three major factors, including litter substrate, climatic conditions, soil animals and microorganisms (Xu et al., 2006). The litter quality significantly influenced nutrient release (Wang et al., 2017), and increased temperature also enhanced nutrient release (Li, Lv, et al., 2022). Litter Na accumulated during the first 259 days, which may be because litter has more easily degradable substances that can be directly used by decomposers in the early stage of decomposition (Chen, Sun, et al., 2023; Chen, Zhu, et al., 2023). In the subsequent 321–710 days of decomposition time, the rapid release of Na can be attributed to litter has to maintain Na balance, because both Na deficiency and excess are not conducive to decomposers and consumers (Jia et al., 2015; Yue et al., 2016). In contrast, Mn showed a negative release trend throughout the whole decomposition process, and in 1053 days, it accumulated up to 140% of the initial value. As Mn occurs in ionic form, it has potentially higher mobility (Berg et al., 2013). The Mn concentration accumulated faster than Na, which is probably due to its lower initial concentration in needle litter (Brun et al., 2008). Our results showed that Na was released and Mn was accumulated with litter mass loss (Figure 6), which agrees with the findings of Ji et al. (2020). Litter Na exists in ionic state in plants, and its release may be due to the release of elements in litter when they reach a certain threshold (He et al., 2014). Mn enrichment accelerated decomposition of leaf litter with high lignin concentration (Wu et al., 2022).

The main patterns and influencing factors of element changes during litter decomposition

Totally, Na and Mn showed accumulation pattern with litter decomposition, indicating a significant immobilization pattern. The characteristic of this pattern is that the dominant effect of element flow may be different during different decomposition periods (Wang et al., 2003). Compared to our results, different species and their habitats can also cause differences in the element transfer pattern. For instance, litter K and Ca showed net release pattern and release–accumulation pattern in a natural evergreen broadleaved forest in the rainy area of western China (Hu et al., 2020). Ma et al. (2015) suggested that the nutrients release in litter were greatly influenced by seasonal rainfall. Litter species, decomposition time and their interaction have shown significant effects on element concentration (Wang, 2016). The dynamics of Na and Mn were basically consistent at all canopy coverage and elevations, but there were significant differences in Na and Mn concentrations among canopy coverage and elevations at partial decomposition time, differences that we ascribe to different climatic conditions. The concentration of Na and Mn both were accumulated fastest at low canopy coverage, which indicates strong microbial activity at low canopy coverage with sufficient light and high soil temperature (Wei et al., 2017). We found that the temperature was higher at lower canopy coverage during partial decomposition time, but humidity was highest at higher canopy coverage (Appendix S1: Figure S4). Of course, the nutrient cycle of litter decomposition cannot be simply explained by atmospheric temperature and humidity. It is also necessary to consider the interaction of environmental factors (such as soil physical and chemical properties, light, etc.), litter chemical properties, and soil microbial communities (Xu et al., 2006, 2019). The concentration of Na was faster at higher elevations (3250 and 3450 m), while Mn accumulated faster at lower elevations (2850 and 3050 m). This may be due to the elements mass loss was significantly affected by elevations, sampling date and their interaction (Xu et al., 2010). The difference in temperature and humidity were the main factors affecting soil microbial activity and litter decomposition along the elevation gradient (Zhang et al., 2022). Xu et al. (2010) suggested that higher temperatures significantly increased element litter mass losses. Temperature was highest at 2850 m elevation at most times, and humidity was highest at 3050 and 3250 m at most times (Appendix S1: Figure S5). Previous studies have shown that temperature decreased with the rise in elevations, and microbial activity decreased, thereby slowing litter decomposition. However, our study did not find this rule in the release and accumulation of Na and Mn with elevation changes, which may be due to difference in microbial activities caused by soil bulk density and soil organic carbon (Andren et al., 2007; Trogisch et al., 2016; Wang et al., 2020). The dynamic mechanisms of Na and Mn were relatively complex, which are also closely related to the characteristics of the elements themselves and the fixation effect of microorganisms (He et al., 2014). Consequently, the main and secondary factors affecting the accumulation and release of Na and Mn during litter decomposition of Qinghai spruce in the Qilian Mountains have not been studied. As such, these effects of elements dynamics in decomposing litter need to be further explored. Our results provide relevant basic reference on understanding the biogeochemical cycles and material migration processes.

Our study has some innovations. Firstly, we discussed Na and Mn return from trees to soil. Secondly, we observed a long-term element dynamic during the litter decomposition period of about 4 years. Finally, few studies considered the accumulation and release trend of Na and Mn during litter decomposition at different elevations and canopy coverage in forest ecosystems. However, there are still several knowledge gaps that need to be addressed. Firstly, studies mainly have focused on elements dynamics during litter decomposition, which ignored the driving factors that cause element dynamics. Secondly, we did not collect litter samples in winter due to the limitation of experimental conditions, which led to the inability to get detailed understanding the mechanism of element cycling in winter. Finally, studies mainly have focused on Na and Mn dynamics, which limited the potential covariations among various elements. Therefore, we recommend that further research focus on the driving mechanism affecting element release and accumulation.

CONCLUSION

In summary, the results of this study show that the annual Na and Mn concentrations were 312.34 and 621.19 mg kg^{-1}, and the annual fluxes of Na and Mn were 236.67 and 343.16 g ha^{-1}, respectively. The concentrations and fluxes of Na and Mn showed obvious seasonal differences. Litter Na and Mn concentrations both showed accumulation pattern with litter decomposition time. The concentrations of Na and Mn both were accumulated fastest at low canopy coverage. The concentrations of Na and Mn were different at different elevations, but there was no obvious regularity. However, Na and Mn release rates decreased with the decomposition time. These findings are useful for mitigating nutrient imbalances and understanding forest material cycling and related ecological processes.

AUTHOR CONTRIBUTIONS

Xinning Zhao performed investigation, data curation, and wrote the original draft. Fei Zang performed investigation and contributed to writing, review, and editing of the manuscript and funding acquisition. Fangyuan Huang performed investigation and data curation. Na Li performed investigation. Chuanyan Zhao performed formal analysis and contributed to writing, review, and editing. All authors read and approved the final manuscript.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (32271710) and "Innovation Star" project of Gansu Province's outstanding graduate students (2022CXZX-094).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Zang, Zhao et al., 2024) are available from Dryad: https://doi.org/10.5061/dryad.j9kd51cnk.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Zhao, Xinning, Fei Zang, Fangyuan Huang, Na Li, and Chuanyan Zhao. 2024. "Accumulation of Sodium and Manganese during Litter Decomposition of Qinghai Spruce (*Picea Crassifolia*) Forest in China." *Ecosphere* 15(12): e70097. https://doi.org/10.1002/ecs2.70097