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ORIGINAL PAPER

Nitrogen addition promotes foliar litterfall and element return in a subtropical forest, southwestern China

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Abstract Nitrogen deposition has a considerable impact on biogeochemical cycling in terrestrial ecosystems. However, how litter production and element return respond to N addition remains poorly understood in nitrogen-rich subtropical regions. In this study, a 4-year nitrogen addition experiment explored its effects on foliar litter production and carbon, nitrogen and phosphorus in a subtropical *Michelia wilsonii* forest. A clear seasonal pattern in foliar litterfall was observed, regardless of nitrogen treatments, with a peak in spring and a smaller one in autumn. Foliar litter increased with increasing nitrogen but did not affect litter carbon concentrations and often decreased nitrogen and phosphorous concentrations. The effect of nitrogen addition was dependent on time (month/year). Carbon, nitrogen and phosphorous return showed similar bimodal seasonal patterns. Nitrogen addition increased carbon and nitrogen return but did not affect phosphorous. Our results suggest that the addition of nitrogen stimulates carbon and nutrient return via litterfall.

Keywords Nitrogen addition · Litterfall · Seasonal patterns · Element return · Subtropical forest

Introduction

Forest litterfall is a key pathway connecting above- and below-ground ecological processes and has a crucial role in maintaining long-term carbon (C) and nutrient balance (Vitoussek and Sanford 1986). In forests, over 80% of the carbon fixed via photosynthesis falls as litter and most of the nitrogen (N) and phosphorus (P) absorbed by plants is derived from decomposed litter (Bowden et al. 2019; Jia et al. 2019). The quality and quantity of C, N, and P from foliar litter are important in regulating the biogeochemical cycle in forest ecosystems (Jasinska et al. 2020).

Atmospheric N deposition has been increasing because of the rapid development of agriculture and industry in China (Liu et al. 2013; Stevens 2019). As one of the most important research fields of global change, increasing atmospheric N deposition can alter ecosystem carbon and nutrient cycling (Cabal et al. 2017; Liu et al. 2021a). Changes in litterfall and concentrations of C and nutrients, which is a vital component of biogeochemical cycling, can reflect ecosystem nutrient status and acquisition mechanisms (Liu et al. 2016; Wen et al. 2020). Recent meta-analyses indicated that N addition stimulates plant growth and alters leaf nutrient contents (Tian et al. 2018; You et al. 2018b). The effects of the addition of N on litterfall, however, have been inconsistent, depending on ecosystem types, site conditions, and levels of N addition (Cabal et al. 2017; Lu et al.

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2018; Mao et al. 2020). For example, the addition of 30 and 60 kg N ha^{-1} a^{-1} accelerated litterfall production in a Moso bamboo plantation, while 90 kg N ha^{-1} a^{-1} had no effect (Zhang et al. 2017a).

Litter nutrient return varies with biotic (species and composition) and abiotic factors (climate and soil fertility) (You et al. 2017; Shen et al. 2019; Park et al. 2020). Earlier studies have shown that N addition-induced changes in soil properties affected litter production, which in turn influenced nutrient return in forest ecosystems (Fu et al. 2019; Li et al. 2021). In addition to altering the amount of litterfall, the addition of N also affects litter quality, and further regulates litter nutrient return (Chen et al. 2015; Mao et al. 2020). For example, litter nutrient concentrations are regulated by the absorption and dilution by plants under N addition (Zhang et al. 2017b; Feng et al. 2019). However, current N deposition studies have scarcely focused on litterfall and nutrient return, particularly in medium- and long-term (3–10 years) studies. A clearer understanding of the effects of N deposition on biotic and abiotic factors and the dynamics of litterfall and nutrient return is essential for accurately modeling and predicting C and nutrient cycling in N-enhanced subtropical regions.

Soils of the western edge of the Szechwan Basin in southwest China are undergoing pronounced N accumulation because of heavy rainfalls and active N input (Xu et al. 2013). Previous studies have indicated that N addition significantly inhibited litter decomposition in this area (Liu et al. 2018). However, the effects of the addition of N on the dynamic of litter production and element return remain unknown in the unique subtropical ecosystems in this area. A 4-year experiment was conducted to determine the effect of N addition (0 controls, 20 and 40 kg N ha^{-1} a^{-1}) on foliar litter production and on C, N and P return in a subtropical *Michelia wilsonii* Finet & Gagnepain forest. The questions addressed were: (1) Does the addition of N affect foliar litterfall and C, N and P fluxes accompanying litterfall? (2) What are the roles of seasonal changes in regulating N effects? It was hypothesized that (1) N addition would increase foliar litter production, C and nutrient concentrations and returns; (2) the effect of N addition would be dependent on seasonal changes of biotic and abiotic factors.

Materials and methods

Study site

This study was conducted in a subtropical forest stand at the Forest Research Station of Lingyan Mountain of the Sichuan Agricultural University on the western edge of the Szechwan Basin (31°01′–31°04′ N, 103°37′–103°43′ E, 896–1320 m a.s.l). The research area is characterized by a temperate continental monsoon climate. The mean annual temperature is 14.4 °C, with a minimum of 4.9 °C in January and a maximum of 23.5 °C in August. The mean annual precipitation is approximately 1475 mm, with 80.9% occurring in the growing season (May to September) (Fig. 1). This stand is mainly dominated by *Michelia wilsonii* (> 80% of the basal area), a rare native species of the Szechwan Basin. The canopy cover is approximately 0.9 and the average diameter at breast height (DBH) is 18.9 cm. The soil is a ferralsol with old alluvial yellow loam according to the Chinese Soil Taxonomy (RGCST 2001). The organic C, N, P and pH in the upper 20-cm layer were 15.8 g kg^{-1}, 1.9 g kg^{-1}, 0.3 g kg^{-1} and 5.7, respectively (Liu et al. 2018).

Experimental design

In November 2015, nine 10 × 10 m plots at 10-m intervals were established. According to the ambient atmospheric wet N deposition (36.2 kg N ha^{-1} a^{-1}) in the study site (Yang et al. 2018), three treatments, three replicate plots per treatment, were set up: controls (0 kg N ha^{-1} a^{-1}), low-N addition (20 kg N ha^{-1} a^{-1}), high-N addition (40 N ha^{-1} a^{-1}). Both low-N and high-N addition simulate the scenarios that wet N deposition would be approximately increased by 50% and 100%, respectively. Our previous study has shown that both NH_4^+ and NO_3^- account for about 80% of the wet N deposition in the study area (Yang et al. 2018). In addition, a recent study has reported that atmospheric wet N deposition is dominated by almost equal parts NH_4^+ and NO_3^- in China (Yu et al. 2019). Therefore, a solution of NH_4NO_3 was sprayed on the forest surface once a month from December 2015 to December 2019. NH_4NO_3 was weighed, and dissolved in 10 L of water; each control plot received 10 L of nitrogen-free water. The total solution applied per year to

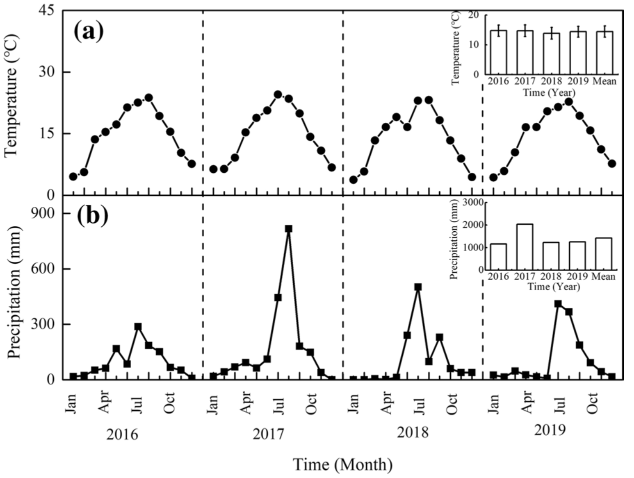


Fig. 1 Monthly dynamics of **a** temperature and **b** precipitation from 2016 to 2019 in the study area

each plot was equivalent to 1 mm of precipitation, less than 1% of the total annual precipitation (1475 mm). The small amount of additional water was considered to have no effect on the rainfall distribution pattern (see Zhuang et al. (2020) for further details).

Litterfall collection and chemical analysis

Eighteen litter traps (two traps/plot) were set in the plots 2-m from the quadrat boundary. The litter traps were funnel shaped with a 1-m diameter opening and a collection area of 0.78 m^2. The litter of each trap was collected monthly from January 2016 to December 2019. Several studies have demonstrated that forest litter production is dominated by foliage, and the other components have great spatial heterogeneity (You et al. 2017; Zhu et al. 2019). Our prior study also showed that litter production is mainly from foliar input in this forest stand (Pu et al. 2019). As a result, this study only focused on the foliar litter of the dominant tree species. Litter production was estimated after oven drying (65 °C, 72 h) to constant weight. Organic C, total N and total P concentrations were measured using dichromate oxidation, Kjeldahl determination (KDN, Top Ltd., Zhejiang, China) and phosphomolybdenum yellow spectrophotometry (TU-1901, Puxi Ltd., Beijing, China), respectively (Zhuang et al. 2018). The amount of C, N and P returned from forest litter was calculated by multiplying the monthly litter production by the corresponding C, N and P concentrations:

$$\text{Element return} = \text{Litter production} \times \text{Element concentration} \quad (1)$$

Data and statistical analyses

Repeated measure analysis of the variance was used to test the effect of N addition, time (month or year), and their interaction on foliar litter production and element (C, N and P) concentration and return. A correlation analysis assessed the relationships between the measured variables and environmental factors. Partial least squares (PLS) with coefficients and variable importance were performed to assess the relative importance of climate factor, element concentration and litter production to the element return under N addition. Statistical tests were considered significant at the $P < 0.05$ level. All statistical analyses were performed with SPSS software (SPSS 25.0 for windows; SPSS Inc., Chicago, IL, USA) and SIMCA 14.1 (Umetrics, Umeå, Sweden). Graphs were drawn with Origin (version 9.0 and 2019b).

Results

Dynamics of foliar litter production

There was a significant seasonal variation in foliar litterfall (Fig. 2). Regardless of N treatments, the monthly foliar litter

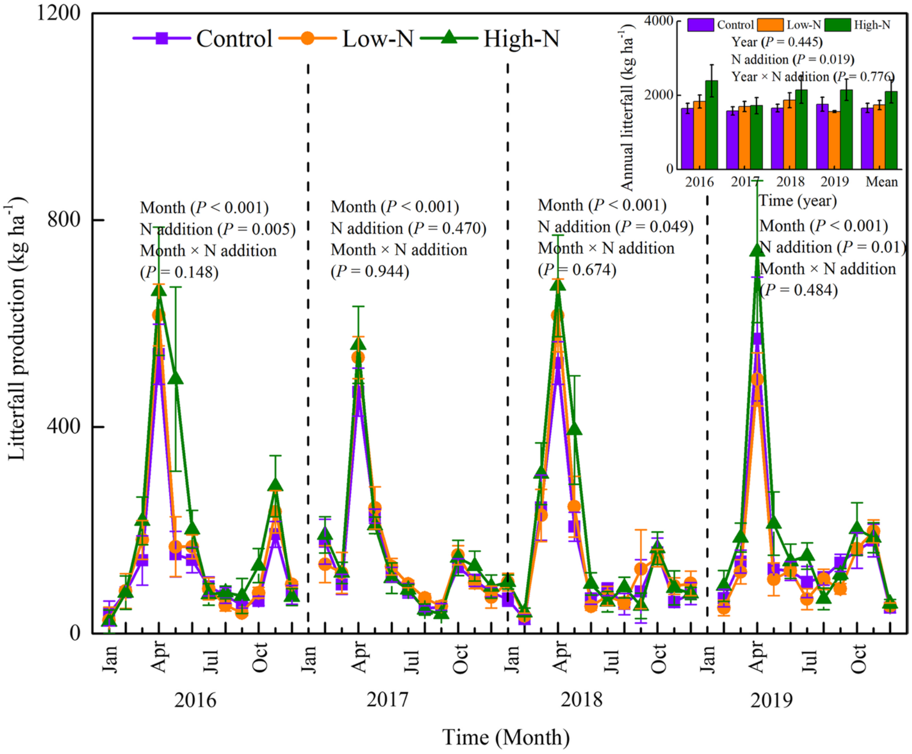


Fig. 2 Monthly dynamics of *M. wilsonii* foliar litter production; control (0 kg N ha^{-1} a^{-1}), low-N addition (20 kg N ha^{-1} a^{-1}), high-N addition (40 kg N ha^{-1} a^{-1}), values are means ± standard errors

production showed a bimodal pattern, with a major peak in spring (April) and a minor one in autumn (October–November) (Fig. 2). Annual production was 1957.2 kg ha^{-1}, 1665.1 kg ha^{-1}, 1890.8 kg ha^{-1} and 1823.2 kg ha^{-1}, respectively, in 2016, 2017, 2018 and 2019 (Fig. 2). The addition of N significantly increased litter production (Fig. 2). Particularly, high-N addition increased annual litterfall by 45.3%, 9.3%, 29.8%, and 22.0%, respectively. However, time (year) did not affect foliar litter production (Fig. 2).

Dynamics of C, N and P concentrations

C, N and P concentrations of the foliar litter showed monthly and yearly variations regardless of N treatments (Fig. 3). C concentration did not change monthly but there were interannual variations (Figs. 3 and 4). N and P concentrations were higher in the warm months (June to October) compared to the other seasons (Fig. 3). The annual average concentrations of C, N and P were 363.6–468.5 g kg^{-1}, 11.7 –13.4 g kg^{-1} and 0.6–0.8 g kg^{-1}, respectively (Fig. 3). The addition of N did not affect the concentration of C in the litter but it decreased N and P (Fig. 4). The effect of N addition on litter N and P concentrations was regulated by time (month or year) (Figs. 3 and 4).

3.3 Dynamics of C, N and P return.

Like litter production, the monthly fluctuations in C, N and P showed a bimodal pattern under both treatments, with a major peak in spring and a minor one in autumn (Fig. 5). Regardless of the addition of N, annual C, N, and P return were 672.2–854.1 kg ha^{-1} a^{-1}, 19.9–22.3 kg ha^{-1} a^{-1}, and 1.0–1.4 kg ha^{-1} a^{-1}, respectively (Fig. 5). The addition of N increased foliar litter C and N return but did not affect P (Figs. 4 and 5). High-N addition increased annual C return by 32.2%, 16.0%, 24.2%, and 20.2% in 2016, 2017, 2018, and 2019, respectively (Fig. 4). In general, the interaction between the addition of N and time (year and month) had no effect on element return (Figs. 4 and 5).

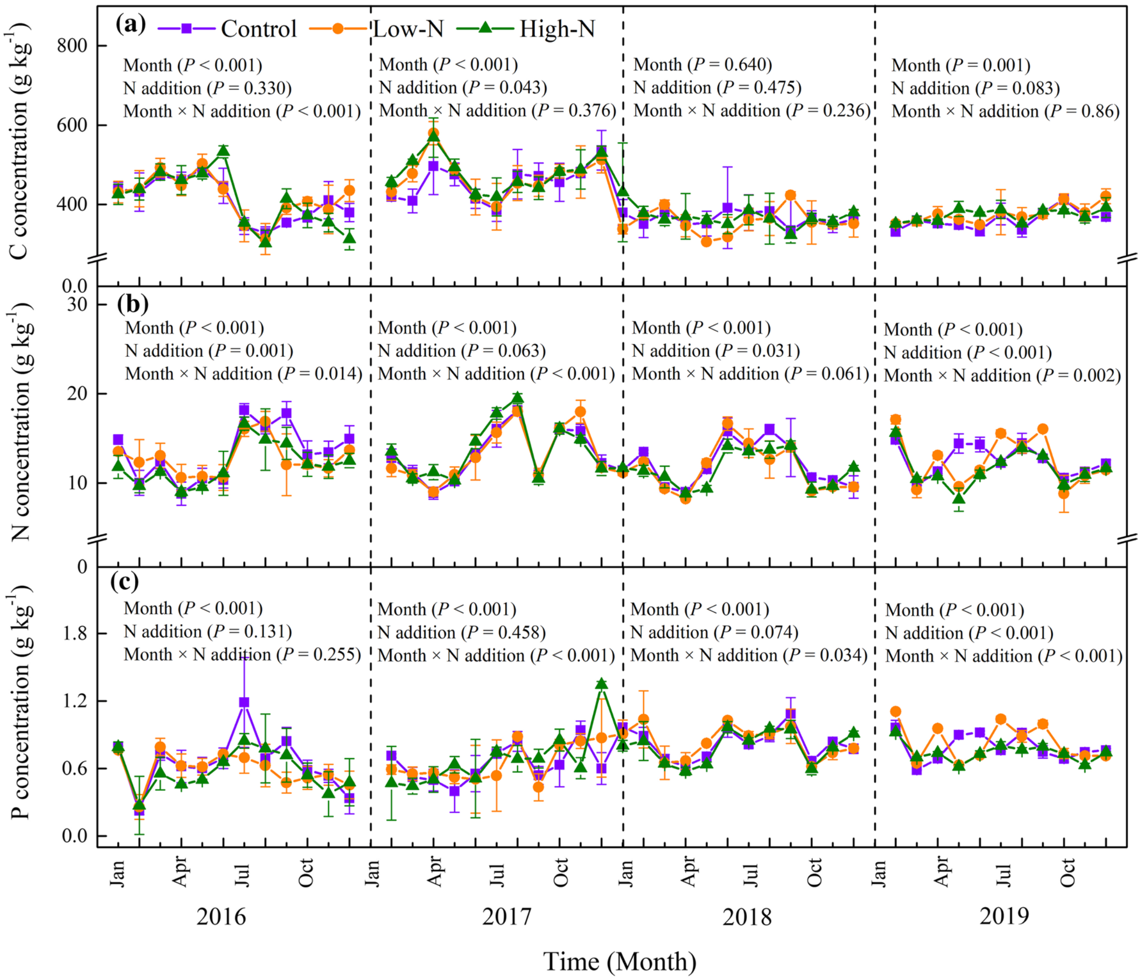


Fig. 3 Monthly fluctuations of carbon (C), nitrogen (N) and phosphorus (P) concentrations in *M. wilsonii* forest under different N additions; control (0 kg N ha^{-1} a^{-1}), low-N addition (20 kg N ha^{-1} a^{-1}), high-N addition (40 kg N ha^{-1} a^{-1}); values are means ± standard errors

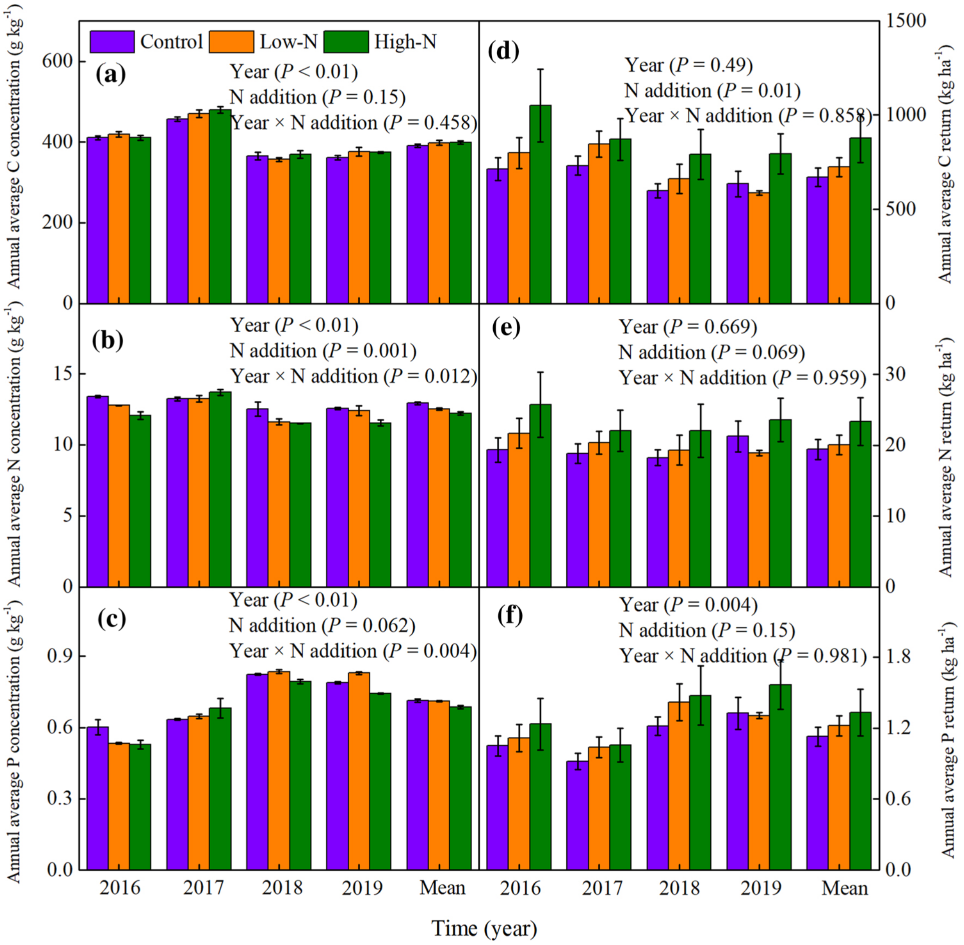


Fig. 4 Annual fluctuations of carbon (C), nitrogen (N) and phosphorus (P) in *M. wilsonii* forest under different N additions; control (0 kg N ha^{-1} a^{-1}), low-N addition (20 kg N ha^{-1} a^{-1}), high-N addition (40 kg N ha^{-1} a^{-1}), values are means ± standard errors

Relation between element return and climate factors

Correlation analysis showed that temperature was positively correlated with litter N concentration and precipitation was negatively correlated with litterfall, C, N and P return (Fig. 6). Litter production was negatively correlated with N and P concentrations (Fig. 6). In addition, PLS analysis showed that N addition induced increases in element return were attributed to litter production rather than climate or element concentration (Fig. 7).

Discussion

Effects of N addition on litterfall

A recent synthesis indicated that litterfall of evergreen broadleaved forests accounted for 37% of total global forest litterfall (Shen et al. 2019). Therefore, quantifying the leaf litterfall of subtropical evergreen broadleaved forests is crucial to understanding the global biogeochemical cycle. The litter production noted in this study is similar to observations of other evergreen broad-leaved forests, such as *Dendrocalamus brandisii* (Munro) Kurz (2072 kg ha^{-1} a^{-1}) (Bahru and Ding 2020) and *Cunninghamia lanceolata* (Lamb.) Hook. (2655 kg ha^{-1} a^{-1}) (Guo et al. 2015) in subtropical China but much lower than observed in other subtropical forests (Yang et al. 2005; Zhou et al. 2016; Park et al. 2020). The relatively low litter production in this study may be because only foliar litter was collected but other tissues (flowers, branches, fruits) were excluded (You et al. 2017). In addition, litter production varies with forest types (You et al. 2017; Shen et al. 2019) and depends on community composition, species abundance and basal area (Huang et al. 2018; Park et al. 2020).

The addition of N resulted in greater soil nutrient availability, leading to an increase in litter production (Tu et al. 2011; Li et al. 2021). Consistent with previous studies (Maaroufi et al. 2016; Zhang et al. 2017a; Zhao and Zeng 2019), and our initial hypothesis, the addition of N increased litter production. In contrast, N addition decreased litter production in a *Larix gmelinii* (Rupr.) Kuzen. forest and a *Cinnamomum camphora* (L.) Presl forest (Lv et al. 2013; Fu et al. 2019). Meta-analysis suggests that the response to N addition by litter is closely dependent upon plant functional types (Xia and Wan 2008). For example, the positive effect

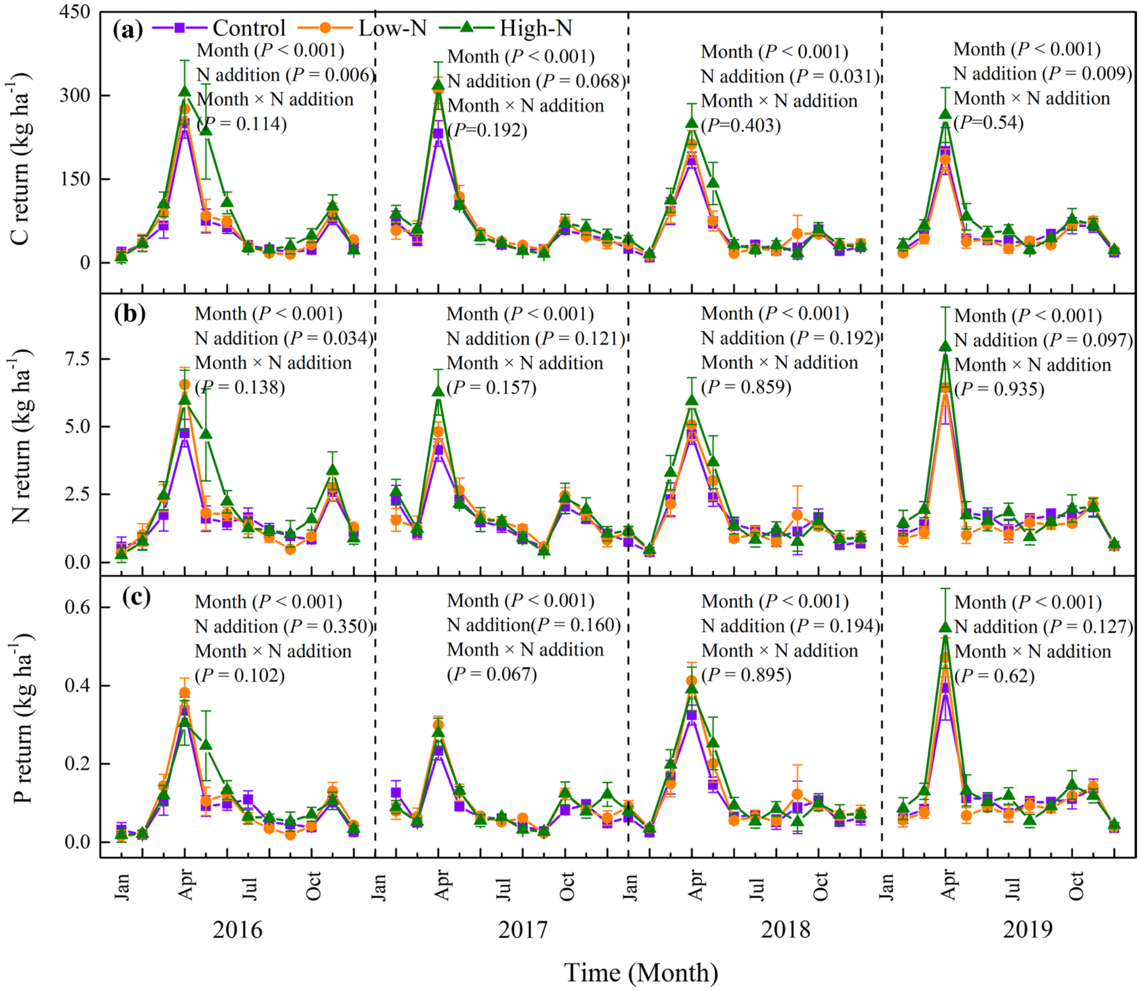


Fig. 5 Monthly fluctuations of carbon (C), nitrogen (N) and phosphorus (P) return in *M. wilsonii* forest under different N additions; control (0 kg N ha^{-1} a^{-1}), low-N addition (20 kg N ha^{-1} a^{-1}), high-N addition (40 kg N ha^{-1} a^{-1}), values are means ± standard errors

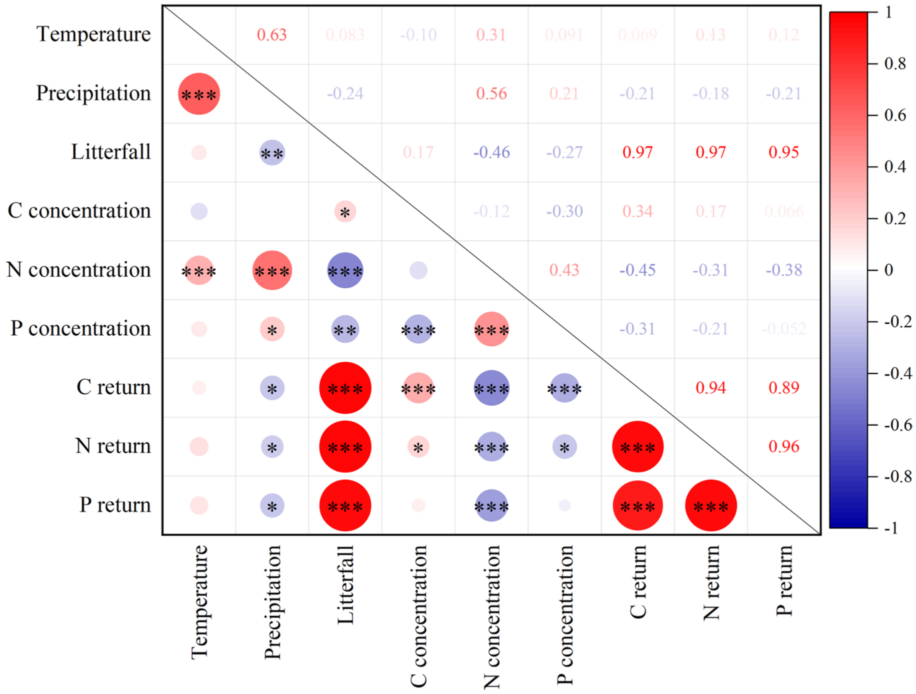
of N addition on broadleaved tree biomass is greater than that of coniferous trees (Xia and Wan 2008). Nutrient-limited conditions determine the response of plants to N addition (You et al. 2018b). In a N-rich forest, excessive N may acidify soils which in turn could reduce litter production (Fu et al. 2019). Further, the effects of adding N on stoichiometric and reabsorption efficiency of N and P in leaves varied with nutrient-limited conditions (You et al. 2018a, 2018b). The effects of N addition could also be modulated by the level of N addition. A previous study noted that low dose and medium dose N (30 and 60 kg N ha^{-1} a^{-1}) increased litterfall production, whereas high dose N (90 kg N ha^{-1} a^{-1}) addition had no effect in a *Moso* bamboo plantation (Zhang et al. 2017a).

Most subtropical forests are characterized by strong seasonality in leaf litterfall (Zhang et al. 2014; Park et al. 2020; Peng et al. 2020). Our results show a similar clear bimodal seasonal litterfall with a major peak in spring and a minor one in autumn. In addition, significant inter-annual differences in climate variables (e.g., temperature and rainfall) have potential to alter the phenology of tree species, which in turn may result in irregular production of leaves, flowers, and fruit, and ultimately affects inter-annual variations in litterfall (Ehbrecht et al. 2021). However, there were no inter-annual differences in litterfall detected in this study, which could be due to the lack of reproductive litter, i.e., flowers and fruit (You et al. 2017).

Effect of the addition of N on C and nutrient concentration

The average concentrations of C, N, and P were 413.7 g kg^{-1}, 12.6 g kg^{-1}, and 0.6 g kg^{-1}, respectively. Litter C concentration is lower than in other subtropical evergreen forests (Ge et al. 2017; Zeng et al. 2017; Huang et al. 2021). However, N and P concentrations were comparable to the average values in Chinese forest ecosystems (Tang et al. 2015). In addition, higher concentrations of N and P in the warm season (June

Fig. 6 Correlation analysis of N addition, month, temperature, precipitation, litterfall, concentration and return of C, N, P; asterisks indicate significant differences (*$P<0.05$, **$P<0.01$, ***$P<0.001$)



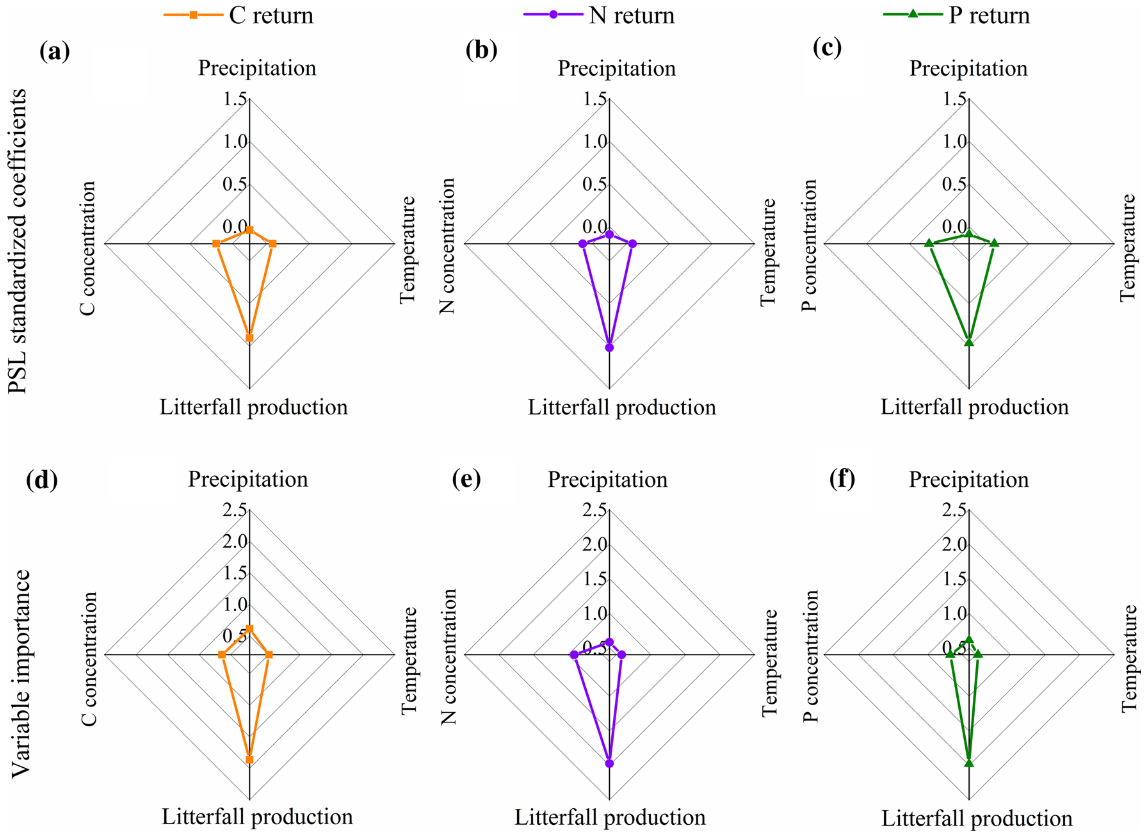


Fig. 7 Results of partial least squares (PLS) analysis for the effects of litterfall, element concentration and environmental factors on element return. PLS standardized coefficients show the direction and magnitude of each variable on the element return, the variable important values (VIP) greater than 1 are significant ($P<0.05$). **a**, **b** and **c** are PLS standardized coefficients of each variable to C, N, P return, respectively; **d**, **e** and **f** are the importance value of each variable to C, N and P return, respectively

to September) reflect a high nutrient demand for new leaves. In contrast, lower N and P concentrations in the dormant season might be a nutrient-conserving strategy to reduce nutrient losses through retranslocation to new tissue production and/or storage in twigs (You et al. 2018b). Further, the relatively high availability of nutrients in the growing season is favorable for nutrient uptake (You et al. 2018b; Zhang et al. 2018). Lastly, heavy rainfalls or strong winds in the growing season can lead to irregular litterfall and corresponding nutrient return (Park et al. 2020).

The addition of N has potential to mediate nutrients in both green leaves and the subsequent litter across global biomes (Liu et al. 2016; Yang et al. 2019). In this study, litter C was not affected by N addition. Similar results have been reported for other forest ecosystems (Smaill et al. 2008; Maaroufi et al. 2016; Fu et al. 2019). As a poorly mobile element, C is steadily accumulated in plant tissues (Jasinska et al. 2020). However, the addition of N decreased the concentration of N in the litter. Similar results were also found in a savanna in central Brazil (Kozovits et al. 2007) and in a Norway spruce forest (Maaroufi et al. 2016). On one hand, N addition can promote photosynthesis and consumption of the element (Fu et al. 2019). On the other hand, N addition can stimulate the accumulation of biomass, which may in turn dilute N concentration in leaf tissues (Zhang et al. 2017b). In addition, high-N addition decreased litter P in this study, which agrees with the findings in a *Larix gmelinii* forest (Fu et al. 2019) and a savanna in central Brazil (Kozovits et al. 2007). Nitrogen and P have been widely reported to interactively affect plant growth (Liu et al. 2021b). Thus high-N addition may increase P demand and reabsorption efficiency in leaves, which could in turn decrease litter P (Li et al. 2016).

It is important to note that the effects of the addition of N on litter N and P were time dependent (year and month). This may be attributed to the lag and superposition effect of N addition on the ecosystem, which is often regulated by season-related temperatures (Kozovits et al. 2007; Zhang et al. 2017c). For example, the positive effect of N addition on litter production increased with the extent of the duration of N addition (Kozovits et al. 2007).

Effect of the N addition on C and nutrient return

In contrast to deceases of N and P concentrations after N addition, this study found that litter C and nutrient return increased. Similar results were found in a *Cinnamomum camphora* (L.) Presl forest (Zhao et al. 2016) and a *Schima superba* Gardn. et Champ. forest (Lv et al. 2013). As noted earlier, element return is determined by both litter production and element concentration, and the former is more important in this study (Figs. 6, 7). As a result, nutrient return also showed a bimodal pattern.

It can be predicted that increased litter C and nutrient return will increase C and nutrient input to the soil through litterfall in this subtropical forest ecosystem (Tu et al. 2011; Bowden et al. 2019). Our previous study found that simulated N deposition delayed nutrient release by *M. wilsonii* leaf litter over a 1-year deposition in the same experimental stand (Zhuang et al. 2020). The residual C, N and P levels in *M. wilsonii* litter, were approximately 1.2–1.3, 1.6–1.9 and 1.6–3.2 times greater, respectively, in the N addition treatments than the controls. A previous study in a bamboo ecosystem in southwestern also reported that simulated N deposition can promote soil C sequestration by increased litter input (Tu et al. 2011). These results indicate that increasing nitrogen increased soil C and nutrient pools in this specific subtropical forest ecosystem.

Conclusions

This study examined the effects of the addition of N on monthly and yearly dynamics of foliar litter production, C, N, and P concentration and return in a N-rich subtropical *M. wilsonii* forest on the western edge of the Szechwan Basin. Foliar litterfall and C, N, and P return exhibited a bimodal pattern (a major peak in spring and a minor one in autumn). Nitrogen and P concentrations in foliar litter in the growing season were higher than in the dormant period. The addition of N stimulated foliar litter production during the 4-year experiment, and promoted C, N and P return, although their concentrations were not affected by the addition of N, indicating that increased C and N return was mainly attributed to stimulated litter production. Based on the results of litter decomposition in *M. wilsonii* forests, nitrogen deposition may increase carbon and nutrient pools in N-rich subtropical forest ecosystems.

Author contribution YZ: Methodology, formal analysis, investigation, writing—original draft. Shichen Xiong: Investigation. CY: Conceptualization, writing—original draft. SL, LW, LZ, HL: Investigation, software. BT: Project administration, validation. YL: Validation. ZX: Conceptualization, supervision, writing—original draft and editing.

Availability of data and materials The datasets used during the current study are available from the corresponding author on reasonable request.

References

Bahru T, Ding YL (2020) Effect of stand density, canopy leaf area index and growth variables on *Dendrocalamus brandisii* (Munro) Kurz litter production at Simao District of Yunnan Province, southwestern China. Glob Ecol Conserv 23:e01051. https://doi.org/10.1016/j.gecco.2020.e01051

Bowden RD, Wurzbacher SJ, Washko SE, Wind L, Rice AM, Coble AE, Baldauf N, Johnson B, Wang JJ, Simpson M, Lajtha K (2019) Long-term nitrogen addition decreases organic matter decomposition and increases forest soil carbon. Soil Sci Soc Am J 83:82–95

Cabal C, Ochoa-Hueso R, Pérez-Corona ME, Manrique E (2017) Long-term simulated nitrogen deposition alters the plant cover dynamics of a Mediterranean rosemary shrubland in Central Spain through defoliation. Environ Sci Pollut Res 24:26227–26237

Chen FS, Niklas KJ, Liu Y, Fang XM, Wan SZ, Wang HM (2015) Nitrogen and phosphorus additions alter nutrient dynamics but not resorption efficiencies of Chinese fir leaves and twigs differing in age. Tree Physiol 35:1106–1117

Ehbrecht M, Seidel D, Annighöfer P, Kreft H, Köhler M, Zemp DC, Puettmann K, Nilus R, Babweteera F, Willim K, Stiers M, Soto D, Boehmer HJ, Fisichelli N, Burnett M, Juday G, Stephens SL, Ammer C (2021) Global patterns and climatic controls of forest structural complexity. Nat Commun 12:519. https://doi.org/10.1038/s41467-020-20767-z

Feng CY, Zheng CY, Tian D (2019) Impacts of nitrogen addition on plant phosphorus content in forest ecosystems and the underlying mechanisms. Chin J Plant Ecol 43:185–196 (**in Chinese**)

Fu Q, Xing YJ, Yan GY, Dong XD, Zhang JH, Wang QG (2019) Response of litter dynamics of boreal forest to long-term nitrogen deposition. Chin J Ecol Environ Sci 28:1341–1350 (**in Chinese**)

Ge JL, Wang Y, Xu WT, Xie ZQ (2017) Latitudinal patterns and climatic drivers of leaf litter multiple nutrients in Chinese broad-leaved tree species: does leaf habit matter? Ecosystems 20:1124–1136

Guo J, Yu LH, Fang X, Xiang WH, Deng XW, Lu X (2015) Litter production and turnover in four types of subtropical forests in China. Chin J Ecol Sin 35:4668–4677 (**in Chinese**)

Huang YY, Ma KP, Niklaus PA, Schmid B (2018) Leaf-litter overyielding in a forest biodiversity experiment in subtropical China. For Ecosyst 5:38. https://doi.org/10.1186/s40663-018-0157-8

Huang YR, Gao W, Huang SD, Lin J, Tan FL, You HM, Ynag L (2021) Ecostoichiometric characteristics of carbon, nitrogen and phosphorus in Fujian evergreen broad-leaved forest. Chin J Ecol Sin 41:1991–2000 (**in Chinese**)

Jasinska J, Sewerńiak P, Puchałka R (2020) Litterfall in a scots pine forest on inland dunes in Central Europe: mass, seasonal dynamics and chemistry. Forests 11:678. https://doi.org/10.3390/f11060678

Jia YY, Gu DL, Wu CW, Yang WF, Du XF, Wen TG, Lv YN, Kong XS, Tian XJ (2019) Nitrogen deposition slows down the litter decomposition induced by soil macrofauna in the soil of subtropical forests in China. Ecol Res 34:360–369

Kozovits AR, Bustamante MMC, Garofalo CR, Bucci S, Franco AC, Goldstein G, Meinzer FC (2007) Nutrient resorption and patterns of litter production and decomposition in a Neotropical Savanna. Funct Ecol 21:1034–1043

Li Y, Niu SL, Yu GR (2016) Aggravated phosphorus limitation on biomass production under increasing nitrogen loading: a meta-analysis. Glob Chang Biol 22:934–943

Li Q, Lv JH, Peng CH, Xiang WH, Xiao WF, Song XZ (2021) Nitrogen-addition accelerates phosphorus cycling and changes phosphorus use strategy in a subtropical Moso bamboo forest. Environ Res Lett 16:024023. https://doi.org/10.1088/1748-9326/abd5e1

Liu XJ, Zhang Y, Han WX, Tang AH, Shen JL, Cui ZL, Vitousek P, Erisman JW, Goulding K, Christie P, Fangmeier A, Zhang FS (2013) Enhanced nitrogen deposition over China. Nature 494:459–462

Liu J, Wu NN, Wang H, Sun JF, Peng B, Jiang P, Bai E (2016) Nitrogen addition affects chemical compositions of plant tissues, litter and soil organic matter. Ecology 97:1796–1806

Liu Q, Zhuang LY, Ni XY, You CM, Yang WQ, Wu FZ, Tan B, Yue K, Liu Y, Zhang L, Xu ZF (2018) Nitrogen additions stimulate litter humification in a subtropical forest, southwestern China. Sci Rep 8:1–8

Liu Q, Yin R, Tan B, You CM, Zhang L, Zhang J, Xu ZF, Schädler M, Scheu S (2021a) Nitrogen addition and plant functional type independently modify soil mesofauna effects on litter decomposition. Soil Biol Biochem 160:108340. https://doi.org/10.1016/j.soilbio.2021.108340

Liu YZ, Zhao CC, Guo JW, Zhang LN, Xuan J, Chen AQ, You CM (2021b) Short-term phosphorus addition augments the effects of nitrogen addition on soil respiration in a typical steppe. Sci Total Environ 761:143211. https://doi.org/10.1016/j.scitotenv.2020.143211

Lu XK, Vitousek PM, Mao QG, Gilliam FS, Luo YQ, Zhou GY, Zou XM, Bai E, Scanlon TM, Hou EQ, Mo JM (2018) Plant acclimation to long-term high nitrogen deposition in an N-rich tropical forest. Proc Natl Acad Sci 115:5187–5192

Lv Y, Zheng ZM, Meiliban M, Lu J, Wang XH (2013) Effects of nitrogen and phosphorus fertilization on litterfall production and nutrient dynamics in a *Schima superba* forest in Zhejiang Province of East China. Chin J Appl Ecol 24:3027–3034 (**in Chinese**)

Maaroufi NI, Nordin A, Palmqvist K, Gundale MJ (2016) Chronic nitrogen deposition has a minor effect on the quantity and quality of aboveground litter in a boreal forest. PLoS One 11:1–16

Mao JH, Mao QG, Zheng MH, Mo JM (2020) Responses of foliar nutrient status and stoichiometry to nitrogen addition in different ecosystems: a Meta-analysis. J Geophys Res Biogeosci 125:e2019JG005347. https://doi.org/10.1029/2019JG005347

Park BB, Rahman A, Han SH, Bin YW, Hyun HJ, Hernandez J, An JY (2020) Carbon and nutrient inputs by litterfall in evergreen and deciduous forests in Korea. Forests 11:1–15

Peng Y, Song SY, Li ZY, Li S, Chen GT, Hu HL, Xie JL, Chen G, Xiao YL, Liu L, Tang Y, Tu LH (2020) Influences of nitrogen addition and aboveground litter-input manipulations on soil respiration and biochemical properties in a subtropical forest. Soil Biol Biochem 142:107694. https://doi.org/10.1016/j.soilbio.2019.107694

Pu Y, Mao HY, Liu Q, Zhuang LY, Yang KJ, Xu ZF (2019) Dynamic characteristics of C, N, and P and leaf litterfall in a *Michelia wilsonii* and *Camptotheca acuminate* mixed forest on the western edge of the sichuan basin. Chin J Appl Environ Biol 25:262–267 (**in Chinese**)

Shen GR, Chen DM, Wu Y, Liu L, Liu CJ (2019) Spatial patterns and estimates of global forest litterfall. Ecosphere 10:e02587. https://doi.org/10.1002/ecs2.2587

Smaill SJ, Clinton PW, Greenfield LG (2008) Nitrogen fertiliser effects on litter fall, FH layer and mineral soil characteristics in New Zealand Pinus radiata plantations. For Ecol Manag 256:564–569

Stevens CJ (2019) Nitrogen in the environment. Science 363:578–580

Tang SS, Yang WQ, Wang HP, Xiong L, Nie FY, Xu ZF (2015) Stoichiometri characteristics and controlling factors of N and P in forest leaf litter of China. Chin J Appl Environ Biol 21:316–322 (**in Chinese**)

Tian D, Du E, Jiang L, Ma SH, Zeng WJ, Zou AL, Feng CY, Xu LC, Xing AJ, Wang W, Zheng CY, Ji CJ, Shen HH, Fang JY (2018) Responses of forest ecosystems to increasing N deposition in China: a critical review. Environ Pollut 243:75–86

Tu LH, Hu TX, Zhang J, Li RH, Dai HZ, Luo SH (2011) Short-term simulated nitrogen deposition increases carbon sequestration in a Pleioblastus amarus plantation. Plant Soil 340:383–396

Vitoussek PM, Sanford RL (1986) Nutrient cycling in moist tropical forest. Annu Rev Ecol Syst 17:137–167

Wen Z, Xu W, Li Q, Han MJ, Tang AH, Zhang Y, Luo XS, Shen JL, Wang W, Li KH, Pan YP, Zhang L, Li WQ, Collett JL, Zhong BQ, Wang XM, Goulding K, Zhang FS, Liu XJ (2020) Changes of nitrogen deposition in China from 1980 to 2018. Environ Int 144:106022. https://doi.org/10.1016/j.envint.2020.106022

Xia JY, Wan SQ (2008) Global response patterns of terrestrial plant species to nitrogen addition. New Phytol 179:428–439

Xu ZF, Tu LH, Hu TX, Schädler M (2013) Implications of greater than average increases in nitrogen deposition on the western edge of the Szechwan Basin, China. Environ Pollut 177:201–202

Yang DX, Song L, Jin GZ (2019) The soil C:N: P stoichiometry is more sensitive than the leaf C:N: P stoichiometry to nitrogen addition: a four-year nitrogen addition experiment in a Pinus koraiensis plantation. Plant Soil 442:183–198

Yang YS, Guo JF, Chen GS, Xie JS, Gao R, Li Z, Jin Z (2005) Litter production, seasonal pattern and nutrient return in seven natural forests compared with a plantation in southern China. Forestry 78:403–415

Yang KJ, Yang WQ, Zhuang LY, Li ZJ, He RY, Tan B, Zhang L, Xiao JJ, Xu ZF (2018) Characteristics of atmospheric wet nitrogen deposition in Dujiangyan, western edge of Sichuan Basin. Chin J Appl Environ Biol 24:107–111 (**in Chinese**)

You CM, Wu FZ, Yang WQ, Tan B, Yue K, Ni XY (2017) The National Key Forestry Ecology Project has changed the zonal pattern of forest litter production in China. For Ecol Manag 399:37–46

You CM, Wu FZ, Yang WQ, Xu ZF, Tan B, Yue K, Ni XY (2018a) Nutrient-limited conditions determine the responses of foliar nitrogen and phosphorus stoichiometry to nitrogen addition: a global meta-analysis. Environ Pollut 241:740–749

You CM, Wu FZ, Yang WQ, Xu ZF, Tan B, Zhang L, Yue K, Ni XY, Li H, Chang CH, Fu CK (2018b) Does foliar nutrient resorption regulate the coupled relationship between nitrogen and phosphorus in plant leaves in response to nitrogen deposition? Sci Total Environ 645:733–742

Yu GR, Jia YL, He NP, Zhu JX, Chen Z, Wang QF, Piao SL, Liu XJ, He HL, Guo XB, Wen Z, Li P, Ding GA, Goulding K (2019) Stabilization of atmospheric nitrogen deposition in China over the past decade. Nat Geosci 12:424–429

Zeng YL, Fang X, Xiang WH, Deng XW, Peng CH (2017) Stoichiometric and nutrient resorption characteristics of dominant tree species in subtropical Chinese forests. Ecol Evol 7:11033–11043

Zhang HC, Yuan WP, Dong WJ, Liu SG (2014) Seasonal patterns of litterfall in forest ecosystem worldwide. Ecol Complex 20:240–247

Zhang JH, Tang ZY, Shen HH, Fang JY (2017a) Responses of growth and litterfall production to nitrogen addition treatments from common shrublands in Mt. Dongling, Beijing China. Chin J Plant Ecol 41:71–80 (**in Chinese**)

Zhang JB, Lv JH, Li Q, Ying YQ, Peng CH, Song XZ (2017b) Effects of nitrogen deposition and management practices on leaf litterfall and N and P return in a Moso bamboo forest. Biogeochemistry 134:115–124

Zhang QF, Xie JS, Lyu M, Xiong DC, Wang J, Chen Y, Li YQ, Wang MK, Yang YS (2017c) Short-term effects of soil warming and nitrogen addition on the N: P stoichiometry of Cunninghamia lanceolata in subtropical regions. Plant Soil 411:395–407

Zhang Y, Yang JP, Yang WQ, Tan B, Fu CK, Wu FZ (2018) Climate, plant organs and species control dissolved nitrogen and phosphorus in fresh litter in a subalpine forest on the eastern Tibetan Plateau. Ann For Sci 75:51. https://doi.org/10.1007/s13595-018-0731-9

Zhao Q, Zeng DH (2019) Nitrogen addition effects on tree growth and soil properties mediated by soil phosphorus availability and tree species identity. For Ecol Manag 449:117478. https://doi.org/10.1016/j.foreco.2019.117478

Zhao J, Yan WD, Zheng W, Li ZW (2016) Nutrient contents and fluxes in the litterfall from *Cinnamomum camphora* plantation in response to simulated nitrogen deposition. Chin J Ecol Sin 36:350–359 (**in Chinese**)

Zhou J, Lang XF, Du BY, Zhang H, Liu HY, Zhang YP, Shang LH (2016) Litterfall and nutrient return in moist evergreen broad-leaved primary forest and mixed subtropical secondary deciduous broad-leaved forest in China. Eur J For Res 135:77–86

Zhu XA, Liu WJ, Chen H, Deng Y, Chen CF, Zeng HH (2019) Effects of forest transition on litterfall, standing litter and related nutrient returns: Implications for forest management in tropical China. Geoderma 333:123–134

Zhuang L, Yang WQ, Wu FZ, Tan B, Zhang L, Yang KJ, He RY, Li ZJ, Xu ZF (2018) Diameter-related variations in root decomposition of three common subalpine tree species in southwestern China. Geoderma 311:1–8

Zhuang LY, Liu Q, Liang ZY, You CM, Tan B, Zhang L, Yin R, Yang KJ, Bol R, Xu ZF (2020) Nitrogen additions retard nutrient release from two contrasting foliar litters in a subtropical forest, southwest China. Forests 11:377. https://doi.org/10.3390/f11040377