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RESEARCH PAPER

# Effect of nitrogen addition on soil $CO_2$ efflux and fine root biomass in maple monocultures of the hyrcanian region

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## Abstract

- ***Key message*** **Nitrogen (N) addition (10 and 15 g N $m^{-2}$ $year^{-1}$ as dissolved $NH_4NO_3$) significantly increased the $CO_2$ efflux from the forest soil and the fine root biomass in a maple (Acer velutinum Bioss.) plantation. Following a seasonal pattern, soil $CO_2$ efflux showed an exponential relationship with the fine root biomass and soil temperature.**
- ***Context*** The effect of increased atmospheric Nitrogen (N) deposition on forest soil $CO_2$ efflux is still unclear in the Hyrcanian forests and has received considerable attention in the context of global climate change.
- ***Aims*** Aims of this study were to determine how soil $CO_2$ efflux and fine root biomass change after N addition in a maple (Acer velutinum Bioss.) plantation.
- ***Methods*** Since the wet N deposition in these areas is 3–5 g N $m^{-2}$ $year^{-1}$, four treatments including N1 (5 g N $m^{-2}$ $year^{-1}$), N2 (10 g N $m^{-2}$ $year^{-1}$), N3 (15 g N $m^{-2}$ $year^{-1}$), and N0 (control) were selected. Twelve plots (10 × 20 m) were established, and a $NH_4NO_3$ solution was sprayed monthly below the trees' canopy for 1 year. Soil temperature, moisture, and soil $CO_2$ efflux were measured monthly with static dark closed chambers. Fine root biomass was seasonally measured by soil sampling at the same depth.
- ***Results*** Soil temperature, moisture, and soil $CO_2$ efflux were affected by different levels of N addition. Soil $CO_2$ efflux significantly increased with N addition, and N3 displayed the highest rate (174 ± 16.1 mg $CO_{2\text{-}}C$ $m^{-2}$ $h^{-1}$). Fine root biomass increased significantly in N3.
- ***Conclusion*** The predicted levels of N deposition in such plantations will probably lead to enhanced CO2 efflux from soils in reforested areas close to industrial sites in the Hyrcanian forest.

**Keywords** $CO_2$ efflux · Enhanced nitrogen addition · Hyrcanian maple forest · Fine root growth

## 1 Introduction

Human activities such as consumption of fossil fuels, disturbance of forests, land-use change, and agricultural fertilization have substantially increased the rate of atmospheric Nitrogen deposition, specifically under the form of N oxides ($NO_x$) (Galloway et al. 2004; Dentener et al. 2006; Bobbink et al. 2010; Song et al. 2017). Although atmospheric nitrogen deposition has positive effect such as increased tree growth in N-limited forests (Wardle et al. 2004; Li et al. 2019; Liu et al. 2020), it has many negative ecological effects on terrestrial and aquatic ecosystems, such as eutrophication and loss of biodiversity (Maskell et al. 2010; Janssens et al. 2010). Atmospheric deposition of N is already a serious problem in Europe and the USA; in addition, the fastest rate of increase in N deposition has been documented in the developing industrial regions of Asia (Mo et al. 2006;

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Zhu et al. 2015a, b; Jia et al. 2016; Zheng et al. 2018). Moreover, atmospheric N deposition is predicted to increase from 25–40 Tg per year to 60–100 Tg per year until the end of this century at global scale (Lamarque 2005; Zhang et al. 2014; Wei et al. 2020). Therefore, concern about the ecological effects of elevated N deposition on terrestrial ecosystems is currently increasing (Magill et al. 2004), especially on forest ecosystems (Keenan et al. 2015).

Chronic N deposition has many negative effects on forest ecosystems globally (Carter et al. 2017; Deng et al. 2018; Schulte-Uebbing and De Vries 2018; Shi et al. 2018) including the biodiversity (Riofrío-Dillon et al. 2017; Vitousek et al. 1997), forest soils (e.g. decrease in pH and electrical conductivity (EC)), foliar chemistry, and soil biomass (Lupi et al. 2013; Novotný et al. 2016; Zhang et al. 2018; Gentilesca et al. 2018; Tafazoli et al. 2019). Considering that forests are known as a sink for carbon (C) with an important role in the global C cycle (Naik et al. 2018), the impacts of increased N inputs on the forest soil organic carbon (SOC) dynamics and cycle are of great concern (Janssens et al. 2010; Wieder et al. 2015; Chen et al. 2018). Since $CO_2$ efflux from forest soils is through plant root respiration, rhizomicrobial respiration, and soil organic matter decomposition (Jiang et al. 2010), N deposition can alter the rates of microbial N and C turnover, and thus affect the $CO_2$ efflux from forests' soil (Liu and Greaver 2009).

Due to differences in vegetation and soil properties in different forests, the responses of soil $CO_2$ efflux and fine root biomass to N deposition may include promotion (Cleveland and Townsend 2006; Peng et al. 2011; Tu et al. 2011), decrease (Janssens et al. 2010; Ramirez et al. 2010), and no effect (Allison et al. 2008; Samuelson et al. 2009).To date, it is not clear how atmospheric N deposition affects the soil $CO_2$ efflux and fine root biomass in the Hyrcanian Forests; therefore, understanding how N additions alter these two factors still remains an important scientific challenge (Tu et al. 2013).

Iran, especially the northern part where the Hyrcanian forests are located, is experiencing the release of a great amount of N into the atmosphere. The main sources include developing industrial regions, combustion of fossil fuels, and use of artificial fertilizers (Salahi et al. 2014; Nobakht et al. 2018). The Hyrcanian forests, which were recently registered as a UNESCO World Heritage Site, are a green belt on the northern slopes of Alborz Mountains and cover the southern coasts of the Caspian Sea (SaghebTalebi et al. 2014). These forests are mixed deciduous and temperate forests; they appear to be very similar to the broadleaf forests of central Europe, northern Turkey, and the Caucasus (SaghebTalebi et al. 2014). Unfortunately, degradation of Hyrcanian forests along with N deposition not only may have some negative local effect but also can have significant effects on the global C cycle. Since Hyrcanian forests are N-limited, N deposition can stimulate primary production and sequestration of C in these ecosystems (De Vries et al. 2006; Sutton et al. 2008; Högberg, 2012; Schulte-Uebbing and De Vries, 2018; Du and De Vries 2018; Schwede et al. 2018). However, when the levels of N deposition are high (e.g., above 1.5–2.5 g N $m^{-2}$ $year^{-1}$, De Vries et al. 2014a), the stimulating effect on forest growth is likely to diminish over time due to the accompanying side effects, such as soil acidification and imbalances between N and other nutrients such as phosphorous (P), calcium (Ca), and magnesium (Mg) (Aber et al. 1998; Bowman et al. 2008; De Vries et al. 2014b; Du and Fang 2014; Schwede et al. 2018).

The wet deposition in the Iranian Hyrcanian forests is about 3–5 g N $m^{-2}$ $year^{-1}$ (Salahi et al. 2014), which is considered as the critical amount (De Vries et al. 2014a). Despite the projection that the amount of N deposition in the Hyrcanian forests will be twofold (6–10 g N $m^{-2}$ $year^{-1}$) by the end of this century (Galloway et al. 2008; Salahi et al. 2014; Nobakht et al. 2018), the effect of N deposition on the $CO_2$ efflux and fine root biomass and their consequences in this ecosystem are still unclear. As a common act to plant pioneer trees such as *Acer velutinum* Bioss. near the industrial areas after clearcutting, the main objective of this study was to quantify soil $CO_2$ efflux and fine root biomass in the different treatments of N addition to a maple (*Acer velutinum* Bioss.) plantation for the first time in Iran. It is hypothesized that the different rates of N addition (5, 10, 15 g N $m^{-2}$ $year^{-1}$) significantly increase $CO_2$ efflux and fine root biomass in the maple plantation.

## 2 Materials and methods

### 2.1 Study area

This study was carried out in a maple (*Acer velutinum* Bioss.) plantation in the educational and research forest of Darabkola, located in the Western Hyrcanian forests, Sari City, Mazandaran Province, Iran (53° 16′ East, 36° 31′ North and an elevation of 360 m asl). The maple plantation was established following the clearing of a natural forest in 1990 (this stand is far from the industrial areas and highways in order to avoid the effect of those kinds of anthropogenic activities). The plantation area is 1.1 ha, and the average tree diameter (at breast height) and stand height is 20 ± 0.5 cm and 19 ± 1 m, respectively. The average slope and main aspects are 20% and north-west, respectively. The mean annual rainfall (1992–2015) is 753 mm. November is the rainiest month (114 mm), and June is the driest one (26 mm). The mean annual temperature is 18 °C (Anonymous 1996).

## 2.2 Experimental design

In April 2015, 12 rectangular 20- × 10-m plots were placed in a complete randomized design and each plot was surrounded by a 10-m-wide buffer strip (Appendix Fig. 5). Four treatments of N addition with three replicates (i.e., 3 plots for each treatment) were selected: 5 g N $m^{-2}$ $year^{-1}$ (N1), 10 g N $m^{-2}$ $year^{-1}$ (N2), 15 g N $m^{-2}$ $year^{-1}$ (N3), and control (without N addition, N0) (Xian-Kaiet al. 2009). Nitrogen addition was conducted using ammonium nitrate ($NH_4NO_3$) (Xu et al. 2007; Zhang and Han 2012).

N was added through spraying on the forest floor (litter layer) in this study. Starting from April 2015, the solution was sprayed monthly (on the third or fourth day after rainfall events) on the forest floor under the canopy with a backpack sprayer. The control plots received 20 L of distilled water without N addition (Tu et al. 2011). The study started 1 month after the first N addition and was carried out from May 2015 to April 2016.

## 2.3 Data collection

In April 2015, before the first N addition, three soil samples were taken from the topsoil layer (0–10 cm) in each plot (Xian-Kai et al. 2009; Wei et al. 2014; Liu et al. 2015), in a diagonal direction, using the coring method (diameter 8 cm; height 10 cm). Air-drying and grinding were performed, and the samples were passed through a 0.5-mm sieve. Then the physical and chemical properties of the soil were analyzed in the laboratory. Soil texture (hydrometer method, Bouyoucos 1951), bulk density (volumetric core method), pH (digital pH meter, in a 1:2.5 soil/water suspension), EC (EC meter, in water-saturated soil extract at 20 °C; Anonymous 1980), total N (Kjeltec System-Instrument, TECATOR; Anonymous 1990; Vogt et al. 2015), $NO_3^-$(Manual Cd reduction method, APHA 1998), $NH_4^+$(manual indophenols colorimetric method; Dorich and Nelson 1983), and organic carbon (Walkley and Black procedure) were measured.

Soil $CO_2$ efflux was measured using dynamic closed chambers. In April 2015, three polyvinyl chloride (PVC) collars (10 cm in diameter and 20 cm in height) were inserted into the soil at a depth of 10 cm (into organic and mineral soil), away from the edge of the plots, in order to measure soil $CO_2$ efflux (three points in each rectangular plot in a diagonal direction). Soil $CO_2$ efflux was measured once a month before each N addition by placing a PVC lid over each column and using the infrared method with a $CO_2$ port device (Messwert company GmbH-Göttingen), which was a developed version of the infrared gas analyzer, Edinburgh Sensors- Gascard II (Bekku et al. 1995; Hojjati 2008; Hojjati and Lamersdorf 2010). The measurement was done immediately after closing the chamber. The soil $CO_2$ efflux was measured three or four days after the rainfall events in order to avoid any pulse effect of precipitation. All the measurements were performed between 08:00 a.m. and 11:00 a.m. (local time).

Soil temperature (°C) and moisture were determined simultaneously with the soil $CO_2$ efflux measurements close to the soil collar in each plot (at three points in each rectangular plot in a diagonal direction). Soil temperature was measured using a digital thermometer (Model: 6300, Spectrum Technologies, Inc., USA) at the depth of 10 cm, and volumetric soil moisture was determined using a soil moisture meter (Model: DSMM500, General Tools and Instruments, New York, USA) at the depth of 10 cm.

Fine root biomass was measured seasonally (once in the mid-season). In each plot, three soil cores (diameter: 8 cm; height: 10 cm) were taken at the depth of 10 cm (Argiroff et al., 2019; Li et al., 2021). Fine roots were collected after washing with a 2-mm sieve. To measure dry weight, all the samples were dried in an oven at 85 °C (Zhang et al. 2014).

## 2.4 Statistical analysis

The effect of N addition treatments and month on soil temperature, moisture, $CO_2$ efflux, and fine root biomass were tested by Repeated measures analysis of variance for

**Table 1** Physical and chemical properties (mean values ± SE, $n = 3$) of soil (depth of 0–10 cm) in each treatment in the *Acer velutinum* Bioss. stand before N addition (April 2015)

| Soil properties | Treatment plots | | | |
|---|---|---|---|---|
| | N0 | N1 | N2 | N3 |
| % Sand:Silt:Clay | 58:30:12 | 50:34:16 | 60:28:12 | 56:30:14 |
| Bulk density (g $cm^{-3}$) | 1.72 ± 0.02 | 1.77 ± 0.02 | 1.69 ± 0.01 | 1.70 ± 0.02 |
| pH | 7.17 ± 0.01 | 7.20 ± 0.01 | 7.18 ± 0.01 | 7.12 ± 0.02 |
| Electrical conductivity (dS $m^{-1}$) | 0.89 ± 0.02 | 0.91 ± 0.01 | 0.90 ± 09 | 0.87 ± 03 |
| Total N (g 100 $g^{-1}$) | 0.38 ± 0.01 | 0.37 ± 0.01 | 0.37 ± 0.01 | 0.39 ± 0.01 |
| $NH_4^+$ (mg $kg^{-1}$) | 4.13 ± 0.13 | 4.08 ± 0.09 | 4.15 ± 0.07 | 4.19 ± 0.10 |
| $NO_3^-$ (mg $kg^{-1}$) | 4.87 ± 0.05 | 4.79 ± 0.07 | 4.71 ± 0.08 | 4.85 ± 0.10 |
| OC (g 100 $g^{-1}$ soil) | 3.94 ± 0.04 | 4.08 ± 0.18 | 3.85 ± 0.16 | 3.95 ± 0.06 |
| Fine root biomass (g $m^{-2}$) | 46.9 ± 0.95 | 47.1 ± 3.59 | 49.8 ± 0.73 | 46.8 ± 1.95 |

**Table 2** Total chemical properties (mean values ±SE, *n* = 3) of soil (depth of 0–10 cm) in each treatment in the *Acer velutinum* Bioss. plantation after N addition at the end of study period (April 2016). Different letters represent significant differences between treatments within each property

| Soil properties | Treatment plots | | | |
|---|---|---|---|---|
| | N0 | N1 | N2 | N3 |
| pH | 7.13 ± 0.01 a | 7.08 ± 0.01 b | 6.86 ± 0.01 c | 6.76 ± 0.01 d |
| Electrical conductivity (dS $m^{-1}$) | 0.84 ± 0.03 a | 0.78 ± 0.01 b | 0.75 ± 0.01 c | 0.66 ± 0.01 d |
| Total N (g 100 $g^{-1}$) | 0.36 ± 0.01 d | 0.41 ± 0.01 c | 0.47 ± 0.02 b | 0.58 ± 0.01 a |
| $NH_4^+$(mg $kg^{-1}$) | 4.93 ± 0.18 d | 6.04 ± 0.14 c | 7.23 ± 0.10 b | 8.53 ± 0.17 a |
| $NO_3^-$(mg $kg^{-1}$) | 5.06 ± 0.18 d | 7.21 ± 0.12 c | 9.95 ± 0.30 b | 20.5 ± 0.33 a |

the study period (significance was at 0.05 level). One-way ANOVA was used to test the difference in soil chemical properties in each treatment after N addition at the end of study period. Mean values in the text are averages of 3 plots per N addition treatment (N0, N1, N2, and N3). The relationships between soil $CO_2$ efflux and soil temperature were determined using nonlinear regression models (exponential equation, $R = \alpha e^{\beta T}$). For the regression models, the standard error of estimation (Std. Err. Est) and the normalized root-mean-square error (RMSE) were calculated. All the statistical analyses were performed using the IBM SPSS statistic 26 software (USA). Excel software was used to draw statistical graphics.

## 3 Results

### 3.1 Soil properties

The results showed no significant difference in the soil properties between the treatments before the N addition (Table 1). At the end of the study period, N addition (N2 and N3) led to lower soil pH and EC. Moreover, after the completion of the study period, the soil total N, ammonium ($NH_4^+$), and nitrate ($NO_3^-$) were significantly higher in the N addition plots than the control plots and they also significantly increased from N0 to N3 (Table 2).

There was no significant difference ($P > 0.05$) between each N addition treatments and the control for each month (Table 3). Soil temperature and moisture exhibited distinct seasonal patterns in all the treated plots. The highest and lowest soil temperatures were observed in July and January, respectively (Fig. 1a). The highest and lowest soil moistures were observed in January and July, respectively (Fig.1b).

### 3.2 Effects of N addition on soil $CO_2$ efflux

ANOVA results revealed that N additions had a significant effect ($P < 0.01$) on soil CO2 efflux (Table 3). The highest N addition resulted in a higher rate of $CO_2$ efflux than the other treatments during the study period (Fig. 2a). In all plots, mean soil CO2 efflux was significantly higher during the growing season (spring and summer) than winter. The annual averages of $CO_2$ effluxes were 115 ± 3.00, 122 ± 7.3,

**Table 3** ANOVA results on soil temperature, moisture, $CO_2$ efflux, and fine root biomass, based on repeated measurements (months, N addition, and their interaction during the study period)

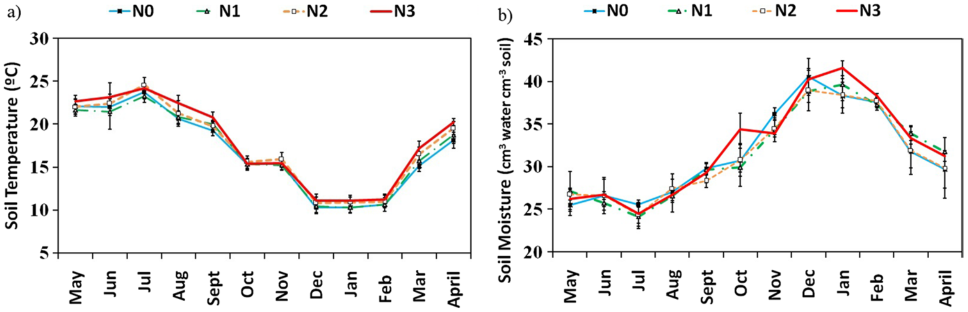
| Soil properties | Source | df[a] | Mean square | *F* |
|---|---|---|---|---|
| Soil temperature | Month | 11 | 276.9 | $1044.009^{**}$ |
| | Month × Nitrogen addition | 33 | 0.534 | $2.014^{**}$ |
| | Nitrogen addition | 3 | 8.194 | $0.272^{ns}$ |
| Soil moisture | Month | 11 | 333.387 | $154.666^{**}$ |
| | Month × Nitrogen addition | 33 | 2.937 | $1.362^{ns}$ |
| | Nitrogen addition | 3 | 2.172 | $0.182^{ns}$ |
| Soil $CO_2$ efflux | Month | 11 | 21920.442 | $648.249^{**}$ |
| | Month × Nitrogen addition | 33 | 698.675 | $20.662^{**}$ |
| | Nitrogen addition | 3 | 24097.282 | $429.214^{**}$ |
| Fine root biomass | Season | 3 | 11.942 | $13.674^{**}$ |
| | Season × Nitrogen addition | 9 | 0.694 | $0.794^{ns}$ |
| | Nitrogen addition | 3 | 42.360 | $18.494^{**}$ |

*ns* not significant

**Significance at the level of 0.01

[a] Degree of freedom

**Fig. 1** **a** Seasonal variations (mean ± SD; $n = 3$ per month) of the soil temperature; **b** seasonal variations (mean ± SD; $n = 3$ per month) of the soil moisture measured at control plot (no N addition) at depth of 10 cm



141 ± 10.7, and 174 ± 16.1 mg $CO_2$-C $m^{-2}$ $h^{-1}$ in N0, N1, N2, and N3, respectively.

Soil $CO_2$ efflux followed a seasonal pattern with maximum and minimum during summer and winter, respectively (Fig. 2). The rates for $CO_2$ efflux in the control plots ranged from 76.0 ± 1.7 mg $CO_2$-C $m^{-2}$ $h^{-1}$ in July to 175 ± 6.1 mg $CO_2$-C $m^{-2}$ $h^{-1}$ in January. There was no significant difference between N0 and N1; however, a significant difference was observed between N0, N2, and N3. Soil CO2 efflux was exponentially related to the soil temperature (Fig. 3). Exponential relationships between the soil $CO_2$ efflux and soil temperature were significant ($P < 0.01$) for all the treatments with $R^2$ values between 0.81 and 0.87.

### 3.3 Effects of N addition on root biomass

The results indicated an effect of N addition ($P < 0.01$) on fine root biomass (Table 3). There was no difference between N0, N1, and N2; however, fine root biomass was significantly higher in N3 than the other treatments (Table 4). The relationship between soil $CO_2$ efflux and fine root biomass was exponential (Fig. 4). Exponential relationships between fine root biomass and soil $CO_2$ efflux were significant ($P < 0.01$) for all the treatments with $R^2$ values between 0.41 and 0.59.

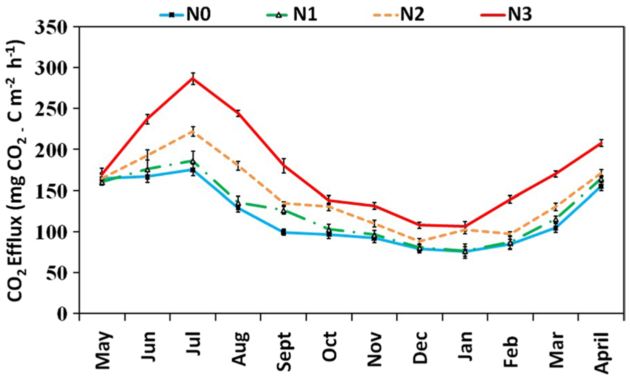


**Fig. 2** Seasonal variations (mean ± SD; $n = 3$ per month) of soil CO2 efflux measured at different level of N addition (N0: Control, N1: 5, N2: 10, and N3:15 g N $m^{-2}$ $year^{-1}$)

## 4 Discussion

According to the results, N additions increased the available N concentration at the end of the study period. Nitrogen addition directly affects the soil N cycling by enhancing the available N and also has an indirect effect on the rate of nutrient input by altering the litter decomposition and nutrient release. Geng et al. (2017) and Zhang et al. (2019) reported that the N addition significantly increased the available N in the soil. In the N-limited forest ecosystems such as Hyrcanian forests, adding N to the soil can increase the net N mineralization in the forest floors, which can increase the available concentration of N in the soil (Gundersen et al. 1998; Zhu et al. 2015a, b; Gao et al. 2015; Ye et al. 2018).

In the current study, N additions significantly decreased soil pH and EC. Reduction in soil pH following N additions has been reported in other studies as well (Hong et al. 2019; Guo et al. 2010; Yang et al. 2012; Yang et al. 2015). Nitrogen addition is known as the main cause of the reduction of soil pH (Guo et al. 2010; Yang et al. 2012, 2015). Adding N to the soil, especially as $NO_3^-$, may enhance the co-leaching loss of the base cations (e.g., $K^+$, $Ca^{2+}$, and $Mg^{2+}$) (Gundersen et al. 2006; Lu et al. 2018).

The present results showed that N2 and N3 (10 and 15 g N $m^{-2}$ $year^{-1}$) significantly increased annual soil $CO_2$ efflux. Increased soil $CO_2$ efflux by N addition has also been reported in previous studies (Tu et al. 2013; Gao et al. 2014; Deng et al. 2018; Li et al. 2019; Zhao et al. 2020). There was no significant difference between the different treatments in the terms of soil temperature, moisture, or physical and chemical properties before the N addition. Therefore, it can be stated that the difference in the $CO_2$ efflux in the different treatments might have been caused by the N addition. Soil $CO_2$ efflux includes heterotrophic and autotrophic respiration and is mainly regulated by the size of the soil microbial population, amount of fine roots, and biomass of litter (Baggs 2006). It has been reported that adding N to N-limited forests, such as the Hyrcanian forest soils in this study, can increase the soil $CO_2$ efflux rate (Li et al. 2019; Zhang et al. 2017b). Moderate addition of N to N-limited forests

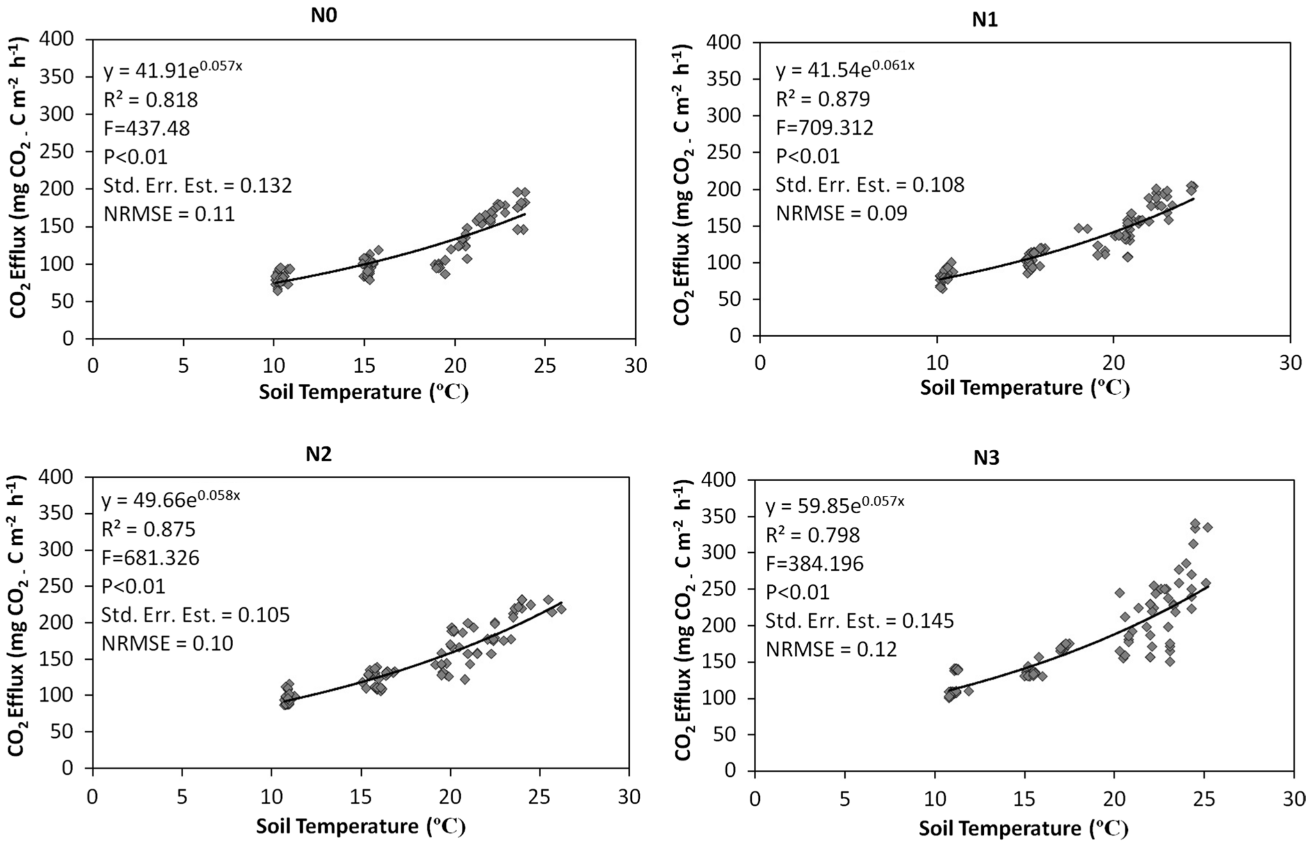


**Fig. 3** Relationships between soil CO2 efflux and soil temperature measured at different levels of N addition (N0: Control, N1: 5, N2: 10, and N3:15 g N m$^{-2}$ year$^{-1}$); Std. Err. Est standard error of estimate, NRSME normalized RMSE

may increase the N content of soil and thus decrease the soil C/N, which is beneficial to the microbial biomass and activity as well as the plant growth (Chu et al. 2010; Li et al. 2016) and therefore enhances soil CO$_2$ efflux. Moreover, the addition of N to the soil increases the decomposition rates of leaf litter and fine root, which provides more substrates for the microbial communities and finally increases the microbial biomass (Li et al. 2016), enzyme activity, and microbial respiration. On the other hand, C input from the additional aboveground litter and decomposed roots eventually enters into the soil organic matter and stimulates heterotrophic respiration (Bowden et al. 2004; Phillips et al. 2007). Burton et al. (2004) also claimed that NO$_3^-$ addition increased the soil CO$_2$ efflux in a sugar maple stand in Michigan during the first year of the investigation. A similar response to N additions (5 and 15 g N m$^{-2}$ year$^{-1}$) has been observed in an oak (*Quercus velutina*) dominated hardwood in Harvard Forest, with increased soil CO$_2$ efflux occurring in the first year of N addition (Bowden et al. 2004). Mo et al. (2008) in their study in an old-growth broadleaf forest (monsoon evergreen) observed that N deposition (50 kg N ha$^{-1}$ year$^{-1}$) enhanced soil CO$_2$ efflux and high N addition rates (≥ 100 kg N ha$^{-1}$ year$^{-1}$) reduced it, whereas N1 (50 kg N ha$^{-1}$ year$^{-1}$) had no significant effect and N2 (100 kg N ha$^{-1}$ year$^{-1}$) increased the soil CO$_2$ efflux in the present study. Some studies have shown the declining or insignificant effects of N deposition on soil CO$_2$ efflux (Burton et al. 2004; Jiang et al. 2010; Wei et al. 2014; Samuelson et al. 2009; Krause et al. 2013). These inconsistent results might be related to the N addition rates, initial N condition of the soil, soil properties, and the tree species (Gao et al. 2015; Li et al. 2019).

**Table 4** The fine root biomass (g m$^2$) (mean values ± SE) in different treatments. Different letters represent significant differences between treatments within each season (the starting point of this study was summer and finished at the end of spring)

| | Summer | Fall | Winter | Spring |
|---|---|---|---|---|
| N0 | 48.6 ± 1.21 b | 46.6 ± 0.60 b | 47.2 ± 0.31 b | 48.2 ± 0.67 b |
| N1 | 49.0 ± 0.65 b | 47.3 ± 0.19 b | 47.0 ± 0.59 b | 48.2 ± 0.41 b |
| N2 | 49.9 ± 0.32 b | 47.8 ± 0.43 b | 47.6 ± 0.53 b | 49.9 ± 0.56 b |
| N3 | 52.8 ± 0.61 a | 51.3 ± 1.21 a | 50.1 ± 0.45 a | 52.2 ± 0.44 a |

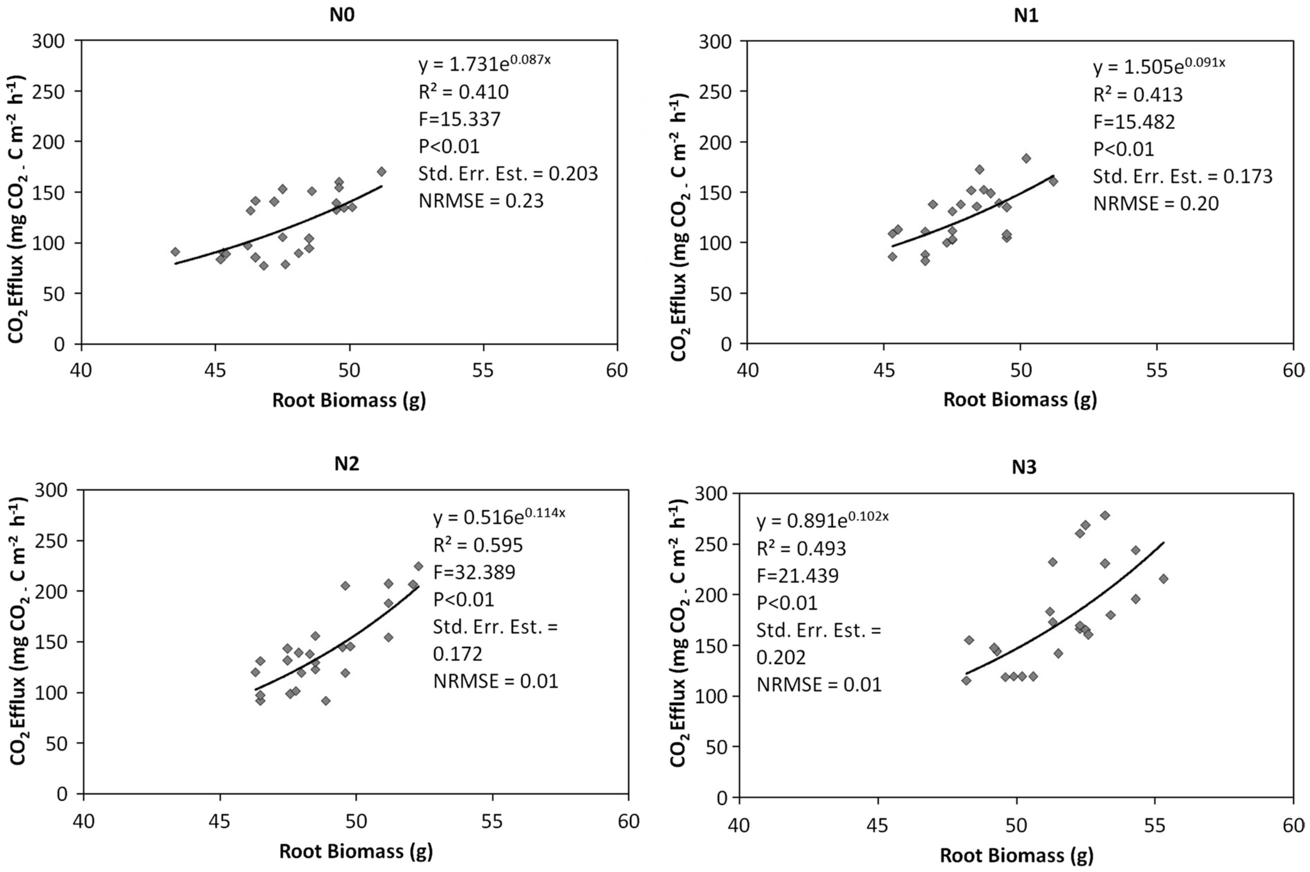


**Fig. 4** Relationships between soil CO2 efflux and fine root biomass measured at different N addition (N0: Control, N1: 5, N2: 10, and N3:15 g N $m^{-2}$ $year^{-1}$); Std. Err. Est Standard Error of Estimate, NRSME normalized RMSE

The results of the current study confirmed that soil $CO_2$ efflux was exponentially related to soil temperature. This is in line with findings in the temperate forests (Bowden et al. 2004; Samuelson et al. 2009) and the subtropical/tropical moist ones (Mo et al. 2008). Moreover, noticeable exponential and linear relationships between soil $CO_2$ efflux and soil temperature have been reported for other vegetation types (Fang and Moncrieff 2001; Samuelson et al. 2004; Jassal et al. 2007; Wang et al. 2019). In the present study, the soil $CO_2$ efflux in the maple plantation stand exhibited a strong seasonal pattern, which reached the maximum rate in the midsummer and the minimum rate in the late winter. Distinct seasonal patterns of the soil efflux relevant to the soil temperature and moisture and plant growth have also been found in other studies (Contosta et al. 2011; Du et al. 2011; Wang et al. 2019).

The treatment of N3 (15 g N $m^{-2}$ $year^{-1}$) significantly increased fine root biomass. Increased fine root biomass by N addition (8-12 g N $m^{-2}$ $year^{-1}$) has also been reported in various studies (Cleveland and Townsend 2006; Xu and Wan 2008; Song et al. 2017; Li et al. 2019; Wang et al. 2019; Ren et al. 2019). According to the minimum limiting factors theory, the increase of N in the soil may intensify the deficiency of other nutrients in the soil. Fine roots need to increase root growth to uptake more nutrients (Wang et al. 2013; Zhang et al. 2020). Yan (2017) reported that the deposition of N to soil may decrease the fine root surface area, but can increase the thickness of fine roots and subsequently may result in an increase in the total biomass of the fine roots. Other studies have found that trees at different growth stages exhibit different characteristics due to their ecological plasticity; fine root production and turnover rates of young trees usually increased with the increase of soil N availability (Børja et al. 2008; Jagodzinski and Katuckd 2011; Xiong et al. 2018).

## 5 Conclusions

The current study presented new data on the soil $CO_2$ efflux in the Hyrcanian forest. According to the results, increased N availability (10 and 15 g N $m^{-2}$ $year^{-1}$) and increased temperature stimulated the fine root biomass, which was observed along with an increase in the soil $CO_2$ efflux in the maple (*Acer velutinum* Bioss.) plantation stand. N addition (10 and 15 g N $m^{-2}$ $year^{-1}$) led to a lower soil pH and EC, and all N addition treatments (5, 10, and 15 g N $m^{-2}$ $year^{-1}$) led to an increase in soil total N, $NH_4^+$, and $NO_3^-$ at the end of the study period. It is projected that the amount of N deposition in the Hyrcanian forests might be doubled by the end of this century (6–10 g N $m^{-2}$ $year^{-1}$); therefore, soil CO2 efflux due to N deposition could be an important challenge in the future. Since the effect of N addition on forest stands is a long-term and complex process, further long-time studies would be needed to clarify the response of the root respiration and enzyme activity to increased N availability. Such studies in these valuable forests could lead to a comprehensive understanding of the effects of the increased N amount on the C cycle.

## Appendix

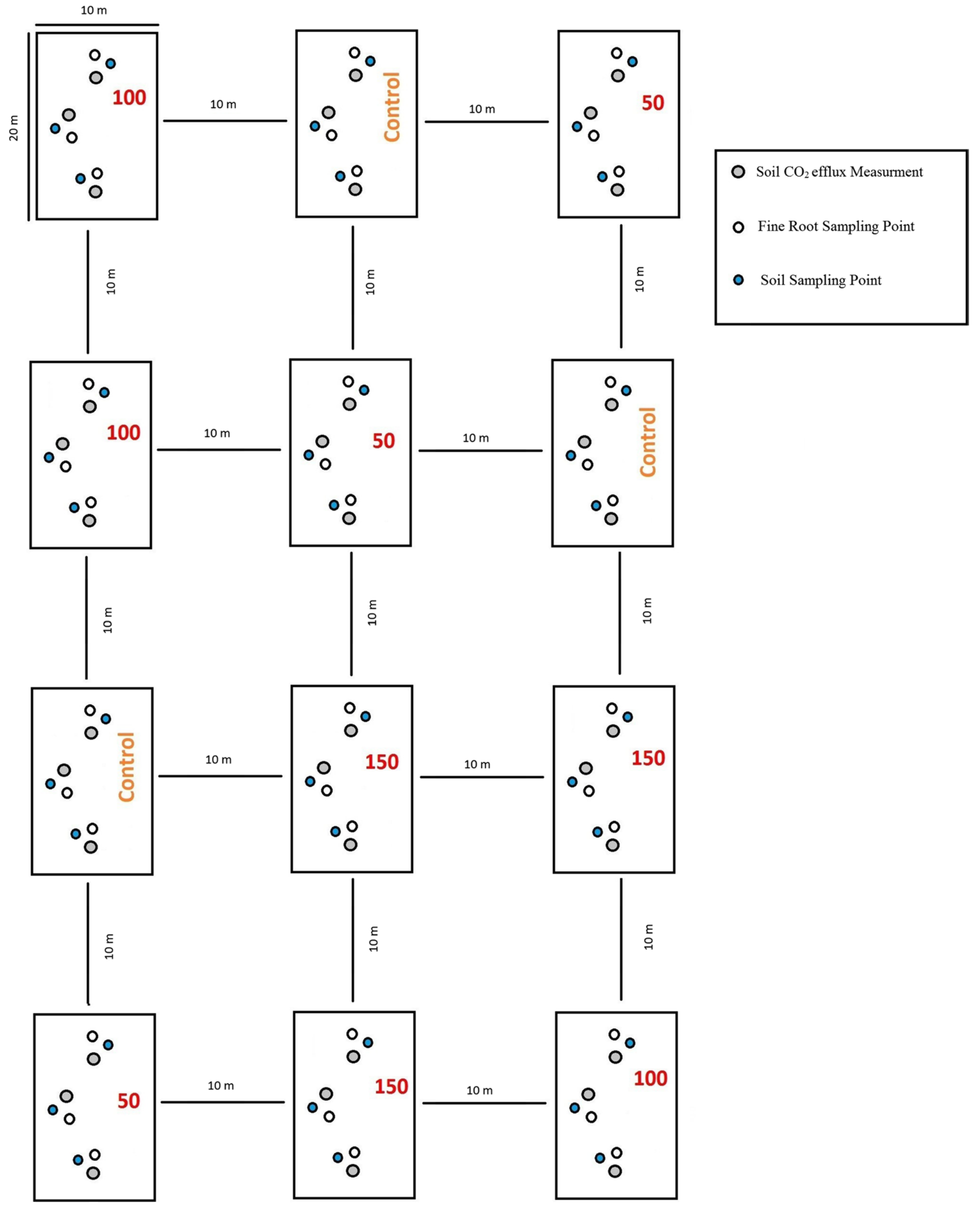


**Fig. 5** Layout of the experimental design (N1: 5, N2: 10, and N3:15 g N $m^{-2}$ $year^{-1}$)

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

Aber J, McDowell W, Nadelhoffer K, Magill A, Berntson G, Kamakea M, McNulty S, Currie W, Rustad L, Fernandez I (1998) Nitrogen saturation in temperate forest ecosystems: hypotheses revisited. BioScience 48:921–934

Allison SD, Czimczik CI, Treseder KK (2008) Microbial activity and soil respiration under nitrogen addition in Alaskan boreal forest. Glob Chang Biol 14:1156–1168

Anonymous (1980) Soil and plant testing and analysis as a basis of fertilizer recommendation. F.A.O, Soils Bulletin, Rome

Anonymous (1990) Kjeltek System 1902 Manual. TECATORAB, Hoganas

Anonymous (1996) Forest management plan of darabkola forest. Published by Forests, Rangeand Watershed Management Organization of Iran

APHA (1998) Standard methods for the examination of water and wastewater. American Public Health Association. American Public Health Association, American Water Works Association, Water Environment Federation, Washington DC

Argiroff WA, Zak DR, Upchurch RA, Salley SO, Grandy AS (2019) Anthropogenic N deposition alters soil organic matter biochemistry and microbial communities on decaying fine roots. Glob Chan Biol 25(12):4369–4382

Baggs EM (2006) Partitioning the components of soil respiration: a research challenge. Plant Soil 284:1–5

Bekku Y, Koizumi H, Nakadai T, Iwaki H (1995) Measurement of soil respiration using closed chamber method: An IRGA technique. Ecological research 10(3):369–373

Børja I, De Wit HA, Steffenrem A, Majdi H (2008) Stand age and fine root biomass, distribution and morphology in a Norway spruce chronosequence in southeast Norway. Tree Physiol 28:773–784

Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, Bustamante M, Cinderby S, Davidson E, Dentener F, Emmett B, Erisman J-W, Fenn M, Gilliam F, Nordin A, Pardo L, De Vries W (2010) Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecol Appl 20:30–59

Bouyoucos GJ (1951) A recalibration of the hydrometer for making mechanical analysis of soils. Agron J 43:434–438

Bowden RD, Davidson E, Savage K, Arabia C, Steudler P (2004) Chronic nitrogenadditions reduce total soil respiration and microbial respiration in temperateforest soils at the Harvard Forest. Forest Ecol Manag 196:43–56. https://doi.org/10.1016/j.foreco.2004.03.011

Bowman WD, Cleveland CC, Halada Ĺ, Hreško J, Baron JS (2008) Negative impact of nitrogen deposition on soil buffering capacity. Nat Geosci 1:767–770

Burton AJ, Pregitzer KS, Crawford JN, Zogg GP, Zak DR (2004) Simulated chronic NO deposition reduces soil respiration in northern hardwood forests. Glob Change Biol 10:1080–1091

Carter TS, Clark CM, Fenn ME, Jovan S, Perakis SS, Riddell J, Schaberg PG, Greaver TL, Hastings MG (2017) Mechanisms of nitrogen deposition effects on temperate forest lichens and trees. Ecosphere 8(3):e01717. https://doi.org/10.1002/ecs2.1717

Chen Z, Xu Y, He Y, Zhou X, Fan J, Yu H, Ding W (2018) Nitrogen fertilization stimulated soil heterotrophic but not autotrophic respiration in cropland soils: a greater role of organic over inorganic fertilizer. Soil Biol Biochem 116(253):e264

Chu H, Fierer N, Lauber CL, Caporaso JG, Knight R, Grogan P (2010) Soil bacterial diversity in the Arctic is not fundamentally different from that found in other biomes. Environ Microbiol 12:2998–3006

Cleveland CC, Townsend AR (2006) Nutrient additions to a tropical rain forest drive substantial soil carbon dioxide losses to the atmosphere. Proc Natl Acad Sci 103(10316):e10321

Contosta AR, Frey SD, Cooper AB (2011) Seasonal dynamics of soil respiration and N mineralization in chronically warmed and fertilized soils. Ecosphere 2:1–21. https://doi.org/10.1890/ES10-00133.1

De Vries W, Dobbertin MH, Solberg S, Van Dobben HF, Schaub M (2014) Impacts of acid deposition, ozone exposure and weather conditions on forest ecosystems in Europe: an overview. Plant Soil 380:1–45

de Vries W, Du E, Butterbach-Bahl K (2014) Short and long-term impacts of nitrogen deposition on carbon sequestration by forest ecosystems. Curr Opin Env Sust 9:90–104

De Vries WI, Reinds GJ, Gundersen PE, Sterba H (2006) The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Global Change Biol 12:1151–1173

Deng L, Peng C, Zhu G, Chen L, Liu Y, Shangguan Z (2018) Positive responses of belowground C dynamics to nitrogen enrichment in China. Sci Total Environ 616(1035):e1044

Dentener F, Drevet J, Lamarque JF, Bey I, Eickhout B, Fiore AM, Hauglustaine D, Horowitz LW, Krol M, Kulshrestha UC, Lawrence M (2006) Nitrogen and sulfur deposition on regional and global scales: a multimodel evaluation. Glob Biogeochem Cycl 20:GB4003

Dorich RA, Nelson DW (1983) Direct colorimetric measurement of ammonium in potassium chloride extracts of soils. Soil Sci Soc Am J 47:833–836. https://doi.org/10.2136/sssaj1983.03615995004700040042x

Du E, Fang J (2014) Weak growth response to nitrogen deposition in an old-growth boreal forest. Ecosphere 5:art109

Du E, de Vries W (2018) Nitrogen-induced new net primary production and carbon sequestration in global forests. Environ Pollut 242:1476–1487

Du S, Wang YL, Kume T, Zhang JG, Otsuki K, Yamanaka N, Liu GB (2011) Sapflow characteristics and climatic responses in three forest species in the semiarid Loess Plateau region of China. Agric For Meteorol 151:1–10. https://doi.org/10.1016/j.agrformet.2010.08.011

Fang C, Moncrieff JB (2001) The dependence of soil $CO_2$ efflux on temperature. Soil Biol Biochem 33:155–165. https://doi.org/10.1016/S0038-07170000125-5

Galloway JN, Capone Dentener FJ, DG, Boyer, EW Howarth, RW, Seitzinger, SP, Asner. GP, Cleveland, CC, Green, PA, Holland, EA, Karl, DM, Michaels, AF, Porter, JH, Townsend, AR, Vorosmarty, CJ, (2004) Nitrogen cycles: past, present, and future. Biogeochemistry 70:153–226

Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. Sci 320:889–892

Gao Q, Hasselquist NJ, Palmroth S, Zheng Z, You W (2014) Short-term response of soil respiration to nitrogen fertilization in a subtropical evergreen forest. Soil Biol Biochem 76:297–300

Gao W, Yang H, Kou L, Li S (2015) Effects of nitrogen deposition and fertilization on N transformations in forest soils: a review. J Soil Sediments 15(4):863–879

Geng J, Cheng S, Fang H, Yu G, Li X, Si G, He S, Yu G (2017) Soil nitrate accumulation explains the nonlinear responses of soil $CO_2$ and $CH_4$ fluxes to nitrogen addition in a temperate needle-broadleaved mixed forest. Ecol Indic 79:28–36. https://doi.org/10.1016/j.ecolind.2017.03.054

Gentilesca T, Rita A, Brunetti M, Giammarchi F, Leonardi S, Magnani F, van Noije T, Tonon G, Borghetti M (2018) Nitrogen deposition outweighs climatic variability in driving annual growth rate of canopy beech trees: evidence from long-term growth reconstruction across a geographic gradient. Glob chan biol 24(7):2898–2912

Gundersen P, Emmett BA, Kjønaas OJ, Koopmans CJ, Tietema A (1998) Impact of nitrogen deposition on nitrogen cycling in forests: a synthesis of NITREX data. For Ecol Manage 101:37–55. https://doi.org/10.1016/S0378-11279700124-2

Gundersen P, Schmidt IK, Raulund-Rasmussen K (2006) Leaching of nitrate from temperate forests effects of air pollution and forest management. Environ Rev 14(1):1–57

Guo JH, Liu XJ, Zhang Y, Shen JL, Han WX, Zhang WF, Christie P, Goulding KW, Vitousek PM, Zhang FS (2010) Significant acidification in major Chinese croplands. Science 327(5968):1008-1010

Högberg P (2012) What is the quantitative relation between N deposition and forest carbon sequestration? Global Change Biol. 18:1–2

Hojjati SM (2008) The impact of canopy composition on the nutritional statusof an admixed spruce and beech forest at Solling, central Germany (Doctoral dissertation, Niedersächsische Staats-und Universitätsbibliothek Göttingen)

Hojjati SM, Lamersdorf NP (2010) Effect of canopy composition on soil CO 2 emission in a mixed sprucebeech forest at Solling. Central Germany. J For Res 21(4):461–464

Hong S, Gan P, Chen A (2019) Environmental controls on soil pH in planted forest and its response to nitrogen deposition. Environ res 172:59–165

Jagodzinski AM, Kalucka I (2011) Fine root biomass and morphology in an age-sequence of post-agricultural *Pinus sylvestris* L. stands. Dendrobiology 66:71–84

Janssens IA, Dieleman W, Luyssaert S, Subke JA, Reichstein M, Ceulemans R, Ciais P, Dolman AJ, Grace J, Matteucci G, Papale D (2010) Reduction of forest soil respiration in response to nitrogen deposition. Nat Geosci 3(315):e322

Jassal RS, Black TA, Cai T, Morgenstern K, Li Z, Gaumont-Guay D, Nesic Z (2007) Components of ecosystemrespiration and an estimate of net primary productivity of an intermediate-aged Douglas-fir stand. Agric For Meteorol 144:44–57. https://doi.org/10.1016/j.agrformet.2007.01.011

Jia Y, Yu G, Gao Y, He N, Wang Q, Jiao C, Zuo Y (2016) Global inorganic nitrogen dry deposition inferred from ground- and space-based measurements. Sci Rep 6:19810

Jiang C, Yu G, Fang H, Cao G, Li Y (2010) Short-term effect of increasing nitrogen deposition on CO2, $CH_4$ and $N_2O$ fluxes in an alpine meadow on the Qinghai-Tibetan Plateau, China. Atmos Environ 44:2920–2926. https://doi.org/10.1016/j.atmosenv.2010.03.030

Keenan RJ, Reams GA, Achard F, de Freitas JV, Grainger A, Lindquist E (2015) Dynamics of global forest area: results from the FAO global forest resources assessment 2015. Forest Ecol Manag 352:9–20

Krause GH, Cheesman AW, Winter K, Krause B, Virgo A (2013) Thermal tolerance, net CO2 exchange and growth of a tropical tree species, Ficus insipida, cultivated at elevated daytime and nighttime temperatures. J Plant Physiol 170:822–827

Lamarque JF (2005) Assessing future nitrogen deposition and carbon cycle feedback using a multimodel approach: analysis of nitrogen deposition. J Geophys Res 110

Li Q, Song X, Chang SX, Peng C, Xiao W, Zhang J, Xiang W, Li Y, Wang W (2019) Nitrogen depositions increase soil respiration and decrease temperature sensitivity in a Moso bamboo forest. Agric for meteor 268:48–54

Li Y, Ning Z, Cui D, Mao W, Bi J, Zhao X (2016) Litter decomposition in a semiarid dune grassland: neutral effect of water supply and inhibitory effect of nitrogen addition. PloS One 11(9):e0162663

Liu L, Greaver TL (2009) A review of nitrogen enrichment effects on three biogenic GHGs: the CO2 sink may be largely offset by stimulated N2O and CH4 emission. Ecol Let 12:1103–1117

Liu T, Mao P, Shi L, Eisenhauer N, Liu S, Wang X, He X, Wang Z, Zhang W, Liu Z, Zhou L, Shao Y, Fu S (2020) Forest canopy maintains the soil community composition under elevated nitrogen deposition. Soil Biol Biochem 143:107733

Li X, Zhang C, Zhang B, Wu D, Zhu D, Zhang W, Ye Q, Yan J, Fu J, Fang C, Ha D (2021) Nitrogen deposition and increased precipitation interact to affect fine root production and biomass in a temperate forest: implications for carbon cycling. Sci Total Environ p.144497

Lu X, Vitousek PM, Mao Q, Gilliam FS, Luo Y, Zhou G, Zou X, Bai E, Scanlon TM, Hou E, Mo J (2018) Plant acclimation to long-term high nitrogen deposition in an N-rich tropical forest. Proceedings of the National Academy of Sciences 115(20):5187–5192

Lupi C, Morin H, Deslauriers A, Rossi S, Houle D (2013) Role of soil nitrogen for the conifers of the boreal forest: a critical review. Int J Plant Soil Sci 2:155–189. https://doi.org/10.9734/IJPSS/2013/4233

Magill AH, Aber JD, Currie WS, Nadelhoffer KJ, Martin ME, McDowell WH, Melillo JM, Steudler P (2004) Ecosystem response to 15 years of chronic nitrogen additions at the Harvard Forest LTER, Massachusetts, USA. For Ecol Manage 196:7–28

Maskell LC, Smart SM, Bullock JM, Thompson KE, Stevens CJ (2010) Nitrogen deposition causes widespread loss of species richness in British habitats. Glob Chan Bio 16(2):671–679

Mo J, Brown S, Xue J, Fang Y, Li Z (2006) Response of litter decomposition to simulated N deposition in disturbed, rehabilitated and mature forests in subtropical China. Plant soil 282(1–2):135–151

Mo J, Zhang WE, Zhu W, Gundersen PE, Fang Y, Li D, Wang HU (2008) Nitrogen addition reduces soil respiration in a mature tropical forest in southern China. Glob Chan Biol 14(2):403–412

Naik SK, Sarkar PK, Das B, Singh AK, Bhatt BP (2018) Predictive models for dry biomass and carbon stock estimation in Litchi chinensis under hot and dry sub-humid climate. Arch Agron Soil Sci 64(10):1366–1378

Nobakht AA, Hojjati SM, Pourmjidian MR, Khorrami RA (2018) Investigation on livestock presence in forest on plant biodiversity and soil properties in Zalemroud, Neka, Mazandaran province. Iranian J For Poplar Res 26(3):382–392

Novotný R, Buriánek V, Šrámek V, Hunova I, Skorepová I, Zapletal M, Lomský B (2016) Nitrogen deposition and its impact on forest ecosystems in the Czech Republic - change in soil chemistry and ground vegetation. iForest 10(1):48. 10.3832/ IFOR1847-009

Peng Q, Dong Y, Qi Y, Xiao S, He Y, Ma T (2011) Effects of nitrogen fertilization on soil respiration in temperate grassland in Inner Mongolia. China. Environ. Earth Sci 62:1163–1171

Phillips RP, Fahey TJ (2007) Fertilization effects on fineroot biomass, rhizosphere microbes and respiratory fluxes in hardwood forest soils. New Phytol 176(3):655–664

Ramirez KS, Craine JM, Fierer N (2010) Nitrogen fertilization inhibits soil microbial respiration regardless of the form of nitrogen applied. Soil Biol Biochem 42:2336–2338

Ren GQ, Li Q, Li Y, Li J, Adomako MO, Dai ZC, Li GL, Wan LY, Zhang B, Zou CB, Ran Q (2019) The enhancement of root biomass increases the competitiveness of an invasive plant against a co-occurring native plant under elevated nitrogen deposition. Flora 261:151486

Riofrío-Dillon G, Gégout JC, Bertrand R (2017) Decreasing before increasing: evolution of nitrogen availability conditions in French forest ecosystems over the last century according to forest herbs. bioRxiv 1:103721

SaghebTalebi KS, Sajedi T, Pourhashemi M (2014) Forests ofIran: A treasure from the past, a hope for the future, vol 10. Springer, Netherlands

Salahi A, Gruber F, Geranfar S, Moniri VR (2014) Investigation on nitrogen deposition in the greater Tehran metropolitan area and Caspian Sea lowland areas of Iran, up to altitude of 2200 meters. Int J Agri Science 4:426–431

Samuelson LJ, Johnsen K, Stokes T, Lu W (2004) Intensive management modifies soil CO2 efflux in 6-year-old Pinus taeda L. stands. Forest Ecol Manag 200(1–3):335–345

Samuelson L, Mathew R, Stokes T, Feng Y, Aubrey D, Coleman M (2009) Soil andmicrobial respiration in a loblolly pine plantation in response to seven years of irrigation and fertilization. Ecol Manag 258:2431–2438. https://doi.org/10.1016/j.foreco.2009.08.020

Schulte-Uebbing L, de Vries W (2018) Global-scale impacts of nitrogen deposition on tree carbon sequestration in tropical, temperate, and boreal forests: a meta analysis. Glob Change Biol 24: e416ee431.

Schwede DB, Simpson D, Tan J, Fu JS, Dentener F, Du E, deVries W (2018) Spatial variation of modelled total, dry and wet nitrogen deposition to forests at global scale. Environ Pollut 243:1287–1301

Shi L, Zhang H, Liu T, Mao P, Zhang W, Shao Y, Fu S (2018) An increase in precipitation exacerbates negative effects of nitrogen deposition on soil cations and soil microbial communities in a temperate forest. Environ Pollut 235(293):e301

Song L, Tian P, Zhang J, Jin G (2017) Effects of three years of simulated nitrogen deposition on soil nitrogen dynamics and greenhouse gas emissions in a Korean pine plantation of northeast China. Sci Total Environ 609:1303–1311

Sutton MA, Simpson D, Levy PE, Smith RI, Reis S, Van Oijen M, De Vries WI (2008) Uncertainties in the relationship between atmospheric nitrogen deposition and forest carbon sequestration. Global Change Biol 14:2057–2063

Tafazoli M, Hojjati SM, Jalilvand H, Lamersdorf N (2019) Simulated nitrogen deposition reduces the concentration of soil base cations in Acer velutinum Bioss. Plantation, North of Iran. J Soil Sci Plant Nutr 19(2):440-449

Tu LH, Hu TX, Zhang J, Li XW, Hu HL, Liu L, Xiao YL (2013) Nitrogen addition stimulates different components of soil respiration in a subtropical bamboo ecosystem. Soil Biol Biochem 58:255–264

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

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Technical Report: human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737-750. https://doi.org/10.2307/2269431

Vogt DJ, Tilley JP, Edmonds RL (2015) Soil and plant analysis for forest ecosystem characterization. Walter de Gruyter GmbH & Co KG

Wang G, Fahey TJ, Xue S (2013) Root morphology and architecture respond to N addition in *Pinus tabuliformis*, west China. Oecologia 171:583–590

Wang J, Fu X, Zhang Z, Li M, Cao H, Zhou X, Ni H (2019) Responses of soil respiration to nitrogen addition in the Sanjiang Plain wetland, northeastern China. PloS one 14(1):e0211456

Wardle DA, Bardgett RD, Klironomos JN, Setälä H, Van Der Putten WH, Wall DH (2004) Ecological linkages between aboveground and belowground biota. Sci 304(5677):1629–1633

Wei D, Liu Y, Wang Y, Wang Y (2014) Three-year study of CO2 efflux and CH4/N2O fluxes at an alpine steppe site on the central Tibetan Plateau and their responses to simulated N deposition. Geoderma 232:88–96. https://doi.org/10.1016/j.geoderma.2014.05.002

Wei HW, Wang XG, Li YB, Yang JJ, Wang JF, Lü XT, Han XG (2020) Simulated nitrogen deposition decreases of soil microbial diversity in a semiarid grassland, with little mediation of this effect by mowing. Pedobiologia 18:150644

Wieder WR, Cleveland CC, Smith WK, Todd-Brown K (2015) Future productivity and carbon storage limited by terrestrial nutrient availability. Nat Geosci 8:441–444

Xian-Kai LU, Jiang-Ming MO, Gundersern P, Wei-Xing ZH, Guo-Yi ZH, De-Jun LI, Zhang X (2009) Effect of simulated N deposition on soil exchangeable cations in three forest types of subtropical China. Pedosphere 19(2):189–198

Xiong D, Yang Z, Chen G, Liu X, Lin W, Huang J, Bowles FP, Lin C, Xie J, Li Y, Yang Y (2018) Interactive effects of warming and nitrogen addition on fine root dynamics of a young subtropical plantation. Soil Biol Biochem 123:180–189

Xu GL, Mo JM, Fu SL, Gundersen P, ZHOU GY, Jing-Hua X, (2007) Response of soil fauna to simulated nitrogen deposition: a nursery experiment in subtropical China. J Environl Sci 19(5):603–609

Xu W, Wan S (2008) Water- and plant-mediated responses of soil respiration to topography, fire, and nitrogen fertilization in a semiarid grassland in northern China. Soil Biol Biochem 40(3):679–687

Yan GY (2017) Effected of simulated nitrogen deposition on fine root dynamics and morphological structure of Larix gmelinii. Northeast Forestry University CDMD 2(1018):811194

Yang Y, Ji C, Ma W, Wang S, Wang S, Han W, Mohammat A, Robinson D, Smith P (2012) Significant soil acidification across northern China's grasslands during 1980s–2000s. Glob Change Biol 18(7):2292–2300

Yang Y, Li P, He H, Zhao X, Datta A, Ma W, Zhang Y, Liu X, Han W, Wilson MC, Fang J (2015) Long-term changes in soil pH across major forest ecosystems in China. Geophys Rese Lett 42(3):933–940

Ye C, Chen D, Hall SJ, Pan S, Yan X, Bai T, Guo H, Zhang Y, Bai Y, Hu S (2018) Reconciling multiple impacts of nitrogen enrichment on soil carbon: plant, microbial and geochemical controls. Ecol Lett 21:1162–1173

Zhang C, Niu D, Hall SJ, Wen H, Li X, Fu H, Wan C, Elser JJ (2014) Effects of simulated nitrogen deposition on soil respiration components and their temperature sensitivities in a semiarid grassland. Soil Biol Biochem 75:113–123. https://doi.org/10.1016/j.soilbio.2014.04.013

Zhang J, Yang H, Wang J, Tian D, Li Y, He N, Niu S (2019) Soil and climate determine differential responses of soil respiration to nitrogen and acid deposition along a forest transect. Eur J Soil Biol 93:103097

Zhang R, Wu J, Li Q, Hänninen H, Peng C, Yao H, Song X, Ying Y (2017) Nitrogen deposition enhances photosynthesis in Moso bamboo but increases susceptibility to other stress factors. Front Plant Sci 8:1975

Zhang TA, Chen HY, Ruan H (2018) Global negative effects of nitrogen deposition on soil microbes. The ISME journal 12(7):1817–1825

Zhang X, Han X (2012) Nitrogen deposition alters soil chemical properties and bacterial communities in the Inner Mongolia grassland. J Environ Sci 24(8):1483–1491

Zhao X, Li Y, Xie Z, Li P (2020) Effects of nitrogen deposition and plant litter alteration on soil respiration in a semiarid grassland. Sci Total Environ 740:1–10

Zhang X, Xing Y, Wang Q, Yan G, Wang M, Liu G, Wang H, Huang B, Zhang J (2020) Effects of long-term nitrogen addition and decreased precipitation on the fine root morphology and anatomy of the main tree species in a temperate forest. Forest Ecol Manag 455:117664

Zheng S, Bian H, Quan Q, Xu L, Chen Z, He N (2018) Effect of nitrogen and acid deposition on soil respiration in a temperate forest in China. Geoderma 329:82–90

Zhu J, He N, Wang Q, Yuan G, Wen D, Yu G, Jia Y (2015) The composition, spatial patterns, and influencing factors of atmospheric wet nitrogen deposition in Chinese terrestrial ecosystems. Sci Total Environ 511:777–785

Zhu X, Zhang W, Chen H, Mo J (2015) Impacts of nitrogen deposition on soil nitrogen cycle in forest ecosystems: A review. Acta Ecologica Sinica 35(3):35–43