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Heavy Nitrogen Application Rate and Long-Term Duration Decrease the Soil Organic Carbon and Nitrogen Sequestration Rates in Forest Ecosystems

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Abstract: Nitrogen addition alters soil organic carbon (SOC) and total nitrogen (TN) accumulation in forest ecosystems, but the responses of SOC and TN sequestration rates and dynamics to nitrogen addition in forest ecosystems worldwide remain unclear. This study conducted a global analysis to evaluate the effects of the nitrogen application rate, nitrogen addition duration (time), and humidity on the SOC and TN accumulation rates from 257 data points (63 articles). Nitrogen addition increased SOC and TN by 4.48% and 10.18%, respectively. The SOC and TN accumulation rates were 0.65 and 0.11 g kg^{-1} yr^{-1}, respectively. Moreover, the percentage changes of SOC and TN overall increased with the nitrogen application rate and duration of nitrogen addition; however, the accumulation rates of SOC and TN overall decreased with the nitrogen application rate and the duration of nitrogen addition. In addition, the percentage changes and change rates of SOC and TN increased overall with the humidity index. In conclusion, nitrogen addition promoted SOC and TN accumulation in forest soil, and the nitrogen application rate and nitrogen addition duration increased the percentage changes in SOC and TN; however, they decreased the accumulation rate, whereas humidity increased the accumulation rates of SOC and TN. These results enhance our understanding of soil carbon and nitrogen cycling in forest soils in the context of global nitrogen deposition.

Keywords: climate change; forest ecosystem; forest soil; nitrogen deposition; nutrient cycle; carbon cycle

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1. Introduction

Burning fossil fuels and the extensive use of fertilizers (causing nitrogen deposition) [1–3] have changed forest community structure [4], forest species composition [5], and forest ecosystem multifunctionality [6]. Nitrogen is a limiting element for plant and microbial growth, and an appropriate amount of exogenous nitrogen is highly important for promoting plant growth, improving plant productivity, and enhancing microbial activity [7–9]. However, large or excessive nitrogen inputs may change the physical structure, nutrient balance, and homeostasis of the soil, leading to soil acidification and limiting plant growth and microbial reproduction [10,11]. An increase in nitrogen input is likely to affect the steady state of soil carbon and nitrogen [12–15].

Nitrogen addition alters SOC and TN accumulation [16,17]. A recent study revealed that nitrogen addition increased the SOC stock and TN content by 5.82% and 6.1%, respectively [18]. However, Ngaba Junior et al. [19] reported that nitrogen addition increased the SOC pools in boreal forests by 17%; however, it decreased the SOC pools in subtropical forests by 0.4%. This difference is due mainly to the different ecosystem types used in the different studies. A unified understanding of the response of SOC and TN to nitrogen addition, particularly the accumulation rates of SOC and TN in forest ecosystems, is lacking.

The changes in SOC and TN accumulation in forest ecosystems involve two main mechanisms: (1) Nitrogen addition changes plant growth and soil nutrient status through nitrogen input, thus affecting forest ecosystem productivity [20,21] and soil microbial activity [22,23]. Changes in microbial activity significantly affect forest litter decomposition and carbon mineralization, thereby affecting SOC and TN accumulation [9,11,24]. (2) The soil microbial community structure affects the release of extracellular enzymes, which in turn affect plant root activities, root exudates, and root turnover [25,26].

The nitrogen application rate and nitrogen addition duration (time) are important factors affecting the SOC and TN accumulation rates [27,28]. Currently, two major perspectives are present. First, plant productivity and the microbial decomposition rate of litter increase with increasing nitrogen application rates and nitrogen addition durations [22], thus increasing SOC and TN. In addition, the heavy nitrogen application rate and long-term nitrogen addition can lead to severe soil acidification [29], resulting in severe nutrient restriction [11] and significantly reduced microbial activity [30], thereby decreasing the accumulation of SOC and TN [11,31]. The nitrogen application rate and duration of nitrogen addition also significantly affect the root turnover rate [22]. Moderate nitrogen addition significantly increases the root turnover rate [7]. Conversely, the heavy nitrogen application rate reduces soil enzymatic activity [32], thereby reducing the root decomposition rate and limiting SOC and TN accumulation [33]. Environmental conditions (humidity indices) also significantly affect SOC and TN accumulation [34,35]. Low humidity leads to soil drought and decreases plant productivity and microbial activity [36,37]. High humidity reduces soil porosity and permeability and negatively affects plant and microbial growth [38,39]. Only moderate soil water availability can improve soil environmental conditions, promote plant growth [40], and increase litter decomposition [41]. However, how the nitrogen application rate, nitrogen addition duration, and environmental conditions affect the SOC and TN in forest ecosystems is insufficiently studied.

Therefore, this study explored the response of SOC and TN accumulation to nitrogen addition in forest ecosystems by collecting 257 data points from 63 articles. We aimed to assess the changes in SOC and TN accumulation rates systematically and to determine how SOC and TN are regulated by the nitrogen application rate, the duration of nitrogen addition, and humidity. We propose three hypotheses: (1) Nitrogen input stimulates plant and microbial growth and enhances forest litter and root decomposition [11,22]. Therefore, we hypothesized that nitrogen addition promotes SOC and TN accumulation in forest ecosystems. (2) Heavy nitrogen application rates and long-term nitrogen addition can promote plant growth; however, they can also lead to soil acidification and microbial activity reduction [42]. Therefore, the SOC and TN accumulation rates decrease with increasing nitrogen application rates and nitrogen addition durations. (3) Soil microorganisms are sensitive to changes in environmental conditions, and relatively high humidity increases soil water availability [40,41]. Therefore, the SOC and TN accumulation rates are significantly positively correlated with humidity.

2. Materials and Methods

2.1. Data Collection

The Web of Science (http://apps.webofknowledge.com/), Google Scholar (https://scholar.google.com), and CNKI (http://www.cnki.net) databases were searched for studies published in the literature. The search terms are shown in Table 1, and the search time was 20 March 2024. The literature screening criteria were as follows:

1. The research objects were forests in terrestrial ecosystems.
2. The research method was an artificial nitrogen addition experiment, and studies based on mathematical model calculations were excluded.

3. Studies that included both a control group and an experimental group and studies without a control group were excluded.
4. The nitrogen application rate and duration of nitrogen addition must be clarified.
5. The research data included mean values and are presented in the form of tables or figures.

Through screening, 257 data points were obtained from 63 articles. The collected variables included pH, SOC, and TN. The mean annual temperature (MAT) and precipitation (MAP) data of the sample sites were also collected.

Table 1. The search terms used in this study.

Keywords 1		Keywords 2
nitrogen addition or nitrogen deposition or nitrogen input or nitrogen application or fertilization	AND	soil organic carbon or soil organic matter or soil chemical or soil nutrient

2.2. Data Analysis

The percentage change [43] and rate of change [44] in the soil pH, SOC, and TN were calculated as follows:

$$\text{Percentage change } (\%) = \frac{X_t - X_c}{X_c} \times 100 \quad (1)$$

$$\text{Change rate of X} = \frac{X_i - X_0}{\Delta T} \quad (2)$$

where X_t and X_c are the pH, SOC, and TN of the nitrogen addition and control groups, respectively. X_i and X_0 are the pH, SOC, and TN after i years of nitrogen addition and the initial pH, SOC, and TN, respectively.

The humidity index was used to evaluate the effects of environmental factors (mean annual precipitation [MAP] and temperature [MAT]) [45].

$$\text{Humidity index} = \frac{\text{MAP}}{\text{MAT} + 10} \quad (3)$$

In this study, the humidity index, nitrogen addition duration, and nitrogen application rate were divided into <30, 30–50, and >50; <5, 5–10, and >10 years; and <5, 5–10, and >10 g m^{-2} yr^{-1}, respectively. One-way ANOVAs were used to test the effects of the humidity index, nitrogen addition duration, and nitrogen application rate on the percentage changes and rates of SOC and TN. Regression analysis was used to analyze the correlations of the nitrogen addition response and change rates of pH, SOC, and TN with the humidity index, nitrogen addition duration, and nitrogen application rate.

3. Results

3.1. Overall Effects

The distributions of the percentage change and change rates of pH, SOC, and TN are shown in Figure 1a,b; all the variables were normally distributed (Figure 1c,d). In total, 124, 221, and 233 data points were obtained for pH, SOC, and TN, respectively (Figure 1c).

The percentage change (%) and change rate of pH were negative (percentage: −5.27%, change rate: −0.10); however, the percentage change and change rates of SOC (+4.48%, +0.65 g kg^{-1} yr^{-1}) and TN (+10.18%, +0.11 g kg^{-1} yr^{-1}) were positive (Figure 2).

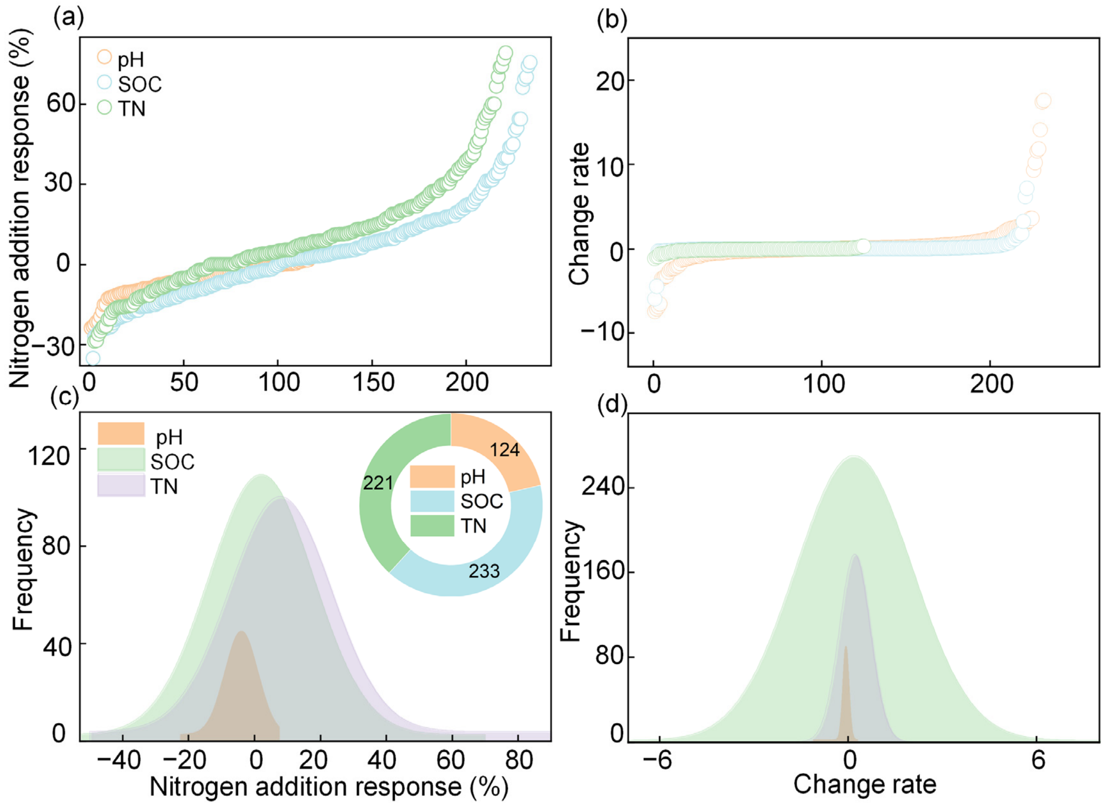

Figure 1. Distribution of the (**a**) percentage and rate (**b**) of soil pH, soil organic carbon (SOC), and total nitrogen (TN) and the frequency of the (**c**) percentage and rate (**d**) of soil pH, SOC, and TN under nitrogen addition.

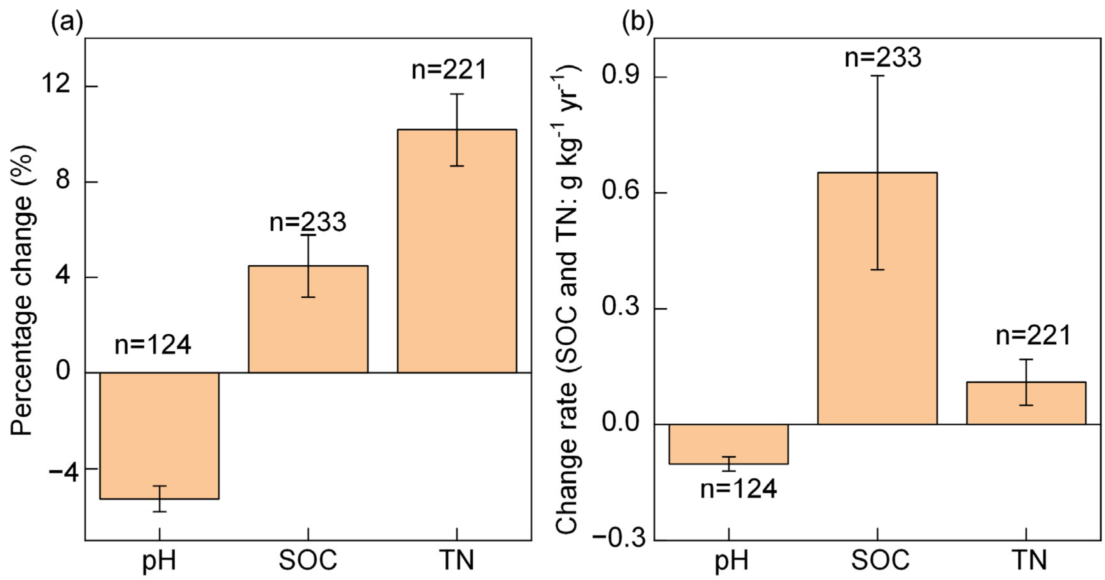

Figure 2. Mean (±SE) values of (**a**) percentage changes in soil pH, soil organic carbon (SOC), and total nitrogen (TN) and (**b**) change rates of soil pH, SOC, and TN in response to nitrogen addition.

3.2. Responses of pH, SOC, and TN to Humidity, Duration of Nitrogen Addition, and Nitrogen Application Rate

The percentage change in pH was lower at humidities of <30 and >50 than at 30–50, at durations of <5 and >10 years than at 5–10 years, and at application rates of 5–10 g N m^{-2} yr^{-1} than at >10 and <5 g N m^{-2} yr^{-1} (Figure 3a). The percentage change in SOC was greater at durations >10 years than at 5–10 and <5 years and at application rates >10 g N m^{-2} yr^{-1}

than at 5–10 and <5 g N m^{-2} yr^{-1} (Figure 3b). The percentage change in TN was greater at durations of <5 and >10 years than at 5–10 years and at application rates of 5–10 and >10 g N m^{-2} yr^{-1} than at <5 g N m^{-2} yr^{-1} (Figure 3c).

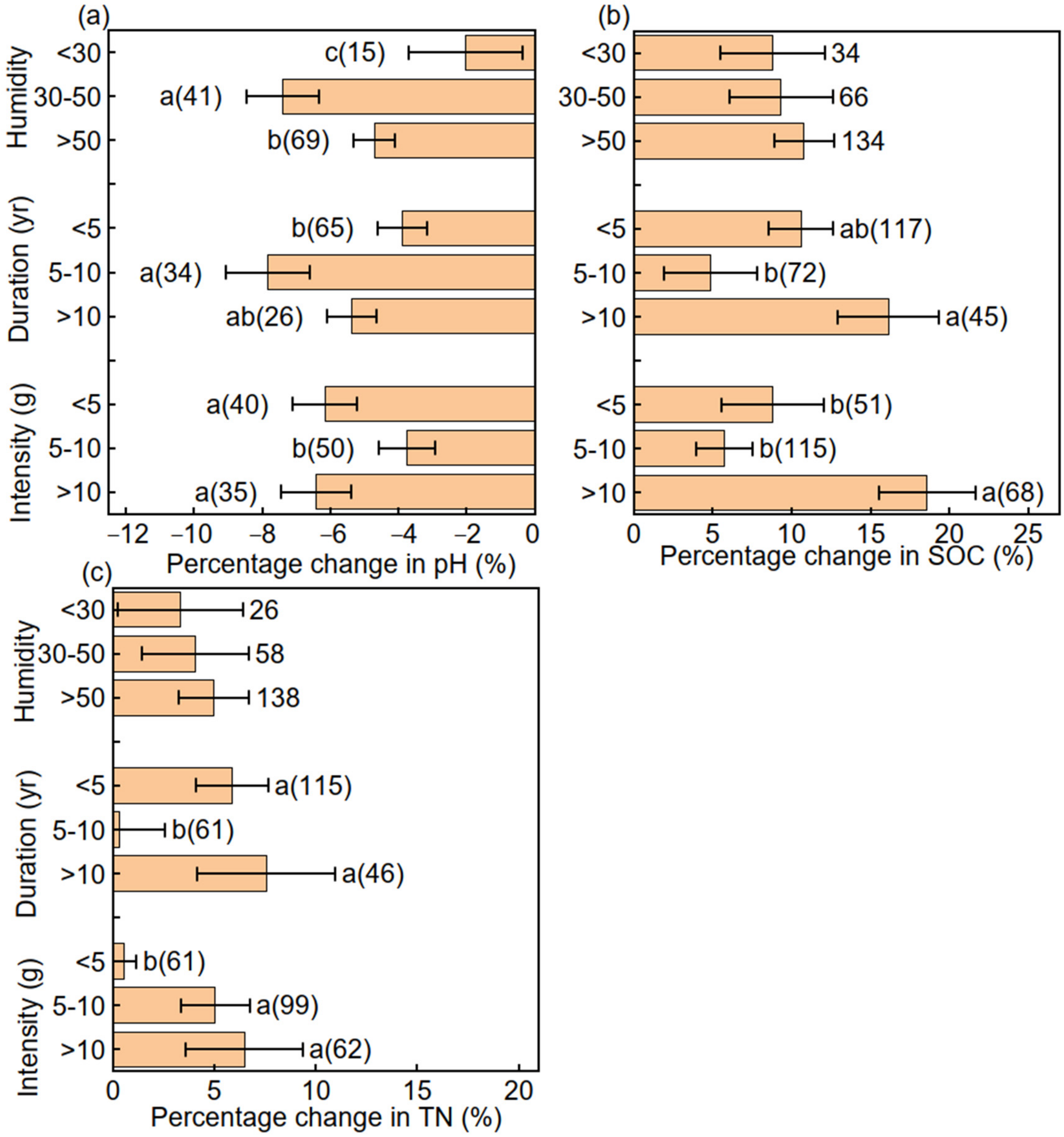

Figure 3. Mean (±SE) percentage changes in (**a**) soil pH, (**b**) soil organic carbon (SOC), and (**c**) total nitrogen (TN) in response to humidity, nitrogen addition duration, and nitrogen application rate. Different letters indicate significant differences in soil pH, SOC, and TN among different groups.

The change rate of pH was greater at humidities of 30–50 and >50 than at <30; at durations of 5–10 and >10 years than at <5 years; and at application rates of 5–10 and >10 g N m^{-2} yr^{-1} than at <5 g N m^{-2} yr^{-1} (Figure 4a). The change rates of SOC and TN were greater at humidities of >50 than at <30 and 30–50 and at durations of <5 years than at 5–10 and >10 years (Figure 4b,c).

The percentage change in pH decreased overall with nitrogen addition duration and nitrogen application rate, whereas the percentage change in SOC and TN increased overall with humidity, nitrogen addition duration, and nitrogen application rate (Figure S1a–i). The change rate of pH tended to increase with humidity, nitrogen addition duration, and nitrogen application rate, whereas the change rates of SOC and TN increased with humidity but decreased with nitrogen addition duration and nitrogen application rate (Figure S2a–i).

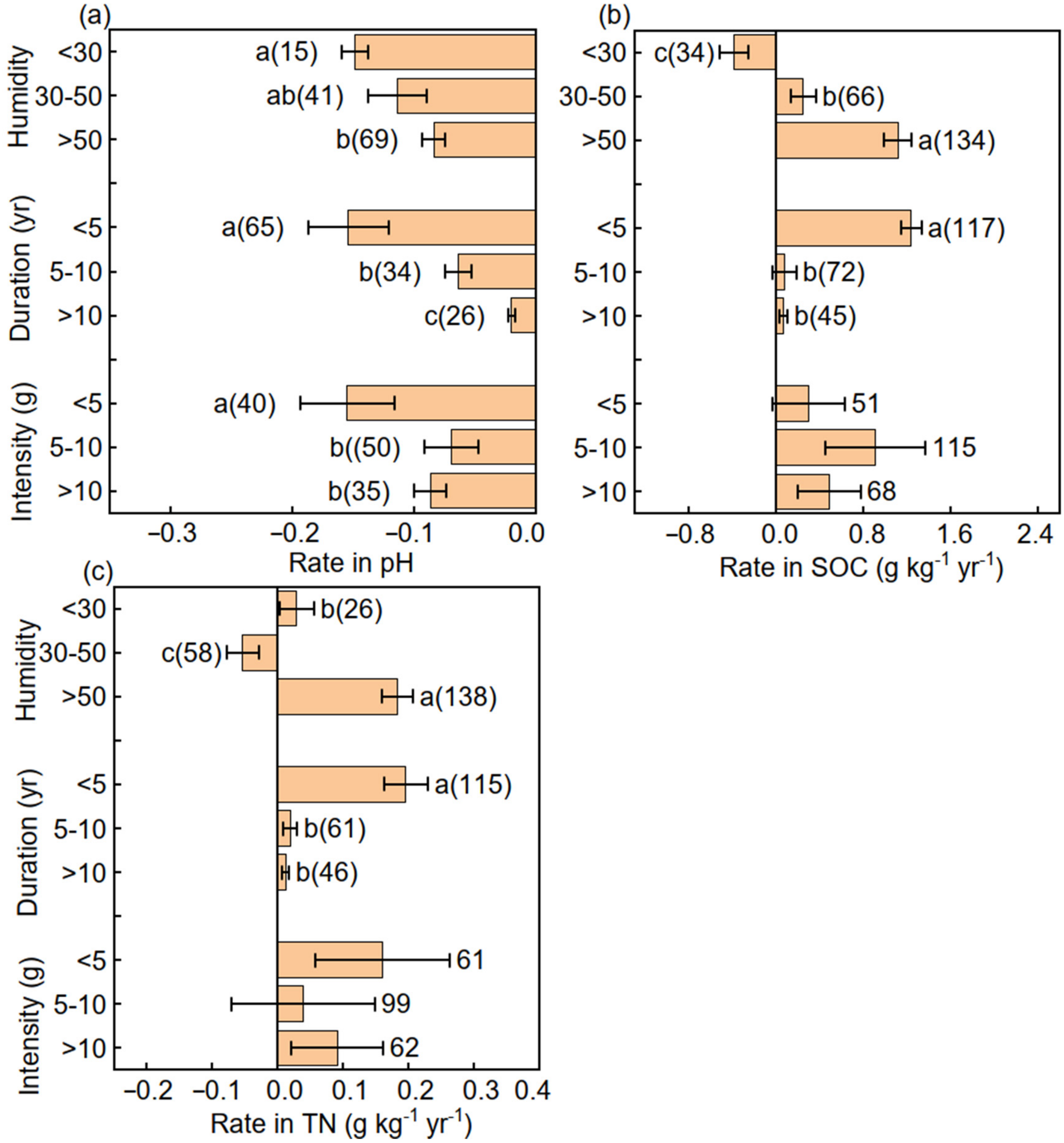

Figure 4. Mean (±SE) change rates of (**a**) soil pH, (**b**) soil organic carbon (SOC), and (**c**) total nitrogen (TN) in response to humidity, nitrogen addition duration, and nitrogen application rate. Different letters indicate significant differences in soil pH, SOC, and TN among different groups.

3.3. Relationships between pH, SOC, and TN

The percentage change in pH was positively correlated with SOC; however, the change rate of pH was negatively correlated with TN (Figure 5a,b). The percentage change and change rate of SOC were significantly positively correlated with TN (Figure 5c,d).

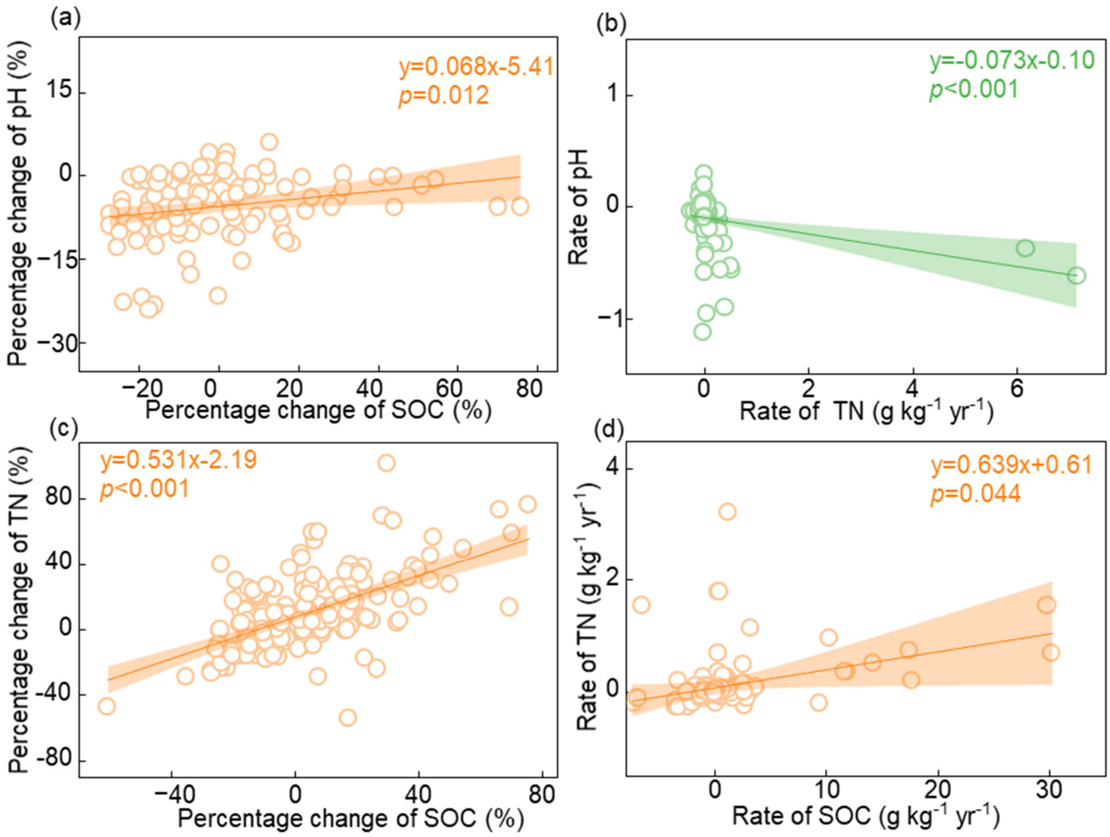

Figure 5. Relationships of (**a**,**b**) soil pH with percentage change and rate of soil organic carbon (SOC) and total nitrogen (TN) and of (**c**,**d**) percentage change and rate of SOC with TN under nitrogen addition.

4. Discussion

4.1. Effects of Nitrogen Addition on SOC and TN Accumulation

Nitrogen addition increased SOC and TN by 4.48% and 10.18%, respectively, in forest ecosystems, confirming Hypothesis 1. Changes in SOC and TN are regulated mainly by the inputs and outputs of carbon and nitrogen [46,47]. The input process comprises two steps. First, nitrogen addition enhances the input of carbon and nitrogen by promoting tree growth [22,48]. An increase in forest ecosystem productivity increases soil microbial activity [11,49], further accelerating the decomposition of litter on the soil surface [50,51]. Second, nitrogen addition enhances the turnover rate of fine roots and alters root exudates, thus increasing soil fertility [25,26]. The output processes include plant root and soil respiration, with soil respiration being the most important, accounting for more than 70% of the total respiration [23,52,53]. Moreover, a recent meta-analysis confirmed that nitrogen addition reduced soil respiration [22]. The increase in carbon input and decrease in carbon output during nitrogen addition promoted SOC accumulation [54]. Previous studies have indicated that SOC and TN are coupled in terrestrial ecosystems [55]. This study also confirmed that SOC and TN were highly coupled with nitrogen addition.

4.2. Different Effects of Nitrogen Addition Duration and Nitrogen Application Rate on SOC and TN Accumulation

This study revealed that the percentage changes in SOC and TN increased overall with increasing nitrogen addition duration and nitrogen application rate; however, the accumulation rate tended to decrease with increasing nitrogen addition duration and nitrogen application rate in forest ecosystems at the global scale, confirming Hypothesis 2.

This can be explained by three mechanisms: (1) Heavy nitrogen application rates and long-term nitrogen addition significantly increase the aboveground biomass of plants in forest ecosystems [22], and litter regression and subsurface carbon allocation provide more substrates for the soil, promoting microbial decomposition of litter into SOC and TN [12] and thereby increasing the SOC and TN contents. However, excessive nitrogen addition reduces the soil C:N ratio and pH [56]. Soil acidification reduces microbial activity [29], thus limiting litter decomposition by microorganisms and enzymes [30] and reducing SOC and TN accumulation. (2) Heavy nitrogen application rates and long-term nitrogen addition promote SOC and TN accumulation by increasing plant root yield [11]. However, the turnover rate of fine roots is closely related to the nitrogen application rate and nitrogen addition duration, and moderate nitrogen addition significantly improves the root turnover rate, which is related mainly to root quality [7]. In contrast, the heavy nitrogen application rate reduces the activity of soil enzymes involved in the decomposition of root litter [32], thus reducing the accumulation rates of SOC and TN [33]. (3) SOC accumulation is affected by microbial carbon use efficiency, which is regulated by microbial nutrient restriction [57]. Small and short-term nitrogen additions cause microbes to experience weak phosphorus limitations, whereas heavy nitrogen application rates and long-term nitrogen additions aggravate microbial carbon and phosphorus limitations [11,28], thereby reducing microbial activity and the accumulation of SOC and TN. This study revealed that the heavy nitrogen application rate and long-term duration increased the SOC and TN contents but decreased the accumulation rate. The results of this study enhance our understanding of soil carbon and nitrogen turnover against the background of future global nitrogen deposition.

4.3. Effects of Humidity on SOC and TN Accumulation

Under nitrogen addition, climate significantly affected SOC and TN accumulation. This study revealed that the percentage changes in and accumulation rates of SOC and TN tended to increase with the humidity index in forest ecosystems under nitrogen addition. First, low humidity reduces the soil water content and even leads to soil drought, thus limiting plant growth and root productivity in forest ecosystems [25]. A decreased litter content weakens the decomposition capacity of microorganisms and the accumulation of SOC and TN [58,59]. Higher humidity increases the soil water content, and the increased availability of soil water stimulates plant growth and the amount of dead leaves imported into the soil [60,61], improving the decomposition of litter and thus increasing SOC and TN accumulation [62]. Moreover, soil microbial activity is strongly affected by hydrothermal conditions [63], and low humidity is not conducive to soil microbial resource acquisition [64], which reduces microbial activity. The increase in litter content and soil nutrients caused by an increase in soil water provides sufficient carbon and energy sources for microorganisms [34,41], thereby increasing microbial activity, increasing extracellular enzyme secretion [36,65], and accelerating SOC and TN accumulation [66]. In addition, increased humidity improves soil water availability and promotes the formation of soil aggregates [67,68], thus facilitating the survival of microorganisms and the accumulation of SOC and TN in global forest ecosystems.

4.4. Limitations

Our study explored the response of SOC and TN accumulation to the nitrogen application rate and nitrogen addition duration; however, three limitations are as follows: (1) The selection of research objects in this study was not comprehensive. The terrestrial ecosystems used in this study include forests. There is considerable uncertainty regarding how SOC and TN respond to nitrogen addition in croplands, grasslands, deserts, and wetland ecosystems. (2) The accumulation of SOC and TN is regulated by plant litter, soil physicochemical properties, and soil microorganisms [10,69]; however, systematic assessments of how these factors respond to nitrogen addition and how nitrogen addition indirectly regulates the accumulation rate of SOC and TN by affecting plant growth and microbial activity are lacking. Therefore, future studies should comprehensively consider the effects of nitrogen addition on carbon and nitrogen fixation, emission processes, and driving mechanisms in different ecosystems to enhance the understanding of soil carbon and nitrogen turnover mechanisms.

5. Conclusions

Nitrogen addition promoted SOC and TN accumulation in forest ecosystems. Moreover, the heavy nitrogen application rate and long-term duration increased the SOC and TN contents but decreased the accumulation rate, whereas humidity increased the SOC and TN contents and promoted the accumulation rate in global forest ecosystems. However, this study did not consider the effects of nitrogen addition on carbon and nitrogen emissions or the mechanisms of carbon and nitrogen accumulation, which limits our understanding of the mechanisms of carbon and nitrogen turnover.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15091585/s1, Figure S1: Relationships of humidity and nitrogen addition duration and intensity with percentage changes of soil pH (a–c), soil organic carbon (SOC; d–f), and total nitrogen (TN; g–i) under nitrogen addition; Figure S2: Relationships of humidity and nitrogen addition duration and intensity with change rates of soil pH (a–c), soil organic carbon (SOC; d–f), and total nitrogen (TN; g–i) under nitrogen addition.

Author Contributions: Conceptualization, Y.Y., J.Y. and H.X.; methodology, J.Y., Q.D., D.L. and B.T.; software, Y.Y.; validation, Y.Y. and Z.X.; data curation, H.X.; writing—original draft preparation, Y.Y. and H.X.; writing—review and editing, Y.Y., Q.W. and H.X.; visualization, Y.Y. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

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