Long-term nitrogen deposition does not exacerbate soil acidification in tropical broadleaf plantations

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Abstract
Nitrogen (N) deposition induces soil acidification in natural forests; however, whether it increases soil acidity in tropical plantations with simple tree structures compared with natural forests remains unclear. This study aimed to investigate the effects of N deposition on the soil acidity of tropical broadleaf plantations dominated by Acacia auriculiformis and Eucalyptus urophylla in South China, which has been enduring N deposition for over 30 years, and investigate the reasons for the changes in soil acidity. Long-term N addition did not affect soil acidity in the two plantations, with no significant changes in soil pH values, and exchangeable non-acidic and acidic cation concentrations. Long-term N deposition did not significantly affect the plant and total soil N concentrations, but significantly increased the soil nitrous oxide emission rates and total dissolved N concentrations in the soil solutions. Our findings indicate that most of the added N was lost via leaching and emissions, such that long-term N addition did not exacerbate soil acidification in broadleaf plantations, thereby providing novel insight into the effects of atmospheric N deposition on forest ecosystems. Overall, our study indicates that long-term N deposition does not always lead to soil acidification in tropical forests, as previously expected.

1. Introduction
Soil acidity significantly influences soil biogeochemical cycles and the growth environment of plant roots and soil microorganisms (Russell et al 2007, Kirk et al 2009, Zhu et al 2018, Kang et al 2021), and controls the relative distribution of acidic (Al³⁺, Fe³⁺, and Mn²⁺) and non-acidic cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) and buffering systems (Bowman et al 2008). Changes in soil acidity, which is characterized by pH, occur gradually under natural conditions and over hundreds to millions of years. However, increases in acidity due to nitrogen (N) fertilizer application and fossil fuel combustion have significantly reduced the soil pH values and induced soil acidification (Guo et al 2010).

Increased N deposition, especially in tropical regions during the past few decades (Gu et al 2015), has contributed more significantly to soil acidification than sulfur deposition (Gu et al 2015, Tian and Niu 2015). The deposited N enters the soil, thus, promoting plants to absorb N (mainly ammonium, NH₄⁺) and the conversion of NH₄⁺ to nitrates (NO₃⁻), while the released H⁺ acidifies the soils (De Vries and Breeuwsma 1987, Zhou 2015). Therefore, N addition induces soil acidification by reducing the concentration of non-acidic cations, such as Ca²⁺ and Mg²⁺, and the soil pH, and stimulating the release of acidic cations (such as Al³⁺ and Fe³⁺, Bowman et al 2008, Huang et al 2014, Tian and Niu 2015). Furthermore, soil acidification negatively affects plant growth (such as the fine root biomass), plant diversity, and microbial activities (Mo et al 2008, Treseder 2008, Eisenlord et al 2013, Freedman and Zak 2014). However, these observations were mainly derived from natural forests, and relatively few studies have been conducted in broadleaf tropical plantations with few tree species and simple tree structures, particularly under long-term N addition.
The forest structure and tree composition may affect the response of soil pH to N deposition, as different tree species utilize different forms of nitrogen (Wang and Macko 2011). Seven years of N addition has resulted in significant soil acidification in an evergreen broadleaf natural forest, but not in plantations (Lu et al. 2015). There have been some other reports of long-term N deposition not causing significant changes in soil pH of the plantations in the temperate (Högberg et al. 2007) and tropical regions (Huang et al. 2015b). Therefore, plantations may not be sensitive to long-term N deposition and could maintain stable soil acidity. Whether the soil acidity of broadleaf plantations composed of a single dominant tree species remains stable under long-term N deposition must be verified.

Eucalyptus and Acacia plantations represent two typical broadleaf plantations in South China. As Eucalyptus is a fast-growing tree species, it is planted extensively and accounts for 15% of the total plantations worldwide, covering an area of more than 20 million ha (Iglesias-Trapado and Wistermann 2008). In South China, Eucalyptus covered an area of approximately 4.5 million ha in 2015 (Xie 2015). Legumes are dominant and widespread tree species in tropical forest ecosystems (Ter Steege et al. 2006). Particularly, N-fixing legumes can adapt to poor soil environments (Epihov et al. 2017); therefore, they have been widely used to regenerate destroyed ecosystems in tropical regions (Wei and Ma 2010, Yang et al. 2011). Acacia, an N-fixing legume, is widely planted in South China (Chen et al. 2011). Due to its N-fixation capacity, Acacia trees require less exogenous N from soils. Eucalyptus plantations commonly have a poor vegetation structure due to allelopathic effects and may require less soil N than other forests. A previous study reported that N addition readily increased soil N leaching in Eucalyptus plantations (Zhang 2015). Compared to natural forests, the single-tree dominated plantations with poor vegetation composition and low plant diversity may have a relatively low demand of total N and low exogenous N retention capacity, indicating that long-term N addition may lead to soil N loss and a lower contribution to soil acidity in plantations.

In this study, we aimed to investigate the effects of N addition for 7 years on the soil acidity in two broadleaf plantations (Eucalyptus and Acacia) in South China, and we further explored the mechanisms underlying the variations in soil acidity. We hypothesized that (a) long-term N addition would not exacerbate soil acidification in the two selected plantations, as it may not affect the soil pH and the non-acidic and acidic cation concentrations of the plants and soils, and (b) long-term N addition may accelerate N loss in plantations via leaching and N₂O emissions, therefore contributing less to soil acidity.

2. Materials and methods

2.1. Study site
The study was conducted at the Heshan National Field Research Station of Forest Ecosystems (112º50'E, 22º34'N) in Heshan County, Guangdong Province, South China. This region experiences a typical monsoon climate, with a mean annual temperature and precipitation of 21.7 ºC and 1295 mm, respectively. Background N addition co-occurring with precipitation in this region was approximately 43.1 kg N ha⁻¹ yr⁻¹ from July 2010 to June 2012 (Huang et al. 2015b) and the forest soil group is lateritic red earth.

We selected two broadleaf plantations, one dominated by an N-fixing legume tree species (Acacia auriculiformis, AA), and the other dominated by a non-legume tree species (Eucalyptus urophylla, EU). Both plantations were established in 1985, each covering an area of approximately 5–8 ha. The plantation soils were strongly acidic, with mean pH values below 4.0. The soil bulk density was 1.2 and 1.3 g cm⁻³ for the EU and AA plantations, respectively, and their soil organic carbon (SOC) concentrations were 19.0 and 24.0 g kg⁻¹, respectively.

2.2. Experimental treatments
Two treatments, low-N (LN, 50 kg N ha⁻¹ yr⁻¹) and high-N (HN, 100 kg N ha⁻¹ yr⁻¹), and a reference control (CK, without N addition) were established within each plantation in July 2010. The experiments were conducted in nine plots (10 × 10 m), each separated by a 10 m wide buffer strip. Ammonium nitrate (NH₄NO₃) solutions prepared by dissolving NH₄NO₃ in 10 l of water were sprayed bimonthly on the ground of each plot from August 2010 using a backpack sprayer, while each CK plot received 10 l of water (Zhang et al. 2012).

2.3. Sample collection and analyses
Soil samples were collected at a depth of 0–10 cm in July 2010 (0 year), July 2011 (1st year), December 2014 (4th year), and December 2017 (7th year) using a 5 cm (inner diameter, ID) corer. Soil samples were collected from three randomly selected locations in each plot, which were then manually mixed thoroughly, passed through a 2 mm sieve after removing roots and stones, and divided into two parts. One part of the composite sample was air-dried to measure the soil pH, exchangeable non-acidic and acidic cations, SOC, and total N, while the other fresh part was used to determine the available soil N concentration. The soil pH was measured using a glass electrode with 1:2.5 soil-deionized CO₂-free water suspensions. Exchangeable non-acidic (K⁺, Na⁺, Ca²⁺, and Mg²⁺) and acidic cations (Al³⁺, Fe³⁺, and Mn²⁺) were extracted with 0.1 mol l⁻¹ of BaCl₂ (50:1 of BaCl₂:solution:soil). The cation concentrations were determined using an inductively coupled
plasma optical emission spectrometer (Perkin Elmer, USA), and the cation exchange capacity (CEC) was calculated as the sum of the charge equivalent of the exchangeable cations. The total soil N concentration was determined using a C/N analyzer (IsoPrime 100, Isoprime). The fresh soil samples were extracted with a KCl solution to measure the soil inorganic N concentrations (NH$_4^+$-N and NO$_3^-$-N). The NH$_4^+$-N concentrations were measured by the indophenol blue method followed by colorimetry, whereas the NO$_3^-$ N concentrations were directly measured using a spectrophotometer (Metash Instruments Corp., Shanghai, China). The soil inorganic N concentrations were determined as the sum of the ammonium and nitrate concentrations. The SOC was determined by wet digestion with a mixture of potassium dichromate and concentrated sulfuric acid (Liu et al. 1996).

In December 2019, at least three trees in each treatment of the two plantations were selected, and mature leaves with no or as few brown flecks (Huang et al. 2014) as possible were collected from three branches of each tree. Additionally, branches and roots (diameter >5 cm) were sampled in January 2020. The samples were washed with deionized water, dried at 65 °C for 48 h, and ground to a fine powder for elemental analyses. The concentrations of leaf nutrients (K, Na, Ca, and Mg) and toxic metals (Al, Fe, and Mn) were measured using an inductively coupled plasma optical emission spectrometer after acid digestion with a mixture of nitric acid (1 ml) and perchloric acid (4 ml). The N concentrations in the leaves, branches, and roots were measured using an elemental analyzer.

Soil cores at 1 m from the trunk were collected at a depth of 0–10 cm using a 30 cm-ID corer. Fine roots (diameter ≤2 mm) were manually separated from the soil cores, and the root samples were washed with distilled water, dried at 65 °C for 48 h, and weighed.

The soil water solution from the CK and LN treatment plots was collected monthly at a depth of 20 cm from February to September 2019 after each rain event (particularly heavy rainfall events). Two replicate zero-tension tray lysimeters (755 cm$^2$ per tray) were installed per plot at a soil depth of 20 cm. Each lysimeter was connected to a 5-l bottle for soil solution collections. Subsequently, the collected samples were filtered through 0.45 mm filters in the laboratory within 24–48 h, and then stored in plastic bottles at 4 °C. The total dissolved N (TDN) was measured using a Lachat QC8000 flow injection analyzer, and included inorganic and dissolved organic N. Mean TDN concentrations in the soil water solutions were calculated from the samples that were collected for 8 months.

The soil nitrous oxide (N$_2$O) emissions were measured monthly from September 2019 to January 2020 following the static chamber method (Zhang et al. 2012). Two static chambers were installed in each plot and were made of polyvinylchloride pipes with an internal diameter of 25 cm, a permanent collar, and a chamber. The collars were permanently installed in the field at a depth of 5 cm. The headspace height of the chamber was 30 cm and the volume was 14719 ml. During gas collection, the chamber was fitted tightly to the collar with a rubber band, and gas samples were collected at 0, 15, and 30 min intervals after closing the chamber. The N$_2$O concentrations were determined within 24 h using a gas chromatograph (Agilent 5890 D, USA) equipped with an electron capture detector. The oven, injector, and detector temperatures were 55 °C, 275 °C, and 330 °C, respectively. Nitrogen (99.999%, 30 ml min$^{-1}$) and hydrogen (99.999%, 30 ml min$^{-1}$) were used as the carrier and fuel gases, respectively, with flow rates of 35 and 30 ml min$^{-1}$, respectively. Soil N$_2$O emission rate was calculated according to a previously used method (Zhang et al. 2014), with the following equation:

$$ F = \rho \times h \times \frac{P}{P_0} \times \frac{T_0}{T} \times \frac{dC_t}{dt} $$

(1)

where $\rho$ is the standard concentration of N$_2$O, $h$ is the height of chamber, $P$ is the air pressure of the atmosphere in the plot, $T$ is air temperature of chamber headspace, $T_0$ and $P_0$ are the temperature and air pressure under standard conditions, respectively, and $C_t$ is the concentration of the mixed volume ratio of gases inside the chamber at time $t$.

2.4. Statistical analyses

One-way analysis of variance (ANOVA) was conducted to examine the effects of N addition on the soil pH, exchangeable non-acidic and acidic cations, CEC, available and total N, fine root biomass, concentrations of leaf nutrients and toxic metals, organ N, TDN in the soil water solution, and soil N$_2$O emission rates. Furthermore, a paired t-test was conducted to identify differences in these parameters between EU with AA. The effects of N addition on soil parameters across the 7 year treatment were determined by repeated-measures analysis of variance. The interactive effects on soil pH and non-acidic and acidic cations from N addition and tree species were also determined by Two-way ANOVA. The correlations between SOC with CEC and with non-acidic cations were also performed. All statistical analyses were conducted using SPSS 13.0 for Windows (SPSS Inc., USA), with statistical significance set at $P < 0.05$ unless otherwise stated. The values were presented as the mean ± standard error of the mean.

3. Results

3.1. Soil pH

The soil pH measured during 2010–2017 at a depth of 10 cm mainly ranged from 3.5 to 4.0 in all plots, excluding three plots, in which the pH exceeded 4.0.
The pH values did not statistically differ between the EU and AA plantations ($P > 0.05$), despite the seven-year addition of N. Furthermore, N addition did not alter the soil pH at 0–10 cm depth in the two plantations ($P > 0.05$, figure 1). Moreover, the repeated-measures analysis of variance indicated that N did not significantly affect the soil pH across the 7 year N addition ($P > 0.05$). Additionally, there was no interactive effects of N addition and tree species on soil pH ($P > 0.05$, table S1 (available online at stacks.iop.org/ERL/16/114042/mmedia)).

3.2. Soil non-acidic and acidic cation concentrations, CEC, and SOC

The concentrations of soil exchangeable non-acidic cations (K$^+$, Na$^+$, Ca$^{2+}$, and Mg$^{2+}$) in the EU and AA plantations were extremely low (mostly < 4 mmol kg$^{-1}$ soil). Among these cations, the concentration of Ca$^{2+}$ was the highest, followed by those of K$^+$, Na$^+$, and Mg$^{2+}$ (figure 2). The concentration of non-acidic cations significantly differed between the two plantations ($P < 0.05$); however, they did not exhibit significant responses to the 7 year N addition ($P > 0.05$, figure 1).

Regardless of N addition, Al$^{3+}$ was the most abundant soil exchangeable cation, accounting for over 80% of the cations in both the EU and AA plantations at a depth of 0–10 cm. Mn$^{2+}$ was the least abundant cation, followed by Fe$^{3+}$. The concentrations of these three acidic cations in the two plantations did not change after the 7 year N addition experiment ($P > 0.05$, figure 3). This observation was consistent with that of non-acidic cations.

N did not affect the CEC in both the EU and AA plantations ($P > 0.05$); however, there was a significant impact on CEC from tree species ($P < 0.01$, figure S1). SOC remained stable in response to the 7 year N addition in both the EU and AA plantation (figure S2); however, the concentrations in the EU plantation were consistently higher than those in the AA plantation, despite of N addition ($P < 0.01$, figure S2). However, there were no significant correlations between SOC with CEC and with non-acidic cations ($P > 0.05$).

3.3. Leaf nutrient and toxic metal concentrations

Among the leaf nutrients (i.e. K, Na, Ca, and Mg), the concentrations of Ca were the highest, followed by K, Na, and Mg in both plantations, which was consistent with their soil concentration trends (figure 2). Long-term N addition did not significantly affect the leaf nutrient concentrations ($P > 0.05$), excluding for Na and Mg in EU and K in AA, both of which exhibited a negative response ($P < 0.05$, figures 4(a), (b) and (d)).

The concentrations of toxic metals (Al, Fe, and Mn), particularly Mn, in EU were higher than those in AA, despite N addition. Moreover, long-term N addition negatively affected the leaf Fe concentrations in both EU ($P < 0.05$) and AA ($P < 0.01$) and the leaf Al in AA ($P < 0.05$); however, negative effects on the leaf Mn concentrations were not observed ($P > 0.05$, figures 4(e)–(g)).

3.4. Fine root biomass

Long-term N addition did not significantly affect the fine root biomass in both AA and EU plantations.
Figure 2. Changes in soil non-acidic cations concentrations at 0–10 cm depth of EU and AA plantations across 7 year N addition. K$^+$ (a and b), Na$^+$ (c and d), Ca$^{2+}$ (e and f), and Mg$^{2+}$ (g and h) in EU and AA plantations, respectively. Error bars indicate ±1 S.E. (N = 3). And ns indicates no significant differences at $P < 0.05$.

Figure 3. Changes in soil acidic cations concentrations at 0–10 cm depth of EU and AA plantations across 7 year N addition. Al$^{3+}$ (a and b), Fe$^{3+}$ (c and d), and Mn$^{2+}$ (e and f) in EU and AA plantations, respectively. Error bars indicate ±1 S.E. (N = 3). And ns indicates no significant differences at $P < 0.05$. 

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(P > 0.10), excluding the EU plot that was subjected to the LN treatment (P < 0.05, figure 5). Moreover, the fine root biomass of the EU plantation was lower than that of the AA plantation (P < 0.05).

3.5. Plant N concentrations
The organ N concentrations in AA were higher than those in EU (P < 0.001). However, long-term N addition did not significantly affect the organ N concentrations in both EU and AA (P > 0.05, figure 6).

3.6. Available and total soil N concentrations
The available soil N concentrations at a depth of 0–10 cm in the AA plantation were higher than those in the EU plantation, despite N addition (P < 0.05). Moreover, the responses of the available soil N concentrations to 7 year N addition in the EU and AA plantations differed. In the EU plantation, the available soil N concentrations increased after the 1 year N addition experiment (P < 0.05), but did not change after the 4 year and 7 year N addition experiments (P > 0.05, figure 7(a)). Meanwhile, the concentrations significantly increased in the AA plantation during the 7 year N addition experiment (P < 0.05, figure 7(b)).

The total soil N concentrations in the AA plantation were higher than those in the EU plantation, despite N addition (P < 0.01). The 1 year HN treatment significantly increased the total soil N concentration in the EU plantation (P < 0.05), but not in the AA plantation (P > 0.05). However, the 7 year N-addition experiment did not affect the total soil N concentrations in both the EU and AA plantations (P > 0.05, figure 8).

3.7. TDN concentrations in soil solutions
The TDN concentrations in the AA plantation were higher than those in the EU plantation (P < 0.05) irrespective of long-term N addition; these concentrations in the long-term N addition treatments for the two plantations were significantly higher than those in CK (P < 0.05, figure S3).

3.8. Soil N emissions
Long-term N addition promoted the soil N₂O emissions in both the EU and AA plantations, but the responses differed. In the EU plantation, N₂O emission rates in December 2019 and January 2020 during the HN treatment significantly increased (P < 0.05). However, in the AA plantation, significant N₂O emissions were observed in September 2019 when subjected to the LN treatment (P < 0.05) and each month from September 2019 to January 2020 when subjected to the HN treatment (P < 0.05, figure 9). However, no differences in the soil N₂O emission rates were observed between the EU and AA plantations (P > 0.05).
Figure 5. Fine root biomass (in g per m$^2$ of forest area) under long-term N addition. Error bars show standard errors ($N = 3$). Fine root samples were collected in May, 2021. Different letters indicate significant differences among N additions at $P < 0.05$, * indicates significant differences between EU and AA plantations at $P < 0.05$, and ns indicates no significant differences at $P < 0.05$.

Figure 6. Nitrogen contents at the organ levels in EU (Eucalyptus urophylla) and AA (Acacia auriculiformis) responding to long-term N addition. The error bars indicate ±1 S.E. (EU: $N = 7–9$, AA: $N = 3–5$). ** indicates significant differences at $P < 0.001$, and ns indicates no significant differences at $P < 0.05$.

4. Discussion

4.1. Effects of N addition on soil acidity
Nitrogen addition causes soil acidification in forest ecosystems, particularly in tropical forests (Huang et al 2014, 2015a, Lu et al 2015, Yang et al 2015), with regular increased N addition maintaining high plant growth (Galloway et al 2008, Pérez et al 2013, Gu et al 2015). However, the features of soil acidification were not observed in the two broadleaf plantations (AA and EU) treated with N addition for 7 years. No significant changes in the soil pH (figure 1), exchangeable non-acidic cation (figure 2) and acidic cation (figure 3) concentrations, and toxic metal concentrations (figure 4) were observed in both the EU and AA plantations. Additionally, the leaf Al and Fe concentrations decreased in AA, indicating that N addition did not stimulate the release of soil $\text{Al}^{3+}$ and $\text{Fe}^{3+}$ in the EU and AA plantations, and did not increase the potential toxicity of Al and Fe to plant growth. Although SOC plays an important role in mediating the availability of non-acidic cations (Jiang et al 2018), we found that SOC remained stable in response to 7 year N addition (figure S2) and there was no significant correlation between SOC with CEC or non-acidic cations. Additionally, no changes in the leaf nutrient (Ca and Mg) concentrations (figure 4) and fine root biomass (figure 5) were observed in both
the EU and AA plantations during long-term N addition, indicating that N addition did not affect the leaf nutrient concentrations or negatively affect fine root growth. These observations demonstrate that N addition did not accelerate soil acidification in the studied tropical broadleaf plantations.

Our findings could be supported by some previous studies conducted in some coniferous plantations, where soil pH and CEC had no significant responses to N addition (Högberg et al. 2007, Lu et al. 2015, Huang et al. 2015a). However, the reason for the lack of soil acidification under N addition currently remains unclear. Therefore, we further examined the changes in the soil and plant N contents and N loss via leaching and emission after N addition as follows.

4.2. Effects of N addition on plant and soil N
To investigate the mechanisms causing the non-significant soil acidification under long-term N addition in broadleaf plantations, we examined whether the added N was retained by plants or soil. As an N-fixing legume species, AA exhibited higher organ N concentrations than EU, which is a non-legume species (figure 6). Furthermore, the AA plantation maintained higher concentrations of available N (figure 7) and total N (figure 8) in the soil than the EU plantation with and without N addition, as N-fixing tree species absorb and require high N concentrations for P acquisition (Deng et al. 2016). However, long-term N addition did not increase N retention in the soil and plants of the two plantations, despite the presence of different tree species, as there were no
significant changes in the organ N concentrations (figure 6) and total soil N concentrations (figure 8) in both the EU and AA plantations. The reason was because that N could only be retained in the soils and plants in N-limited ecosystems (Magill et al. 1997, Johannisson et al. 1999), while N-rich ecosystems have less demand of exogenous N, despite long-term N addition.

4.3. Effects of N addition on N leaching and emission

We further examined whether the added N could be lost via leaching or gas emissions. The results from the soil water solutions extracted from a depth of 20 cm indicated that the TDN concentrations significantly increased in both the EU and AA plantations during long-term N addition (figure S3), suggesting that N leaching was significantly accelerated (Zhang 2015). Furthermore, heavy rainfall in this region could further promote N runoff loss in the plantations (Franklin et al. 2007, Liu et al. 2014). Moreover, the TDN concentrations were higher in the AA plantation than in the EU plantation irrespective of N addition (figure S3), indicating high N leaching loss in the former.

We found that long-term N addition significantly stimulated the soil N₂O emission rates in both plantations, particularly in the HN-treated plantation (P < 0.05, figure 9), thereby indicating high N gas emissions. However, this result was not fully consistent with our previous study, that reported that short-term (1–2 year) N addition enhanced the soil N₂O emissions in the AA plantation but not in the EU plantation (Zhang et al. 2014); therefore, long-term (7 year) N addition caused high N loss in both plantations, regardless of tree species. The N added to in the plantations could quickly and fully complete the N transformation process (De Vries and Breeuwsma 1987) in the surface soil, which is supported by a result obtained in a coniferous plantation, in which added NH₄NO₃ was almost fully converted into NO₃⁻ before reaching the 5 cm soil depth (Huang et al. 2015a). Therefore, high N loss via leaching and emissions could contribute to the absence of N-induced soil acidification in the studied plantations as most of the added N was lost, rather than retained by plants and soil; thus, soil acidification processes (such as Al³⁺ and Fe²⁺⁷ reactions; figures 3 and 4) were not induced under long-term N addition.

Although N loss via emission and leaching, rather than retention, in plantation ecosystems was considered to be the main reason for the observed lack of soil acidification, the absolute amounts of added N that were lost via leaching or emission were not accurately estimated in our study. It is necessary to explore the process of soil N transformation and quantify the N flux and its relationship with soil acidification (for example, by using ¹⁵N isotopic tracing) to accurately understand the mechanisms of the lack of impacts of N addition on soil acidification in tropical plantations. Additionally, other factors affecting soil N leaching, such as the tree structure (Lu et al. 2015) and background N deposition rates (Huang et al. 2015c), should be considered when exploring the lack of an effect N addition on soil acidity in such plantations. Moreover, more studies are required to verify the lack of effects of N addition on soil acidification in other tropical plantations.
5. Conclusions

In this study, we demonstrated that long-term N addition did not accelerate soil acidification in tropical broadleaf plantations, as indicated by the absence of significant changes in the soil pH and exchangeable non-acidic and acidic cation concentrations. Moreover, the fine root biomass was not affected by long-term N addition, and the concentrations of leaf Al and Fe were low in EU and AA, further confirming that soil acidification caused by added N did not negatively affect plant growth. This could be because long-term N addition increased N loss by enhancing the N₂O emission rates and TDN concentrations in the soil solutions in both the EU and AA plantations. However, no changes in the plant and total soil N concentrations were observed in both the EU and AA plantation. Therefore, our study indicated that long-term N deposition did not exacerbate soil acidification in broadleaf plantations with simple tree structures (for example, single tree species and low plant diversity), as most of the added N was readily lost via leaching and emissions, rather than retained by the soil and plants. These findings indicate that long-term N deposition does not always result in soil acidification in tropical forests and provide novel insight into the relationships between soil acidity and N deposition in forest ecosystems.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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