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# Nitrogen Cycling and Soil Amelioration in *Camellia oleifera* Plantations

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## Abstract

*Camellia oleifera* Abel. is one of the four woody edible oil trees around the world, which is also an important economic species in subtropical China. It is mainly cultivated in subtropical region, where the soil constrains the yield of *C. oleifera* oil due to its low fertility and pH. Thereby, intensive management including fertilization practice, especially intensive nitrogen (N) input, has been developed as a vital way to enhance oil yield in *C. oleifera* plantations. However, excessive nitrogen input increases soil nitrous oxide (N<sub>2</sub>O) emissions and soil acidification, limiting sustainable development of economic forests. As one of the important greenhouse gases, N<sub>2</sub>O is 265 times greater than carbon dioxide in global warming potential on 100-year scale. To mitigate soil N<sub>2</sub>O emissions and soil acidification, soil amelioration, including applications of biochar, nitrification inhibitors, and urease inhibitors, played an important role in sustainable management of *C. oleifera* plantations. This chapter reviewed soil nitrogen cycling, N<sub>2</sub>O emissions, and soil amelioration in *C. oleifera* plantations, which will benefit the sustainable management of *C. oleifera* plantations and hence the development of *C. oleifera* industries.

**Keywords:** *Camellia oleifera*, biochar, nitrification inhibitor, soil amelioration, sustainable forest management, urease inhibitor

## 1. *Camellia oleifera*

*Camellia oleifera* Abel. as a native edible oil tree has a long cultivation history in subtropical China [1]. It is a perennial and evergreen species with synchronous flowers and fruits. The cultivation area and total product value of *C. oleifera* have reached 4.47 million ha and 102.4 billion Chinese yuan, respectively [2]. With rapid development, the *C. oleifera* oil accounted for 80% domestic high-end vegetable edible oils in 2018 from China. High habitat suitability area for *C. oleifera* cultivation in China has been up to 4.94% [3].

Specially, *C. oleifera* oil and oils derived from palm, olive, and coconut are the four major woody edible oils in the world [4]. The *C. oleifera* oil is characterized by remarkable antioxidant activity [5] and high content of unsaturated fatty acids (about 83%) [6].

*Camellia oleifera* can survive and adapt to low-fertility acid soil. Generally, it usually is used in the conservation of soil and water as well as afforestation in barren hill. Therefore, *C. oleifera* is an excellent species with both ecological and

economic advantages. Development of *C. oleifera* industry would be beneficial for the safety of edible oil and the conservation of soil and water in China.

As a typical economic tree, intensification such as water management, fertilization, and trimming takes an important part in the management of *C. oleifera* plantations. Notably, organic matter, available phosphorus, and pH value was low in *C. oleifera* plantation soils [7], constraining the yield of *C. oleifera* oil. Therefore, intensive management with fertilization is often performed in *C. oleifera* plantations [1].

## 2. Challenges

Fertilization is the major way of intensive management, efficiently improving the yield of oil in *C. oleifera* plantations. However, a large amount of nitrogen (N) input increased the risk of soil N leaching and gaseous N (e.g., nitrous oxide (N<sub>2</sub>O), nitric oxide (NO), ammonia (NH<sub>3</sub>)) losing [8]. In addition, excessive N input induced soil acidification [9].

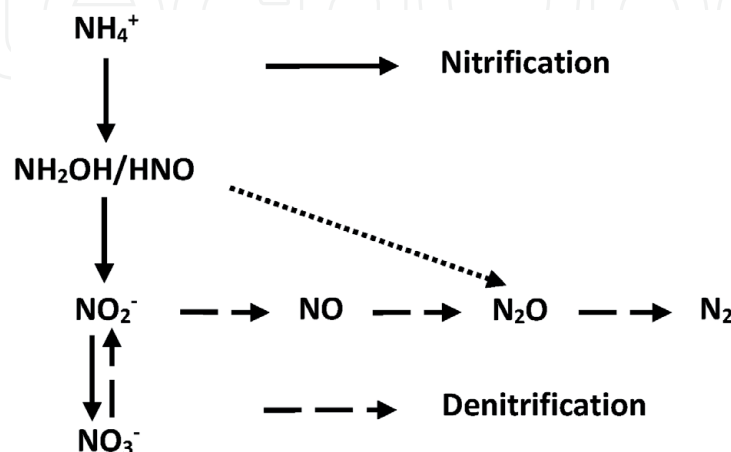
### 2.1 Nitrous oxide emissions

Nitrous oxide, as the major ozone-depleting substance [10], has been recognized to be an important greenhouse gas. Especially, the potential of N<sub>2</sub>O for global warming is 265 times than that of carbon dioxide [11]. The concentration of N<sub>2</sub>O is ranging from 270 ppb in pre-industrial period to 329.9 ppb in 2017 [12].

Soil systems contributed the largest source of N<sub>2</sub>O emissions (13 Tg N<sub>2</sub>O-N yr<sup>-1</sup>), of which human activities accounted for 54% [13]. Nitrogen input such as N deposition and N fertilization often increased N<sub>2</sub>O emissions and altered the process of N transformation [14–17]. Generally, soil N<sub>2</sub>O emissions had a positive and linear relationship with N input [18]. About 120 Tg N was contributed by human activities per year [13]. Therefore, intensive N input often leads to high emissions of soil N<sub>2</sub>O [19].

#### 2.1.1 Nitrification and denitrification

Nitrification and denitrification are the two main pathways of N<sub>2</sub>O emissions (Figure 1) [20–22], which produced global 70% soil N<sub>2</sub>O emissions [13].



**Figure 1.** Nitrification- and denitrification-related pathways [20–22].

### 2.1.2 Influence factors

Soil N<sub>2</sub>O emissions can be influenced by soil environmental factors such as soil moisture, temperature, oxygen (O<sub>2</sub>), and pH condition [23, 24].

#### 2.1.2.1 Soil moisture

Soil moisture is a vital factor that affects soil N<sub>2</sub>O emissions. Generally, soil N<sub>2</sub>O emission rates reached the peak when soil water-filled pore space (WFPS) was 60–70% [25]. For example, soil N<sub>2</sub>O emissions were significantly higher under 60% WFPS conditions than that under flooded conditions [26].

#### 2.1.2.2 Soil temperature

Effects of soil temperature on N<sub>2</sub>O emissions were more complex than that of soil moisture. For example, warming increased soil N<sub>2</sub>O emissions from boreal peatland [27] and alpine meadow [28]. Soil N<sub>2</sub>O emissions had an exponential increased relationship with incubation temperatures [29]. A significant positive correlation was presented in N<sub>2</sub>O emissions and soil temperature from different soil types (paddy, orchard, forest, and mountain) [30]. Although warming did not affect soil N<sub>2</sub>O emissions from northern peatlands, it suppressed N<sub>2</sub>O emissions under N addition conditions [31]. By contrast, the effects of warming on soil N<sub>2</sub>O emissions from alpine meadow soil were not observed [32]. Consistently, no significant increase of soil N<sub>2</sub>O emissions was found with increasing incubation temperatures [33]. Previous study reported that soil moisture and temperature can explain 86% of soil N<sub>2</sub>O emissions [34].

#### 2.1.2.3 Soil O<sub>2</sub> concentration

Soil O<sub>2</sub> concentration was closely related with soil moisture and soil mechanical composition. Generally, soil with higher water content and larger clay fraction had lower soil O<sub>2</sub> concentrations. Lower soil O<sub>2</sub> concentrations mainly promoted soil N<sub>2</sub>O emissions via denitrification [20, 35]. The production of N<sub>2</sub>O and NO was increased when O<sub>2</sub> concentration decreased from 21% to 0.5% in a laboratory study [36]. Similarly, field study reported that soil N<sub>2</sub>O emissions increased with increasing soil O<sub>2</sub> concentrations in wetland [37].

#### 2.1.2.4 Soil pH

pH played an important role in the activity of microbes [38]. Indeed, soil acidification [39] and soil pH amelioration [40] significantly influenced soil N<sub>2</sub>O emissions. However, other researchers reported that there was no significant correlation between N<sub>2</sub>O emissions and pH [41].

pH influenced the activity of nitrification- and denitrification-related enzymes [42]. Generally, soil acidification increased N<sub>2</sub>O emissions [42]. Compared with ammonia-oxidizing bacteria (AOB), ammonia-oxidizing archaea (AOA) were higher in activity and resistance from acid soil [43]. However, the domination of AOB was increased by increasing soil pH [44]. Additionally, archaeal *amoA* genes had a wide pH range of about 3.7–8.65, which had high activity in extreme environments such as high temperature and extreme acid [45].

### 2.1.3 Nitrous oxide emissions from *Camellia oleifera* plantation soils

Our previous field study (1 year) found that soil N<sub>2</sub>O emissions were 92.14 ± 47.01 mg m<sup>-2</sup> in control treatment and were 375.10 ± 60.30 mg m<sup>-2</sup> in fertilization treatment (400 kg NH<sub>4</sub>NO<sub>3</sub>-N ha<sup>-1</sup>) from *C. oleifera* plantations [1].

## 2.2 Soil acidification

Acid soil (pH < 5.5) as a main soil type covers about 30% free ice land [46]. However, soil acidification has been becoming more and more serious [47]. Soil acidification should be taken into consideration due to its constraint in the sustainable development of agricultural sector [48]. In China, soil pH (except alkaline soils at pH 7.10–8.80) from crop fields reduced by 0.13–0.76 during the year 1980–2000 [49]. For example, soil pH (surface layer) decreased by 0.30 units from 1981 to 2012 in Sichuan Province, China [47].

With a long cultivation history, *C. oleifera* was widely cultivated in acid or strongly acid soil in subtropical China [7]. The optimum pH for the growth of *C. oleifera* is 5.5–6.5 [50]. However, acid deposition [51] and intensive N input [49] may stimulate soil acidification from *C. oleifera* plantations. Additionally, long-term N input may also increase the toxicity of aluminum (Al) [52], limiting the sustainable development of *C. oleifera*.

Soil acidification from *C. oleifera* plantations is mainly related to the following factors.

### 2.2.1 Precipitation

Long-term precipitation increased the loss of base cations such as Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, and Na<sup>+</sup>, reducing the soil pH buffering capacity. In addition, long-term precipitation promoted the accumulation of Al<sup>3+</sup> and Fe<sup>3+</sup> in soil, which could further hydrolyze to Fe(OH)<sub>3</sub> or Al(OH)<sub>3</sub> and release 3H<sup>+</sup>.

### 2.2.2 Plant physiology

When plant roots absorb a NH<sub>4</sub><sup>+</sup> from soil, an H<sup>+</sup> will release into soil; in turn, absorbing a NO<sub>3</sub><sup>-</sup> from soil will release an OH<sup>-</sup> into soil [53].

Organic acid (R-COOH) from root exudates can release an H<sup>+</sup> after hydrolysis. In addition, anions of organic acids (e.g., citric acid and malic acid) can chelate with Al<sup>3+</sup> in the soil and inhibit the root system that absorbs Al<sup>3+</sup>, alleviating Al<sup>3+</sup> toxicity to plant growth [48, 54, 55].

Plants such as *C. oleifera* [56] can uptake Al<sup>3+</sup> by roots, promoting the accumulation of Al<sup>3+</sup> in surface soil via litter decomposition [57]. The accumulation of Al<sup>3+</sup> can replace the base cations such as Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, and Na<sup>+</sup> and accelerate leaching, hence reducing the pH buffering capacity of top soil.

### 2.2.3 Microbial-mediated nitrification

For example, NH<sub>4</sub><sup>+</sup> transfers to NO<sub>3</sub><sup>-</sup> along with the 2H<sup>+</sup> release (NH<sub>4</sub><sup>+</sup> + 2O<sub>2</sub> → NO<sub>3</sub><sup>-</sup> + H<sub>2</sub>O + 2H<sup>+</sup>) [53]. AOB, AOA, and fungi can participate in the process of nitrification [20]. Nitrification includes the pathway of ammonia oxidation to hydroxylamine, the pathway of hydroxylamine oxidation to nitrite, and the pathway of nitrite oxidation to nitrate (**Figure 1**) [58]. Ammonia can be oxidized by AOA or AOB to hydroxylamine via ammonia monooxygenase (*amo*).

Hydroxylamine can be oxidized to nitrite by hydroxylamine oxidoreductase. Nitrite can be oxidized to nitrate by nitrite oxidoreductase.

#### 2.2.4 Oxidation of sulfur-containing organics

Oxidation of sulfur mineral, for example, oxidation of  $\text{FeS}_2$ , will produce  $2\text{H}^+$  ( $2\text{FeS}_2 + 7\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{Fe}^{2+} + 4\text{SO}_4^{2-} + 4\text{H}^+$ ).

Oxidation of sulfur-containing organics will release  $4\text{H}^+$  ( $2\text{Organic-S} + 3\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{SO}_4^{2-} + 4\text{H}^+$ ).

#### 2.2.5 Intensive nitrogen fertilization

Intensive  $\text{NH}_4^+$  input can replace the base cations such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$  and accelerate leaching, reducing the pH buffering capacity of top soil [59]. Hydrolysis of soil  $\text{NH}_4^+$  will generate  $\text{NH}_3$  (gas) and consume an  $\text{OH}^-$  ( $\text{NH}_4^+ + \text{OH}^- = \text{NH}_3\uparrow + \text{H}_2\text{O}$ ) [60].

Acidic fertilizers such as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  will gradually release  $\text{H}^+$ , hence increasing soil acidification ( $\text{Ca}(\text{H}_2\text{PO}_4)_2 \rightarrow \text{CaHPO}_4 + \text{H}_3\text{PO}_4$ ,  $\text{H}_3\text{PO}_4 \rightarrow \text{H}^+ + \text{H}_2\text{PO}_4^- \rightarrow 2\text{H}^+ + \text{HPO}_4^{2-} \rightarrow 3\text{H}^+ + \text{PO}_4^{3-}$ ).

#### 2.2.6 Acid deposition

Acid deposition (water-soluble acid gases such as  $\text{CO}_2$  and sulfur dioxide) and N deposition (especially  $\text{NH}_4^+\text{-N}$ ) increased soil acidification [51]. Precipitation with  $\text{H}^+$  can replace the soil base cations such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ , which directly reduce the soil pH buffering capacity [51].

#### 2.2.7 Other factors

For example, deforestation and other land uses can reduce litter accumulation in surface soil, hence declining the accumulation of base cations such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$  that generate from litter decomposition [61].

### 2.3 Effects of soil acidification on nitrous oxide emissions

Acid soils have been facing an increased risk of acidification due to human activities, especially intensive N fertilization [47, 49, 62]. For example, after 6 years of application of  $600 \text{ kg Urea-N ha}^{-1} \text{ yr}^{-1}$ , soil pH was significantly decreased (soil pH in control and fertilization treatment was 5.1 and 4.9, respectively) from a tea plantation in Yixing City, Jiangsu Province, China [63]. A meta-analysis of 1104 field data showed that a negative correlation between soil  $\text{N}_2\text{O}$  emissions and pH (3.34–8.7) ( $\text{N}_2\text{O-N} = -0.67x + 6.55$ ,  $R = 0.22$ ) is negatively related with N fertilization [9]. Moreover, deposition of sulfur dioxide increased soil acidification, stimulating soil  $\text{N}_2\text{O}$  emissions [64].

The mechanism of soil acidification on the stimulation of soil  $\text{N}_2\text{O}$  emissions is complex, which may include (but not limited to) the following points.

#### 2.3.1 Chemical decomposition of nitrous acid

Under acidic conditions,  $\text{pH} < 5.5$ ,  $\text{NO}_2^-$  ( $\text{HNO}_2$ ,  $\text{pK}_a = 3.3$ ) will naturally decompose into  $\text{NO}$  and/or  $\text{NO}_2$  ( $3\text{HNO}_2 \rightleftharpoons 2\text{NO} + \text{HNO}_3 + \text{H}_2\text{O}$  or  $2\text{HNO}_2 \rightleftharpoons \text{NO} + \text{NO}_2 + \text{H}_2\text{O}$ ) [65]. Soil  $\text{NO}$  can be further transformed to  $\text{N}_2\text{O}$  with  $\text{Fe}^{2+}$  when it was not escaping soil [65].

### 2.3.2 Shifts in microbial communities and abundance

Generally, the abundance of AOB was lower in soil pH < 5.5 than that in neutral soil pH. Here, nitrification was weak and almost disappears at soil pH < 4 [66]. However, AOA could mediate the process of ammonia oxidation in extremely strong acidity soil (pH: 4.2–4.47) [43]. Another study reported that the abundance of AOB was positively correlated with pH ( $R^2 = 0.2807$ ), while the abundance of AOA was negatively correlated with pH ( $R^2 = 0.2141$ ) [67]. For example, AOA dominated in acid paddy soil (pH 5.6), while AOB dominated in alkaline soil (pH 8.2) [68]. Previous research indicated that fungi were the main microbial community that mediated N<sub>2</sub>O emissions in acid soil [69, 70]. Additionally, fungi-mediated denitrification accounted for 70% soil N<sub>2</sub>O emissions from a 100-year-old tea plantation (soil pH 3.8) [71].

In acid soils, the activity of N<sub>2</sub>O reductase was inhibited, leading to higher N<sub>2</sub>O emissions in lower soil pH [72]. Indeed, there was a positive correlation between the abundance of *nirS*, *nirK*, or *nosZ* and soil pH (4.0–8.0) and a negative correlation between N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>) and soil pH [73]. In agreement, N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>) was negatively correlated with soil pH (3.7–8.0) ( $R^2 = 0.759$ ,  $P < 0.001$ ), and lime addition decreased N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>) [74]. The ratio of N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>) increased with decreasing pH (5.57–7.06) ( $R^2 = 0.82$ ) [75]. Consistently, soil pH was negatively correlated with N<sub>2</sub>O/N<sub>2</sub> [76]. Intensive management consistently decreased soil pH and increased the ratio of N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>) [77]. Increasing dolomite dosage increased soil pH and hence increased the transcription of *nosZ* genes and reduced the potential of N<sub>2</sub>O production in acid soils [26].

### 2.3.3 Microbes increased resistance to soil acidification

Laboratory study showed that the potential of soil N<sub>2</sub>O emissions was increased with decreasing pH (soil pH ranging from 2.96 to 6.26) from tea plantations in Japanese [78]. In addition, higher soil N<sub>2</sub>O emissions and lower abundance of *nosZ* genes were observed in soil pH at 3.71 (control) than in pH at 5.11, 6.19, and 7.41 (lime amelioration) under NO<sub>3</sub><sup>-</sup>-N fertilization (50, 200, and 1000 mg kg<sup>-1</sup>) from a 100-year-old tea plantation [79]. Field study found a negative correlation between soil N<sub>2</sub>O emissions and pH (pH 3.6–5.9) ( $N_2O-N = 636.6 * e^{-0.8028 * pH}$ ,  $R = -0.93$ ) from *Betula pendula* Roth forest [80]. Thus, denitrifying microorganisms may have been adapted extremely to acid soil environments, resulting in high N<sub>2</sub>O emissions when soil acidification happened.

## 3. Sustainable forest management

Soil amelioration (e.g., application of lime, biochar nitrification inhibitors, and urease inhibitors) plays an important role in mitigation of soil acidification and N<sub>2</sub>O emissions.

### 3.1 Lime

Lime as an ameliorant was often used to amend acid soils in southern China due to increasing soil pH. It can relieve the toxic effect of soil Al<sup>3+</sup> on plant growth by reducing soil exchangeable H<sup>+</sup> [81]. Lime addition increased soil pH and salt saturation [82]. In addition, application of lime can reduce soil N<sub>2</sub>O emissions [40]. For example, under 60% WFPS or flooded conditions, dolomite addition at medium- or high-dose levels (1 or 2 g kg<sup>-1</sup> soil) can reduce N<sub>2</sub>O emissions and increase the transcription of *nosZ* genes (N<sub>2</sub>O → N<sub>2</sub>) by increasing acid soil pH from a rice-rapeseed

rotation system [26]. However, lime addition reduced the content of soluble organic carbon in the soil layer 10–30 cm [83]. Consistently, long-term lime addition increased the soil pH but stimulated the decomposition of soil organic carbon [84].

### 3.2 Biochar

Biochar was stable in the soil from Amazon basin of Brazil, and biochar input improved soil fertility [85]. This discovery accelerated the development of technologies for biochar application in soil amelioration.

Biochar is a carbon (C)-rich solid material by pyrolyzing of organic biomass such as crop straw, forestry by-products, urban waste, industrial by-products, animal manure, and urban sludge at low oxygen and high temperature (250–700°C) condition [86]. Biochar has been characterized by a high pH, specific surface area, degree of aromatization, and porosity. In addition, biochar is rich in C-containing functional groups (e.g., C–H, C–O, C=C and C=O) and relatively stable organic C. The physicochemical properties of biochar were mainly determined by pyrolysis temperature [87].

Presently, biochar was widely used as a soil ameliorant in agriculture and forestry field. For example, our previous studies reported that *C. oleifera* fruit shells are ideal feedstock for producing biochar as they are rich in C and N [1, 88]. Biochar includes the following advantages:

1. Carbon recalcitrance of biochar can increase soil C pool. The potential of biochar in mitigation of greenhouse gas emissions was 1.0–1.8 Pg CO<sub>2</sub>-C<sub>eq</sub> yr<sup>-1</sup> [89].
2. Biochar had excellent physicochemical characteristics in soil nutrient retention and utilization [90, 91] and water conservation [92]. Additionally, biochar can increase the plant resistance to Al<sup>3+</sup> toxicity [81], the clone of arbuscular mycorrhizal fungi, and crop yield [93, 94]. It can decrease continuous cropping obstacles such as root-knot nematode [95] and *Ralstonia solanacearum* [96].
3. Biochar is rich in macro- and microelements [97], which can reduce the dosage of fertilizer.

#### 3.2.1 Effects of biochar on soil nitrous oxide emissions

The physicochemical properties of biochar and soil can interactively influence soil N<sub>2</sub>O emissions [98]. However, the effects of biochar on soil N<sub>2</sub>O emissions varied, including positive effects [99], negative effects [100], and no effects [101].

Biochar addition increased soil N<sub>2</sub>O emissions with the release of N from biochar [102]. By contrast, biochar reduced soil N<sub>2</sub>O emissions with (1) increased NO<sub>3</sub><sup>-</sup>-N immobilization [103]; (2) increased copy numbers of *nosZ* gene [104, 105]; and (3) increased toxic effects of polycyclic aromatic hydrocarbons and other toxic substances (pyrolysis by-products) on N-cycle microorganisms [106].

#### 3.2.2 Effects of biochar on soil pH buffer capacity

Biochar that increased soil pH buffer capacity may predominantly correlate with biochar rich in oxygen-containing functional groups in surface. The anions of weakly acidic functional groups can associate with H<sup>+</sup>, hence increasing soil pH. Meanwhile, exchangeable base cations can release into the solution, thus increasing soil pH buffer capacity [107, 108]. In addition, soluble silicon (Si) such as H<sub>3</sub>SiO<sub>4</sub><sup>-</sup> (present at a high pH) can combine with H<sup>+</sup> and generate H<sub>2</sub>SiO<sub>3</sub> precipitation [107, 108].



### 3.3 Nitrification inhibitor

Nitrification inhibitors are a class of organic compounds that can inhibit the activity of nitrifying bacteria.

Nitrification inhibitors, especially synthetic nitrification inhibitors (e.g., dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP)), were widely used in agriculture for improving N use efficiency. Ammonia-oxidizing bacteria and AOA are the major microbial communities in nitrification and denitrification, and both contain *amo* enzyme that can catalyze ammonia oxidation ( $\text{NH}_4^+ - \text{N} \rightarrow \text{NH}_2\text{OH}$ ). Synthetic nitrification inhibitors such as DCD and DMPP mainly inhibit nitrification by suppressing the activity of *amo* enzyme (a Cu-copper cofactor enzyme). In addition, biological nitrification inhibitors also can inhibit soil nitrification [109, 110]. In the mid-1980s, researchers found that *Brachiaria humidicola* cv. Tully (CIAT 679), a single community forage, had lower nitrification rates than a single legume community or bare land [111]. This phenomenon stimulated further studies on biological nitrification inhibitors. The first biological nitrification inhibitor (methyl 3-(4-hydroxyphenyl) propionate: MHPP) was identified from the root exudate of *Sorghum bicolor* in 2008, which mainly inhibited the activity of *amo* enzyme [112]. Subsequently, biological nitrification inhibitor (brachialactone) from the root exudate of *Brachiaria humidicola* was found to inhibit the activity of *amo* enzyme [113]. The Nanjing Soil Research Institute of China firstly found and identified a biological nitrification, 1,9-decanediol, from the root exudate of rice, which can inhibit the activity of *amo* enzyme [114].

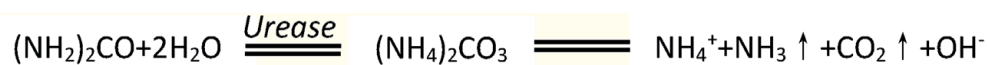
Ammonium N can be adsorbed by soil colloids, while soil  $\text{NO}_3^- - \text{N}$  (the end product of nitrification) easily can be leached to groundwater by precipitation. In addition, microbial-mediated nitrification is closely related with soil  $\text{N}_2\text{O}$  emissions [20–22]. Nitrification inhibitors can effectively inhibit soil nitrification, slowing the transformation of  $\text{NH}_4^+ - \text{N}$  to  $\text{NO}_3^- - \text{N}$  and hence reducing the  $\text{NO}_3^- - \text{N}$  leaching and  $\text{N}_2\text{O}$  emissions.

An evaluation from 62 field studies showed that although nitrification inhibitors increased 20%  $\text{NH}_3$  emissions, they reduced 48% inorganic N leaching, 44%  $\text{N}_2\text{O}$  emissions, and 24%  $\text{NO}$  emissions and increased 58% plant N utilization, 9% grain yield, 5% straw yield, and 5% vegetable yield [115]. Consistently, other studies evaluated that nitrification inhibitors decreased by 38% [116], 50% [117], or 73% [118]  $\text{N}_2\text{O}$  emissions and decreased by  $0.3 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$  [119]. Similarly, DCD did not increase crop yields but reduced 35%  $\text{N}_2\text{O}$  emissions [120]. A meta-analysis showed that DCD rather than DMPP significantly increased 6.5% crop yield as well as DCD and DMPP decreased  $\text{N}_2\text{O}$  emissions by 44.7% and 47.6%, respectively [121].

Therefore, application of nitrification inhibitors could reduce  $\text{N}_2\text{O}$  emissions and mitigate environmental pollution after intensive N inputs.

### 3.4 Urease inhibitors

Urease inhibitors are a class of compounds that can slow soil urease activity (Figure 2). Addition of urease inhibitors after urea input can inhibit the hydrolysis



**Figure 2.**  
The chemical equation of urea hydrolysis with urease catalysis.

of urea via inhibiting the activity of urease, hence reducing  $\text{NH}_3$  volatilizations and  $\text{N}_2\text{O}$  emissions. Additionally, the application of urease inhibitors also contributes to increase N utilization efficiency and reduce  $\text{NO}_3^-$ -N leaching. *N*-(*n*-butyl) thiophosphoric triamide (NBPT) is one of the most wide and effective urease inhibitors.

Urease, a Ni-copper enzyme, has two Ni–O bidentate ligands, specifically catalyzing urea into  $\text{NH}_3$  and  $\text{CO}_2$ . Urea only can bind with one specific Ni–O ligand of urease, but NBPT can bind with two Ni–O bidentate ligands of urease and generate a tridentate ligand [122], hence inhibiting the activity of urease.

Presently, a meta-analysis reported that a nonlinear response was presented in soil  $\text{NH}_3$  volatilizations and N input [123]. Application of NBPT can effectively inhibit  $\text{NH}_3$  volatilizations. For example, 530 mg NBPT  $\text{kg}^{-1}$  urea treatment delayed  $\text{NH}_3$  volatilizations and decreased accumulation of  $\text{NH}_3$  volatilizations compared with the control treatment.  $\text{NH}_3$  volatilizations were linearly related with the NBPT dosage in the range of 0–1000 mg NBPT  $\text{kg}^{-1}$  Urea (0, 530, 850, 1500, and 2000 mg NBPT  $\text{kg}^{-1}$  Urea) [124]. Other study reported that NBPT increased 27% oat yield and 33% crop N uptake [120].

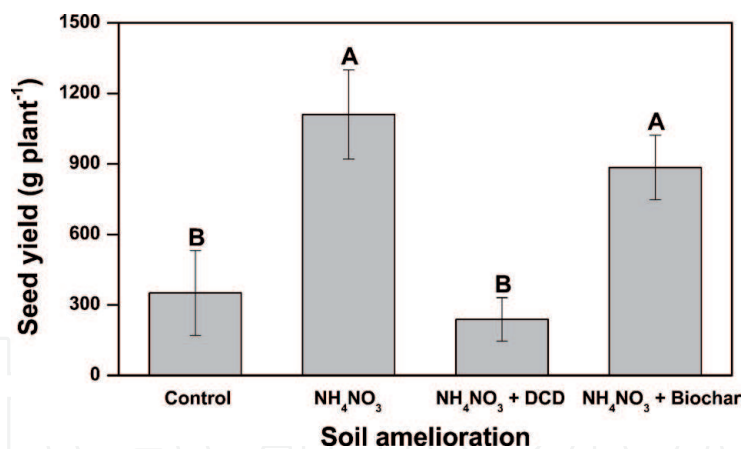
The effects of NBPT on  $\text{N}_2\text{O}$  emissions were controversial. For example, NBPT can reduce 80%  $\text{N}_2\text{O}$  emissions [117]. No effects of NBPT (0.07%, NBPT/Urea-N, w/w) on  $\text{N}_2\text{O}$  emissions were observed [125]. Similarly, there was no change of  $\text{N}_2\text{O}$  emissions with NBPT (250 mg NBPT  $\text{kg}^{-1}$  Urea) addition from urea-fertilized (50 kg Urea-N  $\text{ha}^{-1}$ ) soil [126].

Additionally, NBPT can reduce  $\text{N}_2\text{O}$  emissions from alkaline soils but has no effects on acidic soils [127], which indicated that pH plays a key role in the regulation of NBPT effects on  $\text{N}_2\text{O}$  emissions. Further laboratory study showed that NBPT inhibited nitrification, stimulating  $\text{N}_2\text{O}$  emissions from alkaline soils (pH 8.05) but not affecting  $\text{N}_2\text{O}$  emissions from acid soils (pH 4.85). This finding suggested that the effect of NBPT on soil  $\text{N}_2\text{O}$  emissions is not only influenced by pH but also by other unknown factors [127].

Generally, urease inhibitors correlated with nitrification inhibitor could mitigate  $\text{N}_2\text{O}$  emissions. A meta-analysis showed that urease inhibitors and nitrification inhibitors interactively reduced 30%  $\text{N}_2\text{O}$  emissions [116]. For example, a field study reported that the combination of NBPT (0.3%, NBPT/Urea-N, w/w) and DCD (0.3%, DCD/Urea-N, w/w) reduced 32.1% soil  $\text{N}_2\text{O}$  emissions with the addition of 519 kg Urea-N  $\text{ha}^{-1}$  from banana plantation, but did not affect the yield of banana [128].

#### 4. Sustainable management in *Camellia oleifera* plantations

Our previous incubation study found that although biochar application increased  $\text{N}_2\text{O}$  emissions, DCD addition decreased soil  $\text{N}_2\text{O}$  emissions under urea fertilization from *C. oleifera* field [88]. Our field study showed that  $\text{N}_2\text{O}$  emission rates were inhibited by biochar or DCD application and the effects of biochar application on mitigation of cumulative  $\text{N}_2\text{O}$  were comparable to DCD addition in *C. oleifera* plantations [1]. Compared with control treatment, available N ( $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N) was not affected by  $\text{NH}_4\text{NO}_3$ ,  $\text{NH}_4\text{NO}_3$  + DCD, or  $\text{NH}_4\text{NO}_3$  + biochar treatment [1]. In addition, the seed yield of *C. oleifera* was higher in  $\text{NH}_4\text{NO}_3$  or  $\text{NH}_4\text{NO}_3$  + biochar treatment than that in control or  $\text{NH}_4\text{NO}_3$  + DCD treatment (Figure 3). Soil amelioration is necessary and improves N use efficiency and pH, mitigating  $\text{N}_2\text{O}$  emissions. Soil amelioration plays an important role in the sustainable management of oil safety in *C. oleifera* plantations.



**Figure 3.** The seed yield of *Camellia oleifera* with nitrogen fertilization, in combination with nitrification inhibitor (DCD) or biochar. Bars connected by different letters indicate significant difference in post-hoc tests at  $\alpha = 0.05$  (means  $\pm$  se).

## 5. Conclusions

Soil acidification, especially induced by N fertilization, will inhibit the activity of N<sub>2</sub>O reductase and increase the abundance of N<sub>2</sub>O-producing fungi as well as the acid resistance of N<sub>2</sub>O-producing microorganisms, hence the ratio of N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>). In addition, NO<sub>2</sub><sup>-</sup> will generate NO under soil pH < 5.5 condition, which will further transform into N<sub>2</sub>O. Under the background of global acidification, the soil from *C. oleifera* forest also suffers the potential risks of soil acidification and N<sub>2</sub>O emissions. Mitigation of soil acidification and N<sub>2</sub>O emissions by soil amelioration is necessary and improves N use efficiency and soil pH from *C. oleifera* plantations. Soil amelioration such as biochar and nitrification inhibitor plays an important role in sustainable forest management in *C. oleifera* plantations.

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## Conflict of interest

The authors declare no conflict of interest.

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## References

- [1] Deng B, Fang H, Jiang N, Feng W, Luo L, Wang J, et al. Biochar is comparable to dicyandiamide in the mitigation of nitrous oxide emissions from *Camellia oleifera* Abel. fields. *Forests*. 2019;**10**:1076. DOI: 10.3390/f10121076
- [2] Yuan Z, Liu Y. The national conference on the development of *Camellia oleifera* industries was held in Jiangxi province [Internet]. 2019. Available from: [http://www.jxly.gov.cn/id\\_402848b76e3b763f016e6cbad7e259c9/news.shtml](http://www.jxly.gov.cn/id_402848b76e3b763f016e6cbad7e259c9/news.shtml) [Accessed: 20 January 2020]
- [3] Liu C, Chen L, Tang W, Peng S, Li M, Deng N, et al. Predicting potential distribution and evaluating suitable soil condition of oil tea *Camellia* in China. *Forests*. 2018;**9**:487. DOI: 10.3390/f9080487
- [4] Dong B, Wu B, Hong W, Li X, Li Z, Xue L, et al. Transcriptome analysis of the tea oil camellia (*Camellia oleifera*) reveals candidate drought stress genes. *PLoS ONE*. 2017;**12**:e0181835. DOI: 10.1371/journal.pone.0181835
- [5] Lee C, Yen G. Antioxidant activity and bioactive compounds of tea seed (*Camellia oleifera* Abel.) oil. *Journal of Agricultural and Food Chemistry*. 2006;**54**:779-784. DOI: 10.1021/jf052325a
- [6] Ma J, Ye H, Rui Y, Chen G, Zhang N. Fatty acid composition of *Camellia oleifera* oil. *Journal für Verbraucherschutz und Lebensmittelsicherheit*. 2011;**6**:9-12. DOI: 10.1007/s00003-010-0581-3
- [7] Liu J, Wu L, Chen D, Li M, Wei C. Soil quality assessment of different *Camellia oleifera* stands in mid-subtropical China. *Applied Soil Ecology*. 2017;**113**:29-35. DOI: 10.1016/j.apsoil.2017.01.010
- [8] Martins MR, Sant Anna SAC, Zaman M, Santos RC, Monteiro RC, Alves BJR, et al. Strategies for the use of urease and nitrification inhibitors with urea: Impact on N<sub>2</sub>O and NH<sub>3</sub> emissions, fertilizer-<sup>15</sup>N recovery and maize yield in a tropical soil. *Agriculture, Ecosystems & Environment*. 2017;**247**:54-62. DOI: 10.1016/j.agee.2017.06.021
- [9] Wang Y, Guo J, Vogt RD, Mulder J, Wang J, Zhang X. Soil pH as the chief modifier for regional nitrous oxide emissions: New evidence and implications for global estimates and mitigation. *Global Change Biology*. 2017;**24**:e617-e626. DOI: 10.1111/gcb.13966
- [10] Ravishankara AR, Daniel JS, Portmann RW. Nitrous oxide (N<sub>2</sub>O): The dominant ozone-depleting substance emitted in the 21st century. *Science*. 2009;**326**:123-125. DOI: 10.1126/science.1176985
- [11] IPCC. Synthesis report, climate change 2014. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Geneva, Switzerland. 2014. pp. 1-164
- [12] WMO. WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2017. Geneva: Atmospheric Environment Research Division; 2018. pp. 1-8
- [13] Fowler D, Coyle M, Skiba U, Sutton MA, Cape JN, Reis S, et al. The global nitrogen cycle in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2013;**368**:20130164. DOI: 10.1098/rstb.2013.0164
- [14] Hu Y, Zhang L, Deng B, Liu Y, Liu Q, Zheng X, et al. The non-additive

effects of temperature and nitrogen deposition on CO<sub>2</sub> emissions, nitrification, and nitrogen mineralization in soils mixed with termite nests. *Catena*. 2017;**154**:12-20. DOI: 10.1016/j.catena.2017.02.014

[15] Deng B, Li Z, Zhang L, Ma Y, Li Z, Zhang W, et al. Increases in soil CO<sub>2</sub> and N<sub>2</sub>O emissions with warming depend on plant species in restored alpine meadows of Wugong Mountain, China. *Journal of Soils and Sediments*. 2016;**16**:777-784. DOI: 10.1007/s11368-015-1307-z

[16] Jiang L, Zhang L, Deng B, Liu X, Yi H, Xiang H, et al. Alpine meadow restorations by non-dominant species increased soil nitrogen transformation rates but decreased their sensitivity to warming. *Journal of Soils and Sediments*. 2017;**17**:2329-2337. DOI: 10.1007/s11368-016-1488-0

[17] Wang S, Luo S, Li X, Yue S, Shen Y, Li S. Effect of split application of nitrogen on nitrous oxide emissions from plastic mulching maize in the semiarid Loess Plateau. *Agriculture, Ecosystems & Environment*. 2016;**220**:21-27. DOI: 10.1016/j.agee.2015.12.030

[18] Shcherbak I, Millar N, Robertson GP. Global meta-analysis of the nonlinear response of soil nitrous oxide (N<sub>2</sub>O) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences*. 2014;**111**:9199-9204. DOI: 10.1073/pnas.1322434111

[19] Syakila A, Kroeze C. The global nitrous oxide budget revisited. *Greenhouse Gas Measurement and Management*. 2011;**1**:17-26. DOI: 10.3763/ghgmm.2010.0007

[20] Pauleta SR, Dell Acqua S, Moura I. Nitrous oxide reductase. *Coordination Chemistry Reviews*. 2013;**257**:332-349. DOI: 10.1016/j.ccr.2012.05.026

[21] Hu H, Chen D, He J. Microbial regulation of terrestrial nitrous oxide

formation: Understanding the biological pathways for prediction of emission rates. *FEMS Microbiology Reviews*. 2015;**39**:729-749. DOI: 10.1093/femsre/fuv021

[22] Zhang L, Liu X. Nitrogen transformations associated with N<sub>2</sub>O emissions in agricultural soils. In: Amanullah K, Alexander M, editors. *Nitrogen in Agriculture*. London: IntechOpen; 2017. pp. 17-31. DOI: 10.5772/intechopen.71922

[23] Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2013;**368**:20130122. DOI: 10.1098/rstb.2013.0122

[24] Oertel C, Matschullat J, Zurba K, Zimmermann F, Erasmi S. Greenhouse gas emissions from soils—A review. *Geochemistry*. 2016;**76**:327-352. DOI: 10.1016/j.chemer.2016.04.002

[25] Davidson EA, Keller M, Erickson HE, Verchot LV, Veldkamp E. Testing a conceptual model of soil emissions of nitrous and nitric oxides. *BioScience*. 2000;**50**:667-680. DOI: 10.1641/0006-3568(2000)050[0667:TACMOS]2.0.CO;2

[26] Shaaban M, Wu Y, Khalid MS, Peng Q, Xu X, Wu L, et al. Reduction in soil N<sub>2</sub>O emissions by pH manipulation and enhanced *nosZ* gene transcription under different water regimes. *Environmental Pollution*. 2018;**235**:625-631. DOI: 10.1016/j.envpol.2017.12.066

[27] Cui Q, Song C, Wang X, Shi F, Yu X, Tan W. Effects of warming on N<sub>2</sub>O fluxes in a boreal peatland of Permafrost region, Northeast China. *Science of the Total Environment*. 2018;**616-617**:427-434. DOI: 10.1016/j.scitotenv.2017.10.246

- [28] Shi F, Chen H, Chen H, Wu Y, Wu N. The combined effects of warming and drying suppress CO<sub>2</sub> and N<sub>2</sub>O emission rates in an alpine meadow of the eastern Tibetan Plateau. *Ecological Research*. 2012;**27**:725-733. DOI: 10.1007/s11284-012-0950-8
- [29] Schaufler G, Kitzler B, Schindlbacher A, Skiba U, Sutton MA, Zechmeister-Boltenstern S. Greenhouse gas emissions from European soils under different land use: Effects of soil moisture and temperature. *European Journal of Soil Science*. 2010;**61**:683-696. DOI: 10.1111/j.1365-2389.2010.01277.x
- [30] Lin S, Iqbal J, Hu R, Ruan L, Wu J, Zhao J, et al. Differences in nitrous oxide fluxes from red soil under different land uses in mid-subtropical China. *Agriculture, Ecosystems & Environment*. 2012;**146**:168-178. DOI: 10.1016/j.agee.2011.10.024
- [31] Gong Y, Wu J, Vogt J, Le TB. Warming reduces the increase in N<sub>2</sub>O emission under nitrogen fertilization in a boreal peatland. *Science of the Total Environment*. 2019;**664**:72-78. DOI: 10.1016/j.scitotenv.2019.02.012
- [32] Hu Y, Chang X, Lin X, Wang Y, Wang S, Duan J, et al. Effects of warming and grazing on N<sub>2</sub>O fluxes in an alpine meadow ecosystem on the Tibetan plateau. *Soil Biology and Biochemistry*. 2010;**42**:944-952. DOI: 10.1016/j.soilbio.2010.02.011
- [33] Zhang J, Peng C, Zhu Q, Xue W, Shen Y, Yang Y, et al. Temperature sensitivity of soil carbon dioxide and nitrous oxide emissions in mountain forest and meadow ecosystems in China. *Atmospheric Environment*. 2016;**142**:340-350. DOI: 10.1016/j.atmosenv.2016.08.011
- [34] Schindlbacher A. Effects of soil moisture and temperature on NO, NO<sub>2</sub>, and N<sub>2</sub>O emissions from European forest soils. *Journal of Geophysical Research*. 2004;**109**:1-12. DOI: 10.1029/2004JD004590
- [35] Quick AM, Reeder WJ, Farrell TB, Tonina D, Feris KP, Benner SG. Nitrous oxide from streams and rivers: A review of primary biogeochemical pathways and environmental variables. *Earth-Science Reviews*. 2019;**191**:224-262. DOI: 10.1016/j.earscirev.2019.02.021
- [36] Zhu X, Burger M, Doane TA, Horwath WR. Ammonia oxidation pathways and nitrifier denitrification are significant sources of N<sub>2</sub>O and NO under low oxygen availability. *Proceedings of the National Academy of Sciences*. 2013;**110**:6328-6333. DOI: 10.1073/pnas.1219993110
- [37] Burgin AJ, Groffman PM. Soil O<sub>2</sub> controls denitrification rates and N<sub>2</sub>O yield in a riparian wetland. *Journal of Geophysical Research: Biogeosciences*. 2012;**117**:1-10. DOI: 10.1029/2011JG001799
- [38] Levy-Booth DJ, Prescott CE, Grayston SJ. Microbial functional genes involved in nitrogen fixation, nitrification and denitrification in forest ecosystems. *Soil Biology and Biochemistry*. 2014;**75**:11-25. DOI: 10.1016/j.soilbio.2014.03.021
- [39] Cuhel J, Simek M, Laughlin RJ, Bru D, Cheneby D, Watson CJ, et al. Insights into the effect of soil pH on N<sub>2</sub>O and N<sub>2</sub> emissions and denitrifier community size and activity. *Applied and Environmental Microbiology*. 2010;**76**:1870-1878. DOI: 10.1128/AEM.02484-09
- [40] McMillan AMS, Pal P, Phillips RL, Palmada T, Berben PH, Jha N, et al. Can pH amendments in grazed pastures help reduce N<sub>2</sub>O emissions from denitrification? The effects of liming and urine addition on the completion of denitrification in fluvial and volcanic soils. *Soil Biology and Biochemistry*.

2016;**93**:90-104. DOI: 10.1016/j.soilbio.2015.10.013

[41] Pilegaard K, Skiba U, Ambus P, Beier C, Brüggemann N, Butterbach-Bahl K, et al. Factors controlling regional differences in forest soil emission of nitrogen oxides (NO and N<sub>2</sub>O). *Biogeosciences*. 2006;**3**:651-661. DOI: 10.5194/bg-3-651-2006

[42] Blum J, Su Q, Ma Y, Valverde-Pérez B, Domingo-Félez C, Jensen MM, et al. The pH dependency of N-converting enzymatic processes, pathways and microbes: effect on net N<sub>2</sub>O production. *Environmental Microbiology*. 2018;**20**:1623-1640. DOI: 10.1111/1462-2920.14063

[43] Zhang L, Hu H, Shen J, He J. Ammonia-oxidizing archaea have more important role than ammonia-oxidizing bacteria in ammonia oxidation of strongly acidic soils. *The ISME Journal*. 2012;**6**:1032-1045. DOI: 10.1038/ismej.2011.168

[44] Nicol GW, Leininger S, Schleper C, Prosser JI. The influence of soil pH on the diversity, abundance and transcriptional activity of ammonia oxidizing archaea and bacteria. *Environmental Microbiology*. 2008;**10**:2966-2978. DOI: 10.1111/j.1462-2920.2008.01701.x

[45] Erguder TH, Boon N, Wittebolle L, Marzorati M, Verstraete W. Environmental factors shaping the ecological niches of ammonia-oxidizing archaea. *FEMS Microbiology Reviews*. 2009;**33**:855-869. DOI: 10.1111/j.1574-6976.2009.00179.x

[46] von Uexküll HR, Mutert E. Global extent, development and economic impact of acid soils. *Plant and Soil*. 1995;**171**:1-15. DOI: 10.1007/BF00009558

[47] Li Q, Li S, Xiao Y, Zhao B, Wang C, Li B, et al. Soil acidification and its

influencing factors in the purple hilly area of southwest China from 1981 to 2012. *Catena*. 2019;**175**:278-285. DOI: 10.1016/j.catena.2018.12.025

[48] Kochian LV, Piñeros MA, Liu J, Magalhaes JV. Plant adaptation to acid soils: The molecular basis for crop aluminum resistance. *Annual Review of Plant Biology*. 2015;**66**:571-598. DOI: 10.1146/annurev-arplant-043014-114822

[49] Guo JH, Liu XJ, Zhang Y, Shen JL, Han WX, Zhang WF, et al. Significant acidification in major Chinese croplands. *Science*. 2010;**327**:1008-1010. DOI: 10.1126/science.1182570

[50] Shu QL. Cultivation techniques of *Camellia oleifera*. Hefei: University of Science and Technology of China Press; 2013. pp. 1-201

[51] Zheng S, Bian H, Quan Q, Xu L, Chen Z, He N. Effect of nitrogen and acid deposition on soil respiration in a temperate forest in China. *Geoderma*. 2018;**329**:82-90. DOI: 10.1016/j.geoderma.2018.05.022

[52] Singh S, Tripathi DK, Singh S, Sharma S, Dubey NK, Chauhan DK, et al. Toxicity of aluminium on various levels of plant cells and organism: A review. *Environmental and Experimental Botany*. 2017;**137**:177-193. DOI: 10.1016/j.envexpbot.2017.01.005

[53] Matson PA, McDowell WH, Townsend AR, Vitousek PM. The globalization of N deposition: Ecosystem consequences in tropical environments. *Biogeochemistry*. 1999;**46**:67-83. DOI: 10.1023/A:1006152112852

[54] Delhaize E, Ryan PR, Randall PJ. Aluminum tolerance in wheat (*Triticum aestivum* L.) (II. Aluminum-stimulated excretion of malic acid from root apices). *Plant Physiology*. 1993;**103**:695-702. DOI: 10.1104/pp.103.3.695



- [55] Hue NV, Craddock GR, Adams F. Effect of organic acids on aluminum toxicity in subsoils. *Soil Science Society of America Journal*. 1986;**50**:28-34. DOI: 10.2136/sssaj1986.03615995005000010006x
- [56] Zeng QL, Chen RF, Zhao XQ, Wang HY, Shen RF. Aluminium uptake and accumulation in the hyperaccumulator *Camellia Oleifera* Abel. *Pedosphere*. 2011;**21**:358-364. DOI: 10.1016/S1002-0160(11)60136-7
- [57] Verstraeten G, Vancampenhout K, Desie E, De Schrijver A, Hlava J, Schelfhout S, et al. Tree species effects are amplified by clay content in acidic soils. *Soil Biology and Biochemistry*. 2018;**121**:43-49. DOI: 10.1016/j.soilbio.2018.02.021
- [58] Kuypers MMM, Marchant HK, Kartal B. The microbial nitrogen-cycling network. *Nature Reviews Microbiology*. 2018;**16**:263-276. DOI: 10.1038/nrmicro.2018.9
- [59] Matschona G, Matzner E. Soil chemical properties affecting  $\text{NH}_4^+$  sorption in forest soils. *Journal of Plant Nutrition and Soil Science*. 1996;**159**:505-511. DOI: 10.1002/jpln.1996.3581590514
- [60] Kunhikrishnan A, Thangarajan R, Bolan NS, Xu Y, Mandal S, Gleeson DB, et al. Functional relationships of soil acidification, liming, and greenhouse gas flux. In: Sparks DL, editor. *Advances in Agronomy*. San Diego, USA: Academic Press; 2016. pp. 1-71. DOI: 10.1016/bs.agron.2016.05.001
- [61] Yue K, Yang W, Peng Y, Zhang C, Huang C, Xu Z, et al. Dynamics of multiple metallic elements during foliar litter decomposition in an alpine forest river. *Annals of Forest Science*. 2016;**73**:547-557. DOI: 10.1007/s13595-016-0549-2
- [62] Tian D, Niu S. A global analysis of soil acidification caused by nitrogen addition. *Environmental Research Letters*. 2015;**10**:24019. DOI: 10.1088/1748-9326/10/2/024019
- [63] Cheng Y, Wang J, Zhang J, Müller C, Wang S. Mechanistic insights into the effects of N fertilizer application on  $\text{N}_2\text{O}$ -emission pathways in acidic soil of a tea plantation. *Plant and Soil*. 2015;**389**:45-57. DOI: 10.1007/s11104-014-2343-y
- [64] Cai Z, Zhang J, Zhu T, Cheng Y. Stimulation of  $\text{NO}$  and  $\text{N}_2\text{O}$  emissions from soils by  $\text{SO}_2$  deposition. *Global Change Biology*. 2012;**18**:2280-2291. DOI: 10.1111/j.1365-2486.2012.02688.x
- [65] Cleemput O, Samater AH. Nitrite in soils: Accumulation and role in the formation of gaseous N compounds. *Fertilizer Research*. 1995;**45**:81-89. DOI: 10.1007/BF00749884
- [66] De Boer W, Kowalchuk GA. Nitrification in acid soils: Microorganisms and mechanisms. *Soil Biology and Biochemistry*. 2001;**33**:853-866. DOI: 10.1016/S0038-0717(00)00247-9
- [67] Xiao H, Schaefer DA, Yang X. pH drives ammonia oxidizing bacteria rather than archaea thereby stimulate nitrification under *Ageratina adenophora* colonization. *Soil Biology and Biochemistry*. 2017;**114**:12-19. DOI: 10.1016/j.soilbio.2017.06.024
- [68] Jiang X, Hou X, Zhou X, Xin X, Wright A, Jia Z. pH regulates key players of nitrification in paddy soils. *Soil Biology and Biochemistry*. 2015;**81**:9-16. DOI: 10.1016/j.soilbio.2014.10.025
- [69] Rütting T, Huygens D, Boeckx P, Staelens J, Klemmedtsson L. Increased fungal dominance in  $\text{N}_2\text{O}$  emission hotspots along a natural pH gradient in organic forest soil. *Biology and Fertility of Soils*. 2013;**49**:715-721. DOI: 10.1007/s00374-012-0762-6
- [70] Chen H, Mothapo NV, Shi W. The significant contribution of

fungi to soil N<sub>2</sub>O production across diverse ecosystems. *Applied Soil Ecology*. 2014;**73**:70-77. DOI: 10.1016/j.apsoil.2013.08.011

[71] Huang Y, Xiao X, Long X. Fungal denitrification contributes significantly to N<sub>2</sub>O production in a highly acidic tea soil. *Journal of Soils and Sediments*. 2017;**17**:1599-1606. DOI: 10.1007/s11368-017-1655-y

[72] Bergaust L, Mao Y, Bakken LR, Frostegard A. Denitrification response patterns during the transition to anoxic respiration and posttranscriptional effects of suboptimal pH on nitrogen oxide reductase in *Paracoccus denitrificans*. *Applied and Environmental Microbiology*. 2010;**76**:6387-6396. DOI: 10.1128/AEM.00608-10

[73] Liu B, Mørkved PT, Frostegård Å, Bakken LR. Denitrification gene pool, transcription and kinetics of NO, N<sub>2</sub>O and N<sub>2</sub> production as affected by soil pH. *FEMS Microbiology Ecology*. 2010;**3**:407-417. DOI: 10.1111/j.1574-6941.2010.00856.x

[74] Qu Z, Wang J, Almøy T, Bakken LR. Excessive use of nitrogen in Chinese agriculture results in high N<sub>2</sub>O/(N<sub>2</sub>O + N<sub>2</sub>) product ratio of denitrification, primarily due to acidification of the soils. *Global Change Biology*. 2014;**20**:1685-1698. DOI: 10.1111/gcb.12461

[75] Samad MS, Bakken LR, Nadeem S, Clough TJ, de Klein CAM, Richards KG, et al. High-resolution denitrification kinetics in pasture soils link N<sub>2</sub>O emissions to pH, and denitrification to C mineralization. *PLoS ONE*. 2016;**11**:e0151713. DOI: 10.1371/journal.pone.0151713

[76] Simek M, Cooper JE. The influence of soil pH on denitrification: Progress towards the understanding of this interaction over the last 50

years. *European Journal of Soil Science*. 2002;**53**:345-354. DOI: 10.1046/j.1365-2389.2002.00461.x

[77] Raut N, Dörsch P, Sitaula BK, Bakken LR. Soil acidification by intensified crop production in South Asia results in higher N<sub>2</sub>O/(N<sub>2</sub> + N<sub>2</sub>O) product ratios of denitrification. *Soil Biology and Biochemistry*. 2012;**55**:104-112. DOI: 10.1016/j.soilbio.2012.06.011

[78] Tokuda S, Hayatsu M. Nitrous oxide emission potential of 21 acidic tea field soils in Japan. *Soil Science and Plant Nutrition*. 2001;**47**:637-642. DOI: 10.1080/00380768.2001.10408427

[79] Huang Y, Long X, Chapman SJ, Yao H. Acidophilic denitrifiers dominate the N<sub>2</sub>O production in a 100-year-old tea orchard soil. *Environmental Science and Pollution Research*. 2015;**22**:4173-4182. DOI: 10.1007/s11356-014-3653-6

[80] Weslien P, Kasimir Klemedtsson Å, Börjesson G, Klemedtsson L. Strong pH influence on N<sub>2</sub>O and CH<sub>4</sub> fluxes from forested organic soils. *European Journal of Soil Science*. 2009;**60**:311-320. DOI: 10.1111/j.1365-2389.2009.01123.x

[81] Zhang K, Chen L, Li Y, Brookes PC, Xu JM, Luo Y. The effects of combinations of biochar, lime, and organic fertilizer on nitrification and nitrifiers. *Biology and Fertility of Soils*. 2017;**53**:77-87. DOI: 10.1007/s00374-016-1154-0

[82] Reid C, Watmough SA. Evaluating the effects of liming and wood-ash treatment on forest ecosystems through systematic meta-analysis. *Canadian Journal of Forest Research*. 2014;**44**:867-885. DOI: 10.1139/cjfr-2013-0488

[83] Wang X, Tang C, Baldock JA, Butterly CR, Gazey C. Long-term effect of lime application on the chemical composition of soil organic carbon in acid soils varying in texture and liming history. *Biology and Fertility of*

Soils. 2016;**52**:295-306. DOI: 10.1007/s00374-015-1076-2

[84] Aye NS, Butterly CR, Sale PWG, Tang C. Residue addition and liming history interactively enhance mineralization of native organic carbon in acid soils. *Biology and Fertility of Soils*. 2017;**53**:61-75. DOI: 10.1007/s00374-016-1156-y

[85] Sombroek WG. Amazon Soils: A Reconnaissance of the Soils of the Brazilian Amazon Region. Wageningen: Centre for Agricultural Publications and Documentation; 1966. pp. 1-292

[86] Johannes L, Stephen J. Biochar for Environmental Management. 2nd ed. New York, USA: Routledge; 2015. pp. 1-944

[87] Deng B, Shi Y, Zhang L, Fang H, Gao Y, Luo L, et al. Effects of spent mushroom substrate-derived biochar on soil CO<sub>2</sub> and N<sub>2</sub>O emissions depend on pyrolysis temperature. *Chemosphere*. 2020;**246**:125608. DOI: 10.1016/j.chemosphere.2019.125608

[88] Deng B, Wang S, Xu X, Wang H, Hu D, Guo X, et al. Effects of biochar and dicyandiamide combination on nitrous oxide emissions from *Camellia oleifera* field soil. *Environmental Science and Pollution Research*. 2019;**26**:4070-4077. DOI: 10.1007/s11356-018-3900-3

[89] Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. *Nature Communications*. 2010;**1**. DOI: 10.1038/ncomms1053

[90] Sun HJ, Lu HY, Chu L, Shao HB, Shi WM. Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH<sub>3</sub> volatilization in a coastal saline soil. *Science of the Total Environment*. 2017;**575**:820-825. DOI: 10.1016/j.scitotenv.2016.09.137

[91] Gul SM, Whalen JK. Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biology and Biochemistry*. 2016;**103**:1-15. DOI: 10.1016/j.soilbio.2016.08.001

[92] Castellini M, Giglio L, Niedda M, Palumbo AD, Ventrella D. Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research*. 2015;**154**:1-13. DOI: 10.1016/j.still.2015.06.016

[93] Zhang AF, Liu YM, Pan GX, Hussain Q, Li LQ, Zheng JW, et al. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. *Plant and Soil*. 2012;**351**:263-275. DOI: 10.1007/s11104-011-0957-x

[94] Zhang AF, Bian RG, Pan GX, Cui LQ, Hussain Q, Li L, et al. Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. *Field Crops Research*. 2012;**127**:153-160. DOI: 10.1016/j.fcr.2011.11.020

[95] Huang W, Ji H, Gheysen G, Debode J, Kyndt T. Biochar-amended potting medium reduces the susceptibility of rice to root-knot nematode infections. *BMC Plant Biology*. 2015;**15**:267. DOI: 10.1186/s12870-015-0654-7

[96] Gu Y, Hou Y, Huang D, Hao Z, Wang X, Wei Z, et al. Application of biochar reduces *Ralstonia solanacearum* infection via effects on pathogen chemotaxis, swarming motility, and root exudate adsorption. *Plant and Soil*. 2017;**415**:269-281. DOI: 10.1007/s11104-016-3159-8

[97] Zhao Y, Zhao L, Mei Y, Li F, Cao X. Release of nutrients and heavy metals from biochar-amended soil under environmentally relevant conditions.

Environmental Science and Pollution Research. 2018;**25**:2517-2527. DOI: 10.1007/s11356-017-0668-9

[98] He Y, Zhou X, Jiang L, Li M, Du Z, Zhou G, et al. Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy*. 2017;**9**:743-755. DOI: 10.1111/gcbb.12376

[99] Deng B, Zheng L, Ma Y, Zhang L, Liu X, Zhang X, et al. Effects of mixing biochar on soil N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions after prescribed fire in alpine meadows of Wugong Mountain, China. *Journal of Soils and Sediments*. 2020. DOI: 10.1007/s11368-019-02552-8

[100] Case SDC, McNamara NP, Reay DS, Stott AW, Grant HK, Whitaker J. Biochar suppresses N<sub>2</sub>O emissions while maintaining N availability in a sandy loam soil. *Soil Biology and Biochemistry*. 2015;**81**:178-185. DOI: 10.1016/j.soilbio.2014.11.012

[101] Case SDC, McNamara NP, Reay DS, Whitaker J. Can biochar reduce soil greenhouse gas emissions from a *Miscanthus* bioenergy crop? *GCB Bioenergy*. 2014;**6**:76-89. DOI: 10.1111/gcbb.12052

[102] Mukherjee A, Zimmerman AR. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma*. 2013;**193-194**:122-130. DOI: 10.1016/j.geoderma.2012.10.002

[103] Case SDC, McNamara NP, Reay DS, Whitaker J. The effect of biochar addition on N<sub>2</sub>O and CO<sub>2</sub> emissions from a sandy loam soil—The role of soil aeration. *Soil Biology and Biochemistry*. 2012;**51**:125-134. DOI: 10.1016/j.soilbio.2012.03.017

[104] Tan G, Wang H, Xu N, Liu H, Zhai L. Biochar amendment with fertilizers increases peanut N uptake, alleviates soil N<sub>2</sub>O emissions without affecting NH<sub>3</sub> volatilization in field

experiments. *Environmental Science and Pollution Research*. 2018;**25**:8817-8826. DOI: 10.1007/s11356-017-1116-6

[105] Aamer M, Shaaban M, Hassan MU, Guoqin H, Ying L, Hai Ying T, et al. Biochar mitigates the N<sub>2</sub>O emissions from acidic soil by increasing the *nosZ* and *nirK* gene abundance and soil pH. *Journal of Environmental Management*. 2020;**255**:109891. DOI: 10.1016/j.jenvman.2019.109891

[106] Hale SE, Lehmann J, Rutherford D, Zimmerman AR, Bachmann RT, Shitumbanuma V, et al. Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. *Environmental Science & Technology*. 2012;**46**:2830-2838. DOI: 10.1021/es203984k

[107] Shi RY, Hong ZN, Li JY, Jiang J, Baquy MA, Renkou X, et al. Mechanisms for increasing the pH buffering capacity of an acidic ultisol by crop residue derived biochars. *Journal of Agricultural and Food Chemistry*. 2017;**65**:8111-8119. DOI: 10.1021/acs.jafc.7b02266

[108] Dai Z, Zhang X, Tang C, Muhammad N, Wu J, Brookes PC, et al. Potential role of biochars in decreasing soil acidification—A critical review. *Science of the Total Environment*. 2017;**581-582**:601-611. DOI: 10.1016/j.scitotenv.2016.12.169

[109] Subbarao GV, Sahrawat KL, Nakahara K, Ishikawa T, Kishii M, Rao IM, et al. Biological nitrification inhibition—A novel strategy to regulate nitrification in agricultural systems. *Advances in Agronomy*. 2012;**114**:249-302. DOI: 10.1016/B978-0-12-394275-3.00001-8

[110] Coskun D, Britto DT, Shi W, Kronzucker HJ. Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. *Nature Plants*. 2017;**3**:17074. DOI: 10.1038/nplants.2017.74

- [111] Sylvester-Bradley R, Mosquera D, Méndez JE. Inhibition of nitrate accumulation in tropical grassland soils: Effect of nitrogen fertilization and soil disturbance. *Journal of Soil Science*. 1988;**39**:407-416. DOI: 10.1111/j.1365-2389.1988.tb01226.x
- [112] Zakir HA, Subbarao GV, Pearse SJ, Gopalakrishnan S, Ito O, Ishikawa T, et al. Detection, isolation and characterization of a root-exuded compound, methyl 3-(4-hydroxyphenyl) propionate, responsible for biological nitrification inhibition by sorghum (*Sorghum bicolor*). *New Phytologist*. 2008;**180**:442-451. DOI: 10.1111/j.1469-8137.2008.02576.x
- [113] Subbarao GV, Nakahara K, Hurtado MP, Ono H, Moreta DE, Salcedo AF, et al. Evidence for biological nitrification inhibition in *Brachiaria* pastures. *Proceedings of the National Academy of Sciences*. 2009;**106**:17302-17307. DOI: 10.1073/pnas.0903694106
- [114] Sun L, Lu Y, Yu F, Kronzucker HJ, Shi W. Biological nitrification inhibition by rice root exudates and its relationship with nitrogen-use efficiency. *New Phytologist*. 2016;**212**:646-656. DOI: 10.1111/nph.14057
- [115] Qiao C, Liu L, Hu S, Compton JE, Greaver TL, Li Q. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. *Global Change Biology*. 2015;**21**:1249-1257. DOI: 10.1111/gcb.12802
- [116] Thapa R, Chatterjee A, Awale R, McGranahan DA, Daigh A. Effect of enhanced efficiency fertilizers on nitrous oxide emissions and crop yields: A meta-analysis. *Soil Science Society of America Journal*. 2016;**80**:1121-1134. DOI: 10.2136/sssaj2016.06.0179
- [117] Sanz-Cobena A, Lassaletta L, Aguilera E, Prado AD, Garnier J, Billen G, et al. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agriculture, Ecosystems & Environment*. 2017;**238**:5-24. DOI: 10.1016/j.agee.2016.09.038
- [118] Gu J, Nie H, Guo H, Xu H, Gunnathorn T. Nitrous oxide emissions from fruit orchards: A review. *Atmospheric Environment*. 2019;**201**:166-172. DOI: 10.1016/j.atmosenv.2018.12.046
- [119] Rees RM, Baddeley JA, Bhogal A, Ball BC, Chadwick DR, Macleod M, et al. Nitrous oxide mitigation in UK agriculture. *Soil Science and Plant Nutrition*. 2013;**59**:3-15. DOI: 10.1080/00380768.2012.733869
- [120] Hube S, Alfaro MA, Scheer C, Brunk C, Ramírez L, Rowlings D, et al. Effect of nitrification and urease inhibitors on nitrous oxide and methane emissions from an oat crop in a volcanic ash soil. *Agriculture, Ecosystems & Environment*. 2017;**238**:46-54. DOI: 10.1016/j.agee.2016.06.040
- [121] Yang M, Fang YT, Sun D, Shi YL. Efficiency of two nitrification inhibitors (dicyandiamide and 3,4-dimethylpyrazole phosphate) on soil nitrogen transformations and plant productivity: A meta-analysis. *Scientific Reports*. 2016;**6**:22075. DOI: 10.1038/srep22075
- [122] Manunza B, Deiana S, Pintore M, Gessa C. The binding mechanism of urea, hydroxamic acid and *N*-(*N*-butyl)-phosphoric triamide to the urease active site. A comparative molecular dynamics study. *Soil Biology and Biochemistry*. 1999;**31**:789-796. DOI: 10.1016/S0038-0717(98)00155-2
- [123] Jiang Y, Deng A, Bloszies S, Huang S, Zhang W. Nonlinear response of soil ammonia emissions to fertilizer nitrogen. *Biology and Fertility of Soils*. 2017;**53**:269-274. DOI: 10.1007/s00374-017-1175-3

[124] Mira AB, Cantarella H, Souza-Netto GJM, Moreira LA, Kamogawa MY, Otto R. Optimizing urease inhibitor usage to reduce ammonia emission following urea application over crop residues. *Agriculture, Ecosystems & Environment*. 2017;**248**:105-112. DOI: 10.1016/j.agee.2017.07.032

[125] Volpi I, Laville P, Bonari E, di Nasso NNO, Bosco S. Improving the management of mineral fertilizers for nitrous oxide mitigation: The effect of nitrogen fertilizer type, urease and nitrification inhibitors in two different textured soils. *Geoderma*. 2017;**307**:181-188. DOI: 10.1016/j.geoderma.2017.08.018

[126] van der Weerden TJ, Luo J, Di HJ, Podolyan A, Phillips RL, Saggar S, et al. Nitrous oxide emissions from urea fertiliser and effluent with and without inhibitors applied to pasture. *Agriculture, Ecosystems & Environment*. 2016;**219**:58-70. DOI: 10.1016/j.agee.2015.12.006

[127] Fan X, Yin C, Yan G, Cui P, Shen Q, Wang Q, et al. The contrasting effects of N-(*n*-butyl) thiophosphoric triamide (NBPT) on N<sub>2</sub>O emissions in arable soils differing in pH are underlain by complex microbial mechanisms. *Science of the Total Environment*. 2018;**642**:155-167. DOI: 10.1016/j.scitotenv.2018.05.356

[128] Zhu T, Zhang J, Huang P, Suo L, Wang C, Ding W, et al. N<sub>2</sub>O emissions from banana plantations in tropical China as affected by the application rates of urea and a urease/nitrification inhibitor. *Biology and Fertility of Soils*. 2015;**51**:673-683. DOI: 10.1007/s00374-015-1018-z