Chapter

Nitrogen Cycling and Soil Amelioration in *Camellia oleifera* Plantations

Bangliang Deng and Ling Zhang

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_2O) emissions and soil acidification, limiting sustainable development of economic forests. As one of the important greenhouse gases, N_2O is 265 times greater than carbon dioxide in global warming potential on 100-year scale. To mitigate soil N_2O 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_2O 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_2O), nitric oxide (NO), ammonia (NH_3)) 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_2O for global warming is 265 times than that of carbon dioxide [11]. The concentration of N_2O is ranging from 270 ppb in pre-industrial period to 329.9 ppb in 2017 [12].

Soil systems contributed the largest source of N_2O emissions (13 Tg N_2O-N yr^{-1}), of which human activities accounted for 54% [13]. Nitrogen input such as N deposition and N fertilization often increased N_2O emissions and altered the process of N transformation [14–17]. Generally, soil N_2O 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_2O [19].

2.1.1 Nitrification and denitrification

Nitrification and denitrification are the two main pathways of N_2O emissions (**Figure 1**) [20–22], which produced global 70% soil N_2O emissions [13].

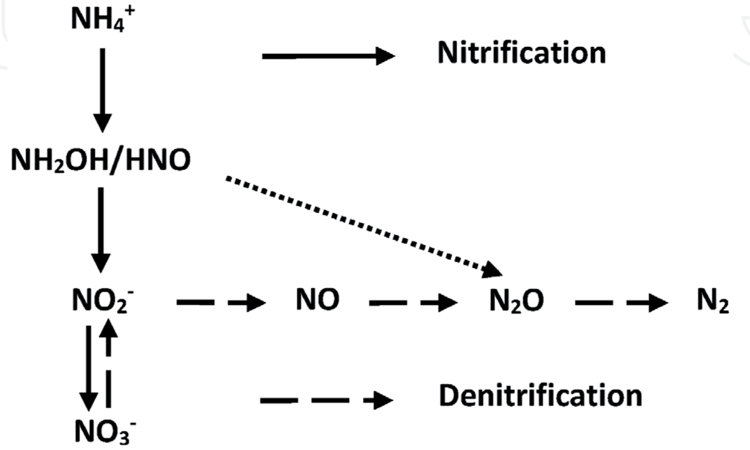

Figure 1.
Nitrification- and denitrification-related pathways [20–22].

2.1.2 Influence factors

Soil N_2O emissions can be influenced by soil environmental factors such as soil moisture, temperature, oxygen (O_2), and pH condition [23, 24].

2.1.2.1 Soil moisture

Soil moisture is a vital factor that affects soil N_2O emissions. Generally, soil N_2O emission rates reached the peak when soil water-filled pore space (WFPS) was 60–70% [25]. For example, soil N_2O 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_2O emissions were more complex than that of soil moisture. For example, warming increased soil N_2O emissions from boreal peatland [27] and alpine meadow [28]. Soil N_2O emissions had an exponential increased relationship with incubation temperatures [29]. A significant positive correlation was presented in N_2O emissions and soil temperature from different soil types (paddy, orchard, forest, and mountain) [30]. Although warming did not affect soil N_2O emissions from northern peatlands, it suppressed N_2O emissions under N addition conditions [31]. By contrast, the effects of warming on soil N_2O emissions from alpine meadow soil were not observed [32]. Consistently, no significant increase of soil N_2O emissions was found with increasing incubation temperatures [33]. Previous study reported that soil moisture and temperature can explain 86% of soil N_2O emissions [34].

2.1.2.3 Soil O_2 concentration

Soil O_2 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_2 concentrations. Lower soil O_2 concentrations mainly promoted soil N_2O emissions via denitrification [20, 35]. The production of N_2O and NO was increased when O_2 concentration decreased from 21% to 0.5% in a laboratory study [36]. Similarly, field study reported that soil N_2O emissions increased with increasing soil O_2 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_2O emissions. However, other researchers reported that there was no significant correlation between N_2O emissions and pH [41].

pH influenced the activity of nitrification- and denitrification-related enzymes [42]. Generally, soil acidification increased N_2O 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_2O emissions were 92.14 ± 47.01 mg m^{-2} in control treatment and were 375.10 ± 60.30 mg m^{-2} in fertilization treatment (400 kg NH_4NO_3-N ha^{-1}) 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^{2+}, Mg^{2+}, K^+, and Na^+, reducing the soil pH buffering capacity. In addition, long-term precipitation promoted the accumulation of Al^{3+} and Fe^{3+} in soil, which could further hydrolyze to $Fe(OH)_3$ or $Al(OH)_3$ and release $3H^+$.

2.2.2 Plant physiology

When plant roots absorb a NH_4^+ from soil, an H^+ will release into soil; in turn, absorbing a NO_3^- from soil will release an OH^- into soil [53].

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

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

2.2.3 Microbial-mediated nitrification

For example, NH_4^+ transfers to NO_3^- along with the $2H^+$ release ($NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$) [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 FeS_2, will produce $2H^+$ ($2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$).

Oxidation of sulfur-containing organics will release $4H^+$ (2Organic-S + $3O_2$ + $2H_2O \rightarrow 2SO_4^{2-} + 4H^+$).

2.2.5 Intensive nitrogen fertilization

Intensive NH_4^+ input can replace the base cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+ and accelerate leaching, reducing the pH buffering capacity of top soil [59]. Hydrolysis of soil NH_4^+ will generate NH_3 (gas) and consume an OH^- ($NH_4^+ + OH^- = NH_3\uparrow + H_2O$) [60].

Acidic fertilizers such as $Ca(H_2PO_4)_2$ will gradually release H^+, hence increasing soil acidification ($Ca(H_2PO_4)_2 \rightarrow CaHPO_4 + H_3PO_4$, $H_3PO_4 \rightarrow H^+ + H_2PO_4 \rightarrow 2H^+ + HPO_4^{2-} \rightarrow 3H^+ + PO_4^{3-}$).

2.2.6 Acid deposition

Acid deposition (water-soluble acid gases such as CO_2 and sulfur dioxide) and N deposition (especially NH_4^+-N) increased soil acidification [51]. Precipitation with H^+ can replace the soil base cations such as Ca^{2+}, Mg^{2+}, K^+, and 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 Ca^{2+}, Mg^{2+}, K^+, and 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 kg Urea-N ha^{-1} 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 N_2O emissions and pH (3.34–8.7) ($N_2O\text{-}N = -0.67x + 6.55$, $R = 0.22$) is negatively related with N fertilization [9]. Moreover, deposition of sulfur dioxide increased soil acidification, stimulating soil N_2O emissions [64].

The mechanism of soil acidification on the stimulation of soil N_2O emissions is complex, which may include (but not limited to) the following points.

2.3.1 Chemical decomposition of nitrous acid

Under acidic conditions, pH < 5.5, NO_2^- (HNO_2, $pK_a = 3.3$) will naturally decompose into NO and/or NO_2 ($3HNO_2 \rightleftharpoons 2NO + HNO_3 + H_2O$ or $2HNO_2 \rightleftharpoons NO + NO_2 + H_2O$) [65]. Soil NO can be further transformed to N_2O with 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_2O emissions in acid soil [69, 70]. Additionally, fungi-mediated denitrification accounted for 70% soil N_2O emissions from a 100-year-old tea plantation (soil pH 3.8) [71].

In acid soils, the activity of N_2O reductase was inhibited, leading to higher N_2O 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 $N_2O/(N_2O + N_2)$ and soil pH [73]. In agreement, $N_2O/(N_2O + N_2)$ was negatively correlated with soil pH (3.7–8.0) (R^2 = 0.759, P < 0.001), and lime addition decreased $N_2O/(N_2O + N_2)$ [74]. The ratio of $N_2O/(N_2O + N_2)$ increased with decreasing pH (5.57–7.06) (R^2 = 0.82) [75]. Consistently, soil pH was negatively correlated with N_2O/N_2 [76]. Intensive management consistently decreased soil pH and increased the ratio of $N_2O/(N_2O + N_2)$ [77]. Increasing dolomite dosage increased soil pH and hence increased the transcription of *nosZ* genes and reduced the potential of N_2O production in acid soils [26].

2.3.3 Microbes increased resistance to soil acidification

Laboratory study showed that the potential of soil N_2O 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_2O 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_3^--N fertilization (50, 200, and 1000 mg kg^{-1}) from a 100-year-old tea plantation [79]. Field study found a negative correlation between soil N_2O emissions and pH (pH 3.6–5.9) ($N_2O\text{-}N = 636.6^* e^{-0.8028 * pH}$, 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_2O 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_2O 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^{3+} on plant growth by reducing soil exchangeable H^+ [81]. Lime addition increased soil pH and salt saturation [82]. In addition, application of lime can reduce soil N_2O emissions [40]. For example, under 60% WFPS or flooded conditions, dolomite addition at medium- or high-dose levels (1 or 2 g kg^{-1} soil) can reduce N_2O emissions and increase the transcription of *nosZ* genes ($N_2O \rightarrow N_2$) 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_2-C_{eq} yr^{-1} [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^{3+} 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_2O emissions [98]. However, the effects of biochar on soil N_2O emissions varied, including positive effects [99], negative effects [100], and no effects [101].

Biochar addition increased soil N_2O emissions with the release of N from biochar [102]. By contrast, biochar reduced soil N_2O emissions with (1) increased NO_3^--N immobilization [103]; (2) increased copy numbers of *nos*Z 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 riches in oxygen-containing functional groups in surface. The anions of weakly acidic functional groups can associate with H^+, 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 $H_3SiO_4^-$ (present at a high pH) can combine with H^+ and generate H_2SiO_3 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 (NH_4^+-N → NH_2OH). 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 NO_3^--N (the end product of nitrification) easily can be leached to groundwater by precipitation. In addition, microbial-mediated nitrification is closely related with soil N_2O emissions [20–22]. Nitrification inhibitors can effectively inhibit soil nitrification, slowing the transformation of NH_4^+-N to NO_3^--N and hence reducing the NO_3^--N leaching and N_2O emissions.

An evaluation from 62 field studies showed that although nitrification inhibitors increased 20% NH_3 emissions, they reduced 48% inorganic N leaching, 44% N_2O emissions, and 24% 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] N_2O emissions and decreased by 0.3 t CO_{2e} ha^{-1} yr^{-1} [119]. Similarly, DCD did not increase crop yields but reduced 35% N_2O emissions [120]. A meta-analysis showed that DCD rather than DMPP significantly increased 6.5% crop yield as well as DCD and DMPP decreased N_2O emissions by 44.7% and 47.6%, respectively [121].

Therefore, application of nitrification inhibitors could reduce N_2O 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

$$(NH_2)_2CO+2H_2O \xrightarrow{Urease} (NH_4)_2CO_3 = NH_4^+ + NH_3\uparrow + CO_2\uparrow + OH^-$$

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

of urea via inhibiting the activity of urease, hence reducing NH_3 volatilizations and N_2O emissions. Additionally, the application of urease inhibitors also contributes to increase N utilization efficiency and reduce 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 NH_3 and 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 NH_3 volatilizations and N input [123]. Application of NBPT can effectively inhibit NH_3 volatilizations. For example, 530 mg NBPT kg^{-1} urea treatment delayed NH_3 volatilizations and decreased accumulation of NH_3 volatilizations compared with the control treatment. NH_3 volatilizations were linearly related with the NBPT dosage in the range of 0–1000 mg NBPT kg^{-1} Urea (0, 530, 850, 1500, and 2000 mg NBPT kg^{-1} Urea) [124]. Other study reported that NBPT increased 27% oat yield and 33% crop N uptake [120].

The effects of NBPT on N_2O emissions were controversial. For example, NBPT can reduce 80% N_2O emissions [117]. No effects of NBPT (0.07%, NBPT/Urea-N, w/w) on N_2O emissions were observed [125]. Similarly, there was no change of N_2O emissions with NBPT (250 mg NBPT kg^{-1} Urea) addition from urea-fertilized (50 kg Urea-N ha^{-1}) soil [126].

Additionally, NBPT can reduce N_2O 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 N_2O emissions. Further laboratory study showed that NBPT inhibited nitrification, stimulating N_2O emissions from alkaline soils (pH 8.05) but not affecting N_2O emissions from acid soils (pH 4.85). This finding suggested that the effect of NBPT on soil N_2O emissions is not only influenced by pH but also by other unknown factors [127].

Generally, urease inhibitors correlated with nitrification inhibitor could mitigate N_2O emissions. A meta-analysis showed that urease inhibitors and nitrification inhibitors interactively reduced 30% N_2O 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 N_2O emissions with the addition of 519 kg Urea-N 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 N_2O emissions, DCD addition decreased soil N_2O emissions under urea fertilization from *C. oleifera* field [88]. Our field study showed that N_2O emission rates were inhibited by biochar or DCD application and the effects of biochar application on mitigation of cumulative N_2O were comparable to DCD addition in *C. oleifera* plantations [1]. Compared with control treatment, available N (NH_4^+-N and NO_3^--N) was not affected by NH_4NO_3, NH_4NO_3 + DCD, or NH_4NO_3 + biochar treatment [1]. In addition, the seed yield of *C. oleifera* was higher in NH_4NO_3 or NH_4NO_3 + biochar treatment than that in control or NH_4NO_3 + DCD treatment (**Figure 3**). Soil amelioration is necessary and improves N use efficiency and pH, mitigating N_2O emissions. Soil amelioration plays an important role in the sustainable management of oil safety in *C. oleifera* plantations.

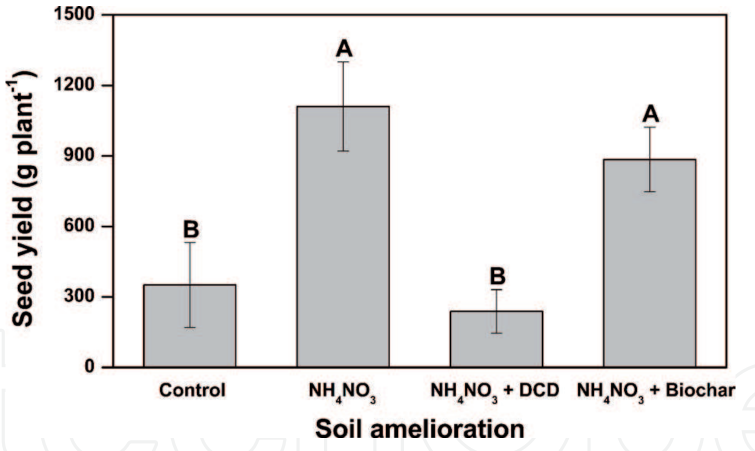

Figure 3.
The seed yield of Camellia oleifera *with nitrogen fertilization, in combination with nitrification inhibitor (DCD) or biochar. Bars connected by different letters indicate significant difference in post-hoc tests at* $\alpha = 0.05$ *(means ± se).*

5. Conclusions

Soil acidification, especially induced by N fertilization, will inhibit the activity of N_2O reductase and increase the abundance of N_2O-producing fungi as well as the acid resistance of N_2O-producing microorganisms, hence the ratio of $N_2O/(N_2O + N_2)$. In addition, NO_2^- will generate NO under soil pH < 5.5 condition, which will further transform into N_2O. Under the background of global acidification, the soil from *C. oleifera* forest also suffers the potential risks of soil acidification and N_2O emissions. Mitigation of soil acidification and N_2O 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.

Acknowledgements

The National Natural Science Foundation of China (grant number: 41967017 and 41501317), Jiangxi and China Postdoctoral Science Foundation (grant number: 2017M106153 and 2017KY18), and Jiangxi Education Department (Project Number: GJJ160348) support this work.

Conflict of interest

The authors declare no conflict of interest.

Author details

Bangliang Deng* and Ling Zhang
Key Laboratory of Silviculture, College of Forestry, Jiangxi Agricultural University, Nanchang, China

*Address all correspondence to: bangliangdeng@gmail.com

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 [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_2O and NH_3 emissions, fertilizer-^{15}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_2O): 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_2 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_2 and N_2O 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_2O) 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_2O 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_2O 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_2O 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_2 and N_2O 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_2O 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_2O 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_2, and N_2O 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_2O 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_2 controls denitrification rates and N_2O 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_2O and N_2 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_2O 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_2O). 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_2O 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*. Heifei: 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] Matschonat G, Matzner E. Soil chemical properties affecting 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 N_2O-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 NO and N_2O emissions from soils by 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: Micro-organisms 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, Klemedtsson L. Increased fungal dominance in N_2O 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_2O 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_2O 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_2O and N_2 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 $N_2O/(N_2O + N_2)$ 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_2O 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 $N_2O/(N_2 + N_2O)$ 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_2O 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_2O and CH_4 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_2 and N_2O 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_3 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_2O, CO_2, and CH_4 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_2O 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_2O and CO_2 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_2O emissions without affecting NH_3 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_2O 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-dimethypyrazole 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_2O 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_2O 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