Fingerprint natural soil N₂O emission from nitrification and denitrification by dual isotopes (¹⁵N and ¹⁸O) and site preferences

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Abstract: Nitrification and denitrification are the main contributors to soil N₂O production and emission, and distinguishing their contributions to N₂O emission under natural conditions is vital to deciphering nitrogen biogeochemistry. Stable isotopes have provided insight to resolve this problem, of which $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$ (¹⁵N abundance in N₂O), dual isotopes ($\delta^{15}\text{N}$, $\delta^{18}\text{O}$) and site preference (SP) are the most effective methods currently. $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$ is useful in tracing substrates yielding N₂O, but it is helpless to make accurate differentiation between nitrification and denitrification; The dual isotopes, $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$, introduce O atom sources in partitioning N₂O source and this method could roughly apportion N₂O from nitrification and denitrification. However, expensive equipment requirements and the inherent uncertainties on $\delta^{18}\text{O}$ determination owing to few data available hamper its accuracy and applicability on distinguishing nitrification and denitrification. Site preference (SP) provides new insight on distinguishing contribution of nitrification and denitrification on N₂O emission and results in more accuracy results. We summarized that the average values of $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$, $\delta^{18}\text{O}$ and SP during denitrification, which were -29.29‰, 19.78‰, and 2.43‰, respectively, are much lower than the corresponding values during nitrification, which were -7.87‰, 48.03‰ and 24.14‰, respectively.

Keywords: N₂O; Nitrification; Denitrification; $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$; $\delta^{18}\text{O}$; Site Preference

Introduction

Nitrous oxide (N₂O), a relatively stable greenhouse gas, has stronger warming potential than CO₂ and CH₄ (Mosier et al., 2006), and its long-term presence in atmosphere would exhaustively deplete O₃ by photochemical reaction and draw secondary harms to biosphere on earth (Rodhe, 1990). The preindustrial atmospheric N₂O content was 270 ng/L, but it has been increasing since 1750 at the rate of 0.2%~0.3%, and reached to 324 ng/L in 2011 (Muñoz et al., 2010; Syakila and Kroeze, 2011). If nothing is done to curb N₂O emission, atmospheric N₂O content is estimated to 350~400 ng/L in 2050, exceeding the current concentration by 83%, and N₂O would exert as the overwhelming O₃ consumer (Ravishankara et al., 2009). Soils are the largest contributors to N₂O emissions, with 6.0 Tg/a from natural soils and 4.2 Tg/a from agricultural soils (Chapuis-Lardy et al., 2007). Despite extensive studies on N₂O produced by nitrification and denitrification, apportionment of N₂O to these two routes is ambiguous.

Microorganism-induced nitrification and denitrification are the main processes yielding N₂O, representing 90% of the total N₂O in global atmosphere (Boer and Kowalchuk, 2001). N₂O is the precursor when N₂ produce is ascribed to nitrate denitrification, and is the

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intermediate during hydroxylamine oxidation (Skiba et al., 1993; Peng and Zhu, 2006) (Figure.1). Generally, aerobic condition facilitates nitrification and ammonia in this situation is easily converted into nitrate by oxidation, which include two stages. The first stage, ammonia is oxidized to nitrite and N_2O simultaneously by nitrite bacteria. The second stage, nitrite is shifted into nitrate by nitrobacteria. Denitrification is to reduce nitrate to N_2 and is regarded as the main soil N_2O source (Opdyke et al., 2009). Denitrification generally occurs under anaerobic conditions, and three models are involved: 1) is defined as denitrifier denitrification, that is to say that denitrifying bacteria successively reduce NO_3^- , NO_2^- , NO and N_2O to N_2 , and N_2O is the by-product and might emit out from soil; 2) is the aerobic denitrification by heterotrophic nitrifiers, namely that some heterotrophic nitrifiers like *Pseudomonas denitrificans* can induce both nitrification and denitrification under aerobic conditions, and N_2O is produced as intermediate or precursor; 3) is nitrifier-denitrification, means that ammonia or hydroxylamine is firstly oxidized into NO_2^- , with complicating reduce into NO , N_2O and N_2 in a gradient. Such nitrifiers are *Nitroso monaseuropaea*, *Nitrosospiramultiformis*, and *methylosinus trichosporium* (Sutka et al., 2006). Recently, some marine ammonia oxidizing archaea also could emulate the nitrifier-denitrification process (Santoro et al., 2011).

In this respect to N_2O yield in soil, many complex mechanisms are involved, and both nitrification or denitrification contribute to N_2O emission, which is concomitantly regulated by soil moisture (Maag and Vinther, 1996; Schindlbacher and Zechmeister-Boltenstern, 2004), oxidation reduction potential (Hou et al., 2000; Yu et al., 2001), microbial communities and activities (Firestone and Davidson, 1989; Conrad, 1996; Wunderlin et al., 2013), organic carbon amounts and qualities, nutrients (N, P, S) availability (Ma et al., 2007) and so on. Elusive shifting between nitrification and denitrification arise confusions on differentiating N_2O source in soil. Increasing atmospheric nitrogen deposition from fuel consumption and agriculture fertilization, in conjunction with climate change, has greatly changed global nitrogen biogeochemistry, motivated or impeded N_2O emission. So, it is obligate to establish the relative contribution of nitrification and denitrification to N_2O yield.

The conventional and traditional technologies are helpless in distinguishing contributions of nitrification from denitrification to soil N_2O fluxes. Some incubation employed inhibitor (acetylene) to eliminate influences of nitrification as much as possible (Felber et al., 2012; Menéndez et al., 2012). However, there are distinct interspaces. On one hand, there is no pure aerobic or anaerobic conditions allowing alternative nitrification or denitrification in natural conditions, and on the other hand, nitrification and denitrification often occur simultaneously and inter-shifting is ubiquitous. Soil environment in natural conditions are generally obviously derived from incubation experiments, drawing incomparable and questionable conclusions. Thereby, how to partition nitrification and denitrification contributions on N_2O yield under natural conditions is the pre-requisite to decipher nitrogen biogeochemistry, and stable isotopic technologies have provided promising approaches to enhance our knowledge on this item.

Fig.1 N_2O production in soils. I is the nitrification process, II is the nitrifier denitrification process; III is the typical denitrification process, and IV is the nitrate ammonification process. In I and II, O_2 or H_2O in the arc represent O atom input or output during nitrification and nitrifier denitrification processes.

1. $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$ fingerprint N_2O from different substances

Despite extensive studies on N_2O emission labeled by ^{15}N , it still proved difficult to quantify contribution of nitrification and denitrification on soil N_2O . One issue raised in previous work was that controlled soil conditions must be involved by regulating soil moisture or adding inhibitor when only ^{15}N abundance in N_2O bulk ($\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$) was used. Li et al. (2013) reported that, by signature forest and grassland soil using ^{15}N , both nitrification and denitrification contributed to soil N_2O emission under oxygen-abundant conditions, of which nitrification process was prevail and yielded about 53.1%~72.0% N_2O . $\delta^{15}\text{N}$ in different substrate, such as chemical fertilizer, natural soil, arable soil and manure (Figure 2), often differ greatly. During N_2O formation, bond energy depends on $^{15}\text{N}\text{-M}$ or $^{14}\text{N}\text{-M}$ (M is the iron connecting N atom) and thereby would induce variation of $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$ from different soil texture or matrix (Table 1), and $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$ is an effective indicator to fingerprint soil matrix. Nitrification and denitrification had different impacts on $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$. When NO_x is reduced, $^{14}\text{NO}_x$ would be preferentially reduced because of the $^{14}\text{N}\text{-O}$ bond is easily broken by less energy, inducing exhausted ^{15}N in N_2O produced (Sinder et al., 2009). However, apportion nitrification and denitrification on N_2O flux could not be carried out just depending on $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$ under natural conditions up to now.

Fig.2 $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ in different substrates. a, nitrate in rainfall; b, nitrate atmospheric deposition in virgin soil, c,

nitrate fertilizer; d, NH_4 in fertilizer and rain; e, Nitrogen in soil, f, animal waste.

Table 1 $\delta^{15}\text{N}^{\text{bulk}}$ of different soils*

Soil	$\delta^{15}\text{N}^{\text{bulk}}\text{-N}_2\text{O}$	Reference
Mature forest soil	-18.4±4.0‰	Park et al., 2011
Agriculture corn soil	-34.3±12.4‰	Park et al., 2011
Haplic Luvisol	-43.82±1.16	Well and Flessa, 2009
Gleyic Podzol	-40.01±1.76	Well and Flessa, 2009
Haplic Luvisol (fertilized)	-50.61±1.00	Well and Flessa, 2009
Gleyic Podzol (fertilized)	-47.53±0.86	Well and Flessa, 2009

*other data can be found in table 2.

2. Dual Isotopes Fingerprint of N_2O

One of the most obvious drawbacks using $\delta^{15}\text{N}^{\text{bulk}}$ to differentiate denitrification and nitrification contributions on N_2O emission is that it is inefficient to trace N_2O yield during nitrifier-denitrification processes. So, another important atom, oxygen, is taken into account to further fingerprint N_2O source, and it seemed as be a promising approach.

N_2O is the most important intermediate during nitrification and denitrification (Barford et al.1999, Well et al.2012). The dual isotopes of N_2O molecular, ^{15}N and ^{18}O , could impress N and O sources and abundance variation during N_2O formation, and then is able to distinguish nitrification from denitrification. O atom in N_2O molecular come from H_2O and soil air with different $\delta^{18}\text{O}$ abundance, which are +23.5‰ in soil air and -10‰ in soil H_2O (Baggs, 2008), and this provides the theoretical basis for dual isotopes fingerprint technology. During nitrification processes, O atoms come from both soil air and soil H_2O (Well et al., 2009), and $\delta^{18}\text{O}$ abundance in N_2O from nitrification occurring in aerobic environment ranked from +13‰ to +35‰ compared with VSMOW (Vienna Standard Mean Ocean Water), respectively (Sinder et al., 2012). This is also proved in N_2O from marine. Ammonia oxidation by ammonia oxidizing archaea (AOA) is the most important pathway for N_2O formation in marine, and $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ in N_2O from this process are much higher than those from N_2O produced by ammonia oxidizing bacteria (AOB). However, in spite of the different biological mechanisms for N_2O , O atoms in N_2O formed in the two processes mentioned above are resemble, of which water and air supply 50% of total O atoms, respectively (Santoro et al., 2011; Andersson and Hooper, 1983) (Figure 2). For denitrification, $\delta^{18}\text{O}$ in N_2O formed are generally much lower than that in soil NO_3^- , indicating that most O in N_2O come from soil H_2O during NO_3^- reduction into N_2O (Well and Flessa, 2009). However, there is still some elusive inconformity between different researches. Frame et al (2010) reported that O atom of N_2O from NH_2OH oxidation just originates from soil air, and O atom of N_2O from nitrifier-denitrification process or denitrification provoked by heterotrophic organisms rooting from both soil H_2O and air, and $\delta^{18}\text{O}$ in N_2O mostly depends on $\delta^{18}\text{O}$ in NO_2^- , a precursor molecule of N_2O . Under anaerobic conditions, O atom source of N_2O differ greatly among ecosystems. Incubation experiments implied that soil water contribute about 86%~96% O atoms in upland soils while 64%~70% in wetland soils when N_2O emission rates increases with soil temperature and moisture rising (Snider et al., 2009), and ^{15}N and ^{18}O would enrich in the residual N_2O during the concomitant reduction of N_2O to N_2 , which might be attributed

to the smaller energy requirements to break $^{14}\text{N-O}$ bond of N_2O .

In laboratory incubation experiments, dual isotopes technology could roughly but quantitatively apportion different sources of N_2O . For example, when marine- β -proteo bacterium from marine sediments is cultured under different O_2 contents, denitrification contribute about 11%~26% of total N_2O when O_2 levels are 20%~43%, and denitrification processes produce most, about 87%, N_2O when O_2 levels reduced to 0.5% (Frame et al., 2010). Wrage et al (2005) reported nitrifier-denitrification processes yield about 44% N_2O by dual isotope, showing a good agreement with previous results, which was 40% by adding inhibitor method. However, dual isotope technology require expensive equipment and truly delicate operation, which have hinder its practicability, and still few $\delta^{18}\text{O}$ data is available during N_2O formation, which hamper its widespread use (Park et al., 2011).

3. The intramolecular ^{15}N -site preference: a promising tool for attribution quantification

Though dual isotope method provide a glimpse into quantitatively apportioning contributions of denitrification and nitrification on soil N_2O emission, its application is hindered by the low accuracy and great-variable but few available $\delta^{18}\text{O}$ data (Reinhard et al., 2012). Benefit from deciphering on N_2O molecular structure and new determination technology, the intramolecular ^{15}N -site preference (SP), a new but effective parameter, is promising for quantifying contributions of nitrification and denitrification on N_2O formation (Koba et al., 2009).

N_2O molecular is asymmetric but line structure, and it expands the concept of "isotope" ratios into "isotopomer" ratios, and yields information independent of conventional nitrogen isotope ratios (Baggs, 2005). In N_2O molecular, two nitrogen atoms connect together and the second N atom connect with O atom, and the middle atom in the line might ^{14}N or ^{15}N . SP is termed as the difference in $\delta^{15}\text{N}$ between the central and outer N atoms. It can be sued to determine the relative importance of the system, as different microbial processes and functional groups have been shown to have distinct SP values (Baggs, 2005, Meijide et al., 2010). The formula is as below. Isotopomer ratios determination principles are shown in Figure 3.

$$\begin{aligned}\delta^{15}\text{N}^{\alpha} &= ^{14}\text{N}^{15}\text{NO}/^{14}\text{N}^{14}\text{O} \\ \delta^{15}\text{N}^{\beta} &= ^{15}\text{N}^{14}\text{NO}/^{14}\text{N}^{14}\text{NO} \\ \text{SP} &= \delta^{15}\text{N}^{\alpha} - \delta^{15}\text{N}^{\beta}\end{aligned}$$

Fig. 3 Schematic diagram of the measurement of N_2O isotopomers on a mass spectrometer. IC, ionization chamber; C, cathode; ET, electron trap; EP, extraction plate; AN, analyzer; MC, multi-collector system. (Toyoda et al., 1999)

Different energy is required to form $^{14}N-O$ and $^{15}N-O$ chemical bond, which leads to ^{15}N enrichment in central (α) or outer (β) position. Denitrification induces ^{15}N concentrating in α position while nitrification have little influence on ^{15}N distribution in α or β position (Toyoda and Yoshida, 1999), so ^{15}N enrichment in α position implies prevailed denitrification while low SP values (about 0‰) indicate nitrification dominance (Alyson et al., 2011). During ammonia oxidation, there are two same substrate-derived precursors before N_2O formation, which are NH_2OH and NO_2^- . SP value of N_2O from NH_2OH nitrification was 33.5‰, and SP value would reduce to -0.8‰ during the denitrification of $NO_2^- \rightarrow N_2O$ (Sutka et al., 2003, 2004, and 2006). When oxygen supply is poor, SP values would reduce to -2.1‰ from 7.5‰ with proceeding denitrification; when N_2O is further reduced to N_2 , SP values would rise and reach to the peak, 8.6‰, which is homologous to the highest N_2 formation rates (Reinhard et al., 2012). Significant positive relationships are often observed between $\delta^{18}O$ and $\delta^{15}N^\alpha$ while relation between $\delta^{18}O$ and $\delta^{15}N^\beta$ is weak (Park et al., 2011), and this is the sentinel of the N_2O reduction to N_2 (Meijide, et al., 2010).

Based on isotope mixing model and responding SP values of denitrification and nitrification, it is easy to evaluate contributions of nitrification and denitrification on N_2O emission in natural conditions. Empirical SP values of nitrification and denitrification were +33‰ and 0‰, respectively (Koba et al., 2009), but SP values of denitrification often are with great variation (Sutka et al., 2003). In tropical forest, SP values confirmed that 19% contribution was from nitrification and 51% from denitrification. But in anaerobic conditions, nitrification-originated N_2O just occupies 3.2% while denitrification accounts for 94.3% of the total N_2O (Koba et al., 2009). In arable soils, soil texture and fertilizer types play important roles in N_2O apportion to nitrification (40%~70%) and denitrification (50%~90%).

One issue raised in previous work was that empirical values of $\delta^{15}N_2O^{bulk}$, $\delta^{18}O$ and SP are

often confused and questionable, and it is vital to summarize these values according to the current literatures so as to better the evaluation accuracy. By reviewing literatures, we conclude that average values of $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$, $\delta^{18}\text{O}$ and SP during denitrification, which were -29.29‰, 19.78‰, and 2.43‰, respectively, are much lower than the corresponding values during nitrification, which were -7.87‰, 48.03‰ and 24.14‰, respectively (Table 2 and Figure 4).

Fig.4 Empirical values of $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$, $\delta^{18}\text{O}$ and SP

4. Future Considerations

Baggs (2005) has compared the benefits and drawbacks of these three methods mentioned above and concluded that current technology was not sufficient to realize quantitatively distinguish denitrification and nitrification for N_2O emission. In fact, this topic is now in tough and dilemma. Most parameters to differentiate nitrification and denitrification come from laboratory incubation, by creating the pure anaerobic or aerobic environment to inhibit even to eliminate nitrification or denitrification. But, in the field, environment is complex, different from incubation conditions, and N_2O formation is regulated by multiple factors, thereby, these empirical values for $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$, $\delta^{18}\text{O}$ and SP are different with those in natural conditions, and would lead to some deviation when applied. On the other hand, if we determine directly the $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$, $\delta^{18}\text{O}$ and SP values on natural conditions, the reference values we got are the mixing results of nitrification and denitrification, and the nitrifier-denitrification process has great interferences on results' accuracies. So, in the coming future, technology development might benefit the complicated problem, or we should try to find another distinguishing index.

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Table 2 $\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$, $\delta^{18}\text{O}$ and SP values from different research

Bacteria Species/ soil	$\delta^{15}\text{N}_2\text{O}^{\text{bulk}}$	$\delta^{18}\text{O}$	SP‰	Systems	Processes	Ref.
<i>Pseudomonas fluorescens</i>	-22.3	15.7-55.9	23.3±4.2	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Toyoda et al., 2005
<i>Methylococcus capsulatus</i>	-2.6-1.8(0.8±1.2)	53.9-61.3(57.3±2.9)	19.7-40.0(30.8±5.9)	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2004
<i>Nitrosomonas europaea</i>	-37.4--19.7(-28.6±6.0)	19.3-37.8(26.5±6.3)	9.2-21.1(14.9±3.7)	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2004
<i>Ammonia Oxidation Bacteria</i>	-	-	30-36	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Wunderlin et al., 2013
<i>Nitrosomonas europaea</i>	-0.3±4.9	38.8±2.9	33.5±1.2	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2006
<i>Nitrospirillum multififormis</i>	-0.3±2.9	38.6±2.5	32.5±0.6	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2006
<i>Methylosinus trichosporium</i>	3.4±1.9	39.7±4.0	35.6±1.4	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2006
<i>N. europaea</i>	-	-	31.4	$\text{NH}_3 \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2006
<i>N. europaea</i>	-	-	14.9	$\text{NH}_2\text{OH} \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2003
<i>M. capsulatus</i>	-	-	30.8	$\text{NH}_2\text{OH} \rightarrow \text{N}_2\text{O}$	Nitrification	Sutka et al., 2003
<i>M. Capsulatus</i>	-	-	5.5	unkonwn	Nitrification	Sutka et al., 2003
<i>N. europaea</i>	-	-	-2.3	unkonwn	Nitrification	Sutka et al., 2003
Arable soil	-	-	9.4	unkonwn	Denitrification	Park et al., 2011
<i>P. fluorescens</i>	-	-	23.3	unkonwn	Denitrification	Toyoda et al., 2005
<i>P. denitrificans</i>	-	-	-5.1	unkonwn	Denitrification	Toyoda et al., 2005
<i>Paracoccus denitrificans</i>	-12.3	27.9-46.5	-5.1±1.8	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Toyoda et al., 2005
<i>Paracoccus denitrificans</i>	(0.08±3.1)	-	-	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Barfod, 1999
<i>Nitrosomonas europaea</i>	-38.4--30.3(-34.0±2.7)	7.3-12.2(8.8±1.4)	-8.7-8.5(-0.8±5.8)	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2004
Soil denitrifiers	-7.1	-		$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sinder et al., 2009
<i>Nitrospirillum multififormis</i>	-22.9±0.6	10.8±0.5	0.1±1.7	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>Pseudomonas chlororaphis</i>	-	-	-0.6	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>Pseudomonas aureofaciens</i>	-	-	-0.5	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>N. europaea</i>			-0.8	$\text{NO}_2 \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2004

unknown	-43.82	13.77	3.14	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Well and Flessa, 2009
unknown	-40.01	21.09	8.86	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Well and Flessa, 2009
unknown	-50.61	17.48	4.84	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Well and Flessa, 2009
unknown	-47.53	20.95	8	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Well and Flessa, 2009
Tropical forest soil	-	-	-18.6	Unknown	Denitrification	Park et al., 2011
Arable soil	-	-	37	Nitrification	Denitrification	Opdyke et al., 2009
<i>N. europaea</i>	-	-	-8.3	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2003
<i>N. multiformis</i>	-	-	0.1	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>P. chloroaphis</i>	-	-	-0.5	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>P. aureofaciens</i>	-	-	-0.5	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>P. chloroaphis</i>	-	-	-0.6	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006
<i>P. aureofaciens</i>	-	-	-0.5	$\text{NO}_3^- \rightarrow \text{N}_2\text{O}$	Denitrification	Sutka et al., 2006