Use and abuse of potential rates in soil microbiology

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Abstract

Potential rate assays are used in soil microbial ecology to determine the maximum rate of a functional process in environmental samples. They assume that all contributing organisms in a community are active at a maximum rate under one set of 'optimal' incubation conditions. Potential rates are then often compared to the abundance of specific taxonomic groups to infer their relative contribution *in situ*. However, while investigators now recognise that populations within communities are physiologically diverse, they often ignore the consequent suboptimal activity, or even inactivity, of the majority of community members performing that function. In this short perspective article, we highlight the underlying conceptual problems associated with potential assays and use potential nitrification rate (PNR) as an example. PNR was originally developed to estimate the size of active ammonia oxidising communities in environmental samples. They are routinely performed in short-term shaken slurry incubations by measuring assumed maximum rates of nitrate or nitrite production under optimal, non-substrate-limiting conditions. As with other functional processes, it is now recognised that a broad diversity of organisms contribute to aerobic ammonia oxidation in terrestrial and other habitats, and this diversity represents a substantial range of physiologies, including variation in substrate affinity, ammonia tolerance, cell specific activity and substrate preference. Despite this, PNR is routinely used in an attempt to determine an ecologically relevant measurement of nitrification activity in soil. As with other potential assays, PNR has inherent biases towards particular functional groups and its use in investigating the ecology of ammonia oxidisers in natural systems is severely restricted.

Main text

Measurement of the potential rate of microbially mediated soil processes has a long tradition. Commonly used examples are measurement of potential nitrification and denitrification rates and substrate-induced respiration. All aim to determine process rate, usually after addition of a relevant substrate, under what are considered to be optimal conditions that enable all organisms capable of performing the process to operate with maximum activity and/or specific growth rate. Potential rate obviously differs from 'actual' process rate, operating under non-optimal environmental conditions, although actual rates are required for most ecological questions. Potential process rates may have some value, and have traditionally been used, in the absence of alternatives, to estimate the biomass (or, less justifiably, abundance) of a functional microbial group. However, the assumptions underlying measurement of potential rate are rarely considered, rarely obeyed and even more rarely tested and have been increasingly challenged

as our understanding of the composition and diversity of microbial communities in natural environments has increased. The limitations and relevance of potential rate measurements in microbial ecology are illustrated below for soil nitrification, but apply equally to other processes, functional groups and ecosystems.

Potential nitrification rate

Nitrification is the sequential oxidation of ammonia (NH_3) to nitrite (NO_2^-) and nitrate (NO_3^-) and is an essential component of reactive nitrogen transformation in soil. While nitrite can accumulate in soil (Giguere et al., 2017; Ma et al., 2015; Taylor et al., 2019; Venterea and Rolston, 2000), particularly after N deposition (Venterea et al., 2020), ammonia oxidation is often assumed to be the rate-limiting step. As a consequence, the activity, diversity and community structure of ammonia oxidisers (AO) receives greatest attention with respect to understanding environmental factors that influence microbially-mediated nitrification. Potential nitrification rate (PNR) assays (also referred to as potential nitrification activity (PNA)) have been used for many decades as a rapid method for estimating net ammonia oxidation (≈nitrification) rates in soils.

While a range of PNR assays have been used, the most common approach is the shaken soil-slurry method (Hart et al., 1994). This typically involves incubation of a suspension of sieved soil in a solution containing NH_4^+, at non-limiting concentration, in a shaken flask, ensuring aeration and mixing, at an incubation temperature that is considered to be optimal. PNR is calculated as the gradient of the linear increase in nitrate concentration in samples taken regularly during a relatively short incubation period (often ≤24 h) (Belser and Mays, 1980; Hart et al., 1994). A potassium phosphate buffer, typically between pH 7.0 and 7.5, can be included in the assay solution, with the intention of optimizing pH for AO. Chlorate, an inhibitor of nitrite oxidation, is also commonly included and NO_2^- rather than NO_3^- is measured in each slurry sample (Belser and Mays, 1980). Growth is assumed to be negligible; hence the assumption of a linear, rather an exponential increase in nitrite or nitrate concentration. PNR therefore measures the activity of the community and not specific growth rate. Linear kinetics are often not tested and it is not unusual for calculations to be based on nitrate concentrations measured only at the beginning and end of incubation or even using just the final value. Any growth, or other divergence from linear kinetics, invalidates calculation of a 'constant' PNR.

Employment of 'ideal' or 'optimal' conditions attempts to ensure that all AO within the sample are active, which is further encouraged by addition of substrate (NH_4^+). The assumption of universal activity was implicit in the traditional use of PNR to estimate AO abundance in

soil. This assumption was always seen as a major limitation of this approach (Woldendrop and Laanbroek, 1989; Hart et al., 1994), particularly given the low growth rates of ammonia oxidisers. (The only alternative was use of the most probable number method, which also relies on incubation of dilutions of soil suspensions under 'ideal' conditions and similar assumptions.)

Physiological diversity of ammonia oxidisers challenges underlying assumptions of PNR

For more than a century, ammonia oxidation was thought to be performed mainly by ammonia oxidising bacteria (AOB) (Prosser and Nicol, 2012). The past 25 years have, however, demonstrated considerable phylogenetic diversity within AOB and also the capacity for ammonia oxidation by ammonia oxidising archaea (AOA) (Könneke et al., 2005) and complete ammonia oxidizers (comammox) of the genus *Nitrospira* (Daims et al., 2015; van Kessel et al., 2015). Evidence from both cultivation-based and ecological studies also provides evidence for substantial physiological diversity in AO. Physiological diversity of cultivated AOB is well established and was used for traditional classification of these organisms (Prosser 1989; Koops et al., 2003). Since the first isolation of the ammonia oxidising archaeon (AOA) *Nitrosopumilus maritimus* (Könneke et al., 2015), several enrichments and isolates of soil AOA have also been obtained. These include, for example, the neutrophile *Nitrososphaera viennensis* EN76 (Tourna *et al.* 2011) and the obligate acidophile *Candidatus* Nitrosotalea devanaterra ND1 (Lehtovirta-Morley *et al*., 2011). In addition, comammox *Nitrospira* are abundant and contribute to ammonia oxidation in soil (Pjevac et al., 2017; Wang et al., 2019a), and a gammaproteobacterial AOB (*Candidatus* Nitrosoglobus terrae) was isolated recently (Hayatsu *et al.*, 2017). This taxonomic diversity is reflected in ecophysiological diversity and the maximum specific growth rate, cell specific activity, inhibitory ammonia and nitrite concentrations and affinity for ammonia of AO all vary by over an order of magnitude among different soil isolates, both within and between the major ammonia oxidiser groups (summarised in Lehtovirta-Morley et al., 2016). In addition, many AO are inhibited by NO_2^-, which accumulates when chlorate is used to inhibit nitrite oxidisers, thereby reducing PNR depending on community composition. Thus, even if the incubation conditions (temperature, pH, oxygen concentration) are appropriate for all AO, the PNR will represent only an aggregate of a wide range of cell activities and will vary with community composition and not just abundance.

Physiological diversity does, however, also mean that incubation conditions required for activity of all AO will not be identical. Cultivation-based studies have demonstrated significant differences in effects of temperature (Jiang and Bakken, 1999; Tourna et al., 2011; Lehtovirta-Morley et al., 2014), pH (Allison and Prosser, 1991; Lehtovirta-Morley et al., 2011)

and salinity (Mosier et al., 2012; Qin et al., 2014; Bello et al., 2019). Similar evidence of physiological diversity is provided by ecological studies (Nicol et al., 2008; Ollivier et al., 2012; Gubry-Rangin et al., 2017; Nacke et al., 2017; Taylor et al., 2017; Lu et al. 2018) and the ubiquity of AO in the full range of soils, in itself, is evidence that a single set of incubation conditions will be insufficient. For example, ammonia supply is an important factor influencing niche differentiation between AOA and AOB populations in soil. AOB often dominate growth at higher concentrations of added inorganic ammonium (e.g. Jia and Conrad, 2009; Xia et al., 2011; Hink et al., 2017), while AOA appear to prefer ammonium that is derived from a mineralised organic N source, i.e. that is part of the native organic component of the soil or added organic N (Levičnik-Höfferle et al., 2012; Hink et al., 2018). In low pH soils, AOA make a greater relative contribution to ammonia oxidation under specific incubation conditions (Gubry-Rangin et al., 2010; Zhang et al., 2012) and, as such, a decreasing proportion of the ammonia oxidising community may preferentially oxidise added inorganic N with decreasing soil pH.

It is therefore impossible to identify incubation conditions that will be 'ideal' for all organisms and the majority of AO will have sub-optimal or no activity and will not contribute to measured PNR. To this must be added the assumption that ammonia available and oxidised in PNR assays will also be available for the same populations in soil.

Potential nitrification rate does not reflect ammonia oxidiser activity in situ

The consequences of these limitations can be seen when correlations are determined between published PNR for soils and sediments and AOA and AOB abundances (using *amoA* gene abundance as a proxy for cell abundance). Results are highly variable. Of 108 studies published from 2007 to 2020 (Supplementary Table 1), only 36% and 75% reported a significant positive correlation between PNR and AOA or AOB abundances, respectively (Figure 1). Ten percent and 46% report a positive correlation with only AOA or only AOB, respectively, 11% correlated with neither and 4% and 5% reported a negative correlation with AOA and AOB, respectively. No correlation has yet been observed between PNR and comammox bacteria (Wang *et al*. 2019b; Luchibia *et al*. 2020; Zhang *et al.*, 2020). While these studies suggest that some populations of AOA are using added ammonium, the majority of studies indicate that only ammonia oxidising bacteria (AOB) contribute to PNR, often leading to the conclusion that AOA are not contributing to ammonia oxidation in a soil *in situ*. If we consider the growth characteristics of AO in both culture and soil, it is evident that correlating results from a single

defined assay with the abundance of communities containing substantial physiological diversity is unlikely to be meaningful and likely to be misleading.

The observed dominance of AOB over AOA in contributing to PNR activity in many soils may reflect differences in their ability to utilise added inorganic nitrogen. To investigate this, soil was sampled across a pH 4.5 to 7.5 gradient that has been fully characterised with respect to AOA and AOB community structure and abundance (Aigle et al., 2019; Gubry-Rangin et al. 2011), where *amoA* transcript and gene abundance of AOA and AOB decrease and increase directly with soil pH, respectively (Prosser and Nicol, 2012). PNR assays were established with both standard 1 mM phosphate buffered and unbuffered 1.5 mM NH_4^+ solution, and parallel incubations were performed in the presence of alkynes to differentiate contributions of all AO, AOA and AOB. Acetylene (C_2H_2) has been extensively used as an inhibitor of all ammonia oxidisers that possess ammonia monooxygenase (AMO) and 1-octyne (C_8H_2) inhibits growth of AOB, but not AOA, in both culture and soil (Taylor et al., 2013). Nitrate accumulation during incubation for 24 h was used to calculate PNR, which increased directly with soil pH across the gradient (Figure 2). However, as this activity was completely inhibited in the presence of both C_8H_2, and C_2H_2, it was attributed solely to AOB. This provides strong evidence that AOA do not contribute to PNR in some soils, PNR severely underestimates their abundance and this prevents any meaningful interpretation of their abundance or actual activity in soil at the time of sampling.

As indicated above, the source of ammonium is also an important factor in defining the ecological niches of AO populations within a community. Using concentrations typical of fertilisation application rates, we compared nitrification activity in both pH 4.5 and 7.5 soil microcosms after the addition of ammonium nitrate or urea (which is fully mineralised to ammonium within 0.5 days). After near stoichiometric conversion of ammonium to nitrate over 12 days, inorganic and urea-derived ammonium were oxidised at comparable rates for both 100 and 200 µg N g^{-1} dry soil applications in the pH 7.5 soil (Figure 3). In contrast, urea-derived ammonium was oxidised at a faster rate in the pH 4.5 soil, and ammonia oxidation was inhibited by application of 200 µg inorganic N g^{-1} dry soil (Figure 3). While these data do not differentiate the contribution of different AO groups, they reveal that sources of N other than inorganic NH_4^+, as used in PNR, are preferred by some AO populations, again preventing meaningful interpretation of PNR data.

Despite the major limitations discussed above, potential process rates are still frequently used in attempting to address ecological questions. Again, nitrification studies illustrate their lack of usefulness. Attempts to understand the relative contribution of AOA and AOB to

nitrification involve correlation of their abundances with PNR, often after a treatment or perturbation (e.g. fertiliser application or temperature change) (Supplementary Table 1). This approach is also used to study niche specialisation, which implicitly assumes that changes in relative abundance of different phylotypes will result from differences in activity under different conditions. Incubation conditions used to measure PNR will favour different members of the AOA and AOB communities and will differentially influence activities of AOA and AOB. It will therefore not be possible to determine whether relationships between abundance and PNR are due to differences in preferences of the different communities for the specific incubation conditions used or due to links between abundance and actual activity. A more fundamental issue is the assumption, implicit in niche specialisation, that changes in community composition result from differences in actual activity, determined by different *in situ*, environmental conditions and do not depend on potential activity under a single set of laboratory conditions.

The limitations of potential assays should discourage their use

PNR does not characterise the contribution of AO to nitrification in soil and knowledge of the diversity of AO physiology and factors controlling their growth clearly challenges a long-established assumption that a single incubation assay measures the activity of all AO. Critically, potential rates also have little relevance to actual rates *in situ* and therefore have limited meaning in most nitrification studies. These fundamental and significant limitations should discourage the use of PNR and apply equally to other potential assays. Our expanding knowledge of the vast diversity and composition of microbial communities in natural environments, emphasises that communities contributing to a functional process comprise a diverse array of ecophysiologies with substantial niche differentiation between populations. This challenges the underlying assumptions in potential rate measurements and severely restricts their relevance and value in studying soil microbial ecology.

References

Aigle, A., Prosser, J.I., Gubry-Rangin, C., 2019. The application of high-throughput sequencing technology to analysis of *amoA* phylogeny and environmental niche specialisation of terrestrial bacterial ammonia-oxidisers. Environmental Microbiome 14, 3.

Allison, S.M., Prosser, J.I., 1991. Urease activity in neutrophilic autotrophic ammonia-oxidizing bacteria isolated from acid soils. Soil Biology and Biochemistry 23, 45–51.

Bello, M., Thion, C., Gubry-Rangin, C., Prosser, J.I., 2019. Differential sensitivity of ammonia oxidising archaea and bacteria to matric and osmotic potential. Soil Biology and Biochemistry 129, 184-190.

Belser, L.W., Mays, E.L., 1980. Specific inhibition of nitrite oxidation by chlorate and its use in assessing nitrification in soils and sediments. Applied and Environmental Microbiology 39, 505-510.

Daims, H., Lebedeva, E.V., Pjevac, P., Han, P., Herbold, C., Albertsen, M., Jehmlich, N., Palatinszky, M., Vierheilig, J., Bulaev, A., Kirkegaard, R.H., von Bergen, M., Rattei, T., Bendinger, B., Nielsen, P.H., Wagner, M., 2015. Complete nitrification by *Nitrospira* bacteria. Nature 528, 504–509.

Giguere, A.T., Taylor, A.E., Suwa, Y., Myrold, D.D., Bottomley, P.J., 2017. Uncoupling of ammonia oxidation from nitrite oxidation: Impact upon nitrous oxide production in non-cropped Oregon soils. Soil Biology and Biochemistry 104, 30-38.

Gubry-Rangin, C., Hai, B., Quince, C., Engel, M., Thomson, B.C., James, P., Schloter, M., Griffiths, R.I., Prosser, J.I., Nicol, G.W., 2011. Niche specialization of terrestrial archaeal ammonia oxidizers. Proceedings of the National Academy of Sciences 108, 21206–21211.

Gubry-Rangin, C., Nicol, G.W., Prosser, J.I., 2010. Archaea rather than bacteria control nitrification in two agricultural acidic soils. FEMS Microbiology Ecology 74, 566–574.

Gubry-Rangin, C., Novotnik, B., Mandič-Mulec, I., Nicol, G.W., Prosser, J.I., 2017. Temperature responses of soil ammonia-oxidising archaea depend on pH. Soil Biology and Biochemistry 106, 61–68.

Hart, S.C., Stark, J.M., Davidson, E.A., Firestone, M.K., 1994. Nitrogen mineralization, immobilisation and nitrification. In: Weaver, R.W., Angle, J.S., Bottomley, P.S. (Eds.), Methods of Soil Analysis. Part 2. Microbial and Biogeochemical Properties. Soil Science Society of America, Madison, pp. 985-1018.

Hayatsu, M., Tago, K., Uchiyama, I., Toyoda, A., Wang, Y., Shimomura, Y., Okubo, T., Kurisu, F., Hirono, Y., Nonaka, K., Akiyama, H., Itoh, T., Takami, H., 2017. An acid- tolerant ammonia-oxidizing γ-proteobacterium from soil. The ISME Journal 11, 1130–1141.

Hink, L., Gubry-Rangin, C., Nicol, G.W., Prosser, J.I., 2018. The consequences of niche and physiological differentiation of archaeal and bacterial ammonia oxidisers for nitrous oxide emissions. The ISME Journal 12, 1084–1093.

Hink, L., Nicol, G.W., Prosser, J.I., 2017. Archaea produce lower yields of N_2O than bacteria during aerobic ammonia oxidation in soil. Environmental Microbiology 19, 4829-4837.

Jia, Z., Conrad, R., 2009. Bacteria rather than Archaea dominate microbial ammonia oxidation in an agricultural soil. Environmental Microbiology 11, 1658–1671.

Jiang, Q.Q., Bakken, L.R., 1999. Comparison of *Nitrosospira* strains isolated from terrestrial environments. FEMS Microbiology Ecology 30, 171-186.

Könneke, M., Bernhard, A.E., de la Torre, J.R., Walker, C.B., Waterbury, J.B., Stahl, D.A., 2005. Isolation of an autotrophic ammonia-oxidizing marine archaeon. Nature 437, 543–546.

Koops H.-P., Purkhold U., Pommerening-Röser A., Timmermann G., Wagner M., 2003. The Lithoautotrophic Ammonia-Oxidizing Bacteria. In: Dworkin M., Falkow S., Rosenberg E., Schleifer, K.H., Stackebrandt, E. (eds) The Prokaryotes. Springer, New York, NY.

Lehtovirta-Morley, L.E., Ge, C., Ross, J., Yao, H., Nicol, G.W., Prosser, J.I., 2014. Characterisation of terrestrial acidophilic archaeal ammonia oxidisers and their inhibition and stimulation by organic compounds. FEMS Microbiology Ecology 89, 542-552.

Lehtovirta-Morley, L.E., Ross, J., Hink, L., Weber, E.B., Gubry-Rangin, C., Thion, C., Prosser, J.I., Nicol, G.W., 2016. Isolation of "*Candidatus* Nitrosocosmicus franklandus", a novel ureolytic soil archaeal ammonia oxidiser with tolerance to high ammonia concentration. FEMS Microbiology Ecology 92, fiw057.

Lehtovirta-Morley, L.E., Stoecker, K., Vilcinskas, A., Prosser, J.I., Nicol, G.W., 2011. Cultivation of an obligate acidophilic ammonia oxidizer from a nitrifying acid soil. Proceedings of the National Academy of Sciences 108, 15892–15897.

Levičnik-Höfferle, S., Nicol, G.W., Ausec, L., Mandic-Mulec, I., Prosser, J.I., 2012. Stimulation of thaumarchaeal ammonia oxidation by ammonia derived from organic nitrogen but not added inorganic nitrogen. FEMS Microbiology Ecology 80, 114–123.

Lu, X., Nicol, G.W., Neufeld, J.D., 2018. Differential responses of soil ammonia-oxidizing archaea and bacteria to temperature and depth under two different land uses. Soil Biology and Biochemistry 120, 272-282.

Luchibia, A.O., Lam, S.K., Chen, Q., O'Mara, B., He, J-Z., 2019. Effects of repeated applications of urea with DMPP on ammonia oxidizers, denitrifiers, and non-targeted microbial communities of an agriculture soil in Queensland, Australia. Applied Soil Ecology 147, 103392.

Ma, L., Shan, J., Yan, X.Y., 2015. Nitrite behavior accounts for the nitrous oxide peaks following fertilization in a fluvo-aquic soil. Biology and Fertility of Soils 51, 563-572.

Mosier, A.C., Lund, M.B., Francis, C.A., 2012. Ecophysiology of an ammonia-oxidizing archaeon adapted to low-salinity habitats. Microbial ecology 64, 955-963.

Nacke, H., Schöning, I., Schindler, M., Schrumpf, M., Daniel, R., Nicol, G.W., Prosser, J.I., 2017. Links between seawater flooding, soil ammonia oxidiser communities and their response to changes in salinity. FEMS Microbiology Ecology 93, fix144.

Nicol, G.W., Leininger, S., Schleper, C., Prosser, J.I., 2008. The influence of soil pH on the diversity, abundance and transcriptional activity of ammonia oxidizing archaea and bacteria. Environmental Microbiology 10, 2966–2978.

Ollivier, J., Wanat, N., Austruy, A., Hitmi, A., Joussein, E., Welzl, G., Munch, J.C., Schloter, M., 2012. Abundance and diversity of ammonia-oxidizing prokaryotes in the root-rhizosphere

complex of *Miscanthus* x *giganteus* grown in heavy metal-contaminated soils. Microbial Ecology 64, 1038-1046.

Pjevac, P., Schauberger, C., Poghosyan, L., Herbold, C.W., van Kessel, M.A.H.J., Daebeler, A., Steinberger, M., Jetten, M.S.M., Lücker, S., Wagner, M., Daims, H., 2017. *AmoA*-targeted polymerase chain reaction primers for the specific detection and quantification of comammox *Nitrospira* in the environment. Frontiers in Microbiology 8, 1508.

Prosser, J.I., 1989. Autotrophic nitrification in bacteria. Advances in Microbial Physiology 30, 125-181.

Prosser, J.I., Nicol, G.W., 2012. Archaeal and bacterial ammonia-oxidisers in soil: the quest for niche specialisation and differentiation. Trends in Microbiology 20, 523-531.

Qin, W., Amin, S.A., Martens-Habbena, W., Walker, C.B., Urakawa, H., Devol, A.H., Ingalls, A.E., Moffett, J.W., Armbrust, E.V., Stahl, D.A., 2014. Marine ammonia-oxidizing archaeal isolates display obligate mixotrophy and wide ecotypic variation. Proceedings of the National Academy of Sciences 34, 12504-12509.

Taylor, A.E., Giguere, A.T., Zoebelein, C.M., Myrold, D.D., Bottomley, P.J., 2017. Modeling of soil nitrification responses to temperature reveals thermodynamic differences between ammonia-oxidizing activity of archaea and bacteria. The ISME Journal 11, 896–908.

Taylor, A.E., Myrold, D.D., Bottomley, P.J., 2019. Temperature affects the kinetics of nitrite oxidation and nitrification coupling in four agricultural soils. Soil Biology and Biochemistry 136, 107523.

Taylor, A.E., Vajrala, N., Giguere, A.T., Gitelman, A.I., Arp, D.J., Myrold, D.D., Sayavedra-Soto, L., Bottomley, P.J., 2013. Use of aliphatic n-alkynes to discriminate soil nitrification activities of ammonia-oxidizing thaumarchaea and bacteria. Applied and Environmental Microbiology 79, 6544-6551.

Tourna, M., Stieglmeier, M., Spang, A., Konneke, M., Schintlmeister, A., Urich, T., Engel, M., Schloter, M., Wagner, M., Richter, A., Schleper, C., 2011. *Nitrososphaera viennensis*, an

ammonia oxidizing archaeon from soil. Proceedings of the National Academy of Sciences 108, 8420–8425.

van Kessel, M.A.H.J., Speth, D.R., Albertsen, M., Nielsen, P.H., Op den Camp, H.J.M., Kartal, B., Jetten, M.S.M., Lücker, S., 2015. Complete nitrification by a single microorganism. Nature 528, 555–559.

Venterea, R.T., Coulter, J.A., Clough, T.J., 2020. Nitrite accumulation and nitrogen gas production increase with decreasing temperature in urea-amended soils: Experiments and modeling. Soil Biology and Biochemistry 142, 10772.

Venterea, R.T., Rolston, D.E., 2000. Mechanisms and kinetics of nitric and nitrous oxide production during nitrification in agricultural soil. Global Change Biology 6, 303–316.

Wang, Z., Cao, Y., Zhu-Barker, X., Nicol, G.W., Wright, A.L., Jia, Z., Jiang, X., 2019a. Comammox *Nitrospira* clade B contributes to nitrification in soil. Soil Biology and Biochemistry 135, 392-395.

Wang, J., Wang, J., Rhodes, G., He, J-Z., Ge, Y., 2019b. Adaptive responses of comammox *Nitrospira* and canonical ammonia oxidizers to long-term fertilizations: Implications for the relative contribution of different ammonia oxidizers to soil nitrogen cycling. Science of the Total Environment 668, 224-233.

Woldendorp, J.W., Laanbroek, H.J., 1989. Activity of nitrifiers in relation to nitrogen nutrition of plants in natural ecosystems. Plant and Soil 115, 217-228.

Xia, W., Zhang, C., Zeng, X., Feng, Y., Weng, J., Lin, X., Zhu, J., Xiong, Z., Xu, J., Cai, Z., Jia, Z., 2011. Autotrophic growth of nitrifying community in an agricultural soil. The ISME Journal 5, 1226–1236.

Zhang, L.-M., Hu, H.-W., Shen, J.-P., He, J.-Z., 2012. Ammonia-oxidizing archaea have more important role than ammonia-oxidizing bacteria in ammonia oxidation of strongly acidic soils. The ISME Journal 6, 1032-1045.

Zhang, S., Qin, W., Xia, X., Xia, L., Li, S., Bai, Y., Wang, G., 2020. Ammonia oxidizers in river sediments of the Qinghai-Tibet Plateau and their adaptations to high-elevation conditions. Water Research 173, 115589.

Figures

Figure 1. Meta-analysis of soil and sediment studies finding significant positive correlations of ammonia oxidising archaea (AOA) and/or bacteria (AOB) abundances with potential nitrification rate (PNR). All studies used a shaken slurry method and measured NO_3^- or NO_2^- with the addition of chlorate to inhibit NO_2^- oxidation. A total of 108 studies were included (Supplementary Table S1).

Figure 2. Demonstration of only AOB contributing to PNR. Soils were sampled across a pH gradient and PNR determined using the shaken slurry method. Flasks were established in triplicate using 144 ml serum vial bottles with 6 g soil (dry weight equivalent) and 50 ml of 1.5 mM NH_4Cl, with or without 1 mM potassium phosphate (pH 7.2) buffer. A) Samples were taken after incubation for 0, 3, 6, 9, 12 and 24 h to determine nitrate concentrations (nitrite was not detected). Means (±SE) with different letters within a buffer treatment are significantly different based on Tukey's *post hoc* test following one-way ANOVA ($p<1.1 \times 10^{-7}$). Means annotated with a line are significantly different between buffer treatments based on two sample *t*-tests ($p>0.01<0.05$). B) Example of complete inhibition of nitrification activity in flasks incubated in the presence of 0.01% C_2H_2 or 0.03% C_8H_2 with pH 7.5 soil (unbuffered). Nitrification activity was not detected in any soil in the presence of either alkyne.

Figure 3. Nitrate (NO_3^-) production in soil microcosms amended with varying concentrations of ammonium sulphate or urea (0 – 200 ug N g^{-1} dry soil) in pH 7.5 and 4.5 soil (a) and b), respectively). Soil microcosms were prepared (in triplicate for each treatment and timepoint) with sterile 144 ml serum vial glass bottles using 10 g soil (dry weight equivalent) which was sampled at 0-10 cm depth and sieved (2 mm mesh size). Microcosms were incubated at 30°C for 12 days with 30% soil water content (w/w). Microcosms were aerated every 3 days and destructively sampled before extracting NO_3^- in a 1 M KCl solution. Nitrate concentration was determined colorimetrically following Hink et al. (2018) (nitrite concentrations were below the limit of detection. Error bars represent standard error of the mean. The greatest change in pH in soil microcosms was associated with those with the highest nitrification rates, indicating that pH change was not an inhibiting factor (Supplementary Figure 1). Nevertheless, these results highlight an additional concern, as changing conditions during incubation will influence activity and kinetics will no longer be linear.

Supplementary Figure 1. Soil pH in soil microcosms amended with varying concentrations of ammonium sulphate or urea (0 – 200 ug N g-1 dry soil) in pH 7.5 and 4.5 soil (a) and b), respectively). Error bars represent the standard error of the mean of triplicate microcosms.

Supplementary Table 1. Analysis of 108 studies correlating PNR with the abundance of AOA, AOB or comammox bacteria as (inferred from qPCR analysis of *amoA* gene abundance). Published studies were found with a SCOPUS search (TITLE-ABS-KEY ammonia AND oxidi* AND archaea AND bacteria AND potential AND nitrification) combined with manual refinement for only soil and sediment studies that used a shaken soil-slurry method. Publications are grouped by soil or sediment and NO_2^- or NO_3^- measured as the end product.

Figure 1.

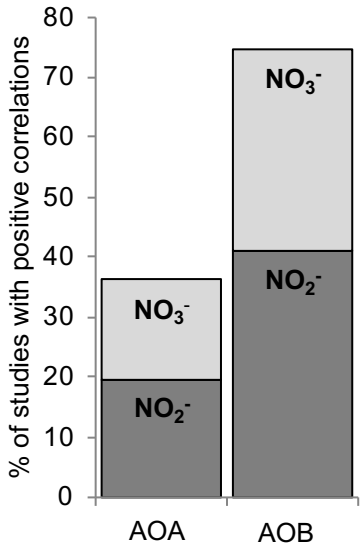

% of studies with positive correlations
80
70
60
50
40
30
20
10
0
NO3-
NO2-
NO3-
NO2-
AOA
AOB

Figure 2.

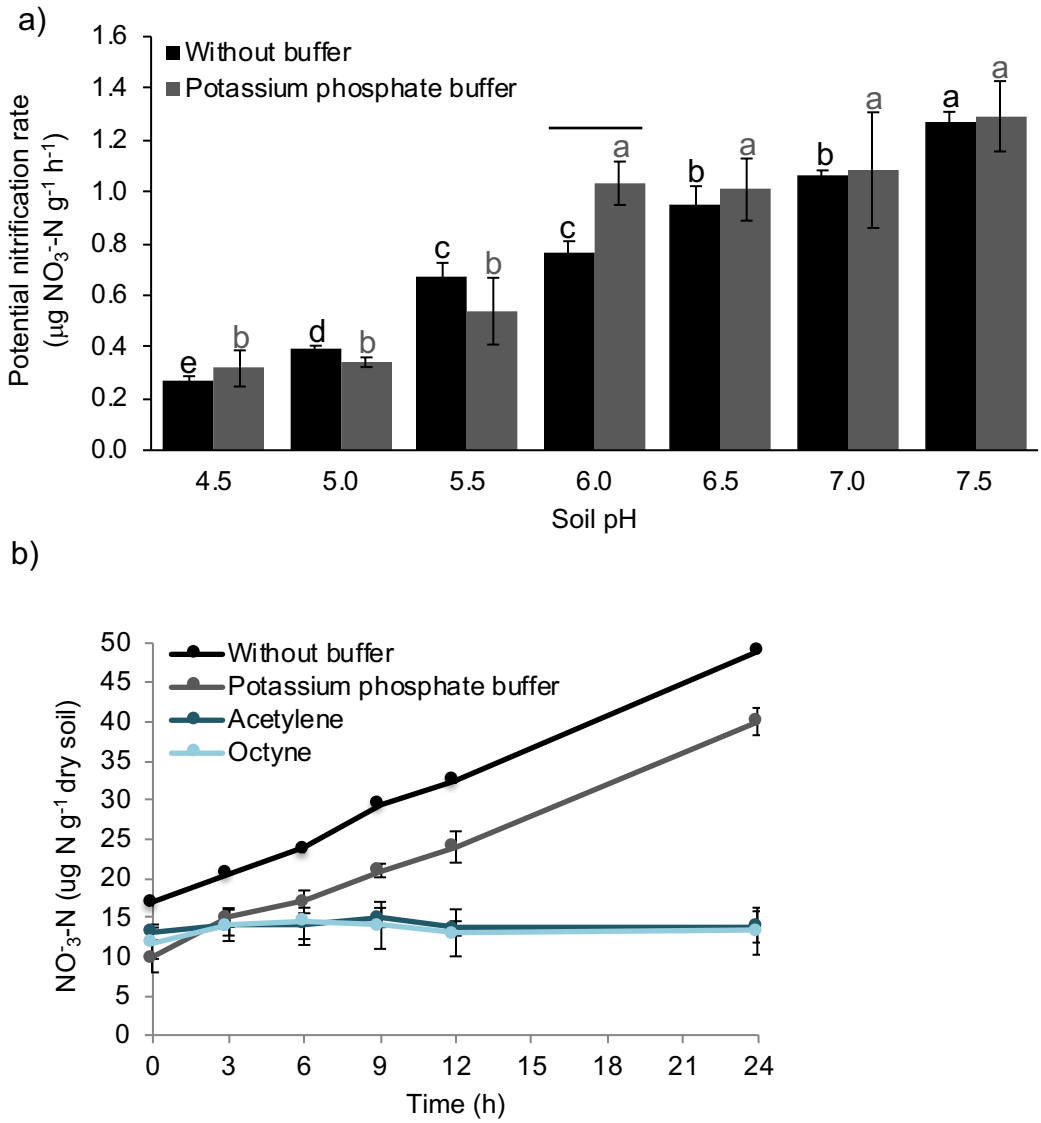
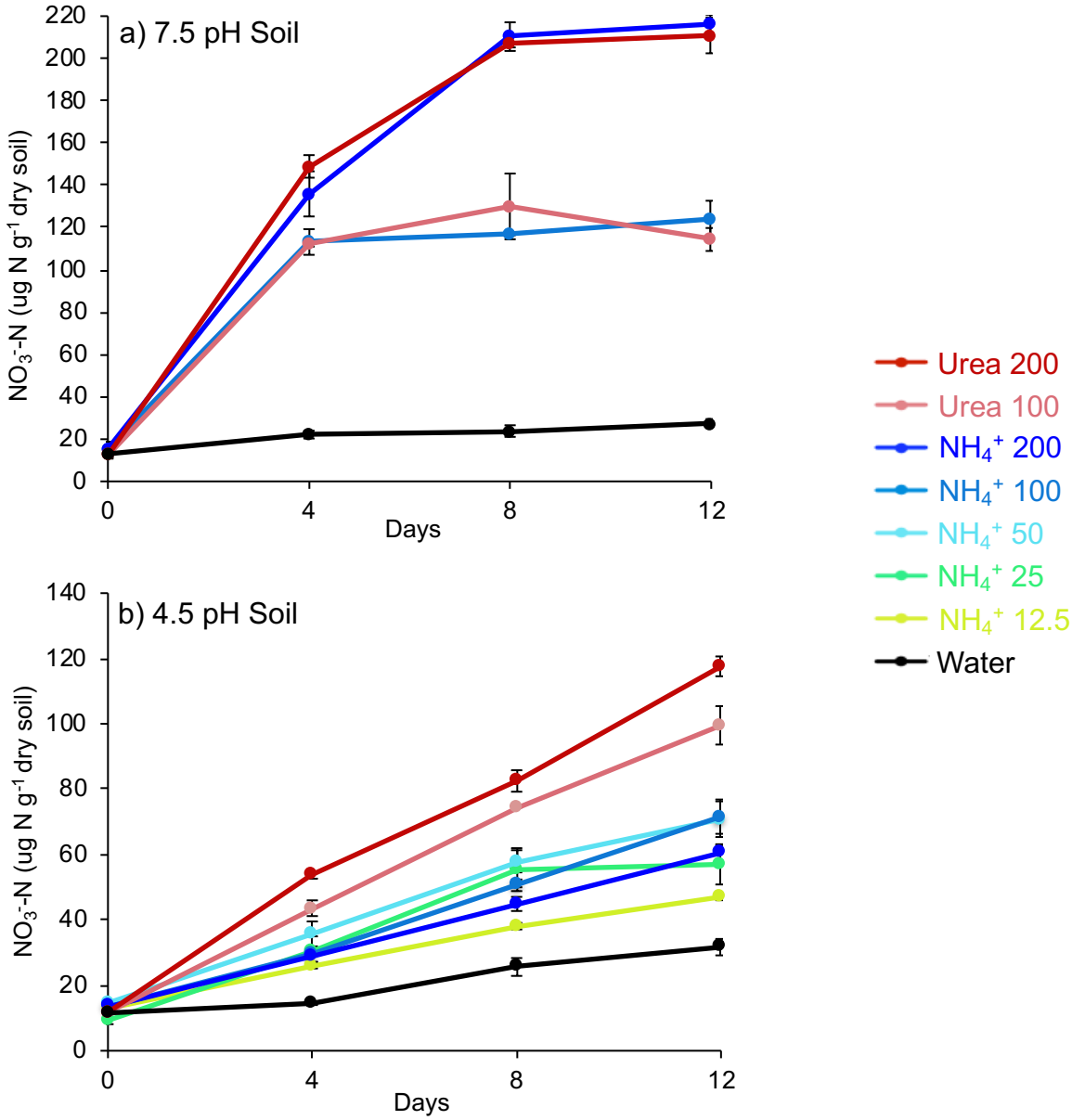
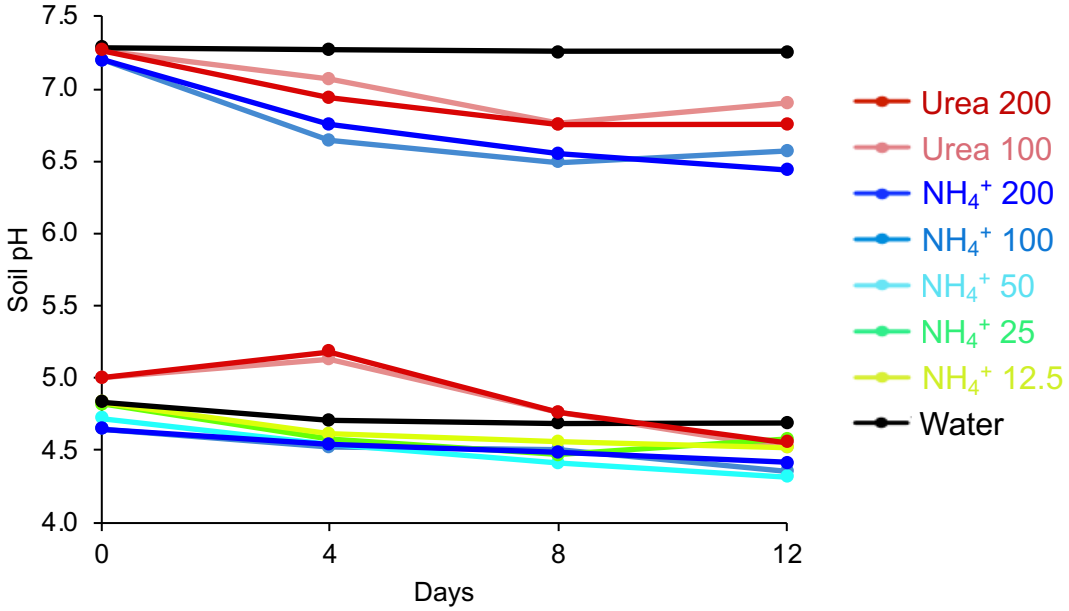

a)
Without buffer
Potassium phosphate buffer
Potential nitrification rate
(µg NO3-N g-1 h-1)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
e
b
d
b
c
b
c
a
b
a
b
a
a
a
4.5
5.0
5.5
6.0
6.5
7.0
7.5
Soil pH
b)
Without buffer
Potassium phosphate buffer
Acetylene
Octyne
NO3-N (ug N g-1 dry soil)
50
45
40
35
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
Time (h)

Figure 3.


a) 7.5 pH Soil
NO_3^--N (ug N g^{-1} dry soil)
220
200
180
160
140
120
100
80
60
40
20
0
0
4
8
12
Days
b) 4.5 pH Soil
NO_3^--N (ug N g^{-1} dry soil)
140
120
100
80
60
40
20
0
0
4
8
12
Days
Urea 200
Urea 100
NH_4^+ 200
NH_4^+ 100
NH_4^+ 50
NH_4^+ 25
NH_4^+ 12.5
Water

Supplementary figure 1