Response to Comment on “Oxygen Regulates Nitrous Oxide Production Directly in Agricultural Soils”

Xu et al. addressed two important questions concerning the reduced soil gas diffusivity when intensive precipitation or irrigation occurred: 1) it contributed to the decrease in soil O$_2$ concentration ([O$_2$]$_{soil}$) and increase in soil N$_2$O concentration ([N$_2$O]$_{soil}$) due to the prevention of soil gaseous exchange with the atmosphere under conditions of surface water ponding or soil saturation; 2) it significantly affected transportation and consumption of N$_2$O within the soil profile and therefore might cause a discrepancy between the [N$_2$O]$_{soil}$ and N$_2$O flux and their responses to the [O$_2$]$_{soil}$ variations.

We know that a complexity of processes are involved in the formation of N$_2$O and its subsequent diffusion in the soil matrix prior to emission to the atmosphere. N$_2$O emissions from the soil surface are ultimately the net result of production, consumption, and transportation of N$_2$O within soil profile. Our paper aimed to explain how [N$_2$O]$_{soil}$ variations corresponded to changes in [O$_2$]$_{soil}$ in the real field conditions of upland soils and how this relationship was affected by the complicated and interacting factors of climate, soil, and agricultural management. This can contribute to an understanding of the mechanism by which the diverse processes of N$_2$O production including nitrification, denitrification, and coupled nitrification denitrification respond to the varying [O$_2$]$_{soil}$ considering the contrasting yield of N$_2$O by these processes.

Undoubtedly, N$_2$O production would be stimulated by increasingly anaerobic conditions (decreased [O$_2$]$_{soil}$) when intensive precipitation or irrigation occurs, and surface water ponding would indeed prevent diffusion of the produced N$_2$O to be emitted from the soil surface, which may cause N$_2$O accumulation thus increasing [N$_2$O]$_{soil}$ to some extent, rather than increasing [N$_2$O]$_{soil}$ solely by enhanced N$_2$O production. It is still difficult to differentiate between these two processes of an increase in [N$_2$O]$_{soil}$. However, it is noteworthy that upland soils with a loamy texture such as our studied soil have good drainage ability. Water infiltration through the top soil layer (0–20 cm) could be generally finished within 4 h following irrigation as indicated by our hourly monitoring of soil [O$_2$]$_{soil}$ and [N$_2$O]$_{soil}$ during these events (data unpublished). It is consistent with the conceptual infiltration model that demonstrates that soil surface water can infiltrate through 20 cm within about 4 h. The initial infiltration rates of the normally dry upland soils could be very high once flooded by intensive precipitation or irrigation and decrease to a steady infiltration rate after 2–3 h generally ranging between 5 and 10 mm/h in the loamy soil. Thus, the theoretical infiltration time for 60 mm irrigation should be less than 6–12 h in loamy soil. Our results showed that soil water-filled pore space (WFPS) only reached 60–68%, even immediately following extreme rainfall on 21 July, 2016, and then dropped slightly to 55–62% in the next week (Figure S4). This also illustrates a rapid infiltration of water through the top soil layer and left the pore space not completely blocked by water but still having some air-filled porosity (around 20%). Under these circumstances, gas exchange between the atmosphere and soil profile was not totally blocked thus allowing O$_2$ diffusion into soil and N$_2$O emission out of soil. The maximum N$_2$O emissions from soils occurred at 67–80% WFPS with a bulk density ranging between 1.1 and 1.5 g cm$^{-3}$, in which the relative soil gas diffusivity ($D/D_0$) consistently fell to a critical value of 0.006, indicating an unrestricted gas diffusion under this relatively high range of soil moisture. Therefore, the ponded soil surface or saturated soil layer after heavy rainfall or irrigation would not last long enough to incur any severe restrictions on gas transport in these upland soils, unlike the situation in rice paddy or wetland soils. Soil water holding capacity, that is, the maximum water content that could be stably held by soil aggregates after saturation and a thorough infiltration, is far smaller when measured using intact soils under field conditions (around 25%) than measured using sieved soils in the laboratory (around 45%), which explains the relatively low WFPS in the in situ structured soils even under waterlogged conditions.

Nevertheless, how the reduced gas diffusivity affects N$_2$O transportation and consumption in the soil profile and subsequent emission to the atmosphere is also a key question we are interested in investigating. In our ongoing work, we are simultaneously measuring the N$_2$O flux at the soil surface, [N$_2$O]$_{soil}$ and [O$_2$]$_{soil}$ in the soil matrix. The preliminary results show that the dynamics of [N$_2$O]$_{soil}$ and N$_2$O flux are relatively consistent in timing and patterns which both respond to the changes in [O$_2$]$_{soil}$ in the upland soils (data unpublished). The effect of the reduced gas diffusivity was weaker when gas concentrations were high and did not cause significant inconsistency between [N$_2$O]$_{soil}$ N$_2$O flux and their responses to the varying [O$_2$]$_{soil}$. However, the comment by Xu et al. highlights the importance of combining the [N$_2$O]$_{soil}$
with N$_2$O flux in response to [O$_2$]$_{soil}$ by considering changes in soil gas diffusivity to provide an explicit prediction of N$_2$O production and emission.

Our results demonstrate that upland soils were mostly well aerated with only intermittent lower [O$_2$]$_{soil}$ in the soil matrix especially following periods of intensive precipitation or irrigation, and [O$_2$]$_{soil}$ was the most closely correlated variable with [N$_2$O]$_{soil}$ compared to other environmental factors. Previous field studies on N$_2$O emissions have mostly investigated the correlation between N$_2$O fluxes and soil environmental factors such as temperature, moisture, ammonium, and nitrate concentrations rather than [O$_2$]$_{soil}$, which are not sufficient to understand N$_2$O producing mechanisms in field conditions. This explains the high uncertainties in models for predicting soil N$_2$O emissions. Our results help to link the N$_2$O producing mechanisms identified under laboratory conditions with more realistic field conditions. Further studies are needed to explore the whole processes of N$_2$O production, diffusion, and emission as well as the related soil O$_2$ status under different climates, soil types, and agricultural management.

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Notes
The authors declare no competing financial interest.

■ REFERENCES
(3) Hink, L.; Lycus, P.; Gubry-Rangin, C.; Frostegård, Å.; Nicol, G. W.; Prosser, J. I.; Bakken, L. R. Kinetics of NH$_3$-oxidation, NO-turnover, N$_2$Oproduction and electron flow during oxygen depletion in model bacterial and archael ammonia oxidisers. Environmental Microbiology 2017, 19 (12), 4882−4896.