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Research paper

Determining optimum nitrogen input rate and optimum yield-scaled nitrous oxide emissions: Theory, field observations, usage, and limitations

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ABSTRACT

Nitrous oxide (N_2O) is one of the major greenhouse gases causing global warming and climate change. Recently, studies showed that the nitrogen (N) input producing optimum amount of crop yields may minimise yield-scaled N_2O emissions in agricultural production. Objectives of the study were to 1) investigate theoretical backgrounds of yield, N_2O emission, and yield-scaled N_2O emission responses to N input, 2) suggest concepts of optimum N input rate and optimum yield-scaled N_2O emission and derive equations for them and 3) test with field observations, and 4) assess usage and limitations and suggest future studies. We have proposed a concept and equations for optimum N input rate and optimum yield-scaled N_2O emission, and applied them to field-measured data from 10 independent experimental studies worldwide. Field-measured data showed that the suggested equations could be used to determine optimum N input rate and optimum yield-scaled N_2O emissions. However, in some cases, any N input resulted in increased yield-scaled N_2O emission and minimum yield-scaled N_2O emissions occurred when N input was zero. The suggested optimum N input rate and optimum yield-scaled N_2O emission can be useful indicators for best management practices to mitigate greenhouse gas emissions and secure food supply. However, in some cases, taking into account yields and N_2O emissions separately is required to identify best management practices. Further studies are needed to better understand the characteristics of yield-scaled N_2O emissions response to N input and its use for management purposes.

1. Introduction

Nitrous oxide (N_2O) is one of the major greenhouse gases causing global warming and climate change. The global warming potential of N_2O is 298 times that of carbon dioxide (CO_2) in a 100-year time horizon (Forster et al., 2007). Also N_2O depletes the atmospheric ozone layer (Crutzen, 1970; Liu et al., 1977). Studies over the past few decades have improved our understanding of the mechanisms and factors controlling N_2O emissions, its budget and mitigation strategies (e.g., Bouwman, 1996; Snyder et al., 2009; Kim et al., 2013). Nitrous oxide is mainly produced by 1) aerobic autotrophic nitrification, the stepwise oxidation of ammonia (NH_3) to nitrite (NO_2^-) and to nitrate (NO_3^-) (e.g., Kowalchuk and Stephen, 2001), 2) anaerobic heterotrophic denitrification, the stepwise reduction of NO_3^- to NO_2^-, nitric oxide (NO), N_2O and ultimately molecular nitrogen (N_2), where facultative anaerobic bacteria use NO_3^- as an electron acceptor in the respiration of organic material under low oxygen conditions (e.g., Knowles, 1982) and 3), nitrifier denitrification, which is carried out by autotrophic NH_3 oxidizing bacteria. This is the pathway whereby NH_3 is oxidized to NO_2^-, followed by the reduction of NO_2^- to NO, N_2O and N_2 (e.g., Webster and Hopkins, 1996; Wrage et al., 2001). It has been suggested that N fertilizer use, land use and its management, and climate are the major factors controlling N_2O emissions from agricultural lands (e.g., Smith, 2010). Agricultural soils produce 61% (3.5 Tg N_2O–N yr^{-1}) of total anthropogenic N_2O emissions (5.7 Tg N_2O–N yr^{-1}) (IPCC, 2006). Use of N fertilizers and animal manure are the main anthropogenic N_2O source, and are responsible for roughly 24% of total annual emissions (Bouwman, 1996; Forster et al., 2007).

One of the important remaining questions would be how to connect N_2O mitigation with global food security. In many previous studies, crop or grass production was not well accounted for in N_2O budgets and mitigation strategies. Therefore, these studies created a strong perception that there was a trade-off between N_2O mitigation and global food security. It has been proposed that mitigating N_2O emissions would be equal to reducing N input and, consequently, reducing crop or grass production. Recently, studies have used the concept of yield-scaled N_2O emission (Eq. (1)) to account for both crop or grass yields and N_2O emissions (e.g., Mosier et al., 2006; Van Groenigen et al., 2010;

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Venterea et al., 2011; Qin et al., 2012; Pittelkow et al., 2013; Feng et al., 2013; Kim et al., 2016; Sainju, 2016).

$$Yield - scaled\ N_2O\ emission = \frac{N_2O\ emissions\ over\ crop\ or\ grass\ growing\ period}{Grain\ or\ grass\ yield} \quad (1)$$

For example, a meta-analysis found that N inputs of 150–200 kg N ha^{-1} yr^{-1} reduced yield-scaled N_2O emissions by 37%, compared with the non-fertilization control in rice fields in China (Feng et al., 2013). The lowest yield-scaled N_2O emissions were reported for N application rates ranging from 100 to 150 kg N ha^{-1} in agricultural lands of sub-Saharan Africa (Kim et al., 2016). Their results showed that the N input producing optimum amount of crop yields may minimise yield-scaled N_2O emissions in agricultural production. The results currently available suggest that yield-scaled N_2O emission may be an alternative means to balance food security with mitigating N_2O emissions (e.g., van Kessel et al., 2013; Sainju, 2016). Along with increasing numbers of studies reporting yield-scaled N_2O emission, we are here suggesting the concept of optimum N input rate and optimum yield-scaled N_2O emission, and have taken a close look at published results to assess their usage and limitations.

Objectives of the study were to 1) investigate theoretical backgrounds of yield, N_2O emission, and yield-scaled N_2O emission responses to N input, 2) suggest concepts of optimum N input rate and optimum yield-scaled N_2O emission and derive equations for them and 3) apply method to field observations, and 4) assess usage and limitations and suggest future studies.

2. Theoretical background of yield, N_2O emission, and yield-scaled N_2O emission responses to N input

Since yield-scaled N_2O emission is defined as emitted N_2O per mass of grain or grass produced it is determined by dividing the N_2O emitted with the grain or grass yield obtained (dry matter or N) (e.g., Van Groenigen et al., 2010; Venterea et al., 2011). Therefore, to understand the response of yield-scaled N_2O emission to N input, we need to know both the response of grain or grass yields and N_2O emissions to N input.

2.1. Response of grain or grass yields to N input

Response of grain or grass yields to N input has been intensively studied for plant types in different regions, as this indicates the optimum N input rate needed to obtain economically maximum yields (e.g., Cerrato and Blackmer, 1990; Webb et al., 1998; Schabenberger and Pierce, 2002; Scharf et al., 2005). The response of grain or grass yields to N input may vary with weather, plant type, site and climatic conditions. This relationship has often been described by the Michaelis-Menten function (Eq. (2)) (e.g., Cerrato and Blackmer, 1990; Webb et al., 1998; Schabenberger and Pierce, 2002; Scharf et al., 2006; Valkama et al., 2013; Bell et al., 2016). The Michaelis-Menten curve is usually used to describe enzyme kinetics, and has the property that the Y-axis variable increases as the X-axis variable increases for low values of X. However, there is a maximum Y value and the increase in Y diminishes as it approaches this maximum (Morrison, 2002). The grain or grass yield increase is approximately linear for low values of N fertilizer input rate. However, the increase in the rate of grain or grass yield with fertilizer input diminishes as the N fertilizer input rate increases. At high fertilizer N inputs the increase in grain or grass yield approaches zero and the yield approaches a constant value (yield potential) (e.g., Lawlor, 2002). The Michaelis-Menten curve is similar to the general pattern of observed yield gain following N application.

$$Yields = \frac{ax + c}{b + x} \quad (2)$$

Where x = the amount of N fertilizer input and there are 3 parameters to fit. The yield with no fertilizer is c/b, the yield limit at high fertilizer is a, and b is the value of N input that gives a yield half-way between the maximum and minimum values.

2.2. Response of N_2O emissions to N input

Response of N_2O emissions to N input has earlier been described as a linear relationship (e.g., Bouwman, 1996; Dobbie et al., 1999) (Eq. (3)). These early studies suggested a linear relationship between increasing N input and increases in N_2O emissions, and this relationship was adopted by the IPCC Tier I EF methodology (e.g., IPCC, 2006) for estimating direct N_2O emission based on the amount of N added to agricultural soils.

$$N_2O\ emissions = dx + E \quad (3)$$

Where x = the amount of N fertilizer input and there are 2 parameters to fit: d = increase rate of N_2O emissions in response to N input and E = background N_2O emissions

However, it has been found recently that an exponential relationship between N_2O emissions and N input also occurs (Eq. (4)) (e.g., McSwiney and Robertson, 2005; Hoben et al., 2011; Kim et al., 2013; Shcherbak et al., 2014; Bell et al., 2016). Initially N_2O emissions increase approximately linearly as N fertilizer input rate increases. However, N_2O emissions increase rapidly as the N fertilizer input rate increases further after passing a certain N input rate (e.g., Hoben et al., 2011; Kim et al., 2013). This response can be primarily associated with excessive N supply beyond plant demands (e.g., > 100 kg N ha^{-1}; Bouwman et al., 2002) and soil microbial mediation. This soil N surplus would lead concomitantly to a lower plant N uptake efficiency (Liang and Mackenzie, 1994; Hong et al., 2007) and, therefore, result in soil residual N as a substrate for additional N_2O production (e.g., Kim et al., 2013). The response is similar to the exponential increase function expressed as follows (Eq. (4)):

$$N_2O\ emissions = m\ \exp(kx) \quad (4)$$

where x = the amount of N fertilizer input and there are 2 parameters to fit: m = background N_2O emissions, k = constant

The formula is reasonable for N fertilizer input below a certain limit, but will be inaccurate at high N fertilizer input as the curve is unbounded for very high N fertilizer input levels. Eventually the curve would predict N losses greater than N input, which is not tenable. However, the level of N input required for this is very high and is rarely seen in practice.

2.3. Response of yield-scaled N_2O emission to N input

Since yield-scaled N_2O emission is defined as emitted N_2O per grain or grass produced (e.g., Van Groenigen et al., 2010; Venterea et al., 2011) yield-scaled N_2O emissions are determined by dividing cumulative N_2O emission by grain or grass yield (Eq. (1)). We consider linear and exponential responses of N_2O emission to N input. This gives 2 formulae for yield-scale N_2O emissions (Eqs. (5) and (6)) as follows:

$$Yield - scaled\ N_2O\ emissions = \frac{dx + E}{\frac{ax+c}{b+x}} = \frac{(dx + E)(b + x)}{ax + c} = \frac{dx^2 + (db + E)x + Eb}{ax + c} \quad (5)$$

$$Yield - scaled\ N_2O\ emissions = \frac{m.\ \exp\ (kx)}{\frac{ax+c}{b+x}} = \frac{(b + x)m.\ \exp\ (kx)}{ax + c} \quad (6)$$

3. Optimum N input rate and optimum yield-scaled N_2O emission: concept and equations

Optimum N input rate is defined as the N input rate that minimizes