Assessment of the boundary line approach for predicting N$_2$O emission ranges from Australian agricultural soils

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Abstract
This study aimed to assess the feasibility of predicting ranges in N$_2$O emission with a boundary line approach using a few key driving factors. Intact soil cores (9 cm dia. and ~20 cm in depth) were collected from pasture, cereal cropping and sugarcane lands and incubated at various temperature and moisture conditions after addition of different forms of mineral nitrogen (NH$_4^+$ and NO$_3^-$). The pasture and sugarcane soils showed greater N$_2$O production capacity than the cropping soils with similar mineral N and organic C contents or under similar temperature and water filled pore space (WFPS%), and thus different model parameters need to be used. The N$_2$O emission rates were classified into three ranges: low (< 16 g N$_2$O/ha/day), medium (16 –160 g N$_2$O/ha/day) and high (> 160 g N$_2$O/ha/day). The results indicated that N$_2$O emissions were in the low range when soil mineral N content was below 10 mg N/kg for the cropping soils and below 2 mg N/kg for the pasture and sugarcane soils. In soils with mineral N content exceeding the above thresholds, the emission rates were largely regulated by soil temperature and WFPS and the emission ranges could be estimated using linear boundary line models that incorporated both temperature and WFPS. Using these key driving factors (land use, temperature, WFPS and mineral N content), the boundary line models correctly estimated the emission ranges for 85% of the 247 data points for the cropping soils and 59% of the 271 data points for the pasture and sugarcane soils. In view of the fact that N$_2$O emissions from soil are often very variable and difficult to predict and that the soil and environmental conditions applied in this study differed substantially, the above results suggested that, in terms of accuracy and feasibility, the boundary line approach provides a simple and practical alternative to the use of a single emission factor and more complex process-based models.

Key Words
Greenhouse gas, nitrous oxide, boundary line model.

Introduction
Three types of modelling approaches of varying complexity are available for estimating regional or national scale N$_2$O emissions. The simplest and coarsest is the emission factor approach that estimates an annual loss of N$_2$O as a fixed percentage of fertiliser N applied (IPCC 2006), which does not account for the effects of climate, soil type, cropping regime, and management practices on N$_2$O emissions. The most complex approach is the process-based models, which generally require large amounts of input data and need to be calibrated under different climatic, soil and cropping systems. In the middle of the complexity spectrum are the empirical models, where N$_2$O emissions are estimated as a function of a number of key driving factors (Conen *et al*. 2000; Roelandt *et al*. 2005). The relationships between the N$_2$O emission rate and the driving factors are often restricted to the experimental conditions under which they were derived. In recognition of the large spatial and temporal variability and the difficulties in prediction of N$_2$O emissions from soil, Conen *et al*. (2000) used soil temperature, WFPS, and mineral N content and a boundary line approach to predict N$_2$O emissions in three ranges: low (< 10 g N$_2$O-N/ha/day), medium (10 – 100 g N$_2$O-N/ha/day) and high (> 100 g N$_2$O-N/ha/day). Conen *et al*. (2000) found that the prediction accuracy of this approach was comparable to those of the process-based models (Frolking *et al*. 1998). Given the small number of parameters required, this technique raises the prospect for large-scale application. However, the major drivers for N$_2$O production may differ in different regions or ecosystems. The objective of this study was to test and, if necessary, modify the boundary line model of Conen *et al*. (2000) for spatial prediction of N$_2$O fluxes.

Methods
Intact soil cores were collected from eight different locations in southern Queensland (including 1 sugarcane, 3 cereal croping and 4 pasture sites) by driving PVC tubes (35 cm length and 10.5 cm i.d.) about 25 cm below the soil surface and pulling out with a hydraulically driven sampling rig. Mean annual temperature for the sites ranged from 14.4 to 20.7°C, and mean annual rainfall from 517 to 1706 mm. The basic properties in

the 0 – 20 cm depth were: pH (1:5 in water), 5.0 – 7.2, clay, 6 – 63%, TOC, 5 – 55 mg/kg, TON, 0.38 – 5.4 mg/kg, and bulk density, 0.73 – 1.61 g/cm³.

Following a pre-incubation at room temperature (~22°C) and field moisture for 5-10 days in the laboratory, each soil core was applied with zero or 130 mg N as NH_4^+ and/or NO_3^- on the soil surface. Water was then added gradually using a fine sprayer to bring soil moisture content to different water filled pore space (WFPS). After equilibrating for several hours, initial soil samples were destructively taken to measure soil mineral N and water contents in 0 – 10, 10 – 20 and > 20 cm depths. The remaining soil cores were covered with a cap that had a hole in the middle and incubated at 5, 10, 15 and 25°C for 3 days. Gas samples were taken daily from the head space before and after sealing the cap with a rubber septa for 30 – 60 minutes and later analysed for N_2O and CO_2 concentrations with a gas chromatograph equipped with ECD and TCD detectors. The soil cores were destructively sampled after the incubation and determined for mineral N and water content in 3 depths as described before.

Results

Classification of soils

Under the same temperature, or similar WFPS, mineral N, DOC and TOC contents, the pasture and sugarcane soils generally had higher emission rates than the cropping soils (data not presented). The pasture soil cores had living plant roots, which could supply bio-available C to microbes from root exudates and fine root turnover and thus enhance N_2O production capacity. Thus, separate model parameters should be developed for the cropping soils and the pasture and sugarcane soils.

Boundary lines of the emission ranges

Figure 1 shows that N_2O emissions generally fell in the low range if mineral N content was below 10 mg N/kg for the cropping soils and below 2 mg N/kg for the pasture and sugarcane soils, regardless of soil temperature and WFPS values. The difference in the mineral N threshold values between the cropping soils and the pasture/sugarcane soils could be related to the difference in their N_2O production capacities as discussed above.
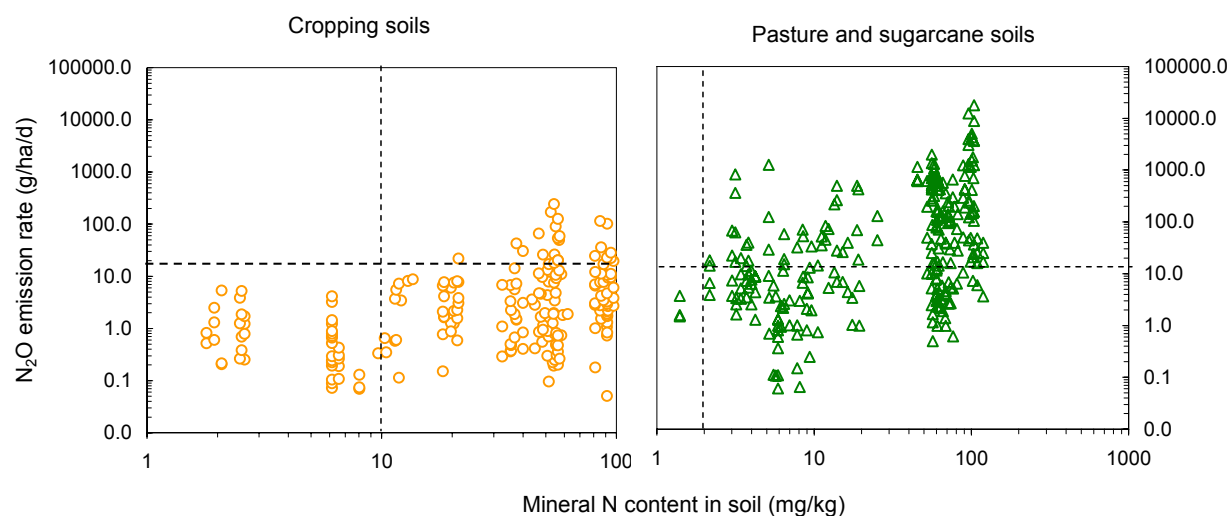

Figure 1. Determination of the threshold value (vertical dotted lines) of soil mineral N content in the 0-20 cm layer below which N_2O emission rates were limited to the low emission range.

For soils with mineral N content above the threshold values, N_2O emission rates varied substantially, presumably controlled primarily by other factors. To further assess the effects of these factors on the magnitude of N_2O emissions, the observed emission data were arranged into low (< 16 g N_2O/ha/d), medium (16 to 160 g N_2O/ha/d) and high (> 160 g N_2O/ha/d) emission ranges. The distribution of the data points in each emission range in relation to soil temperature and WFPS is shown in Figure 2. Similar analyses were conducted using other possible regulating factors such as TOC, DOC, clay content and pH in various combinations with temperature and moisture content (WFPS%, w/w% or v/v%). These alternative analyses resulted in no significant improvement compared to the results shown in Figure 2. This suggested that temperature and WFPS were the main driving factors for soils with high mineral N content, although their effects might be interactively affected by other factors.

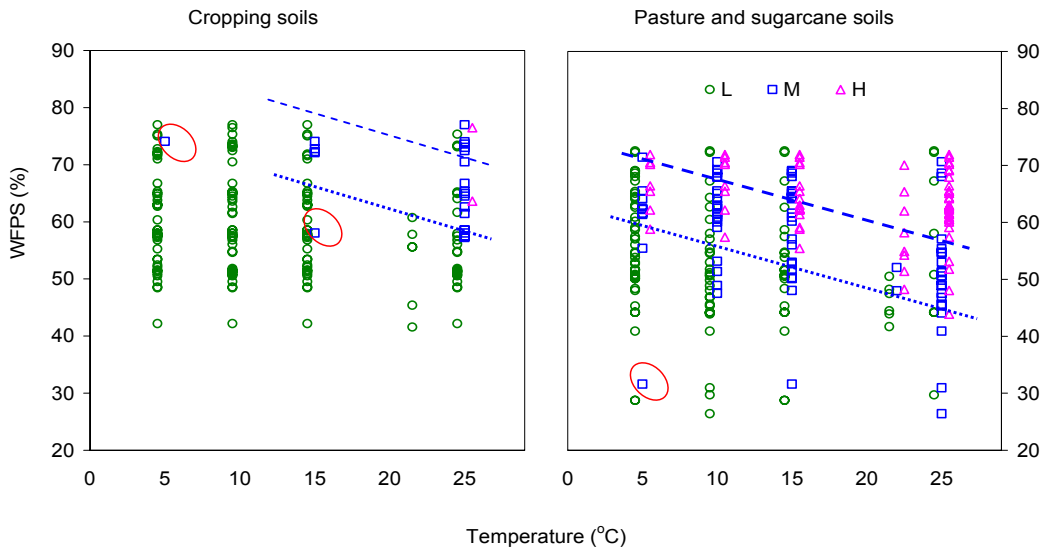**Figure 2. Distribution of N₂O emissions in the low (<16 g N₂O/ha/d), medium (16 to 160 g N₂O/ha/d) and high (>160 g N₂O/ha/d) ranges in relation to temperature and WFPS in soils where mineral N was presumably not limiting. The dotted and dashed lines represent the boundaries between the low and medium, and between the medium and high ranges respectively. Horizontal separation of the data points at the same temperature into low, medium and high ranges were for clear illustration only.**

Figure 2 shows that N₂O emissions at lower temperature/WFPS combinations were mostly in the low range, whilst the high emissions tended to occur at higher temperature/WFPS combinations. However, there was no clear cut-off point for the boundary conditions between the low and medium or between the medium and high ranges, further indicating the complex relationships between N₂O emissions and the regulating factors. After removing one or two outlier data points (in red circles in Figure 2), a linear regression analysis using only the data in the medium emission range of each land use type indicated that there was a complementary effect between temperature and WFPS on N₂O emission rates. This was consistent with the findings of Conen *et al.* (2000). The trend line of this relationship could be described by:

$$\text{WFPS (\%)} + 0.76\, T\, (^{o}C) = 84 \text{ for the cropping soils.} \tag{1}$$
$$\text{WFPS (\%)} + 0.71\, T\, (^{o}C) = 69 \text{ for the pasture and sugarcane soils.} \tag{2}$$

By mathematically treating WFPS as the dependent variable in the regression analysis, the lower and upper boundary lines of the medium emission range could be estimated by vertically shifting the trend line down and up, respectively, by a magnitude of the residual standard error of WFPS.

For the cropping soils, the boundary line below which N₂O emission was limited to the low emission range was given by:

$$\text{WFPS (\%)} + 0.76\, T\, (^{o}C) = 78 \tag{3}$$

when T ≥10°C. N₂O emissions from the cropping soils were generally in the low emission range at <10°C (Figure 3). The boundary line separating the medium and high emission ranges was given by:

$$\text{WFPS (\%)} + 0.76\, T\, (^{o}C) = 90 \tag{4}$$

For the pasture and sugarcane soils, the boundary lines between the low and medium emission ranges and between the medium and high emission ranges were given, respectively, by:

$$\text{WFPS (\%)} + 0.71\, T\, (^{o}C) = 63, \text{ and} \tag{5}$$
$$\text{WFPS (\%)} + 0.71\, T\, (^{o}C) = 75 \tag{6}$$

Therefore, with the knowledge of land use, temperature, WFPS and mineral N content in the upper 20 cm soil, the N₂O emission rate from a soil can be estimated as summarised in Table 1.

Table 1. Summary of the boundary line model for predicting N₂O emission ranges.

Land use	Mineral N (mg/kg)		Temperature (T °C) and WFPS (%)	Flux ranges (g N₂O/ha/d)
Cropping	≤ 10	or	T ≤ 10 or WFPS + 0.76 T ≤ 78	< 16 (L)
	> 10	and	T > 10 and 78 < WFPS + 0.76 T ≤ 90	16 – 160 (M)
	> 10	and	T > 10 and WFPS + 0.76 T > 90	> 160 (H)
Pasture or sugarcane	≤ 2	or	T < 5 or WFPS + 0.71 T ≤63	<16 (L)
	> 2	and	T ≥ 5 and 63 < WFPS + 0.71 T ≤ 75	16 – 160 (M)
	> 2	and	T ≥ 5 and WFPS + 0.71 T > 75	> 160 (H)

Altogether 247 and 271 N_2O emission measurements (mean values within the first 3 days) were available for the cropping soils and for the pasture and sugarcane soils, respectively. On average across all emission ranges, the percentage of correct predictions for the above models was 85 for the cropping soils and 59% for the pasture and sugarcane soils. Considering the contrasting land uses, soil properties and climate conditions in the sampling regions, as well as the wide ranges of temperature, WFPS and mineral N forms and amounts applied in the incubation experiments, accurately predicting N_2O emissions from all the soils presents a challenge for any modelling approach. The boundary line model requires information for only a few input factors and thus has the potential to be used in large-scale predictions.

Conclusion

In terms of accuracy and feasibility, the boundary line modelling approach provides a practical alternative to the use of a single emission factor and more complex process-based models. Similar to the calibration of process-based models, the accuracy of prediction may be improved by adjusting the gradient and intercept of the boundary lines for a specific site. Such adjustment would reflect the impacts of other regulating factors not considered in the model.

Acknowledgement

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