# $N_2O$ mitigation opportunities in subtropical cereal and fibre cropping systems – a modelling approach

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**Abstract**
Agricultural crop and livestock production contribute 78 % to global anthropogenic nitrous oxide ($N_2O$) emissions. Therefore, mitigation of $N_2O$ emissions from agricultural systems is important. In this study, the trade-off between crop yield and $N_2O$ emissions in subtropical cereal and fibre cropping systems under various management practices was investigated to identify potential mitigation options. For this, the APSIM model was first tested against data from a field experiment on a vertosol comprising several irrigation treatments in subtropical Queensland. One soil hydraulic parameter and one parameter in the denitrification sub-model were calibrated against a subset of the data. The validity of the model was confirmed with the remaining data. For the six datasets we found a good correlation between measured and predicted yields ($R^2$ = 0.90) and seasonal $N_2O$ emissions ($R^2$ = 0.49). Long-term scenarios were then calculated with the validated model. Long-term average yield and $N_2O$ emissions both increased under increased nitrogen (N) supply from legumes or extra N fertiliser, and so, there was a trade-off between maximising yield and minimising $N_2O$ emissions. $N_2O$ emissions also increased when crop yields were limited due to water stress, because of increased mineral N availability. Given the annual variability in climate and soil nitrogen availability, mitigating $N_2O$ emissions is not a simple task. A tool for proper yield forecasting could therefore be of great benefit for estimating the amount of nitrogen required and thus assist in managing N efficiently and in mitigating $N_2O$ emissions.

**Key words**
Agricultural systems, simulation, greenhouse gas, wheat, cotton, vertosol

**Introduction**
Agriculture plays an important role in greenhouse gas emissions. About 60 % of global anthropogenic nitrous oxide ($N_2O$) emissions stem from agricultural production systems (Syakila and Kroeze, 2011). Of all global agricultural land 23 % are situated in the subtropics, and more than 15 % of the global $N_2O$ emissions from fertilised land are emitted in the subtropics (Bouwman et al., 2002; Stehfest and Bouwman, 2006). Therefore, efficient $N_2O$ mitigation strategies for subtropical cropping systems are needed, which also enable crop yields to be maintained or increased. To mitigate $N_2O$ emissions, the environmental conditions under which high emissions occur, have to be understood. This can be achieved by monitoring $N_2O$ emissions in crops under varying management practices and measuring relevant environmental factors driving the formation of $N_2O$ at the same time. However, field experiments are constrained in management practices, locations and duration. So, process-based models are valuable supplements to extrapolate these experiments to a wider range of environments and management practices.

We used the agricultural systems model APSIM (Holzworth et al., 2014) to explore possible mitigation options for representative subtropical grain and fibre cropping systems by simulating long-term scenarios comprising various management practices. APSIM was calibrated and validated against data from a field experiment on a vertosol in subtropical Queensland.

**Material and Methods**
APSIM was calibrated and validated using data from a field experiment conducted on a vertosol at Kingsthorpe (27°30′44.5″ S, 151°46′54.5″ E) in the Darling Downs, Queensland. The experiment was conducted during a wheat-cotton sequence and comprised three treatments with varying irrigation intensities, summing up to six crop-treatment combinations (high (HI), medium (MI) and low irrigation (LI); Scheer et

al., 2013, 2012). $N_2O$ emissions and water contents (0.0 – 0.4 m depth) were regularly measured, and crop yields were recorded at harvest. The model was set up with soil hydraulic parameters previously measured at the site (Kodur et al., 2013). A two-step calibration procedure was used. First, the parameter KL ($d^{-1}$) describing the maximum proportion of plant available water that can be extracted by roots in each layer per day was calibrated against yield from one treatment for each crop. Then the parameter $dnit_{lim}$, which describes the water filled pore space threshold above which denitrification occurs, was calibrated against $N_2O$ emission measurements from one treatment. All other parameters were kept at their default values. For both yield and $N_2O$, the remaining four crop-treatment combinations were used for independently validating the model.

The validated model was used to assess possible $N_2O$ mitigation options by simulating long-term (40 yr) crop rotations that involved varying fertilisation and irrigation management strategies. Two winter crop rotations (a wheat monoculture and a wheat-chickpea rotation) and two summer crop rotations (a cotton monoculture and a cotton-mungbean rotation) were simulated. In case of cotton, 90 % of residues were removed from the field while for the other crops residues were retained and crops drilled without tillage.

## Results

*Model validation*

Water dynamics measured at 0.1-0.2 m and 0.2-0.4 m were well predicted (RMSE = 0.04 to 0.07 $m^3 m^{-3}$, data not presented). Yields (Fig. 1a) and seasonal $N_2O$ emissions (Fig. 1b) were also accurately predicted for the validation treatments including different irrigation intensities and both wheat and cotton crops. Seasonal $N_2O$ emissions were found to be very sensitive to the newly introduced parameter $dnit_{lim}$. This highlights the importance of accurately predicting the water dynamics, which this parameter relates to.

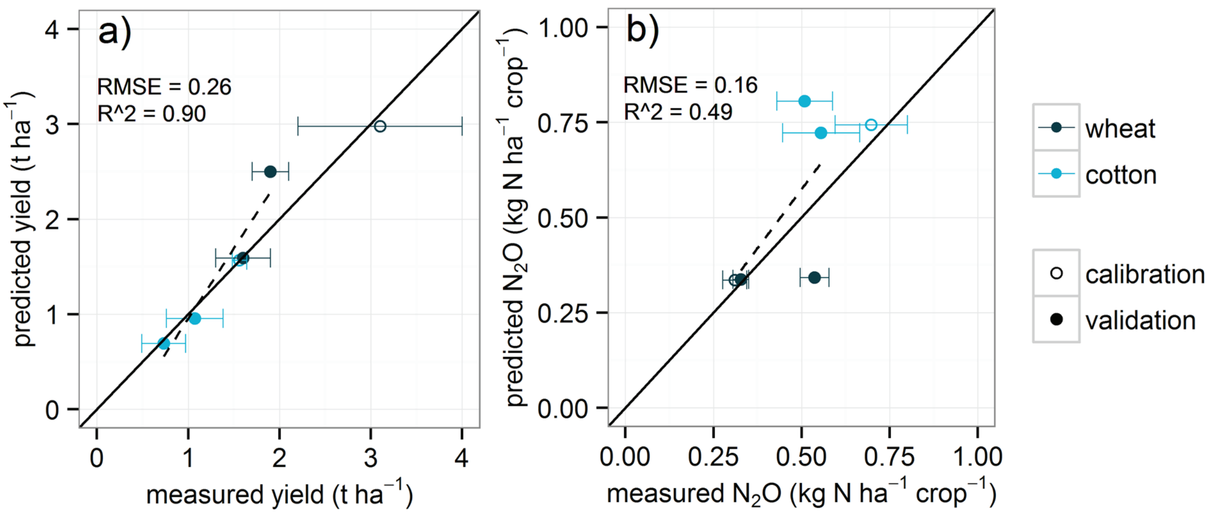


**Figure 1. Predicted against measured (a) crop yields and (b) seasonal $N_2O$ emissions for the calibration (dots) and validation (circles) data from the vertosol at Kingsthorpe. Standard deviation of the observations, 1:1 (solid) and regression lines (dashed) are shown. RMSE (root mean square error) and $R^2$ (coefficient of determination) are given.**

*Mitigation options*

With respect to N-rate, two general relationships between yield and $N_2O$ emissions were identified for the wheat and cotton monocultures in long-term scenarios (Fig. 2, left). Firstly, at low nitrogen (N) rates, e.g., up to 100 kg N $ha^{-1}$ in rainfed crops, (small, closed symbols), both $N_2O$ emissions and yields increased with increasing N rates. However, at N rates > 100 kg N $ha^{-1}$ in the rainfed crops (large, closed symbols in Fig. 2), only $N_2O$ emissions increased while yields remained constant. Split fertiliser application did not provide any benefit to yield or $N_2O$ mitigation compared to applying all N at sowing (data not presented). For all crops, yields of irrigated crops (open symbols) were significantly higher than rainfed crops (closed symbols). Highest average yields under irrigation more than doubled compared to rainfed crops for wheat (Fig. 2, top) and tripled for cotton (Fig. 2, bottom). In wheat, $N_2O$ emissions at high N rates were lower in irrigated than in rainfed crops. On the other hand, in cotton at all N rates and in wheat at low N rates, $N_2O$ emissions were higher in the irrigated than in the rainfed treatments.

When a legume (chickpea or mungbean) was included in a crop rotation, maximum yields for wheat and cotton were reached at lower fertiliser N rates compared to the respective monocultures (Fig. 2). This provided savings of up to 50 kg N $ha^{-1}$ per wheat crop in the irrigated wheat-chickpea systems. However, the maximum yield for rainfed wheat remained ~20 % smaller when in rotation with chickpea than under monoculture. Maximum cotton yields under rainfed conditions were ~30 % higher when in rotation with mungbean compared to the monoculture. There was no difference in the maximum yield of wheat or cotton crops grown in a monoculture or in rotation with a legume if the crops were irrigated. When a legume was included in the rotation in rainfed wheat, $N_2O$ emissions were reduced by 3.0 kg N $ha^{-1}$ $yr^{-1}$ at an N-rate of 200 kg N $ha^{-1}$. However, at N-rates below 100 kg N $ha^{-1}$and in irrigated wheat there was no difference. In irrigated cotton, $N_2O$ emissions were up to 0.8 kg N $ha^{-1}$ $yr^{-1}$ higher when mungbean was included in the crop rotation compared to the cotton monoculture.

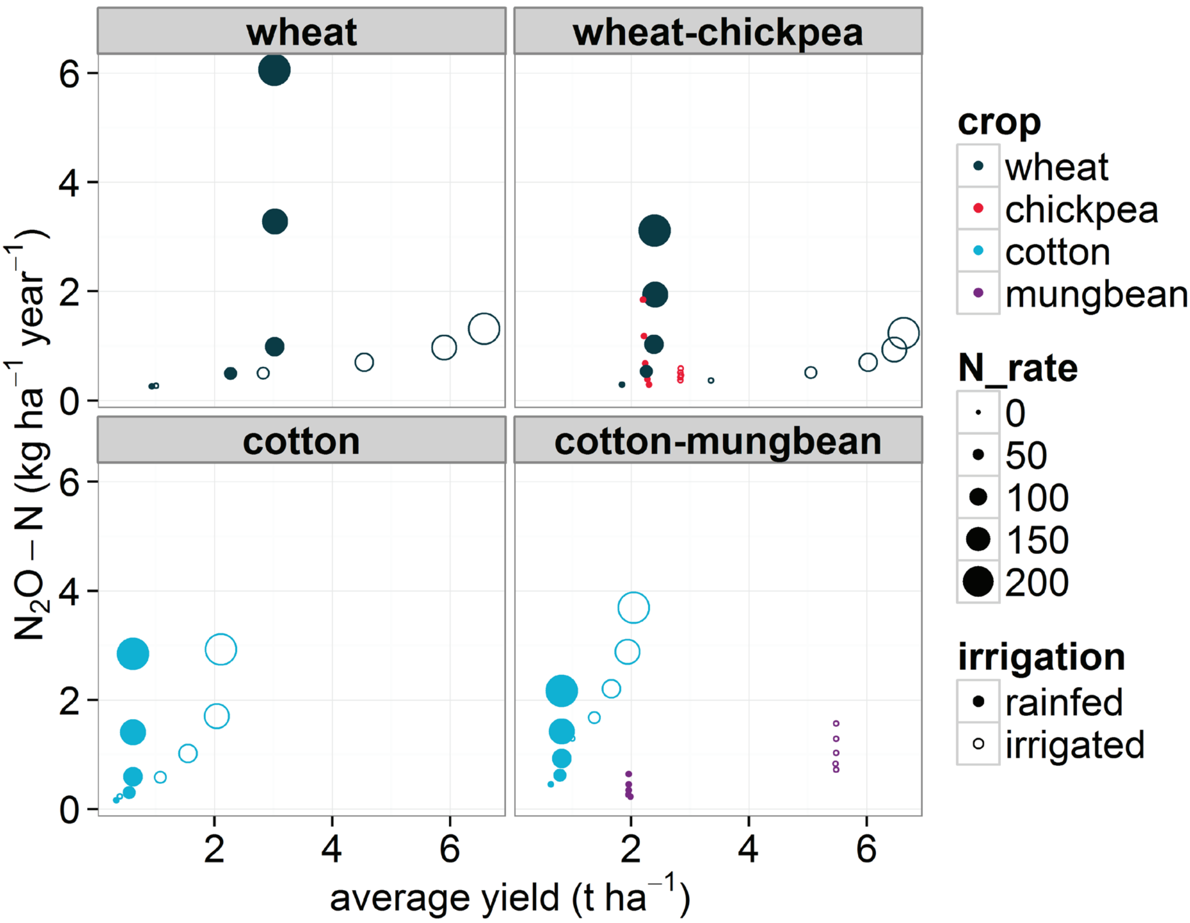


**Figure 2. Trade-off between yield and $N_2O$ emissions for four crop rotations simulated on the vertosol at Kingsthorpe. Nitrogen was applied at five rates: 0, 50, 100, 150 and 200 kg N $ha^{-1}$ (size of bubbles) to non-legume crops. Irrigation was applied at two rates: zero irrigation (rainfed) and irrigation applied when plant available water in the upper 0.6 m of the soil was < 50% of plant available water capacity (irrigated).**

## Discussion

*Model validation*

Close prediction of yields and seasonal $N_2O$ emissions in validation data (Fig. 1) confirmed the capacity of APSIM to reliably simulate these outputs with minimal calibration (i.e. calibrating only two model parameters). This justifies confidence in the capacity of the model to reliably simulate other treatments at the site and identify mitigation options by analysing long-term scenarios of a variety of management strategies.

*Interactions between yield and $N_2O$ emission in response to N and water availability*

Two main interactions were identified from the modelled scenarios. The first finding was that there was a trade-off between increasing yield and minimising $N_2O$ emissions at low N rates, while at high N rates a further increase in N input resulted in a negative outcome for both variables. These results are consistent with a yield plateau attained by crops at adequate N supply, while N losses continued to increase at higher N rates.

Our second finding of higher $N_2O$ emissions in rainfed than in irrigated wheat under high N rates appears counterintuitive because soil moisture, an important driver for $N_2O$ emissions, is generally higher under irrigation. However, this result occurred because water stress in the highly-fertilised rainfed wheat crops resulted in higher surplus N and higher soil N concentrations compared to the irrigated treatments. So there was more substrate available for denitrification in these crops. After high rainfall events this higher soil N led to a few large denitrification peaks each year which contributed the majority of $N_2O$ emissions.

*Mitigation options*

There was high interannual variability of $N_2O$ emissions and yields in the long-term scenarios. Hence, results from short-term experiments may not be representative of the long-term behaviour of these subtropical agro-ecosystems, and so simulation studies may be an important addition to field studies to gain insights into long-term emissions and mitigation options.

In this study, $N_2O$ emissions were not caused by only one management factor (e.g. irrigation or fertilisation) but by the complex interaction of several factors. Hence, a holistic approach needs to be taken to identify strategies that mitigate $N_2O$ emissions without compromising yield. Such strategies would utilise an optimal N rate for the current plant environment that would maximise yield and limit $N_2O$ emissions, and thus maximise nitrogen use efficiency (NUE). Therefore, N fertiliser should be applied taking into account available soil N and expected yield. The latter strongly depends on available water, including soil water storage, expected rainfall and irrigation. Soil testing for mineral N in combination with weather forecasts and yield forecasting tools would provide great benefit in managing N application and thus optimising the dynamic trade-off between crop yields and $N_2O$ emissions.

**Acknowledgements**

This research was undertaken as part of the National Agricultural Nitrous Oxide Research Program (NANORP) funded by the Australian Grains Research and Development Corporation (GRDC) and the Australian Government Department of Agriculture.

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