

Simulation of N₂O emissions from rain-fed wheat and the impact of climate variation in southeastern Australia

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Abstract The Water and Nitrogen Management model (WNMM) was applied to simulate N₂O emissions from a rain-fed wheat cropping system on a loam-textured soil for two treatments, conventional cultivation with residue burn (CC+BURN+N) and direct drill with residue retention (DD+RET+N), at Rutherglen in southeastern Australia from January 2004 to March 2005. Both treatments received the same amount of nitrogen (N) fertiliser. The WNMM satisfactorily simulated the soil water content, mineral N contents and N₂O emissions from the soil, as compared with the field observations for both treatments. The simulated nitrification-induced N₂O emissions accounted for 45% and 34% of total N₂O emissions for the treatments CC+BURN+N and DD+RET+N, respectively. The cal-

ibrated WNMM was used to simulate N₂O emissions from this soil using historic daily weather data from 1968 to 2004 and applying seven scenarios of fertiliser N application. Correlation analysis found that the annual N₂O emissions for this rain-fed wheat cropping system were significantly correlated to the annual average of daily maximum air temperature ($r=0.51$ for CC+BURN+N and 0.56 for DD+RET+N), annual rainfall ($r=-0.56$ for CC+BURN+N and -0.59 for DD+RET+N) and fertiliser N application rate ($r=0.43$ for CC+BURN+N and 0.31 for DD+RET+N). Based on the 37-year historic simulations, multivariate regression models for estimating annual N₂O emissions were developed to account for climatic variation, and explained about 50% of variations of annual N₂O emissions estimated by WNMM.

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Introduction

Nitrous oxide (N₂O) is one of the greenhouse gases causing global warming (IPCC 1997). Soils are the most important source of N₂O emissions to the atmosphere, contributing 57% of total global annual emissions. Thirty-five percent of global N₂O emissions are estimated to come from agricultural industries (FAO/IFA 2001; Mosier et al. 1998), mainly due to the use of N fertilisers. In recent years, research has fo-

cused on the development of more accurate estimates of N₂O emissions from agricultural soils (Sozanska et al. 2002). N₂O emissions from soils are principally produced by microbial nitrification and denitrification. These processes are controlled by several factors: soil moisture content or oxygen availability, substrate availability (ammonium and nitrate), soil temperature, soil pH, and in the case of denitrification, labile organic carbon, as reviewed by Granli and Bøckman (1994). The relative importance of these two processes on N₂O emissions depends on climatic conditions. For example, in arid and semi-arid agroecosystems nitrification-induced N₂O may contribute more to total N₂O emissions than in moist temperate regions.

The empirical methodology for estimating N₂O emissions from soils is provided by the Intergovernmental Panel on Climate Change (IPCC 2006). Based on the IPCC recommendation, a default emission factor (EF) of 1% of applied fertiliser N is recommended to estimate direct N₂O emissions from soils (Bouwman 1996; Bouwman et al. 2002; Mosier 1994; Mosier et al. 1996), regardless of variations in soil types, land management, topography and climate. However, Smith et al. (1998) indicated that soil management, cropping systems and rainfall inputs are all relevant in predicting N₂O emissions from agricultural systems. Dobbie et al. (1999) concluded that, in Scottish climatic conditions at least, the EF was affected by short-term weather patterns that affected soil water-filled pore space (WFPS) and crop type. Clayton et al. (1994) showed that N₂O emissions from non-grazed grass were related to air temperature, soil nitrate concentration and recent rainfall. Sozanska et al. (2002) applied a regression model, comprised of fertiliser N input, WFPS, soil temperature and land use, to the prediction of annual N₂O emissions for the national UK inventory, demonstrating the limitation of the simulation was due to insufficient information pertaining to soil and land use combinations. Corre et al. (1999) reported a relationship between N₂O emissions and topography in Saskatchewan, Canada. Lilly et al. (2003) determined the annual N₂O emissions in two Scottish regions based on land use type, soil wetness, fertiliser N application, and crop growth stage, with a principal objective of identifying localised areas with large emissions. It is therefore inadequate to use a single default EF to estimate annual N₂O emissions for a national greenhouse gas inventory. Crop type, management and climate need to be included to accu-

rately estimate annual N₂O emissions and EFs from agricultural soils.

Process-based models simulating dynamic processes of soil nitrification and denitrification, and their contributions to N₂O production, have the advantage of incorporating all relevant variables of soil, crop, management and climate (Chen et al. 2008), but these models are often constrained by requirements for substantial data inputs (e.g. hourly or daily weather variables) and comprehensive parameters. A number of simulation studies using process-based models have been carried out to estimate annual national N₂O emissions from agricultural soils in many countries, such as Costa Rica (Plant 1999), China (Li et al. 2001), UK (Brown et al. 2002), the USA (Li et al. 1996), and Canada (Smith et al. 2004). The obvious advantage of using process-based models is the ability to demonstrate inter-annual variation of national N₂O emissions from agricultural soils. However, the significant disadvantage of this kind of simulation is that it only provides estimates of historical N₂O emissions and is unable to predict future N₂O emissions due to lack of detailed daily weather information. For a specific crop and soil, a robust regression model, which incorporates both agricultural management and yearly climatic variation, will have the potential to provide a more accurate estimate of annual N₂O emissions than the recommended IPCC EF approach.

In this study, we applied the Water and Nitrogen Management Model (WNMM; Li et al. 2007) to simulate N₂O emissions, as well as soil water, N dynamics, and plant growth, from a rain-fed wheat system under conventional and conservation tillage practices in southeastern Australia. Based on 37-year historic simulations, regression models for annual N₂O emissions were developed for this site. The derived regression models have the potential to be used to predict annual N₂O emissions under different future climate change scenarios provided by regionalised climate models, such as OzClim (Page and Jones 2001).

Materials and methods

Study site

The field experiment was carried out in a long-term wheat cropping system on a sandy clay loam soil at Rutherglen (36.10° S, 146.51° E) in northeast Victoria,

southeastern Australia. The site has a semi-arid continental-oceanic climate with an annual average temperature of 14.4°C and a mean annual precipitation of 610 mm, most of which falls in winter (June–August) and the rest is distributed through spring (September–November), summer (December–February) and autumn (March–May). The soil is classified as a Stillards loam (Mottled-Sodic Eutrophic Yellow Dermosol; Imhof et al. 1996). The top 20 cm of soil has a sand, silt, and clay content of 62%, 23% and 15%, respectively; soil organic matter of 15.5 g kg⁻¹; total N of 1.0 g kg⁻¹; pH (1:5 H₂O) of 5.4; soil cation exchange capacity of 4.3 cmol kg⁻¹ soil; and bulk density of 1.54 g cm⁻³. The soil hydraulic properties at this site are presented in Table 1.

Treatments

Experimental plots (4.25×20 m) used for the trial were sown to winter wheat (*Triticum aestivum*, L., cv. Diamondbird). The effects of fertiliser N, cultivation and stubble management practices were observed, resulting in three treatments: conventional cultivation, stubble burned with (CC+BURN+N) or without (CC+BURN-N) N fertiliser and direct drilled, stubble retained with N fertiliser (DD+RET+N). Crop stubble was left standing following harvest (December) and stubble burning occurred prior to cultivation and sowing (May). Cultivated plots were tilled, while the direct-drilled plots received no soil disturbance other than sowing. Granular fertiliser (Pasture Gold: 14% P and 14% S) was applied at sowing at a rate of 145 kg ha⁻¹, and urea was applied by hand to each of the selected (+N) treatments during the growing season at 55 and 27 kg N ha⁻¹ on 8 and 27 September 2004, respec-

tively (Barker-Reid et al. 2005). Each treatment was replicated for a total of six experimental plots.

Measurement of N₂O fluxes from March 2004 to March 2005

Automated chambers (Meyer et al. 2001) were used to collect samples of gas emitted from the soil. Chambers (two for each treatment) were alternated between two bases (two per chamber) after each sampling period to minimise the impact on crop health, and chamber extensions were also fitted to increase chamber height as the crop grew. Gas samples were automatically collected from within the chamber, with samples collected at 3 and 48 min after lid closure. Chamber lids remained open between sample collection periods, which occurred every 4 h. Gas samples were aggregates of samples collected over 2- or 3-days, and samples were collected in separate tedlar gas-tight bags. During periods of anticipated increased N₂O emissions (e.g. after fertilisation), samples were aggregated on a daily base. N₂O concentrations were determined using a gas chromatograph.

Measurement of soil water content and mineral N contents from January/March 2004 to March 2005

Soil water content was monitored using ThetaTM probes (integrating from soil surface to ~6 cm) within each chamber base, and ThetaTM probes were calibrated against gravimetric soil water measurements during periods of both moist and dry soil. Six soil cores (0–10 and 10–20 cm) were collected at least once per month from each of the plots and combined to produce one composite soil sample for each depth per plot for measurement of ammonium and nitrate.

Table 1 Soil hydraulic properties at Rutherglen site (Imhof et al. 1996)

Soil layer (cm)	Dry bulk density (g cm ⁻³)	Air-dry water content (cm ³ cm ⁻³)	Water content at wilting point (cm ³ cm ⁻³)	Water content at field capacity ^a (cm ³ cm ⁻³)	Saturated hydraulic conductivity ^a (mm h ⁻¹)
0–10	1.49	0.021	0.054	0.345	20.00
10–20	1.58	0.023	0.061	0.301	5.00
20–40	1.65	0.034	0.089	0.300	1.00
40–70	1.72	0.047	0.123	0.295	0.25
70–150	1.72	0.062	0.161	0.295	0.05

^a Estimated using Rosetta 1.0 and calibrated during the simulation

WNMM

WNMM (Li et al. 2005, 2007) is a spatially referenced biophysical model that simulates the key processes of water and C and N dynamics in the soil-crop system, including evapotranspiration, canopy interception, water infiltration and redistribution, groundwater fluctuations, soil temperature, solute transport, crop growth, C and N cycling and agricultural management practices (crop rotation, irrigation, N fertiliser application, harvest, and tillage). The model runs at a daily or hourly time step and requires the following data: land use, soil properties, agricultural management, crop biological data and weather information. A detailed description of simulating soil water dynamics, C and N cycling, solute transport and crop growth in WNMM is presented in Li et al. (2007).

WNMM simulates N₂O emissions from nitrification and denitrification processes within soil. There are three options for simulating nitrification and denitrification: the WNMM gas module (Li et al. 2005), the DAYCENT gas module (Parton et al. 2001) and the DNDC gas module (Li et al. 1992; Li 2000). A comparison of estimating N₂O emissions from light-textured soils using these three gas modules indicated that the WNMM gas module was superior in simulating soil nitrification and denitrification and their contribution to N₂O emissions (Li et al. 2005); therefore, the WNMM gas module was selected to carry out N₂O simulation in this study from January 2004 to March 2005.

Meteorological data

The WNMM requires daily weather variables, including maximum and minimum air temperature, solar radiation, rainfall and pan evaporation. Data for Rutherglen, from 1968 to 2005, were obtained from the SILO Patched Point Dataset, managed by the Australian Bureau of Meteorology and Queensland Department of Natural Resources and Mines (<http://www.nrw.qld.gov.au/silo/ppd/index.html>).

Methodology

As there was only one year of continuous N₂O measurements (March 2004 to March 2005), the treatment CC+BURN+N was used for calibrating WNMM and DD+RET+N for model validation. The treatment CC+BURN-N was excluded because there are a few unex-

plained large N₂O emissions within the dataset. The validation of a model for the purpose of accounting for climatic variation using a one-year dataset, as applied in this study, has obvious drawbacks because the weather and climate act differently in influencing N₂O emissions from soils. The impact of weather variables on N₂O emissions focuses on variations at micro time-scales, such as not emitting or emitting less/more N₂O on a specific day due to lower/higher rainfall and air temperature, whilst the impact of climate on N₂O emissions is associated with emission variations responding to annual dry/wet and cold/warm seasons and the pattern change of these seasons among different years, which are eventually represented by daily air temperature and rainfall. Thus, the climatic effect on N₂O emissions is the integration of the weather effect, but it might be confounded by other factors that are also impacted by climate variations, such as crop growth/N uptake and N leaching as they influence the mineral N dynamics in the topsoil. Therefore, year-round data at a daily time-scale should provide sufficient information to calibrate the inter-annual variations of N₂O emissions from soil nitrification and denitrification as simulated by WNMM, if crop growth and soil organic N mineralisation are accurately simulated.

Seven fertiliser N application scenarios (−100%, −50%, −25%, 0%, +25%, +50% and +100% of 82 kg N ha^{−1} yr^{−1}) were generated for the simulation. For each treatment (CC+BURN+N or DD+RET+N), sowing date, dates and methods of fertiliser N applications, and harvest date remained the same for all seven scenarios. The model was run for each agricultural practice scenario and re-initialised on the first day of each year, from 1968 to 2004 (the weather data for 2005 was only partially available, and thus year 2005 was excluded), to overcome the influence of any cumulative changes in the soil C and N conditions on N₂O emissions. Annual N₂O emissions for each fertiliser N application scenario, over the 37-year simulation period, were statistically analysed using Pearson correlation analysis, correlating annual N₂O emissions against a number of climatic variables, including annual averages of daily maximum and minimum air temperature, annual solar radiation, annual rainfall and annual pan evaporation. Thereafter, a backward stepwise multiple linear regression was used to derive a relationship between annual N₂O emissions, climatic variables and fertiliser N application.

R package (www.R-Project.org) was used for all statistical analyses in this paper. The statistical sig-

nificance, the high significance and the very high significance are defined at the 0.05, 0.01, 0.001 levels (two-tailed), respectively. The performance of the models was evaluated by the agreement between the observations and the predictions using indices of the linear regression: adjusted determining coefficient (adjusted R^2), residual standard error (RSE) and probability (p) value.

Results and discussion

Calibration and validation of WNMM

The WNMM was pre-calibrated to rain-fed wheat cropping conditions as it had been previously optimised for intensive irrigated wheat and maize systems in the North China Plain (Li et al. 2005). Using limited field observations, including grain yield, crop N content and topsoil mineral N content measured in the end of 2003, various modules (including crop growth, C and N cycling and other related processes) were calibrated. For the simulation of January 2004–March 2005, the prediction errors of crop aboveground biomass, grain yield and crop N uptake by WNMM for both treatments were all within 10% of the observed values (data not presented).

Soil water content

In this study, 80% of pan evaporation was used to estimate the potential evapotranspiration, and the tipping-bucket water balance hydraulic module was deployed to predict soil water dynamics in WNMM. The separation of potential transpiration and potential soil evaporation is controlled by the wheat leaf area index. Because there was no measurement of soil saturated hydraulic conductivity (K_{sat}) at this site, the pedo-transfer function software Rosetta 1.0 developed by USDA Salinity Laboratory (www.ussl.ars.usda.gov/MODELS/rosetta/rosetta.htm) was used to estimate these values at soil depths based on soil bulk density, organic matter content and sand-silt-clay composition. The calibration process related to soil water dynamics was mainly focused on determining reasonable K_{sat} for each soil layer, with most attention paid to the top 20 cm and the bottom layer of the soil profile. Daily maximum/minimum air temperature and rainfall between January 2004 and March 2005 at the Rutherglen site are shown in Fig. 1.

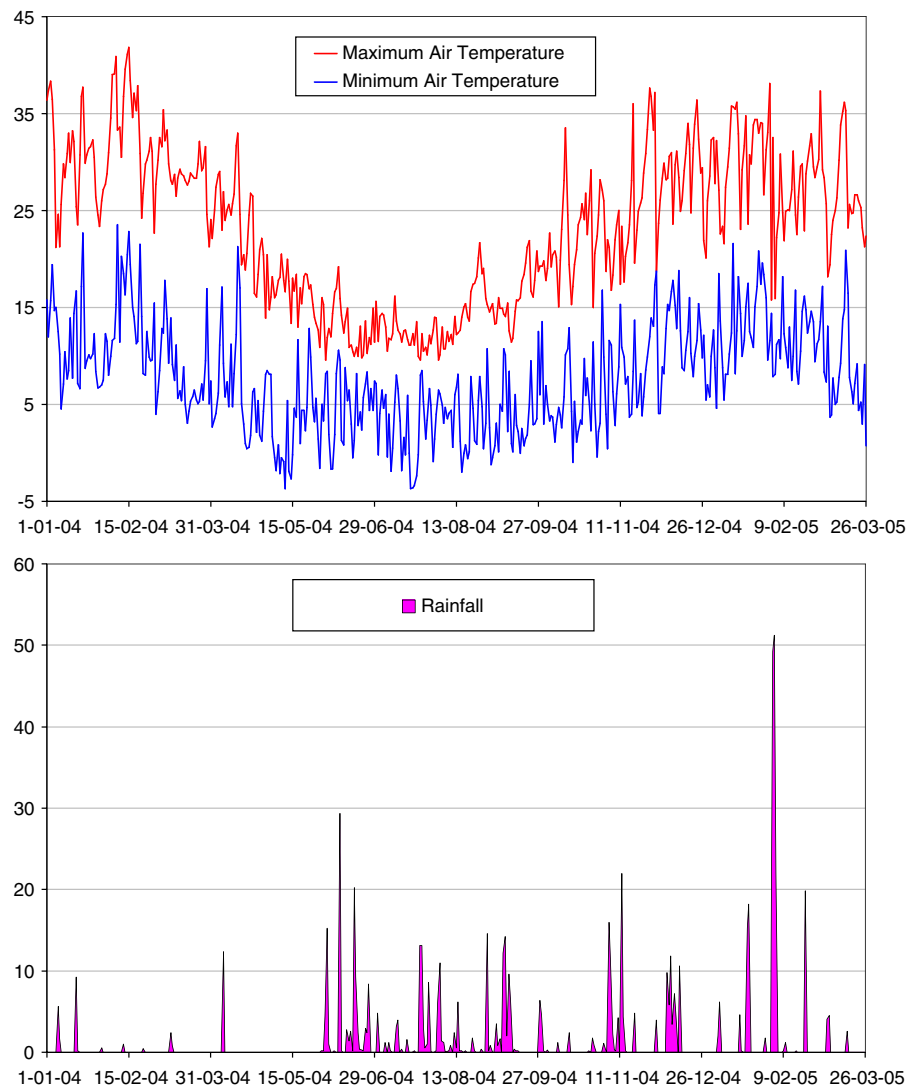
Observed and simulated soil water contents of 0–6 cm topsoil are presented in Fig. 2, demonstrating that WNMM provides a good prediction at both calibration and validation stages. It is also apparent that soil water dynamics for both treatments respond well to rainfall events (Fig. 1 and 2). There was a slight over-prediction during mid-November 2004 to mid-January 2005, as the absence of tillage and the retention of stubble on the soil surface at harvest in DD+RET+N was expected to retain more water in the soil relative to the CC+BURN+N treatment.

Soil mineral N

Theoretically, the ammonium-N concentration in the soil is dynamically controlled by inputs (organic N mineralisation, fertiliser N addition and rainfall N deposited) and losses (ammonia volatilisation, nitrification, downward leaching and crop uptake), while soil nitrate-N concentration is controlled by different inputs (nitrification and rainfall N deposited) and losses (denitrification, downward leaching and crop uptake). It was expected that the treatment DD+RET+N would have a higher soil mineral N content than the treatment CC+BURN+N, because the wheat straw retained on the soil surface will produce more mineral N when decomposed. During the calibration process, the internal parameters for organic N mineralisation, ammonia volatilisation, nitrification, denitrification and leaching processes were optimised to make the predicted soil mineral N content fit the field measurements.

For the treatment CC+BURN+N, as shown in Fig. 2a, the measured ammonium-N concentration of 0–20 cm topsoil had few fluctuations compared to nitrate-N, except for two fertiliser N applications in early and late September 2004, and most were under 5 mg N kg⁻¹ soil. In general, the WNMM-predicted ammonium-N concentration of the 0–20 cm topsoil matched the field measurements well. From January 2004, the nitrate-N in the 0–20 cm topsoil accumulated, then declined with wheat emergence, and reached its low point in August and early September. N transformations appear to be very different in this wheat cropping system, as compared to those in the North China Plain (Li et al. 2005), and may be due to low soil pH and high clay content in the topsoil at this site. Soil nitrate-N did not increase dramatically as soil ammonium-N sharply declined after fertiliser N application. Based on the WNMM simulation, which accounted the

Fig. 1 Measured daily maximum/minimum air temperature ($^{\circ}\text{C}$) and rainfall (mm d^{-1}) at the Rutherglen site from January 2004 to March 2005



ammonium losses by ammonia volatilisation, nitrification and wheat N uptake, N immobilisation was dominant during that short period. The WNMM prediction well matched the observed nitrate-N concentration of the 0–20 cm topsoil shown in Fig. 2a.

The validation simulation of mineral N contents of the 0–20 cm topsoil for the treatment DD+RET+N is shown in Fig. 2b. The pattern of topsoil ammonium-N concentrations is very similar to CC+BURN+N, but the topsoil had higher nitrate-N concentration, which is attributed to the decomposition of wheat straw retained on the soil surface. A large discrepancy between measured and predicted nitrate-N concentrations occurred during the autumn and winter time period in 2004, although the cause is not clear.

Nitrous oxide (N_2O)

The WNMM calibration of N_2O emissions (January 2004 to March 2005) for the treatment CC+BURN+N was in reasonable agreement with the chamber observations (Fig. 2a) but the correlation coefficient between the predicted and measured daily N_2O emissions was low although statistically significant ($R^2=0.05$, $\text{RSE}=0.0008$, $n=106$ and $p<0.05$). The correlation for monthly emissions was much better ($R^2=0.34$, $\text{RSE}=0.0049$, $n=11$ and $p\approx 0.05$; data not presented), indicating some mismatch between measured and simulated emissions at a daily time step. There is an obvious discrepancy between the observed and the predicted values in August 2004 (Fig. 2a) when the topsoil had a very low

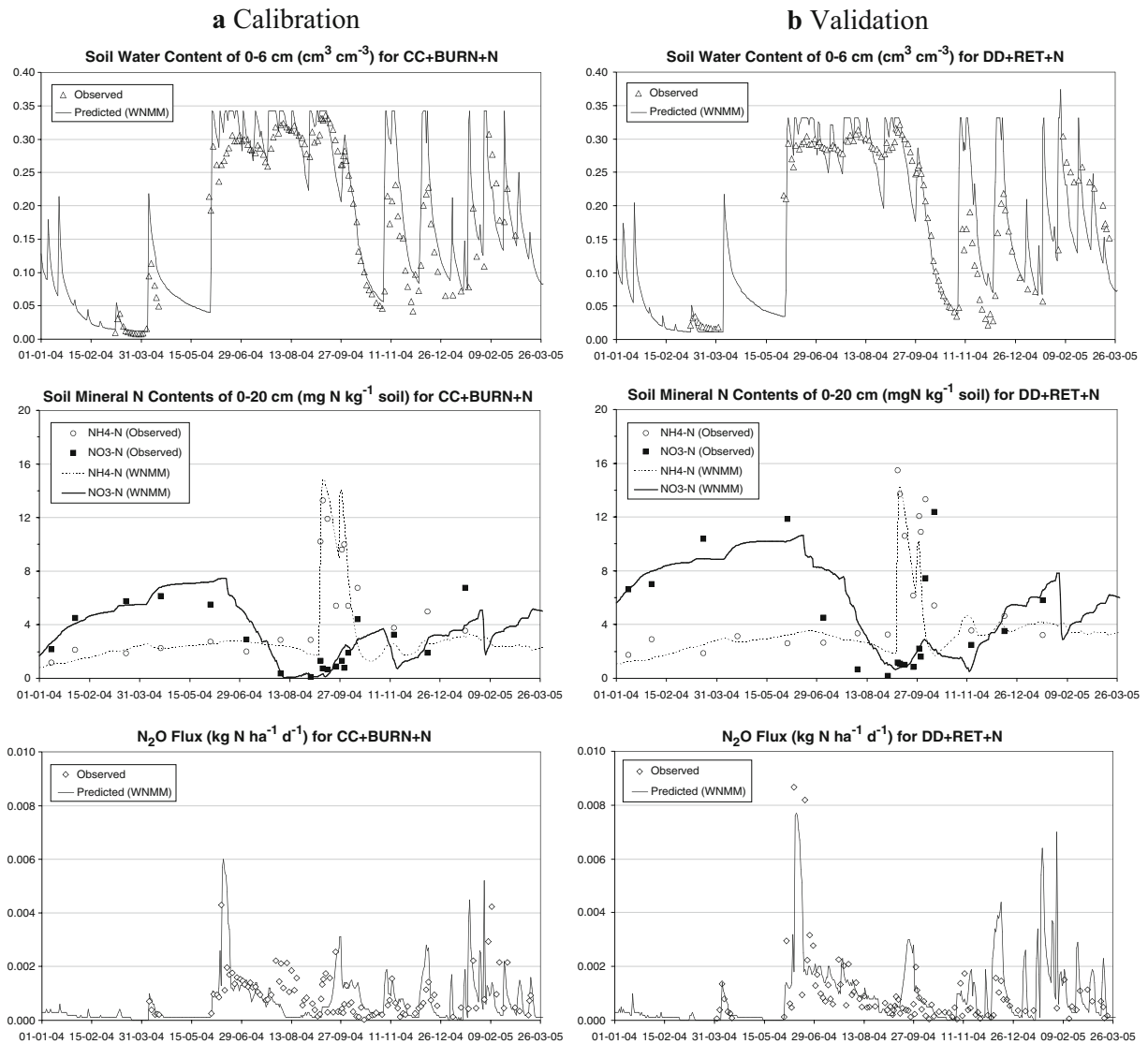


Fig. 2 Field-measured and WNMM-simulated soil water content of 0–6 cm, soil mineral N contents of 0–20 cm and N_2O emissions for the treatments CC+BURN+N (a, Calibration) and DD+RET

+N (b, Validation) from January 2004 to March 2005. Note that NH_4 is for ammonium and NO_3 is for nitrate

nitrate concentration but the responding N_2O emissions were relatively high. These higher emissions could be associated with the soil nitrification process at low soil temperatures (e.g. less than 5°C) or simply caused by spatial variability. They could also reflect the discrepancy in the frequency of measurements (soil samples only collected monthly, being correlated with 2- or 3-day N_2O measurements). In the current version of WNMM, the soil nitrification process at low soil temperatures is kept very slow, and would not produce adequate N_2O emissions to match the observed cham-

ber data. A modification to the WNMM gas production module, to account for the above situation, will be conducted when the specific laboratory incubation experiment is carried out in the future.

The validation results for N_2O emissions from the treatment DD+RET+N (Fig. 2b) were promising at a daily ($R^2=0.12$, $\text{RSE}=0.0009$, $n=102$ and $p<0.01$) and monthly (data not presented; $R^2=0.71$, $\text{RSE}=0.0039$, $n=11$ and $p<0.01$) time step. In particular, the performance of the WNMM N_2O gas production module during August 2004 was improved for this treatment.

As shown in Fig. 1 and 2, N_2O gas production is more sensitive to rainfall events than fertiliser N applications (on 8 and 27 September 2004), especially in early June 2004 when winter rainfall started, after a long dry summer and autumn period, and a substantial amount of mineral N accumulated in the topsoil.

The annual N_2O emissions estimated by WNMM from January to December 2004 are 0.223 and 0.310 kg N ha⁻¹ yr⁻¹ for the treatments CC+BURN+N and DD+RET+N, respectively, comparable to 0.160 and 0.196 kg N ha⁻¹ yr⁻¹ for the two treat-

ments, respectively, estimated by Barker-Reid et al. (2005) based on chamber observations. Compared to reports from USA (Li et al. 1996), UK (Dobbie and Smith 2003) and China (Li et al. 2005), the annual N_2O emissions from this rain-fed wheat cropping site in southeastern Australia are very small, accounting for only 0.33% of applied fertiliser N, where it is uncorrected for background emissions. Based on the WNMM simulation, the nitrification process contributed 45% and 34% of the total emissions for CC+BURN+N and DD+RET+N, respectively.

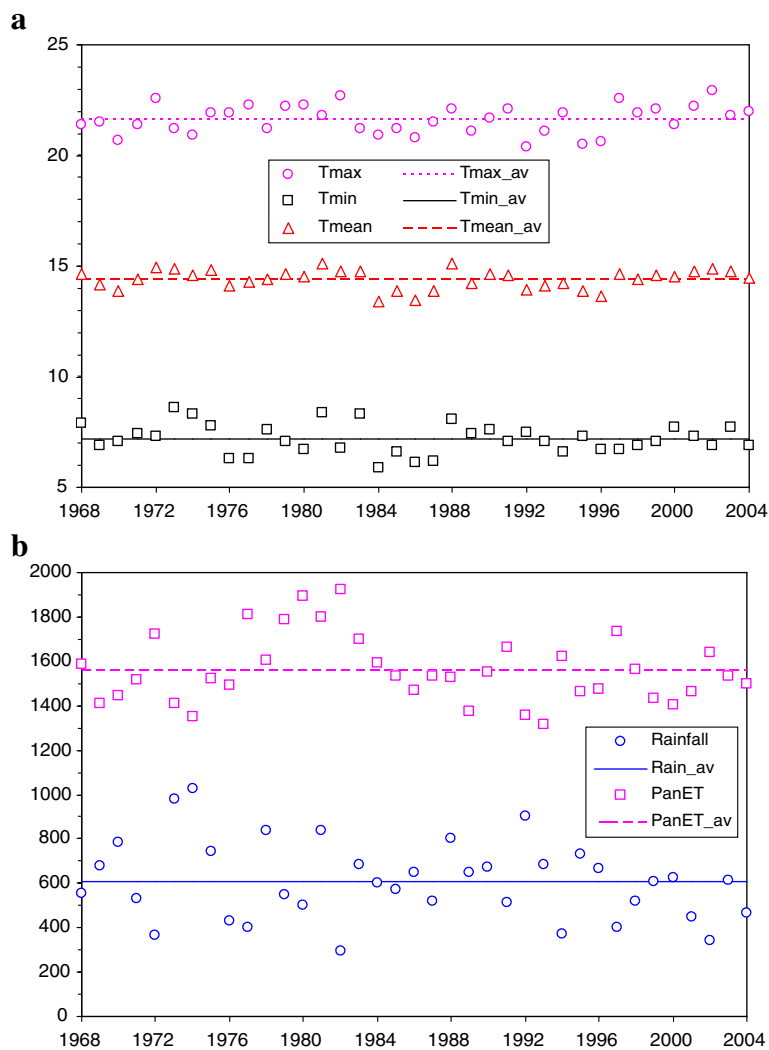


Fig. 3 Annual averages of daily minimum (T_{min}), maximum (T_{max}) and mean (T_{mean}) air temperature (°C) (a), and annual rainfall (Rainfall) (mm) and annual pan evaporation (PanET)

(mm) (b) at the Rutherglen site from 1968 to 2004. T_{min_av} , T_{max_av} , T_{mean_av} , $Rainfall_av$ and $PanET_av$ are the 37-year averages

Development of N₂O emission regression models to account for climatic variation

37-year simulations

For each treatment, the calibrated and validated WNMM was re-initialised on the first day of each year, using simulated soil moisture and soil profile mineral N contents at the Rutherglen site, and was run for seven proposed fertiliser N application scenarios using the daily weather dataset from 1968 to 2004. The yearly variations of annual averages of daily minimum/maximum/mean air temperature, annual rainfall and annual pan evaporation are shown in Fig. 3. The annual average temperature fluctuated little although there is a slight increasing trend for the annual average of daily maximum air temperature ($y=0.0026x+16.52$, $n=37$ and $R^2=0.003$). The annual rainfall varied clearly with a declining trend ($y=-1.1358x+2,849.3$, $n=37$ and $R^2=0.008$). Neither of these trends is not statistically significant.

The 37-year daily N₂O emissions for both treatments and seven fertiliser N application scenarios were simulated by WNMM, and the annual N₂O emissions were summarised as shown in Fig. 4. Emissions from CC+BURN+N appear to be significantly less than those from DD+RET+N ($p=0.007$). The annual N₂O emissions at this site increase very small with increasing fertiliser N application rate, ranged from

0.01% to 0.15% (average of 0.07%) of applied N, much lower than the IPCC default value of 1%.

The between-year variation of annual N₂O emissions was dramatic. The simulated annual N₂O emissions for the treatment DD+RET+N at the current fertiliser N application rate (82 kg N ha⁻¹ yr⁻¹) ranged from 0.12 to 0.65 kg N ha⁻¹ yr⁻¹ (Fig. 5a). This indicates the strong influence of climatic variation on N₂O emissions. Annual N₂O emissions increase with the increase of annual average of daily maximum air temperature, but decrease when annual rainfall increases (Fig. 5b,c).

Correlation analysis

The Pearson correlation analysis was carried out separately for both treatments in order to study the statistical relationship between the 37-year WNMM-estimated annual N₂O emissions and related indices (including annual nitrification-induced N₂O, annual denitrification-produced N₂O, fraction of annual nitrification-induced N₂O in annual N₂O emissions and EF), and climatic variables and fertiliser N application rate. In this study, EF was calculated as the percentage of applied fertiliser N lost as N₂O emissions, not corrected for background emissions. The results for such an analysis are summarised in Table 2.

The two treatments have very similar correlation patterns with selected variables. Regardless of the treat-

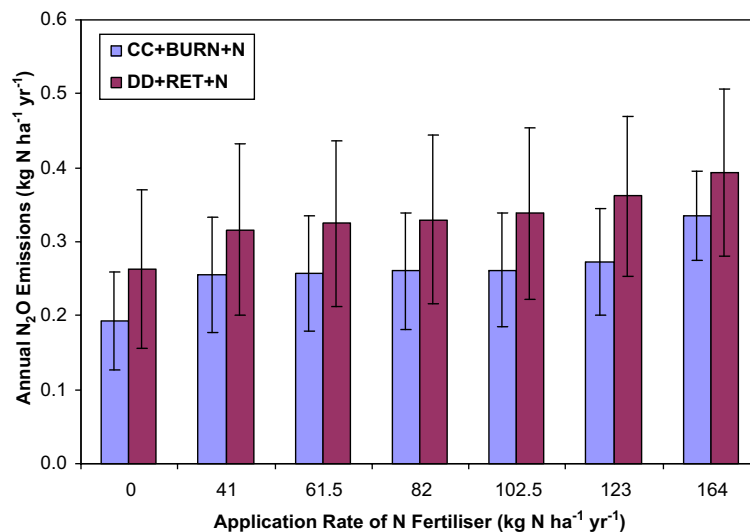


Fig. 4 The 37-year averages of WNMM-estimated annual N₂O emissions for seven fertiliser N application scenarios for the treatments CC+BURN+N and DD+RET+N at the Rutherglen site. The bars represent ± 1 standard deviation

Fig. 5 Yearly variation of the WNMM-estimated annual N_2O emissions (a) and the effects of the annual average of maximum air temperature (b) and annual rainfall (c) on the WNMM-estimated annual N_2O emissions for the treatment DD+RET+N at the current fertiliser N application rate ($82 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) at the Rutherglen site from 1968 to 2004

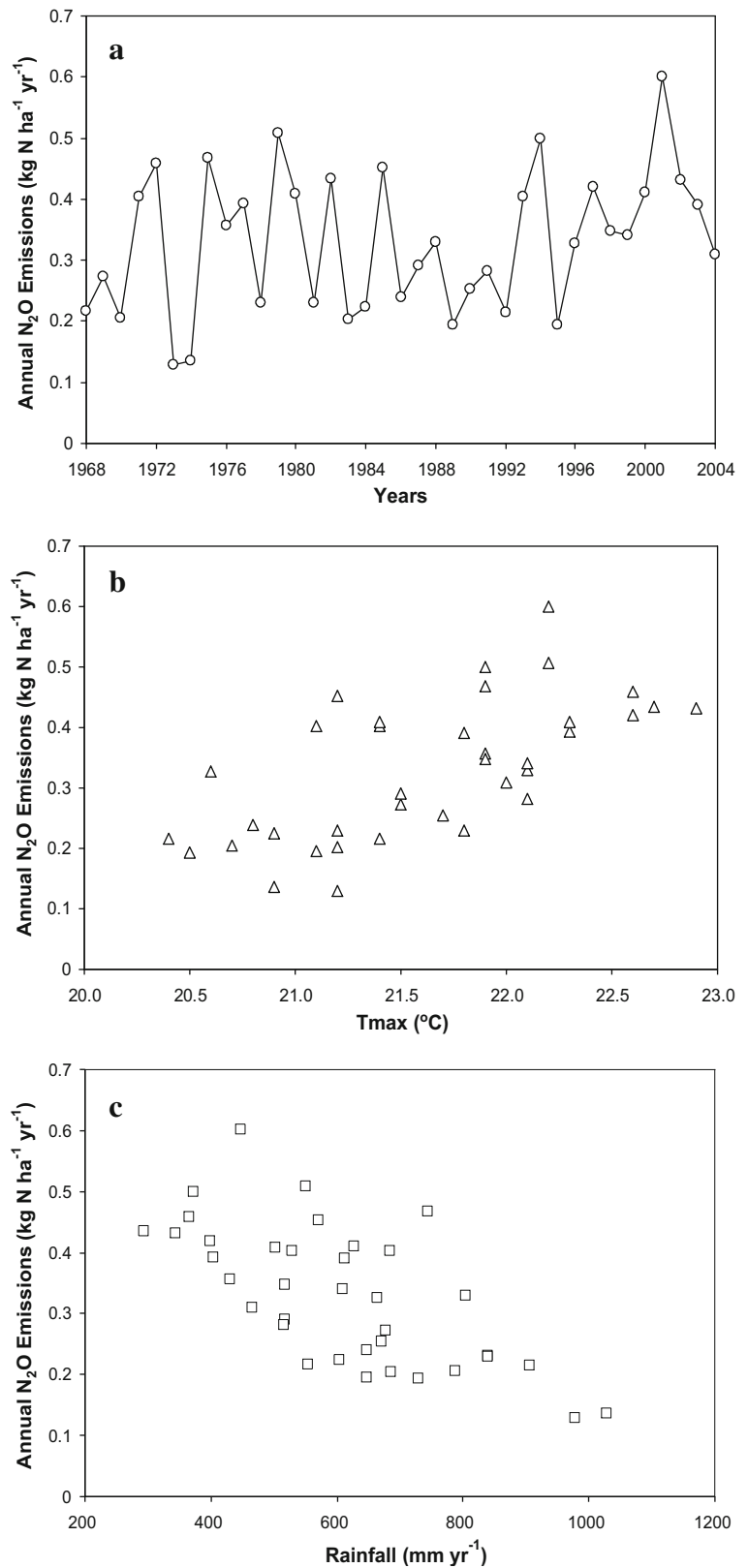


Table 2 Correlation coefficients (r) of WNMM-estimated annual N₂O emissions and related indices against climatic variables and fertiliser N application rate ($n=259$, except for EF with $n=222$) for 37-year historic simulations under seven fertiliser scenarios

r	Tmax		Tmin		Tmean		Rainfall		PanET		N	
	CC	DD	CC	DD	CC	DD	CC	DD	CC	DD	CC	DD
N ₂ O	0.51 ^b	0.56 ^b	-0.26 ^b	-0.27 ^b	0.19 ^b	0.21 ^b	-0.56 ^b	-0.59 ^b	0.28 ^b	0.27 ^b	0.43 ^b	0.31 ^b
N ₂ O_Nit	0.27 ^b	0.17 ^a	-0.15 ^a	-0.12	0.09	0.03	-0.29 ^b	-0.19 ^b	0.27 ^b	0.14 ^a	0.73 ^b	0.81 ^b
N ₂ O_Den	0.48 ^b	0.56 ^b	-0.24 ^b	-0.25 ^b	0.18 ^b	0.22 ^b	-0.53 ^b	-0.58 ^b	0.19 ^b	0.25 ^b	0.11	0.08
fNit	-0.18 ^b	-0.34 ^b	0.12	0.24 ^b	-0.04	-0.07	0.22 ^b	0.41 ^b	0.02	-0.14 ^a	0.54 ^b	0.51 ^b
EF	0.32 ^b	0.37 ^b	-0.17 ^a	-0.18 ^a	0.11	0.14 ^a	-0.36 ^b	-0.39 ^b	0.19 ^b	0.18 ^a	-0.71 ^b	-0.67 ^b

N Application rate of fertiliser N, kg N ha⁻¹ yr⁻¹; CC the treatment CC+BURN+N; DD the treatment DD+RET+N; N₂O annual N₂O emissions, kg N ha⁻¹ yr⁻¹; N₂O_Nit annual nitrification-induced N₂O, kg N ha⁻¹ yr⁻¹; N₂O_Den: annual denitrification-produced N₂O, kg N ha⁻¹ yr⁻¹; fNit fraction of annual nitrification-induced N₂O in annual N₂O emissions, 0–1; EF emission factor (not corrected for background emissions), %

^aSignificant at the 0.05 level (two-tailed)

^bSignificant at the 0.01 level (two-tailed)

ment, annual N₂O emissions have positive and highly significant correlations with the annual average of daily maximum air temperature and fertiliser N application rate, but a negative and highly significant correlation with annual rainfall. As expected, the responses of annual N₂O emissions to fertiliser N application rates were positive and statistically significant. The positive impact of temperature on annual N₂O emissions was similar to results reported by Li et al. (1992), Smith et al. (1998) and Chatskikh et al. (2005), but in this case, annual N₂O emissions were more sensitive to the annual average of daily maximum air temperature than to the minimum or mean. The negative relationship between annual N₂O emissions and annual rainfall observed in this study was similar to findings by Li et al. (1992), Smith et al. (1998) and Chatskikh et al. (2005). It is generally expected that higher rainfall results in more denitrification, therefore, potentially contributing to more N₂O emissions from the soil. It is also possible that the increase in rainfall may increase crop growth resulting in more N uptake and possibly nitrate leaching, consequently reducing the nitrate availability in the topsoil for soil denitrification process. The negative re-

lationship between annual rainfall and annual N₂O emissions can occur under specific circumstances, such as mid-range annual rainfall, high sensitivity of crop growth to rainfall and a well-drained soil.

For annual nitrification-induced N₂O, there is a positive and highly significant relationship with fertiliser N application rate, a positive and significant correlation with the annual average of daily maximum air temperature, but a negative and significant correlation with annual rainfall. The fraction of annual nitrification-induced N₂O in annual N₂O emissions is positively and highly significantly correlated to fertiliser N application rate and annual rainfall, but negatively and significantly correlated to the annual average of daily maximum air temperature. Annual denitrification-produced N₂O has a similar correlation pattern to annual N₂O emissions, except for fertiliser N application rate, which is not significantly correlated, indicating that denitrification was not limited by the substrate supply (nitrate) in this system. The EF has highly significant correlations with the annual average of daily maximum air temperature (positive), annual rainfall (negative) and fertiliser N application rate (negative).

Table 3 Coefficients of linear regression models used to estimate annual N₂O emissions (kg N ha⁻¹ yr⁻¹) for the treatments CC+BURN+N and DD+RET+N at the Rutherglen site ($n=259$)

Coefficient	N	Tmax	Rainfall	Intercept	Adj. R ²	RSE	p
CC+BURN+N	0.000708 (0.000070)	0.0307 (0.0075)	-0.000185 (0.000027)	-0.346 (0.174)	0.53	0.056	<0.001
DD+RET+N	0.000728 (0.000104)	0.0534 (0.0112)	-0.000256 (0.000041)	-0.725 (0.261)	0.48	0.084	<0.001

The values in parentheses represent the standard errors of the coefficients

Derivation of regression models for estimating annual N₂O emissions

Based on the correlation analysis, the most significant climatic variables driving yearly variation of annual N₂O emissions and EF for this rain-fed wheat cropping system were the annual average of daily maximum air temperature and annual rainfall. Including the fertiliser N application rate as another input variable, multivariate regression models were developed for estimating annual N₂O emissions for the treatments CC+BURN+N and DD+RET+N (Table 3), and explained about 50% of the yearly variations of annual N₂O emissions predicted by WNMM for both treatments ($n=259$ and $p<0.001$).

A multivariate regression model developed by Sozanska et al. (2002) for British soils, $\ln[\text{N}_2\text{O}]$ ($\text{kg N ha}^{-1} \text{ yr}^{-1}$) = $-2.7 + 0.60 \ln[\text{N input}]$ ($\text{kg N ha}^{-1} \text{ yr}^{-1}$) + $0.61 \ln[\text{WFPS}]$ (%) + 0.035 [soil temperature at 30 cm] ($^{\circ}\text{C}$) - 0.99 [land use], explained ~40% the yearly variation of annual N₂O emissions ($R^2=0.40$, $n=107$ and $p<0.001$). Because our regression models were developed specifically for a rain-fed wheat cropping system, no land use term was required. The models developed in this study have the advantage of using only the annual average of daily maximum air temperature and annual rainfall to account for the soil water and temperature impacts on annual N₂O emissions. Similar work has been reported by Freibauer (2003) and Clayton et al. (1994), but climatic variables were less of a concern.

The multiple regression models are very useful in estimating long-term annual N₂O emissions when there is a paucity of detailed daily weather information. However, it should be pointed out that the input predictors have to be within the domain of independent variables used to generate such multiple regression models, otherwise the predictions become unreliable.

Conclusions

The WNMM model was used to estimate N₂O emissions from a rain-fed wheat cropping system on a loam-textured soil for two treatments of CC+BURN+N and DD+RET+N in Rutherglen, Australia from January 2004 to March 2005. The simulations carried out in this study indicated that WNMM was capable of simulating soil water content and mineral N content of

the topsoil, as compared to field observations. The dynamics of N₂O emissions simulated by WNMM matched those measured by automatic chambers for both treatments. In particular, monthly accumulated N₂O emissions showed good agreement between simulated and measured values. In contrast to research reported by Mosier (1994), Mosier et al. (1996) and others, annual soil N₂O emissions were characterised by relatively large emissions at the onset of winter rainfall and very little response to fertiliser N applications.

The 37-year (1968–2004) historic simulations, using the calibrated WNMM under seven scenarios for fertiliser N application, indicated that for this rain-fed wheat system annual N₂O emissions and EFs were significantly correlated to the annual average of daily maximum air temperature (positively), annual rainfall (negatively), and fertiliser N application rate (positively). Based on these simulations, multivariate regression models were developed to estimate annual N₂O emissions to account for climatic variation.

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