Prediction of carbon dioxide and nitrous oxide fluxes from a legume-pasture soil at Wagga Wagga

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Abstract The model DNDC is one of the very few process-based models that simulates carbon dioxide (CO_2) and nitrous oxide (N_2O) fluxes from field soils. We have significantly improved DNDC by including a surface energy balance, by using better formulations for soil evaporation, plant transpiration, plant growth, and plant nitrogen uptake, and by using an implicit difference scheme to solve the diffusion equations governing heat and water fluxes in the soil.

Fluxes of CO_2 and N_2O were measured from a legume pasture system at Wagga Wagga, New South Wales, Australia in 1993. The data were used to test the modified model (DNDC-DAR). The modified model predicted soil temperature and moisture well. The soil evaporation may be overestimated during the early spring season. The simulated seasonal variations in CO_2 and N_2O are also consistent with the observations. The model significantly underestimated the measured CO_2 fluxes during the winter and summer seasons, since plant respiration is not included in the model.

1. INTRODUCTION

Carbon dioxide (CO_2) and nitrous oxide (N_2O) are two important greenhouse gases in the atmosphere. Major sources of CO_2 and N_2O in Australia are land-use change and agricultural ecosystems (Galbally *et al.* 1991). While several models have been developed to simulate the CO_2 exchange between the terrestrial ecosystem and the atmosphere (Wang & Polglase 1995), few models have been developed to simulate the N_2O fluxes (Grant *et al.* 1993, Li *et al.* 1992). Recent measurements by Galbally *et al.* (1995) showed that N_2O fluxes from agricultural ecosystems in Australia are about one order of magnitude smaller than those from similar agricultural ecosystems in the Northern Hemisphere. Therefore one challenge for these models is to successfully simulate these extreme differences in trace gas fluxes from agricultural systems.

Li *et al.* (1992) recently developed a model, DNDC, to simulate CO_2 and N_2O fluxes from agricultural ecosystems. This model was tested against several field data sets collected in the Northern Hemisphere where soils are generally more fertile than in Australia. The DNDC model has recently been extended to include a plant growth model (Li *et al.* 1994). In this paper, we present some further modifications to the extended DNDC model and compare the simulation results of our modified model (DNDC-DAR) with field measurements.

2. MODEL DESCRIPTION

DNDC is composed of four submodels: physical climate, plant growth, denitrification and decomposition. The physical climate submodel simulates the hourly vertical profiles of temperature and moisture of the soil, and the plant submodel simulates the daily plant biomass production, water and nitrogen uptake. The denitrification submodel becomes active when the fraction of soil pores occupied by water exceeds a threshold value (60%) after rainfall, otherwise the aerobic processes of organic matter decomposition, carbon or nitrogen transformations are active. To account for the vertical variations of soil physical and chemical properties, the modelled soil profile is divided into a number of layers (2.5 cm depth). The total depth of the modelled soil is 50 cm. The model structure excluding the physical climate submodel is shown schematically in Fig. 1. The solid and dotted lines represent the flows of carbon and nitrogen, respectively.

The DNDC model has been modified for this study by including a pasture growth model, plant nitrogen uptake and a detailed energy balance at the soil surface. Soil evaporation and plant transpiration are simulated as functions of potential evapo-transpiration rate and soil water content. Potential evapotranspiration is simulated using the Priestly-Taylor equation rather than the Thornthwaite equation, as the former is better suited for calculating latent heat fluxes at hourly to daily time steps and smaller spatial scales (< 1 km^2). Potential evapotranspiration is partitioned between soil and plants according to Tanner and Jury (1976).

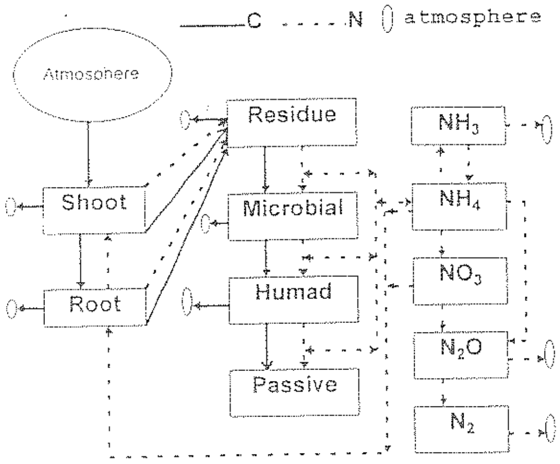

Fig. 1. A schematic diagram of the DNDC model.

Diffusion equations governing the heat and water flow in the vertical of the soil are solved using the implicit difference scheme, which is less prone to numerical errors than an explicit difference scheme used in the DNDC model.

A brief description of the new submodels is given below.

Plants are separated into shoot and root components, the daily growth rates of which are:

$$dW_s / dt = \eta_s P - \tau_s W_s$$
$$dW_r / dt = (1-\eta_s) P - \tau_r W_r$$

where P is the daily dry matter production (g C m^{-2} d^{-1}), W_s and W_r are dry weight of the shoot and roots (g C m^{-2}), respectively; τ_s and τ_r are the relative tissue death rates of shoots and roots (d^{-1}), respectively; η_s is fraction of dry matter production allocated to the shoots, t is time in days. P is calculated as (Tanner and Sinclair 1983):

$$P = e\, E_c / D$$

where e is a constant (g C kg H_2O^{-1} kPa), and E_c is the daily crop transpiration rate (kg H_2O m^{-2} d^{-1}) and D is the daily mean water vapour pressure deficit (kPa).

Daily nitrogen uptake rate (N_u, g N m^{-2} d^{-1}) is modelled using Michaelis-Menten kinetics (Nye and Tinker 1977), i.e.

$$N_u = \min\left(\frac{N_{u\max} C_N}{K_N + C_N} + N_f, N_d\right)$$

where N_{umax} is the maximum rate of nitrogen uptake at a given temperature, C_N is the concentration of total available inorganic nitrogen in the rooting zone (g N m^{-3}), and K_N is the inorganic nitrogen concentration at which nitrogen uptake proceeds at one-half its maximum rate (g N m^{-3}), N_f is biological fixation of nitrogen (g N m^{-2} d^{-1}), and N_d is the nitrogen demand due to plant growth (g N m^{-2} d^{-1}).

The energy balance at the soil surface is given by:

$$\begin{aligned} &\lambda E_s + \rho\, C_p(T_s - T_a)/r_a \\ &= [(1-\alpha)I_0 + \varepsilon_a \sigma\, T_a^4]\exp(-kL) \\ &\quad + (1-\exp(-kL))\varepsilon_c \sigma\, T_c^4 \\ &\quad - \varepsilon_s \sigma\, T_s^4 - \kappa_s (T_s - T_s^*)/\Delta z \end{aligned}$$

where λ is the latent heat of vapourisation (J kg^{-1}), E_s is soil evaporation (kg H_2O m^{-2} s^{-1}), ρ is the density of air (kg m^{-3}), C_p is the specific heat of air (J kg^{-1} K^{-1}), T_s is soil surface temperature (K), T_a is air temperature measured at the reference height (K), r_a is the aerodynamic resistance for heat transfer from the soil surface to the reference height at which wind speed was measured (s m^{-1}), α is albedo of the surface, I_0 is incoming short-wave radiation (W m^{-2}), ε_a is the emissivity of the air for long-wave radiation, k is the extinction coefficient of plant canopy for short-wave radiation, L is the canopy leaf area index, ε_c is the canopy emissivity for long-wave radiation, and σ is the Stefan-Boltzmann constant (5.67x10^{-8} W m^{-2} K^{-4}), T_c is canopy temperature (K), ε_s is soil emissivity for long-wave radiation, κ_s is the thermal conductivity (W m^{-1} K^{-1}) of the surface soil layer, T_s^* is the soil temperature at the bottom of the surface soil layer (K), and Δz is the depth of surface soil layer (0.025m).

If we assume $T_c=T_a$, and $\varepsilon_c = \varepsilon_s$, and use the following linearisation

$$\varepsilon_c\sigma T_a^4 - \varepsilon_s\sigma T_s^4$$
$$\approx (\varepsilon_c - \varepsilon_s)\sigma T_a^4 + 4\varepsilon_s\sigma T_a^3(T_a - T_s)$$

Then T_s can be calculated as

$$T_s = T_a - \frac{\lambda E_s - x_1}{x_2}$$

and

$$x_1 = [(1-\alpha)I_0 + (\varepsilon_a - \varepsilon_c)\sigma T_a^4]\exp(-kL)$$
$$+\kappa_s(T_s^* - T_a)/\Delta z$$
$$x_2 = 4\varepsilon_s\sigma T_a^3 + \rho C_p / r_a + \kappa_s / \Delta z\,.$$

Crop transpiration and soil evaporation are calculated as Wang *et al.* (1992).

3. FIELD MEASUREMENTS

Field measurements were conducted at a site on a property at Brooklyn, approximately 45 km south-east of Wagga Wagga in 1993. The site was set up by the Agricultural Research Institute, Department of Agriculture, New South Wales, and the School of Agriculture, Charles Sturt University. Liming was used to ameliorate soil acidity.

The climate at the site is semi-arid, with a mean annual rainfall of 570 mm. The soil is classified as a Solodic (Isbell 1993). Selected physical and chemical properties were measured on soil cores. The soil pH varies from 4 to 5.5. Primary plant species on the plots studied here are annual Wimmera ryegrass and subterranean clover.

Daily solar radiation, temperature, rainfall and wind speed were recorded at the nearby Wagga Wagga airport. Soil temperature was measured hourly using thermocouples placed at different depths (2.5, 7.5 cm, 12.5, 17.5 and 22.5 cm). Soil water content was measured gravimetrically by drying the soils at 105 °C. Soil samples were collected at approximately monthly intervals.

Small plots (area $\approx$0.34 m^2) were chosen for measuring CO_2 and N_2O fluxes. Fluxes were measured using automated static chambers. Air inside the closed chamber (volume $\approx$ 0.1 m^3) was constantly stirred by a fan. The chamber lid was automatically closed for 50 minutes then opened for 70 minutes. Air samples taken at 5 minutes and 45 minutes after chamber closure were accumulated in Tedlar bags. Daytime samples were collected separately from nighttime samples. These bags were changed daily and analysed during the following day. Carbon dioxide concentration was measured by an infra-red gas analysis (NDIR, model 6251 Licor, Nebraska, USA) whereas N_2O was measured using gas chromatography (Hewlett Packard, model 5890 equipped with an electron capture detector). Gas fluxes were calculated from the measured concentrations and corrected for chamber temperature and leakage; both corrections are relatively small (< 5%).

4. RESULTS

Soil temperature is most variable at the surface. The amplitude of diurnal variation in soil temperature decreases exponentially with depth. Therefore it is important that the temperature of the surface layer is accurately simulated. Fig. 2a shows a comparison of the measured with the simulated daily average temperature at a depth of 2.5 cm.

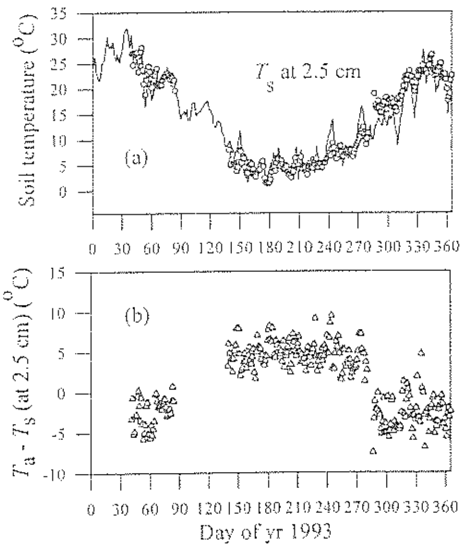

Fig. 2. (a) The simulated (solid curve) and measured (circles) average daily soil temperature at 2.5 cm depth, and (b) the temperature difference between air and soil temperature at 2.5 cm depth. T_a denotes air temperature at the reference height and T_s denotes the soil temperature at 2.5 cm depth.

Discontinuities in the measurements of soil temperature were due to equipment failure. The differences between measured and simulated temperatures usually are less than 2 °C except between day 290 and 340.

The average daily soil temperature at 2.5 cm depth was considerably cooler in the winter than that of the air (up to 9 °C), but was considerably warmer during the summer (up to 6 °C) (see Fig. 2b). The DNDC model assumes that soil temperature at the surface is equal to air temperature. Our data suggest that this assumption is not valid and can lead to significant error in the simulation of soil carbon decomposition. The rate of carbon decomposition is very sensitive to soil temperature. For example, a 9 °C error in temperature during the winter leads to the carbon decomposition rate being overestimated by 100%.

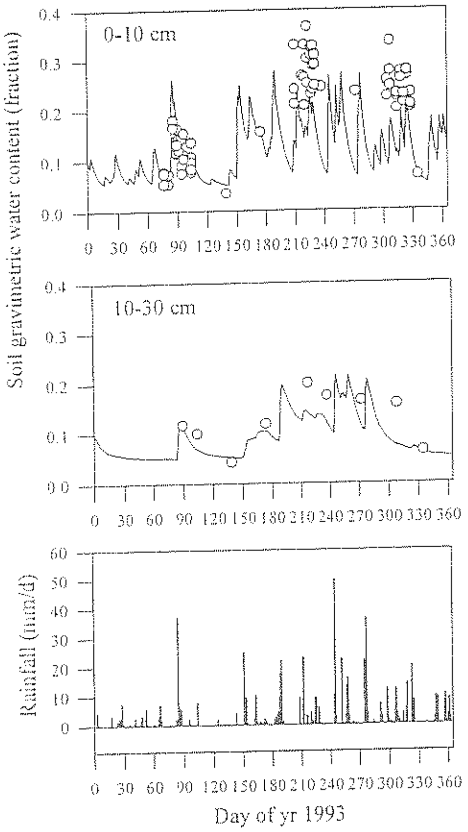

Fig. 3. The simulated (lines) and measured (circles) soil water content at two depths. The observed daily rainfall is also shown in the lower plot.

Soil water plays a key role in the fate of nitrate and the production of N_2O in the soil. The biochemical pathways of soil inorganic nitrogen transformation depends on the oxygen concentration in the soil. The oxygen diffusion coefficient in water is about four orders of magnitude smaller than that in the air. When most soil pores are filled with water, the rate of oxygen consumption by microbes and plant root activities exceeds the rate of oxygen diffusion in the soil. As a result, the soil condition becomes anoxic, and denitrifiers become active. The denitrifiers use nitrate as electron acceptor and consequently reduce it to gaseous N_2O or N_2. The other process producing N_2O is aerobic nitrification. Therefore simulation of soil water dynamics is very important part of this model.

The agreement between the modelled and measured soil water content is good (Fig. 3). The differences between the simulated and measured soil moisture content generally are less than 10%. The depletion of soil water after rain on day 84 (37 mm) was well simulated. However the DNDC-DAR model underestimated soil water content during the periods day 210 to 230 and 310 to 330. The cause for this may be that plant residues on the soil surface reduce soil evaporation and increase rainfall interception. However, the effect of crop residues on the soil water balance is not considered in our model because there was no information to quantify these effects at our site.

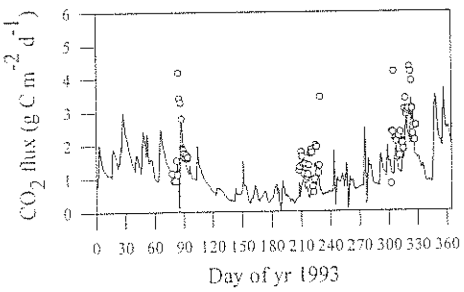

Fig. 4. Comparison of the simulated (curve) and measured (circles) daily average flux of CO_2 from a legume pasture at Wagga Wagga.

The simulated soil CO_2 fluxes are generally smaller than the measured fluxes although the simulated seasonality of CO_2 fluxes is similar to the observed (Fig. 4). The comparison between the simulated and measured fluxes is complicated by 2 factors: (1) the light flux was not measured inside the chamber, therefore plant photosynthetic rate could not be quantified; and (2) it was not possible to measure directly the plant respiration rate. However the net CO_2 fluxes were positive in the day time as well as in the night time, suggesting the plants inside the chambers were a net source of CO_2 throughout the 24-hour period. Furthermore the soil temperature inside the chamber was a few degrees higher than the soil temperature in the open under sunny conditions, therefore respiration of both soil and plants inside the chamber may be significantly higher than those in the open

The simulated N_2O fluxes agree well with the measurements (Fig. 5). When soil is relatively dry (the fraction of water filled pore space is less than 60%), then N_2O is produced from nitrification; and the rate of N_2O production strongly depends on soil temperature (Bremner and Blackmer 1981). During the first and third field trips, when soil temperature at 2.5 cm was about 15 °C, the mean flux was about 0.2 and 0.1 mg N_2O-N m^{-2} day^{-1}, respectively. During the second field trip, the soil temperature at 2.5 cm was about 5 °C, and the mean flux was about 0.03 N_2O-N mg m^{-2} day^{-1}. Between the second and third trip plant growth was rapid and most mineralised nitrogen were taken up by plants. Consequently the concentration of inorganic nitrogen in the soil during the third trip was much lower than that during the first trip, which leads to the observed difference in N_2O fluxes between first and third field trips.

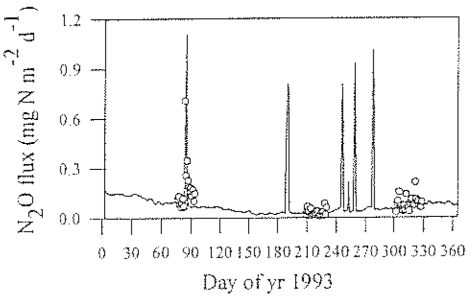

Fig. 5. The simulated (curve) and measured (circles) daily average N_2O flux.

Following rainfall on day 84 of 37 mm, the top 20 cm of soil was saturated (see Fig. 3), the flux of N_2O increased 3 fold. This increase is well simulated by the model.

The model estimate of the annual total N_2O emission from the limed plot is 0.032 g N_2O-N m^{-2} yr^{-1}, of which 88% was emitted during nitrification. Even though N_2O flux from denitrification is up to five times larger than that from nitrification, the soil under the local climate conditions usually is aerobic. The annual nitrogen loss due to denitrification rate was estimated to be 0.185 g N m^{-2} yr^{-1}. These data suggest that 98% of this denitrified nitrate was reduced to N_2.

The simulated nitrogen budget of the limed plot is shown in Fig 6. The annual mineralisation rate was about 35.8 g N m^{-2} yr^{-1}, of which 85% was taken up by plants. Biological fixation was estimated to be 2.9 g N m^{-2} yr^{-1}, and immobilisation was about 5.5 g N m^{-2} yr^{-1}. The total nitrogen lost as N_2O and N_2 from nitrification and denitrification is 0.2 g N m^{-2} yr^{-1}. In this legume pasture system, soil inorganic nitrogen content in the top 50 cm was low (5 to 20 g N m^{-2}). Most of the mineralised nitrogen was taken up by plants, plant growth appears to have been limited by availability of nitrogen.

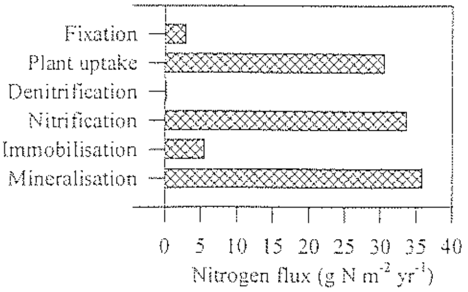

Fig. 6 The simulated annual nitrogen budget for a legume-pasture at Wagga Wagga.

5. CONCLUSION AND DISCUSSION

The model, DNDC, has been modified to include the surface energy budget and pasture growth. These modifications significantly improve the simulation of soil temperature and water balance at smaller temporal and spatial scales.

The simulated soil temperature and water content agree well with the observed values. It is important to include the surface energy budget in the model to account for large difference between soil and air temperatures. This difference can be as large as 9 °C in the winter season, which if ignored, may result in an overestimating the soil decomposition rate by 100%.

The potential evapotranspiration is a function of available energy, and is partitioned between soil and plants. This partitioning is also important, as plants have access to deeper soil water. The plant growth model is based on the well-established theory by Tanner and Sinclair (1985), and nitrogen uptake was simulated using Michaelis-Menten equation (Nye and Tinker 1977).

During 1993, total annual rainfall was 639 mm. The model predicts that rainfall interception, soil evaporation and plant transpiration account for 11%, 41% and 48% of annual total rainfall, respectively. Therefore rainfall interception is a significant amount in the annual water budget for the legume pasture system. These values are similar to the measurements by Leuning et al. (1994) for a wheat crop in the same district. However since effect of plant residues on soil evaporation is not considered in the model, we may have overestimated soil evaporation component of the water balance.

As estimated by the model, the annual mineralisation rate is about 35.8 g N m^{-2} yr^{-1}, of which 85% was taken up by plants. Biological fixation was about 2.9 g N m^{-2} yr^{-1}, and immobilisation was about 5.5 g N m^{-2} yr^{-1}. The total nitrogen lost as N_2O and N_2 from nitrification and denitrification is 0.2 g N m^{-2} yr^{-1}. Therefore the major process contributing to N_2O emission in this dryland pasture system is aerobic nitrification rather than anaerobic denitrification.

6. ACKNOWLEDGMENT

We thank the Australian Rural Industry Research Development Corporation (RIRDC) for supporting this work. We are very grateful to Dr Keith Heyler and Mr Rod Fisher of the New South Wales Department of Agriculture and Mr Bob Chambers of Brooklyn for their help. Dr Li kindly provided the code of his DNDC model.

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