Improving nitrogen use efficiency in subtropical dairy systems – A modelling approach using POAMA and DayCent

Martin Labadz[1], Clemens Scheer[1], David W. Rowlings[1], Beverly Henry[1], William Parton[2], Peter Hayman[3], Oscar Alves[4], Griffith Young[4] and Peter Grace[1]

[1] Institute for Future Environments, Queensland University of Technology, 2 George Street, Brisbane QLD 4000, Australia
[2] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, United States
[3] Government of South Australia, SARDI, 2b Hartley Grove, Urrbrae SA 5064, Australia
[4] Centre for Australian Weather and Climate Research, Melbourne, Victoria, Australia

Abstract
The DayCent biogeochemical model was used to assess the applicability of POAMA-2 weather forecasts to assist dairy farmers in future nitrogen fertiliser decisions. Simulated soil mineral nitrogen, water-filled pore space, and biomass was calibrated and validated against field measurements from a dairy farm in subtropical Queensland, Australia, for the season 2012/2013 with a ryegrass/kikuyu rotation. DayCent was able to predict water movement in the soil profile, soil nitrogen dynamics and biomass production; however, there were some discrepancies between simulated and measured mineral nitrogen content in the soil and biomass production. This study showed that combining weather forecasts with biogeochemical models as a decision support tool for farmers to estimate mineralisation and assess N fertiliser demand is a promising approach to avoid excessive nitrogen application for dairy cropping systems. However, there are still shortcomings in an accurate simulation of soil nitrogen turnover and plant nitrogen uptake, in particular in highly fertilised systems such as the one presented here. More confidence in the accurate representation of the complex nitrogen transformation processes on dairy farms in biogeochemical models is necessary to use weather forecasts as fertiliser nitrogen decision support tool.

Key Words
Weather forecasts, POAMA, DayCent, NUE, Pasture, Subtropical

Introduction
Nitrogen pollution of terrestrial ecosystems is a major concern world-wide. In many parts of the world, excessive use of inorganic and organic fertilisers has led to an increase in nutrient inputs into the environment. Dairy systems are characterised by high fertiliser input, in particular nitrogen (N), but low nitrogen use efficiency (NUE). In Australian pasture-based dairy systems, between 14% and 50% (median: 25 %) of applied fertiliser N is converted to protein N (Gourley et al., 2012). Application rates can exceed 250 kg ha^{-1} yr^{-1}, and excess N is lost to the environment via surface runoff, leaching, or gaseous emissions. In tropical and subtropical regions of Australia, high temperature and rainfall variability can exacerbate these effects (McKee et al., 2000; Murphy and Ribbe, 2004). Under these conditions, the microbial mediated process of denitrification is considered as a major pathway of N losses, in particular in intensively managed pasture-based systems (Friedl et al., 2016).
An effective strategy to identify and estimate N losses in dairy systems is the use of process-based models. In dairy systems, these models can provide long-term mitigation strategies for farmers to minimize their N losses (e.g. Chen et al., 2010; Christie et al., 2014), and can also aid the farmer to minimize potential losses in production due to the inefficient use of N fertilisers and water mismanagement. Recently, the focus has shifted to linking climate scenarios to process-based models to evaluate the effect of climate change on farm N losses (e.g. Chapman et al., 2012). However, to date only limited modelling data exist for subtropical dairy systems as high crop production and N turnover may impose limitations on current numerical models.
The objective of this study was to link the process-based DayCent model with a climate forecast model to provide a decision support tool for farmers to: (i) optimize fertilizer N application and use efficiency, and (ii) reduce N losses from subtropical dairy systems under changing climate conditions. DayCent was coupled with the Predictive Ocean Atmosphere Model for Australia (POAMA-2, Hudson et al., 2013), to simulate the effect of different climate scenarios on crop yield and N_2O emissions. This study is one of the first to link the biogeochemical model DayCent with seasonal climate forecasts.

Methods
Experimental data
Data for this study was collected at a commercial dairy farm in south-east Queensland, Australia (Latitude: 26.19°S; Longitude: 152.74°E), between 2012 and 2013. The climate at the site is humid-subtropical, with

the nearby town of Gympie having a mean annual precipitation of 1133 mm (1870-2013, Bureau of Meteorology). The soil at the site is a clay loam increasing to clay below 25 cm and is classified as a Red Dermosol (Ferric Acrisol, FAO) under the Australian Soil Classification. The grazing cycles were characterised by kikuyu and star grass in summer and ryegrass in autumn and winter. Further details about the trial setup and methodology are described in Rowlings (2016).

Numerical modelling approach

The biogeochemical land surface model DayCent was used in this study, which is the daily time-step version of the CENTURY model (Parton et al., 1998). We used the August 2014 version of DayCent that includes subroutines for photosynthesis and photo-decomposition of surface litter. It was parameterised with site-specific soil and vegetation characteristics, daily weather data, and user-specified management events. The outputs include GHG fluxes and C and N content of vegetation and soil pools. The model simulates N_2O and NO_x fluxes from nitrification and denitrification, as well as N_2 emissions from denitrification. A detailed description of the biogeochemical processes in the model and its inputs and outputs is given in Scheer et al. (2014). **Error! Reference source not found.** shows a summary of the various steps involved in the modelling exercise of this study.

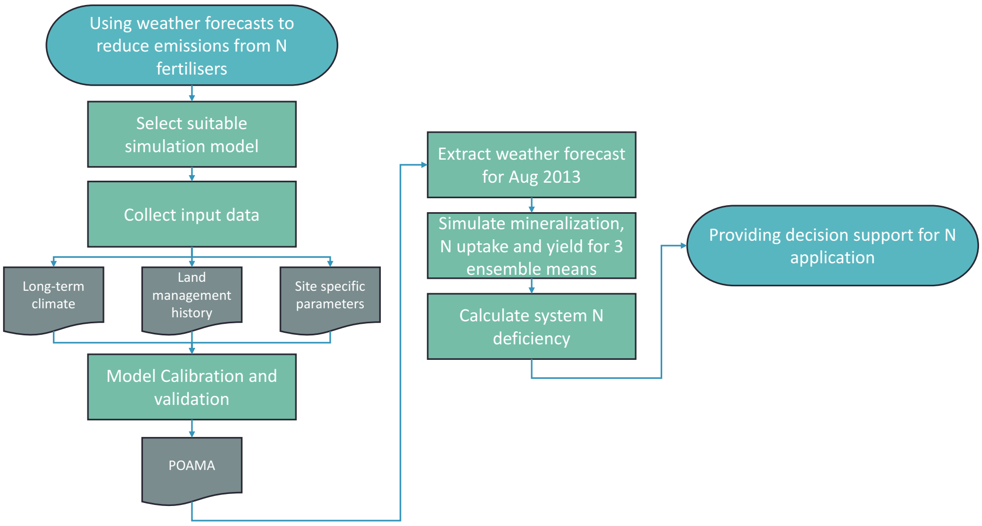

Figure 1. Flow chart showing the processes that were involved in the modelling exercise using weather forecasts to improve nitrogen use efficiency on dairy farms.

DayCent Model calibration and validation

The model was calibrated and validated against daily N_2O measurements, yield data, and soil water and NH_4^+ and NO_3^- levels from a zero and high (45 kg ha^{-1}) urea fertiliser application rate, respectively for the period April 2012 to March 2013, reflecting the rotation of ryegrass and kikuyu. The Bureau of Meteorology provided long-term weather data (minimum and maximum temperature, and daily rainfall).

Simulation of mineralisation, and yield response to weather scenarios

The main model simulation started with the introduction of intensively managed pasture in 1985. Common practice is the application of 45 kg N ha^{-1} as urea by surface broadcasting every 21 days following each grazing in the months April to October each year. In October, the ryegrass naturally finishes and the summer pasture species become dominant with no fertiliser applied during the summer pasture growing season. The Bureau of Meteorology provided data on long-term climate variability for this study. This data comprised of monthly and seasonal climate outlook for the period 1981 to 2013 based on three different climate models (each with 11 ensembles) of the Predictive Ocean Atmosphere Model for Australia (POAMA-2, Hudson et al., 2013). As August is the starting month of each POAMA-2 weather simulation where the smallest spread of error occurs, August 2013 was selected to test the applicability of DayCent using weather forecasts as decision tools for farmers. Daily long-term rainfall, and minimum and maximum temperature averages for each day in August were calculated from long-term weather data for Gympie. The anomalies from POAMA-2 were then subtracted from the long-term weather data from August to derive 33 weather forecasts for August 2013 (three different climate models each comprising of 11 ensembles). Predicted rainfall variability based on POAMA-2 was low during the first two weeks of August 2013 but increased greatly during the remaining weeks of the month. Minimum and maximum temperature variability predicted by the weather model was variable over the entire August. This resulted in 33 different DayCent model simulations for the year 2013 with the main focus being on the month of August. Mean outputs of soil N mineralisation and yield were calculated for the three different ensemble models.

Results

Model validation

Considering the high spatial variability in soil mineral N measurements, DayCent showed a good correlation between simulated and measured soil mineral nitrogen content in the first 10 cm of the profile. Biomass and crop response to fertiliser N applications were simulated within observed ranges over the season (Figure 2). However, mean production during model calibration was slightly overestimated (18 g m^{-2}).

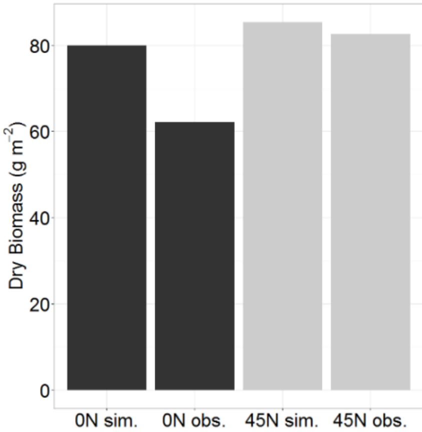

Figure 2. Comparison of simulated versus observed average dry biomass over one ryegrass/kikuyu season 2012/2013 for the DayCent model calibration (0N sim. and 0N obs.) and model validation (45N sim. and 45N obs).

Mineralisation and yield response to weather scenarios

When using the weather forecasts, DayCent predicted a deficiency of N for all three weather models ranging from 0.8 kg N ha^{-1} to 1.8 kg ha^{-1}. Model predictions for the actual weather data showed a deficiency of N in the soil of 3.9 kg N ha^{-1} (Table 1).

Table 1. Mineralisation and yield response simulated by DayCent for the three different POAMA-2 models and under actual weather conditions for August 2013.

		POAMA-2		
	Actual Weather	A	B	C
Yield (kg N/ha)	10.2	10.5	10.6	10.5
Mineralisation (kg N/ha)	6.3	9.3	9.8	8.7
N deficiency (kg N/ha)	3.9	1.2	0.8	1.8

Overall, these rates are relatively low compared to the standard N application rate of 45 kg N ha^{-1} for the trial site and reflect the non N-limiting conditions. Here, weather variability plays a far more important role as shown in **Error! Reference source not found.**. The highest precipitation variability of POAMA-2 was predicted for the last two weeks of August 2013. The non N-limiting conditions are also reflected in the yield response to different fertiliser application rates. DayCent predicted a yield of 50 g m^{-2} for all simulated fertiliser application rates of 0 kg N ha^{-1} to 50 kg N ha^{-1} when using the actual weather data.

Conclusion

The integration of POAMA-2 weather forecasts into the biogeochemical model DayCent showed a promising approach to estimate soil N mineralisation and assess N fertiliser demand to avoid excessive N application for dairy cropping systems. After model calibration and validation, DayCent was able to simulate N turnover and yield response for this specific cropping system. This could lead to a significant reduction of N losses from dairy systems without jeopardising crop yield. However, this study showed how important the availability of calibration and validation data is when using biogeochemical models. Reliable field data is needed for accurately simulating complex biogeochemical processes such as N turnover and yield responses. In addition, the modelling approach presented here needs further testing for months with high yield potential and ideally be combined with irrigation. The integration of weather forecasts into biogeochemical models also needs to be tested for wetter months and over longer period of times. In general, more confidence in the skill of forecasts and a better representation of soil nutrient cycling in biogeochemical models is required to use weather forecast modelling as fertiliser decision support tools.

References

Chapman, D.F., Dassanayake, K., Hill, J.O., Cullen, B.R., Lane, N., 2012. Forage-based dairying in a water-limited future: use of models to investigate farming system adaptation in southern australia. J. Dairy Sci. 95, 4153–75. doi:10.3168/jds.2011-5110

Chen, D., Li, Y., Kelly, K., Eckard, R., 2010. Simulation of N_2O emissions from an irrigated dairy pasture treated with urea and urine in southeastern Australia. Agric. Ecosyst. Environ. 136, 333–342. doi:10.1016/j.agee.2009.12.007

Christie, K.M., Rawnsley, R.P., Harrison, M.T., Eckard, R.J., 2014. Using a modelling approach to evaluate two options for improving animal nitrogen use efficiency and reducing nitrous oxide emissions on dairy farms in southern Australia. Anim. Prod. Sci. 54, 1960–1970. doi:10.1071/AN14436

Friedl, J., Scheer, C., Rowlings, D.W., McIntosh, H. V., Strazzabosco, A., Warner, D.I., Grace, P.R., 2016. Denitrification losses from an intensively managed sub-tropical pasture – impact of soil moisture on the partitioning of N_2 and N_2O emissions. Soil Biol. Biochem. 92, 58–66. doi:10.1016/j.soilbio.2015.09.016

Gourley, C.J.P., Aarons, S.R., Powell, J.M., 2012. Nitrogen use efficiency and manure management practices in contrasting dairy production systems. Agric. Ecosyst. Environ. 147, 73–81. doi:10.1016/j.agee.2011.05.011

Hudson, D., Marshall, A.G., Yin, Y., Alves, O., Hendon, H.H., 2013. Improving intraseasonal prediction with a new ensemble generation strategy. Mon. Weather Rev. 141, 4429–4449. doi:10.1175/MWR-D-13-00059.1

McKee, L., Eyre, B., Hossain, S., 2000. Intra- and interannual export of nitrogen and phosphorus in the subtropical Richmond River catchment, Australia. Hydrol. Process. 14, 1787–1809. doi:10.1002/1099-1085(200007)14:10<1787::AID-HYP42>3.0.CO;2-Z

Murphy, B.F., Ribbe, J., 2004. Variability of southeastern Queensland rainfall and climate indices. Int. J. Climatol. 24, 703–721. doi:10.1002/joc.1018

Parton, W.J., Hartman, M., Ojima, D., Schimel, D., 1998. Daycent and its land surface submodel: description and testing. Glob. Planet. Change 19, 35–48. doi:10.1016/S0921-8181(98)00040-X

Rowlings, D.W., Scheer, C., Liu, S., Grace, P.R., 2016. Annual nitrogen dynamics and urea fertilizer recoveries from a dairy pasture using ^{15}N; effect of nitrification inhibitor DMPP and reduced application rates. Agric. Ecosyst. Environ. 216, 216–225. doi:10.1016/j.agee.2015.09.025

Scheer, C., Del Grosso, S.J., Parton, W.J., Rowlings, D.W., Grace, P.R., 2014. Modeling nitrous oxide emissions from irrigated agriculture: testing daycent with high-frequency measurements. Ecol. Appl. 24, 528–538. doi:10.1890/13-0570.1