Simulating rice in farming systems – modelling transitions between aerobic and ponded soil environments in APSIM

Gaydon, D.S. [1], R. J. Buresh [2], M.E. Probert [1], and H. Meinke[3]

[1] *CSIRO Sustainable Ecosystems, St Lucia, Brisbane, Australia (& APSRU)*
[2] *International Rice Research Institute (IRRI), Los Baños, Philippines*
[3] *Centre for Crop Systems Analysis (CCSA), Wageningen University, The Netherlands*
Email: don.gaydon@csiro.au

Abstract: Adapting farming systems to reduced availability of irrigation water is an emerging research issue in irrigated districts throughout the globe. Water shortages in parts of the rice-growing world have prompted research into a range of alternate agricultural practices, including expansion of rice as a component in diverse farming systems, in rotation with dryland and aerobically irrigated crops and pastures, utilising a range of modified tillage and residue management practices. Evaluation of potential future adaptation strategies can be assisted by well-tested farming systems models that capture interactions between soil water and nutrient dynamics, crop growth, climate and management inputs/practices. APSIM represents such a model, however due to its 'dryland heritage' APSIM has previously been unequipped to describe the soil water, carbon and nitrogen dynamics as soil environments progress from aerobic to anaerobic and back again, such as occurs in crop rotations involving ponded rice and other non-ponded crops (wheat, maize, legumes, pastures etc.). Various relevant chemical and biological processes that occur in long-term ponded water were also unaccounted for in APSIM.

In this paper we describe how we incorporated this new functionality into APSIM. This includes evaluation of previous efforts to model anaerobic soil environments; conceptualization of the required new functionality within the existing APSIM framework; and design of code structure to facilitate seamless transitions between aerobic and anaerobic soil environments in continuous simulation. Included is the development of a new module, APSIM-Pond, to describe biological and chemical processes responsible for system loss/gain of C and N in rice ponds. We conclude by providing some preliminary testing results.

As a starting point we use many process descriptions from the CERES-Rice and RIWER models. However a new element of APSIM-Pond is our representation of algal turnover and biomass soil incorporation in rice-based farming systems. This is in response to criticism of CERES-Rice's ability to capture long-term trends in soil organic carbon. In simulation of long-term (35 yrs +) ponded rice experiments at IRRI, CERES-Rice simulated a rundown in soil organic carbon, when in fact none was measured. We have included algal contributions to the C & N pools in response to this criticism.

No previous modelling framework has addressed the issue of switching between aerobic and anaerobic environments during a simulation, which is particularly important if the focus of the modelling exercise is evaluating new farming system practices that include ponded rice in rotation with non-flooded crops. The ORYZA2000 rice model was previously incorporated into APSIM, and tested in both N- and water-limited environments. This testing highlighted the needs for the improvements to the C & N balances reported here. Similarly, the simulation of greenhouse gas emissions associated with changed practices in rice-based farming systems also requires sensible accounting for C & N in pond and soil. To date, the model developmental work reported in this paper has focused on the soil C & N story with respect to crop production – a future imperative will be partitioning modeled losses sensibly into the relevant greenhouse gases.

Keywords: APSIM, ORYZA2000, rice, farming systems, soil nutrient dynamics

1. INTRODUCTION

1.1. The need for an enhanced modelling functionality

Worldwide, water for agriculture is becoming increasingly scarce. Suggested pathways to increasing water productivity (WP) in rice-based farming systems include the incorporation of non-flooded crops and pastures into traditional rice rotations, changed agronomic and/or irrigation practices, reduction of non-productive water loses, and genetic improvement. Simulation models are excellent tools to explore the limitations and opportunities for increasing WP. The APSIM farming systems model (Keating et al. 2003) has a proven track record in modelling the performance of diverse farming systems, rotations, fallowing, crop and environmental dynamics. However for rice-based systems the major drawback has been the lack of significant descriptions for soil processes under anaerobic conditions. Other models which are able to capture such anaerobic soil processes (DNDC etc) are unable to provide the degree of flexibility for assessing changed management practices that APSIM offers. For that reason work to incorporate the required aerobic-anaerobic soil modelling functionality within APSIM has been undertaken. This work was a joint initiative between the Agricultural Production Systems Research Unit (APSRU), the International Rice Research Institute (IRRI, Philippines) and Wageningen University (WUR, The Netherlands). Each partner has interests in the application of the APSIM modelling framework to assist rice farmers world-wide in the ongoing adaptation process. The ORYZA2000 rice model (Bouman & Van Laar, 2006) has been incorporated into the APSIM framework and validated in several studies (Zhang 2007, Gaydon et al. 2006). In each of these studies, however, N was either assumed to be non-limiting, or calculated for a rice monoculture using a simple N accounting component within ORYZA2000. Up until now, it has been impossible to simulate the complete C&N dynamics in complex farming systems that involve rice in rotation with other crops and pastures. Here we report how we incorporated this functionality into APSIM.

2. ENHANCEMENTS REQUIRED TO APSIM

2.1. The Ponded environment

The following (a-d) is a brief description of the new system elements which were required in APSIM. **a)** *Pond C and N loss and gain mechanisms.* Ponded water introduces a range of C and N loss and gain mechanisms not present in aerobic soil environments. These include significant volatilization of ammonia (NH_3) from the free water surface, and the growth of photosynthetic aquatic biomass (PAB - algae) which plays a significant role in regulation of many processes and may be N-fixing. **b)** *Fertiliser applied into pond.* In rice-based systems, fertiliser is often applied as urea directly into the pond. This fertiliser is then subject to hydrolysis, potential losses via ammonia volatilization, diffusion into the soil via mass flow and adsorption, and ultimately uptake by the rice plant. **c)** *Surface organic matter decomposition in pond.* Surface organic matter decomposition in water take place at slower rates than decomposition in air **d)** *Reduced rates of soil organic matter decomposition and cycling.* In an anaerobic soil profile saturated for extended periods, reduced rates of organic matter decomposition and cycling are likely to be a significant factor in modelling system behaviour (Jing et al 2007).

2.2. Transitional ability

The key challenge for incorporating any new process descriptions into APSIM has been to establish smooth transition within a simulation between modelling of flooded and non-flooded soil environments. It was a design criteria that this transition be contingent on continuous hydraulically-modelled variables, rather than an arbitrary 'switch' when one phase had finished and the next begun.

2.3. Evaluation of previous efforts in modelling anaerobic environments

CERES-Rice (Godwin & Singh 1991) is a well-validated simulation model which captures most of the key processes identified in the anaerobic rice phase of cropping systems. Although the impact of algal *activity* on pond processes such as urea hydrolysis and ammonia volatilization is simulated, CERES-Rice does not include the additions of C & N from algal biomass accumulation into the wider C & N pool, leading to problems in simulating long-term experimental organic carbon at IRRI (R. Buresh pers comms). We have attempted to address this issue in APSIM, as described below in section 3.2. There is also evidence that the CERES-Rice soil organic matter component also did not perform well (Timsina & Humphries 2006). Being a model for ponded rice, CERES-Rice did not need to address the environmental transitional issues that face simulation of rice as a part of a wider crop/pasture rotation. Jing et al (2007) addressed the issue of transitional environments for rice-wheat rotations in their RIWER model. Rather than modifying these

models, we capitalised on the APSIM infrastructure that provides the required flexibility to inform future adaptation studies. To make necessary improvements, we borrowed liberally from both CERES-Rice and RIWER, while introducing some new concepts as described in section 3 below. In this paper, we present details of our conceptualization of the ponded environment for the purposes of modelling in APSIM. We also present our methodology for achieving seamless transitions to and from aerobic soil environments during the course of any simulation, and the structural code changes implemented to achieve this functionality. In addition to necessary changes within existing APSIM modules (SoilN, SurfaceOM, and Fertiliser), the establishment of a new module APSIM-Pond is described. The science within APSIM-Pond is largely adapted from CERES-Rice, however some new assumptions have been made and these are outlined below. We conclude by providing results of some preliminary testing of the new functionality against experimental datasets.

3. MODEL DESCRIPTION

3.1. Layering of the system

When a soil is flooded, the presence of the pond limits oxygen transfer from the atmosphere to the soil. The imbalance between the high respiration rate of soil organisms and the slow rate of oxygen diffusion through the pond quickly results in the soil layers becoming anaerobic, reduced, or depleted of oxygen (Kirk & Olk 2000).
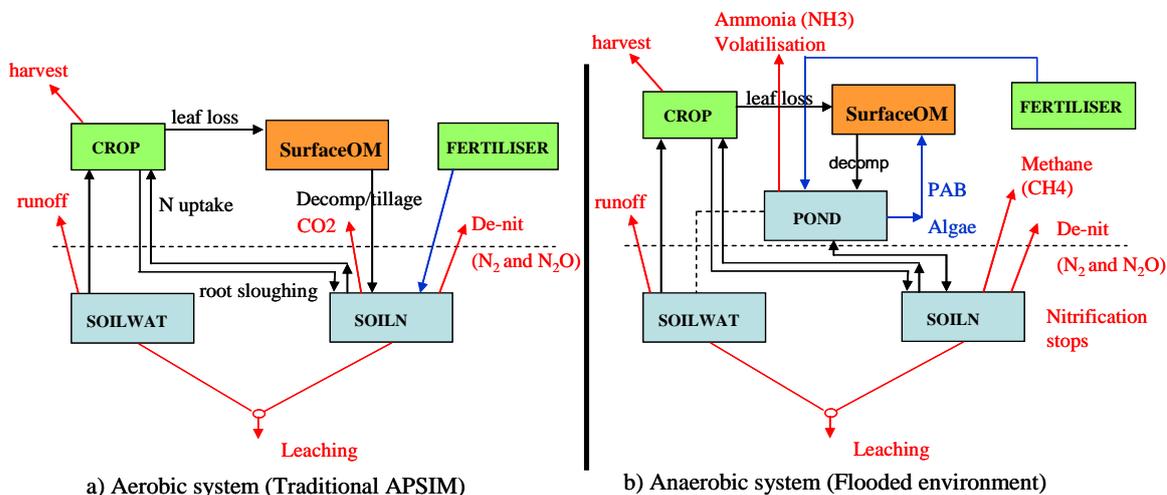
Figure 1. Conceptual structure of APSIM module communications and C&N loss (red) and gain (blue) mechanisms in: a) traditional aerobic systems; and b) flooded systems. The black dotted line represents the soil surface.

Anaerobic organisms then take over nutrient and organic matter cycling within the soil. In modifications to APSIM, we have assumed a two layer system (pond & soil) on the assumption that the thin oxidized soil layer at the soil surface is relatively insignificant when modelling larger-scale nutrient processes. The chemistry of the ponded layer is modelled by APSIM-Pond, and the chemistry of the soil layers by APSIM-SoilN. These two modules communicate with each other on a daily basis to transfer nutrients via a central *engine* according to standard APSIM protocols (Keating et al 2003). We assume that N is only available for uptake by the rice crop once it is in the soil layers (ie from the SoilN module). Figure 1 shows our conceptualization of nutrient flows within APSIM for both flooded and non-flooded soil environments.

The APSIM-Pond module is a transient module in any simulation. It becomes active whenever the soil water balance module (SoilWat or APSwim) determines that water is ponding on the soil surface. The APSIM-Pond module only handles the chemical processes – the soil water balance module simulates the water balance of pond and soil alike, as a continuum. When rainfall and/or irrigation cease, the pond depth will decrease by infiltration into the soil until there is no pond at all. APSIM-Pond checks with the water balance module on a daily basis to see whether it should be 'active' or not, as well as obtaining information on evaporation and current depth. Effectively, the APSIM-Pond module may be conceptualised as a 'filter' of nutrients – not allowing all applied N to reach the crop, and simulating loss (but also) gain mechanisms for both C and N. When the pond has 'drained down', the APSIM-Pond module becomes inactive and the nutrient 'filter' is removed. When the pond is hydraulically re-established (as determined by the soil water

balance module), APSIM-Pond becomes active and once again begins its role filtering N and potentially producing new C and N in the system through algal growth (if conditions are appropriate).

3.2. New Module: APSIM-Pond

The APSIM-Pond module simulates key chemical and biological processes occurring within a ponded layer of surface water (Figure 2). Given that both pond temperature and pH are important variables in modelling key chemical and biological processes, a fully dynamic pond temperature and pH balance is maintained   In accordance with algorithms described in CERES-Rice, we have calculated these balances on a two-hourly timestep basis to capture the rapid reaction rates.

A. Urea hydrolysis. The breakdown of applied urea fertiliser to NH_4^+ is described as a function of pond temperature and a soil-determined hydrolysis rate (a function of organic carbon in top soil layer) or an algal activity determined rate, whichever is greater (Godwin & Singh 1991).

B. Nitrification. Nitrification of NH_4^+ to NO_3 is calculated as a function of pond temperature and pH.

C. Ammonia volatilization. Pond ammonia (NH_3) exists in both aqueous and gaseous forms in equilibrium.   The overall pond ammonia concentration is calculated from the pond ammonium (NH_4^+) concentration as a function of pond temperature and pH. The partial pressure of ammonia is calculated from the overall ammonia concentration as a function of pond temperature. This partial pressure of ammonia provides the potential for ammonia volatilization and N-loss to the atmosphere. This loss potential is a function of wind and pond depth. In the absence of wind data, we use evaporation as a surrogate (Godwin & Singh 1991).

Figure 2. Processes simulated in the APSIM-Pond module.

D. Algal growth and turnover. Godwin & Singh (1991) described the calculation of an algal activity factor which influences urea hydrolysis and floodwater pH. We use this factor but also calculate the daily algal growth and accumulated biomass as follows:

$$dlt\_pab = maxrate\_pab * algact$$

Where *dlt_pab* is the daily growth of algae (kg/ha), *maxrate_pab* is the maximum daily growth rate of algae (20 kg/ha/day, Roger 1996), and *algact* is the daily algal activity factor (Godwin & Singh 1991). Pond algal biomass (PAB) is allowed to reach a maximum of 500 kg DW/ha, with C content of 40% and C:N of approximately 8 (Roger 1996). As PAB accumulates biomass, N uptake is from mineral N in the floodwater. When N demand outstrips supply, we assume that the shortfall is made up via N fixation, and algal growth remains unaffected. A significant new element of APSIM-Pond is our description of algal turnover. The natural limitation on algal growth is rice canopy closure and algal deprivation of solar radiation. If the maximum algal biomass of 500 kg/ha is reached before full canopy closure, further algal production is theoretically possible, and we assume that subsequent potential daily algal growth is matched by algal senescence which is added to the APSIM-SurfaceOM pool on a daily basis. This assumption was made to partially address the criticism of CERES-Rice's inability to capture long-term trends in soil organic carbon (Roland Buresh, pers comms). In simulation of long-term (35 yrs +) rice experiments at IRRI, CERES-Rice simulated a rundown in soil organic carbon, when in fact none was measured. Another key element in addressing this issue is the addition of the complete PAB biomass to the surface organic matter pool after draining-down of the rice paddy. There it can decompose or be incorporated into the soil as per standard APSIM residue simulation. To simulate situations where live algae may sit viably on the wet surface of the soil during intermittent drydown of a rice pond (such as in *alternate wet-and-dry* (AWD) irrigation practice, Bouman et al. 2007) and then spring back to life on re-flooding, we do not add the PAB to the ASPIM surface organic matter pool until a period of 5 days with no ponding has passed.

E. Immobilization of pond mineral N. When surface organic matter is decomposed in traditional dryland APSIM simulations, the APSIM-SurfaceOM module creates an immobilisation demand which it attempts to satisfy from APSIM-SoilN. Now, when APSIM-Pond is present, this demand is sought from APSIM-Pond mineral N pools. Similarly, mineral N released in decomposition becomes part of the APSIM-Pond mineral N pools. If a pond is present, the moisture factor for decomposition of residues is set to 0.5 to account for slower decomposition in water.

F. Flux of solutes to/from soil. APSIM-Pond pools of urea, NH_4^+ and NO_3 are transferred to the soil on a daily basis via the processes of mass flow, diffusion, and in the case of NH_4^+, adsorption. For NO_3 and urea, which are highly soluble, concentrations in the pond are compared with those in soil solution. When the concentrations are different in the two compartments, a "diffusion process" is invoked to determine the flux. The flux of NH_4^+ between pond and soil depend on the soil cation exchange capacity (CEC) as described by Godwin & Singh (1990). This is a new APSIM-SoilN input parameter.

3.3. Changes to APSIM Soil Carbon & Nitrogen Module (SoilN)

Under anaerobic conditions, organic matter cycling takes place in the absence of oxygen. We assumed different governing rate constants (2 to 3 times lower) on the basis of various reports in the literature (Jing et al. 2007, Kirk & Olk 2000). We assumed that anaerobic soil conditions develop rapidly after flooding and there is no lag whilst the micro-organisms adapt to the changed conditions. Each OM decomposition rate constant (input parameters to APSIM SoilN) now has two values instead of one; a value for aerobic conditions and one for anaerobic conditions (from Jing et al. 2007). Figure 3 illustrates the logic diagram for the new APSIM-SoilN code structure enabling seamless switching between aerobic and anaerobic conditions within the soil.
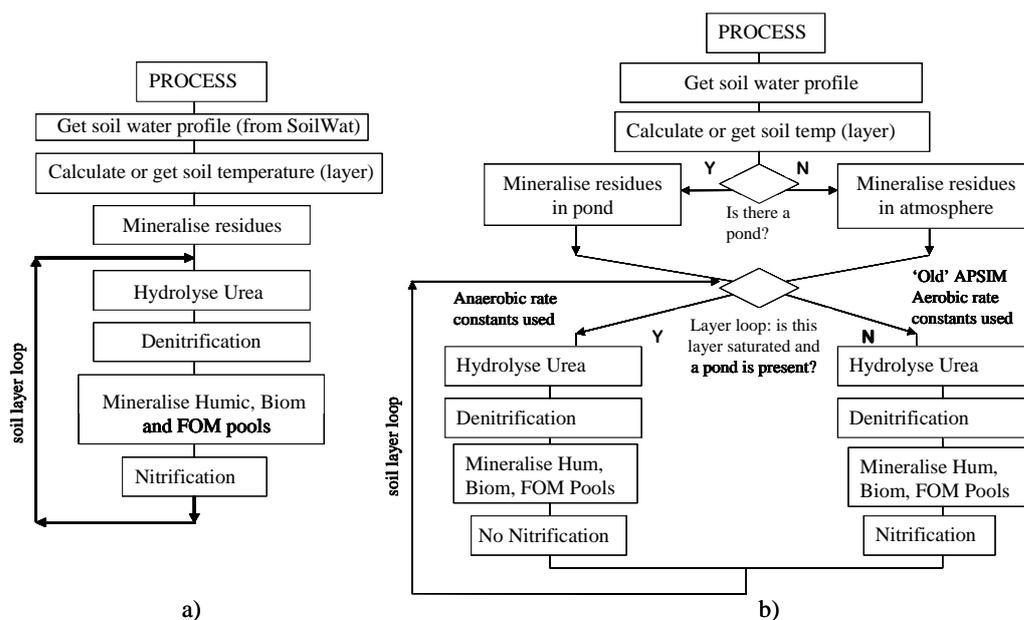
Figure 3. Logic of daily process simulation within APSIM-SoilN illustrating; a) old; and b) new structures. Note that if there is no 'pond', the 'new' is exactly the same as the 'old' process path.

4. MODEL EVALUATION

We provide model evaluation against two experimental datasets. (1) Figure 4 & 5; a one year rice experiment at Pila, Philippines in 1985, conducted by IRRI and designed to examine the impact of various N sources on ammonia loss and rice N uptake. (Reference: Buresh et al. 1988); and (2) Figure 6; a multi-year crop rotation at Coleambally, NSW, conducted by NSW DPI, designed to examine the impact of various land-forming and irrigation practices. We simulated a flat-bed layout with conventional irrigation. (Beecher et al. 2006)
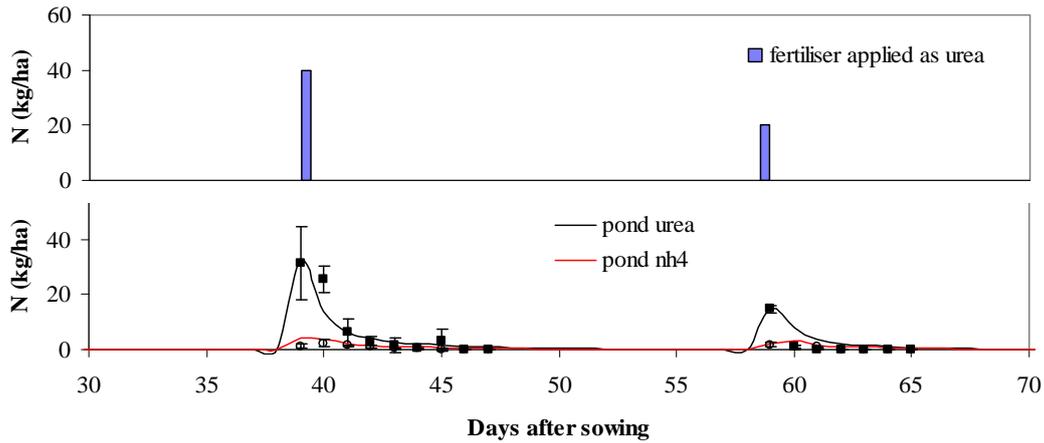
Figure 4. Simulated (line) vs measured data (points) for pond urea and NH$_4$. Experiment at Pila, Philippines 1985, fertiliser application of urea nitrogen 60 kg/ha, split 40/20. Rice variety IR58 (Buresh et al. 1988)
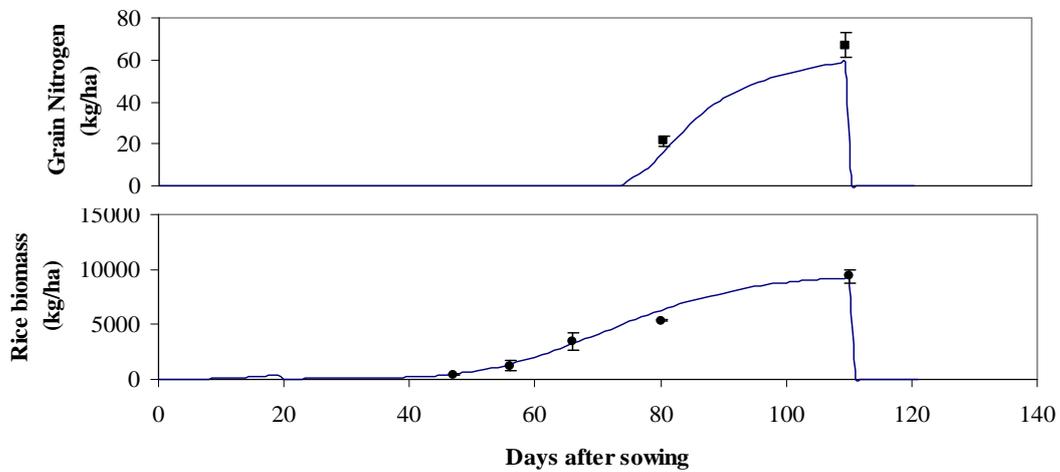
Figure 5. Simulated (line) vs measured data (points) for rice biomass production and grain nitrogen. Experiment at Pila, Philippines 1985, fertiliser application of urea nitrogen 60 kg/ha, split 40/20 as per Figure 4. Rice variety IR58 (Buresh et al. 1988)
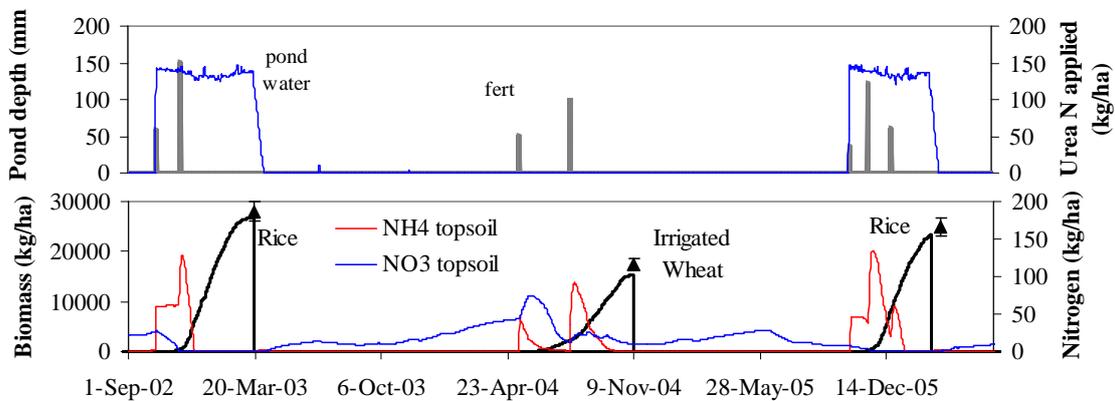
Figure 6. Simulated vs measured biomass data for a rice-wheat-rice experimental rotation on a transitional red brown earth soil at Coleambally, NSW. Simulated pond depth, soil NH$_4$ & NO$_3$ in top 40cms is also shown (Beecher et al. 2006)

5. DISCUSSION & CONCLUSIONS

Figures 4-6 illustrate acceptable model performance in two diverse environments with both temperate and tropical rice cultivars, transplanting and direct-sowing. A future challenge for this modelling framework will be simulation of C & N dynamics in new and emerging rice water management practices such as alternate wet-and-dry (Bouman et al. 2007). However the demonstrated ability of the framework to capture the nutrient dynamics both within (Figures 4-5) and between (Figure 6) anaerobic soil phases is encouraging. The ultimate aim for this modelling framework is to provide a tool for future studies on adaptation in complex farming systems which involve rice in rotation with other crops and pastures. We have yet to test our assumptions on algal turnover and incorporation on long-term system nutrient dynamics, and are actively seeking evidence to test our assumptions. This will be possible in coming months using data from the IRRI long-term experiments, upon which CERES-Rice was evaluated. We will continue to seek datasets which allow evaluation of detailed model process descriptions, and endeavour to simplify within the model where measured evidence suggests this is possible.

As partners in our 'rice modelling consortium', both IRRI and WUR are continuing to invest in enhancement of rice modelling capacity – particularly in the ability of ORYZA2000 to model crop responses to changes in CO_2, extremes of temperature, water-logging, salinity, and genomics. APSRU's major continuing contribution will centre on modelling the transitional rice environment within APSIM. The model developmental work reported in this paper has focused on getting the soil C & N story correct with respect to crop production. Similarly, the simulation of greenhouse gas emissions associated with changed practices in rice-based farming systems also requires sensible accounting for C & N in pond and soil – a future imperative will be partitioning modelled losses sensibly into the relevant greenhouse gases.

ACKNOWLEDGMENTS

REFERENCES

Beecher HG, Dunn BW, Thompson JA, Humphreys E, Mathews SK, Timsina J, (2006), Effect of raised beds, irrigation and nitrogen management on growth, water use and yield of rice in south-eastern Australia, *Australian Journal of Experimental Agriculture,* 46, 1363-1372.

Bouman, B.A.M. and van Laar, H.H., (2006), Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions, *Agricultural Systems*, 87, 249–273.

Bouman BAM, Lampayan R, Tuong T, (2007), Water Management in Irrigated Rice – coping with water scarcity. (International Rice Research Institute publication, Los Banos, Philippines.).

Buresh RJ., De Datta SK., Padilla JL., and Samson MI., (1988), Effect of two urease inhibitors on floodwater ammonia following urea application to lowland rice, *Soil Science of America Society Journal,* 52, 856-861

Gaydon D.S., Lisson S.N., and Xevi E., (2006), Application of APSIM 'multi-paddock' to estimate whole-of-farm water-use efficiency, system water balance and crop production for a rice-based operation in the Coleambally Irrigation District, NSW, Proceedings of the 13th Australian Society of Agronomy Conference, 10-14 September 2006, Perth, Western Australia.

Godwin D.C. and Singh U, (1991), Modelling nitrogen dynamics in rice cropping systems, in "Rice Production on Acid Soils of the Tropics" (Eds Deturek and Ponnamperuma), pp 287-294. (Institute of Fundamental Studies, Kandy, Sri Lanka).

Jing Q, Hengsdijk H, and van Keulen H, (2007), Modeling nitrogen and water dynamics in rice-wheat rotations, Proceedings Third IASTED International Conference "Environmental Modelling and Simulation", Honolulu, Hawaii, USA, pp 121-126. ISBN CD 978-0-88986-682-9..

Keating, BA. et al; (2003), An Overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy*, 18, 267-288.

Kirk G J D and Olk DC, editors (2000), Carbon and nitrogen dynamics in flooded soils, 188p. IRRI, Los Banos, Philippines. 250p.

Roger P A (1996), Biology and management of the floodwater ecosystem in ricefields, IRRI, Los Banos, Philippines.

Zhang, X., Jae-Hong Lee, Abawi, Y., Young-ho Kim, Hee-Dong Kim, (2006), Testing the simulation capability of APSIM-ORYZA under different levels of nitrogen fertiliser and transplanting time regimes in Korea, *Australian Journal of Experimental Agriculture*, 47(12).