Continuous Monitoring of Soil Redox Potential to Compare Layouts for Post-Rice Crops

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ABSTRACT

The effect of different bay layouts (beds vs flat) on crop growth was investigated using continuous monitoring of redox potentials to explain soil O_2 and nutrient (N and P) availability. Paddy rice typically leaves the soil in an anaerobic and water-logged state with low or negative redox potential. These conditions transform nutrients in the soil: free nitrate is reduced to di-nitrogen gas, and iron, phosphorous and manganese are reduced to their soluble forms. Following drainage of bays for rice harvest, re-oxidation of the soil causes other transformations, such as phosphorous and iron precipitation. These may negatively affect cereal crops planted straight after rice harvest. Raised beds may provide better soil conditions for crops after rice, making double cropping more viable and lifting the total water productivity of Australian rice farming systems.

A wireless measurement and data logging system was developed and used to monitor redox potentials continuously. Very high input-impedance amplifiers were used to ensure the data logging system did not influence redox potentials by drawing current through the electrode-soil interface. Connectivity between multiple loggers and the internet was provided using a WiFi hotspot and cellular data connection.

There was no significant effect of layout type on rice yield, but monitoring of redox potentials showed the soil drained and oxidised faster under the beds when bays were drained for harvest. This effect was short lived, as the onset of wet conditions in May 2016 re-saturated the soil and pushed redox potentials down to levels indicative of soil O_2 being limiting to crop growth (i.e. <350 mV) in both beds and flat treatments. These conditions persisted through winter and the wheat crop eventually failed. Soil sampling for soluble N and P showed the primary reason the crop failed was low fertility, presumably caused by denitrification under reduced conditions. An expected tie-up of phosphorous by oxidised iron was not observed. Layout type had no significant effect on nutrient concentrations.

Continuous monitoring of redox potential using the loggers developed for this project provided a low-cost and effective method of evaluating treatments aimed at improving the total water productivity of the Australian rice rotation.

Key words

Surface irrigation; raised beds; rice; wheat;

1. Introduction

The Australian rice industry is under pressure to increase water productivity because of competition for limited water resources from other irrigated summer crops. However, Australian rice yields are some of the highest in the world (the industry average yield across the Riverina was 11 t/ha in 2016; Edgar (2016), crops are grown on soils selected for their very low permeability (Beecher *et al.*, 2002), and there is a requirement for deep ponded water through microspore to provide a thermal blanket and prevent cold induced sterility. Consequently, it will be difficult to appreciably increase the water productivity of the rice phase of the rotation over the short term.

In contrast to the rice phase of the rotation, water productivity in the non-rice phase is relatively low, with yields from wheat crops sown straight after rice in the order of 50% of those sown after a fallow period, or on similar country outside the rice rotation (Humphreys *et al.*, 2003). If yields of wheat after rice can be increased, then there is considerable potential to improve the total water productivity of the rice rotation by making greater use of water left in the soil after rice harvest .

The difficulty in improving the yield of wheat sown after rice occurs because rice is grown in flooded bays and typically leaves the soil in a water-logged and anaerobic condition. These conditions are the antithesis of those required for up-land crops and the reduced soil state causes the transformation of nutrients, leading to both tie-up and toxicity. For instance, free nitrate is reduced to di-nitrogen gas, while iron, phosphorous and manganese are reduced to their soluble forms. Following drainage of water from rice and re-oxidation of the soil, other transformations, such as phosphorous and iron precipitation, may also have a negative impact on nutrient availability for wheat sown after rice harvest.

For double cropping to be successful in Australian rice systems, it is therefore necessary to create more favourable soil conditions for crops sown after rice. One way of possibly doing this is to use permanent raised beds to improve drainage and create more favourable soil conditions in the upper root zone (Beecher *et al.*, 2005) To examine this, a field experiment was established to assess whether total water productivity in Australian rice systems could be improved by double cropping in a raised beds system compared with conventional systems “on the flat”.

Key processes potentially affected by these treatments are soil saturation and drying, and soil reduction and oxidation, which can be measured using matric potential and redox sensors respectively (Setter and Waters, 2003; North, 2012). However, manual measurement is time consuming; costly or impractical for remote sites; and low frequency collection results in poor data resolution under rapidly varying conditions. Automating data collection can over-come this, but the cost of instrumenting all replicates of all treatments can be prohibitive, and data may be lost at remote sites if loggers fail before they can be downloaded. Consequently, new data-logging systems are needed that are low cost, have a low power requirement, have telemetry and continuous internet connectivity to the cloud, and are able to be connected to a wide range of environmental sensors. This paper reports a new data logger system developed to measure environmental variables, including redox potential, in two layout treatments (beds vs flat) in a field experiment.

2. Methods

2.1. Field experiment

A three year field experiment was established in October 2015 in three bays of a contour basin irrigation layout on a brown sodosol (Isbell, 1996) at Rice Research Australia’s Jerilderie, NSW property (35° 19’ 04” S, 145° 31’ 48” E). Table 1 shows selected surface soil properties of the trial block on 23rd September 2015.

Table 1. Chemical properties of the surface (0-10 cm) soil in the experimental paddock at Rice Research Australia, Jerilderie. Sampling was conducted on 23rd September 2015.

Soil texture	Clay loam	Soil colour	Grey-brown
Effective CEC	10.3 cmol+/kg	Nitrate N	10 mg/kg
pH (1:5 H_2O)	5.7	Ammonium N	4 mg/kg
pH (1:5 $CaCl_2$)	4.7	Phosphorus (Colwell)	92 mg/kg
EC (1:5 H_2O)	0.04 dS/m	Phosphorous Buffer Index	136
Electrochemical stability index	0.010	Manganese	16.4 mg/kg
Organic Carbon	1.42%	Iron	249.8 mg/kg

Beds (1.8 m centres) were pulled up in half of each bay in October 2015 to give three replicates (whole plots/bay) of two layout treatments (split plots with beds or flat layouts). A new short-season rice variety (YRM70) was drill-sown in all plots in late November 2015. Loggers were installed on 24th March 2016, two weeks prior to drainage of bays, and connected to sensors to record ponded water depth on bays as well as soil redox potential, matric potential and temperature at three depths (5 cm, 15 cm, and 30 cm).

The rice was harvested on 26th April, with plot grain weights obtained using a portable weigh bin and harvested areas measured by differentially corrected GPS. The rice stubble was mulched (3rd/4th May 2016) and then burnt (6th May 2016). 30 mm of rain fell on the evening of the 6th May, delaying winter crop sowing until 20th May when wheat (var. Condo) was sown at 120 kg/ha with 150 kg/ha of MAP. Very wet conditions followed, reducing emergence and early growth and also preventing urea top-dressing. These factors, topped-off by record rainfall in September 2016, meant the crop failed before harvest.

Soil was sampled at 5, 15 and 30 cm depths in all plots and analysed for nitrate, ammonium and soluble reactive phosphorus. Sampling commenced on 17th March 2016 and was repeated fortnightly until 28th April 2016 and then monthly until 8th Sept 2016. The concentration of N and P in the soil at the redox state on the day of sampling needed to be preserved, so it was not possible to prepare samples conventionally (i.e. sample, air-dry, grind). Instead, samples were placed straight into 2 M KCl in the field. These were kept cool during transport to the laboratory, where they were shaken, spun and filtered prior to an aliquot being frozen and sent to the NSW DPI Wollongbar laboratory for analysis.

2.2. Data loggers

The loggers built for use at this remote site needed to have: low cost telemetry and web connectivity; low cost componentry; low power requirement for extended stand-alone logging; connections for logging multiple sensors and sensors with differing outputs. They were based on WiFi and connected directly to the internet, so data was always up-to-date in the cloud. The connection from all loggers to the internet was through a single cellular data connection which feeds a WiFi hotspot. The suitability of WiFi for on-farm networks has been questioned in the past. However, measurements have indicated reliable connectivity at ranges beyond 1km with limited beam-width antennas and line-of-sight links. Cellular connectivity was boosted by a high gain antenna directed to the nearest cellular tower which provided a robust data connection.

The cost of the electronic components was reduced in part by the internet of things revolution. The loggers use modules from Electric Imp™, which include WiFi connectivity, an antenna and a microcontroller with a variety of digital and analog interfaces for connecting to sensors and controlling power management. Moving to mass-production modules like these, rather than legacy dedicated agriculture-specific data loggers greatly reduced the cost per logger with the benefits of internet connectivity.

The loggers were powered by four Alkaline AA batteries for more than a season. This was possible because the electronics have extremely low-power sleep states (less than 10uA current consumption), with all sensors powered down between readings. The loggers woke once per hour, powered the sensors, read the data, uploaded to the cloud and then went back to sleep. This typically took on the order of 10 seconds, during which current consumption was around 100mA. The sensors that were connected to the loggers included matric potential sensors to monitor soil moisture, digital temperature sensors, ultrasonic water-depth sensors and redox potential sensors

2.3. Redox potential measurement

The literature indicates that redox potential measurements cannot be used quantitatively to calculate equilibrium states of environments and is thus of only qualitative significance in soil solutions (McBride, 1994; Sposito, 2008). However, in environments with significant amounts of organic carbon and microbial activity (i.e. soils), the redox status is best defined by the terminal electron acceptor for degradation of organic carbon: i.e. O_2, NO_3^-, Mn(IV), Fe(III), SO_4^{2-}, etc. (Westall, 2000). Thus, experiments in soils where both redox potential measurement and testing for dissolved O_2, NO_3^-, NH_4^+, Mn_2^+ and/or Fe_2^+ has occurred have been able to show there is a consistent range of soil potentials over which each of these species changes concentration during soil reduction and oxidation. There is good evidence that O_2 is at plant limiting levels in soil (10% v/v) when redox potential measured by a Pt electrode falls below about 350 mV (McBride, 1994; Setter and Waters, 2003; Husson, 2013).

Continuous, real-time, wireless measurement of redox potential presented a number of challenges to the electronic system design. A high impedance (10^{10} ohm) potentiometer is recommended (Blackwell, 1983) to measure the electrical potential between the anode and the cathode at close to zero net current. To achieve this, extremely high input-impedance op-amps (>10^{12} ohm) were used. The input of the op-amp chip was connected directly to the electrode cable to eliminate the possible low impedance path on the printed-circuit board. The op-amps had a very low current consumption (<2 uA) so they remained powered up to eliminate any switching transient effects on the readings.

Another challenge with redox potential measurement is that the potential between the reference electrode (anode) and the Pt electrode (cathode) can become negative when soil is anoxic. The electronic system, however, is powered only by a positive voltage. To measure negative voltages, the reference electrode was connected to a positive voltage (~0.8 V), and the redox potential at the electrode was measured relative to this reference.

Each logger had the ability to measure seven electrodes and one reference potential. Two Paleoterra™ sensors were attached to a logger, each with platinum electrodes at 5, 15 and 30cm. One reference electrode (Ionode™ IJ64 ORP sensors) was placed at 30 cm depth.

3. Results

Header grain yields from the rice in the beds and flat treatments were 11.1 and 12.0 t/ha respectively. The difference in yields was not significant (P=15%). In marked contrast to the rice, the wheat crop failed. Germination was compromised by the wet conditions into which seed was sown in May and establishment and further growth severely limited by the cool and extremely wet conditions that prevailed. Comparison of monthly rainfalls with the long term record clearly shows the unusually wet nature of the 2016 winter season, with May, June and August rainfalls being at least double the long term average (Figure 1).

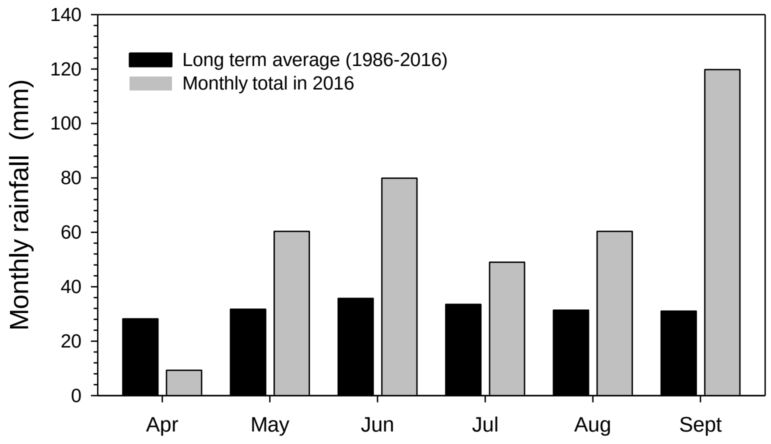

Figure 1. Long term (1986-2016) average monthly rainfall at Finley, NSW and total rainfalls for each month at the same site for the period April to September 2016.

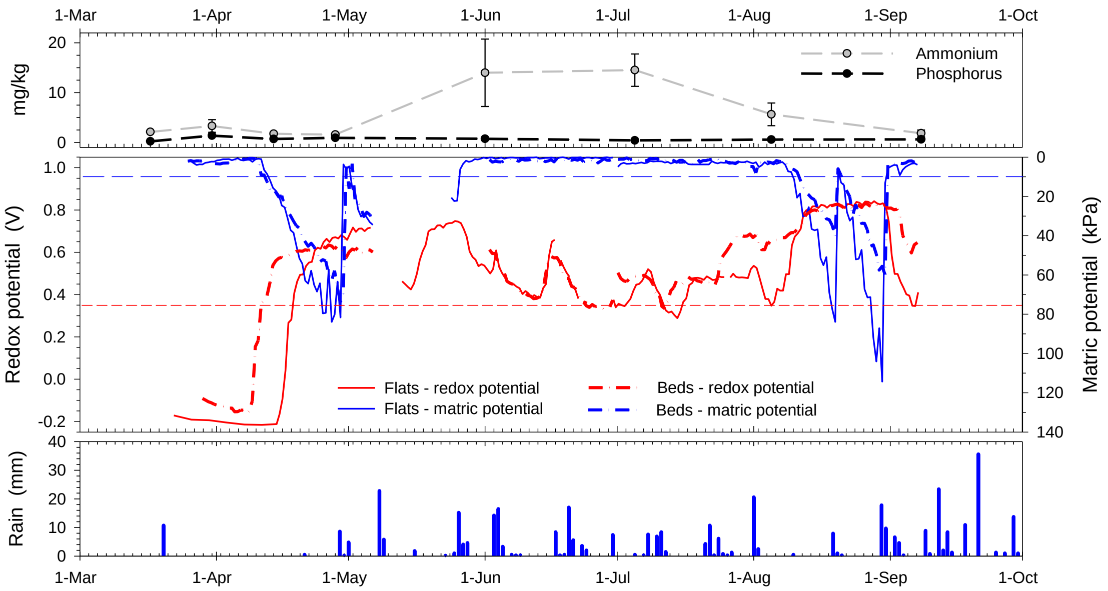

Figure 2. Top – average concentration of ammonium N and soluble reactive phosphorus at 5 cm. Middle – redox and matric potential at 5 cm. Bottom – daily rainfall at Finley.

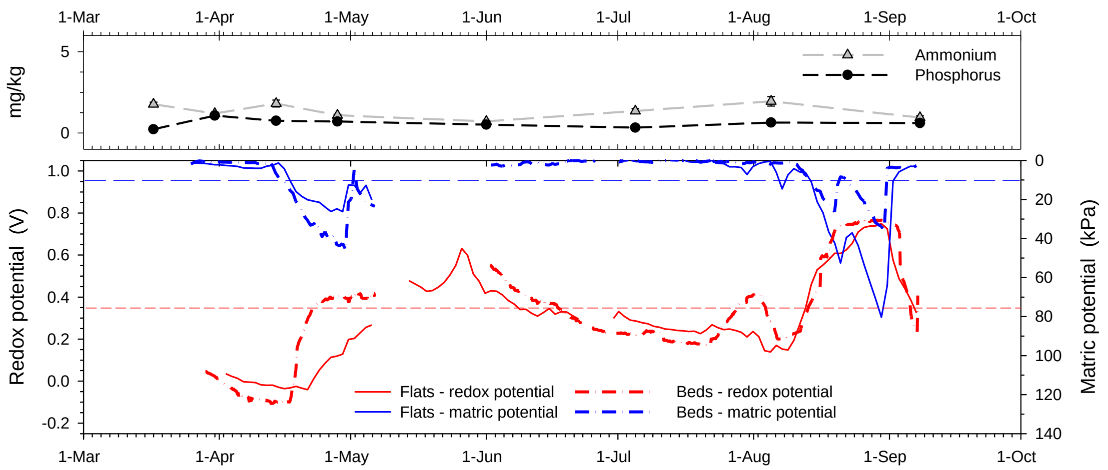

Figure 3. Top – average concentration of ammonium N and soluble reactive phosphorus at 15 cm. Bottom – redox (red) and matric potential (blue) at 15 cm.

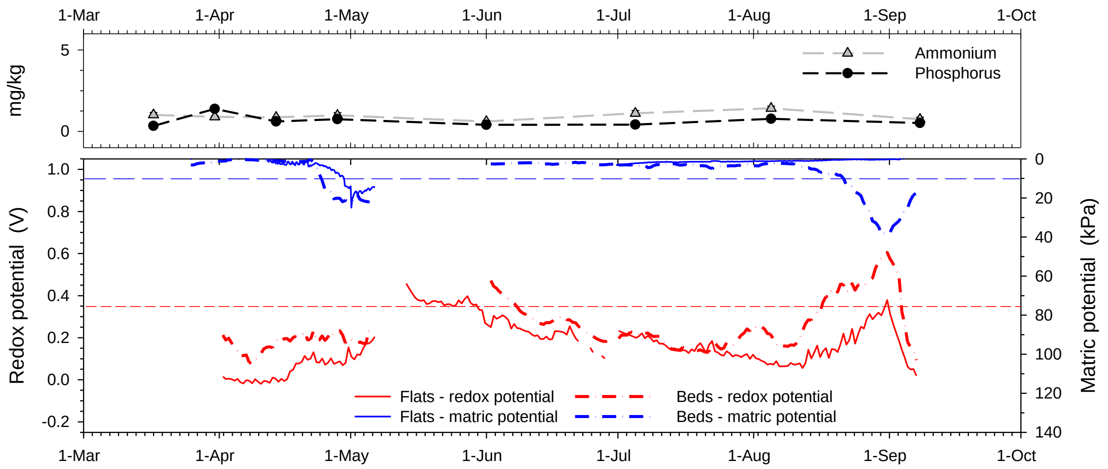

Figure 4. Top – average concentration of ammonium N and soluble reactive phosphorus at 30 cm. Bottom – redox (red) and matric potential (blue) at 30 cm depth.

The time course of redox (E_H) and matric potential (ψ_m) measurements in the beds and flat layout treatments from late March to early September 2016 at 5cm, 15 cm and 30 cm is shown in Figure 2, Figure 3 and Figure 4 respectively. It can be seen that prior to drainage of water from the soil surface on 6-7 April, the soil was saturated (ψ_m >-10 kPa) and E_H was well below the O_2 limiting threshold for plants (350 mV) at all depths monitored. On draining the bays there was an earlier recovery of E_H in the beds at 5 cm to non-limiting levels (Figure 2), though the rate of recovery was similar in both beds and flats. At 15 cm however, recovery of E_H post draining commenced at a similar time in both treatments but occurred at a faster rate in the beds (Figure 3). At 30 cm, recovery of E_H to non-limiting levels was similar in both treatments – i.e. delayed, slow and only partial (Figure 4). At all bar one depth and treatment, the recovery in E_H was preceded by drainage of the soil to ψ_m <-10 kPa. The exception to this was in the beds at 5 cm, where E_H began to recovery before ψ_m declined to less than -10 kPa.

Following paddock drainage and rice harvest, E_H recovered to non-limiting levels at all depths, indicating diffusion of atmospheric O_2 coincident with draining of macropores at the air entry potential. However, this recovery was only short lived, as rainfall from 23rd May onwards saturated the soil at all depths, causing E_H to decline at a similar rate at each depth in both treatments. By mid-June, the soil at 15 and 30 cm was below the O_2 limiting threshold in both treatments and readings in both treatments tracked closely with each other. At 5 cm, there were a number of shorter periods during which E_H rose, peaked, then fell again to levels consistent with that before the rise. These peaks all coincide with significant rainfall events, and could be due to O_2 rich rain water percolating down the side of sensor guide and disrupting the E_H readings at 5 cm until the redox potential of the waters around the electrode come to equilibrium with those in the surrounding soil.

There is a return to oxidised soil conditions in late August at all depths in both treatments. However, by this time the growth of the wheat had been severely affected by the growing conditions. An exceedingly wet September (Figure 1) saw the soil saturated once again and redox readings fall to limiting levels at all depths (though possibly more slowly in the beds at 5 cm - Figure 2). At this point the crop was considered to have failed.

The results from the chemical analysis showed there was no significant differences in P and N availability between the two layout treatments through the sample period. The concentration of soluble reactive phosphorous did not exceed 2.0 mg/kg at any sampling date, with most samples having <1 mg/kg. Ammonium concentrations were slightly higher than P, being 1-2 mg/kg and never over 3 mg/kg, and exhibited a similar lack of trend at the 15 and 30 cm depths (Figure 3-top and Figure 4-top). However, there were increased concentrations of NH_4^+ at 5 cm on 1st June and 5th July, with a decline to lower levels on 5th August (Figure 2-top). Nitrate N, on the other hand, was generally at undetectable levels and when it was detected, the average concentration was only 0.2 mg/kg.

4. Discussion

The use of beds for growing rice may lead to quicker drainage of bays and a return to oxidised soil conditions sooner at depths of up to 15 cm in rice soils similar to that used in this experiment (i.e. sodosols). The principal reason for this is considered due to differences in the drainage characteristics of flat bays compared to furrows. In a flat bay, the surface is irregular and resistance to flow is high, whereas in furrows, flows are concentrated and resistance is lower because the furrow profile approximates a "best hydraulic section". The effect of this is clearly seen in the drainage hydrographs from the two treatments (Figure 5). Between 9am on 1 April and 8am on 4 April when the door was pulled to drain the bay, potential evapotranspiration was 12.7 mm and water draw-down in the bay was 9 mm. This is attributed to evaporative loss (indicating a crop factor of 0.7) and/or seepage. Once the door was pulled, the water level dropped in the beds plot at a faster constant rate until it had drained to the bottom of the furrow. Water was off the top of the beds at about 8am on 6 April, two days after the door was pulled. In contrast to this, the water level dropped at a diminishing rate in the flat plot and it took roughly four days longer for water to be off the soil surface. This probably occurred because the residual depth of water had to evaporate or seep in as it couldn't drain away. This four day delay is mirrored by the four day delay in E_H at 5 cm beginning to rise in the flat plots after E_H had begun rising in the beds plots. This might of course be serendipitous, as it is expected that E_H will not rise until the soil has drained to air-entry (assumed to be -10kPa) and this was not observed in the beds at 5 cm (Figure 2-middle). This may be an artefact arising from the small number of sensors - one matric potential sensor and three Pt electrodes at each of the three depths in each plot.

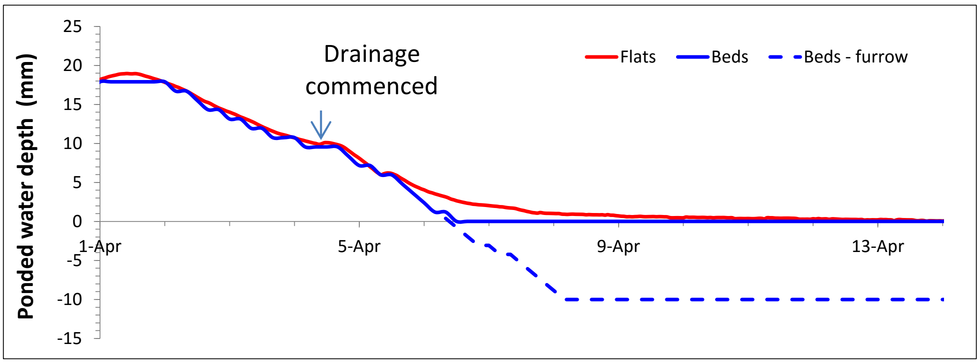

Figure 5. The depth of water ponded above the soil surface during the drainage of water from the beds (blue) and flats (red) treatments prior to rice harvest in April 2016.

Matric potential was >-10kPa at all soil depths from roughly 1 June to 1 August, confirming observations of waterlogged conditions throughout winter. Whilst this had an obvious deleterious effect on wheat growth, this effect may have been primarily due to the exceedingly low levels of plant available N, rather than to O_2 being limited. This is suggested by the fact that E_H was > 350 mV (indicative of aerobic conditions) nearly all winter at 5 cm and from mid-May to mid-June at 15 cm (Figure 2-middle and Figure 3-middle).

Under ponded rice, almost all soil N exists as NH_4^+ and this is readily absorbed by the crop. Additionally, NO_3^- in soils is reduced to N_2 at E_H below 400 mV (McBride, 1994). It is therefore not surprising that the observed levels of NO_3^- and NH_4^+ were so low when monitoring commenced as the rice was nearly mature, water had been ponded on bays for four months, and E_H << 200 mV at all depths. However, it was expected that mineralisation of soil organic matter would lead to an increase in NH_4^+ following rice drainage and drying of the profile and that oxidation of NH_4^+ once E_H > 350 mV would result in increased NO_3^-. While there was an increase in NH_4^+ at 5 cm, this increase was not until well after the soil at this depth had dried past field capacity and re-oxidised, and it did not lead to an increase in NO_3^-. The time lag is significant in that it suggests that rice soils will need become oxidised earlier than we were able to achieve in this experiment if mineralisation is to supply N to crops sown after rice. The fact that NO_3^- could not be consistently detected warrants further investigation, particularly given E_H in the surface soil was at levels where oxidation of NH_4^+ to NO_3^- could have occurred. The soil at the site is acidic (Table 1) and it is possible that pH decreased following draining and drying and this might have impeded mineralisation.

Phosphorus in the soil solution of most agricultural soils ranges from <0.01 to 1 g/kg (Mullins, 2009). Given this, the observed levels of soluble phosphorus were quite high, which might be expected with a Colwell P in the surface soil of 92 mg/kg (Table 1). However, it was also expected that the "high" levels of soluble reactive P under the rice would decline when the soil dried and Fe^{2+} oxidised to Fe^{3+} and bound the P. Theoretically, this should have happened when E_H became >100 mV (McBride, 1994), which was in mid-April at the 5 and 15 cm depths. The lack of change at 30 cm is possibly explained by the fact that the soil in that horizon was mostly in a reduced condition for the duration of the sampling period. However, this did not occur at the 5 and 15 cm depths and further investigation is needed.

Conclusions

Double cropping is proposed as a way of improving the total water productivity of Australian rice farming systems. Our objective has been to determine whether raised beds can improve drainage and soil conditions so higher yields can be attained from non-rice crops in a double cropping rotation. During the first year, in which a rice crop was followed by wheat, continuous monitoring of redox potential and matric potential has shown that this may be partially achieved, but that additional measures will be needed if higher yields of crops sown after rice are to be realised.

The high rice yield attained from such a short season variety (sown in late November and harvested in late April), together with the fact there was no significant effect of irrigation layout, has shown there is potential to improve water productivity in the rice phase of the proposed system. Measurement of irrigation water volumes in the coming seasons will allow this to be quantified.

The early benefit of drier, more oxidised soil from quicker drainage of rice water in the beds treatment was not realised in significantly better wheat establishment and growth. Whilst the failure of the wheat crop can be seen as a function of a rare event, in that the winter/spring period was one of the wettest on record, it is considered that any new system must be able to reliably produce good yields under just such conditions. The simultaneous monitoring of redox and matric potential, together with the sampling for soluble N and P, showed that although waterlogging was the condition, the actual cause of crop failure in the wheat in this instance appears to have been the exceedingly low levels of NO_3^- in the soil at all depths.

Oxidised soil conditions are required for mineralisation of organic N and subsequent nitrification. Highly reduced soil conditions at the time rice bays are drained in autumn, just prior to the onset of cool and wet winter weather, are not conducive to the sort of drying that would be required to oxidise organic N and increase NO_3^-. Raised beds are unlikely to be a successful strategy for double cropping on their own and additional strategies are needed. These could include earlier soil drying through flush finishing or a post-flower drain in the rice, or banding of nitrogenous fertiliser and better timed top-dressing in the wheat.

Identification of the cause of the poor wheat growth would not have been possible without the simultaneous and continuous monitoring of redox and matric potentials.

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