Phosphorus fertiliser requirements of rice under alternate wetting and drying irrigation in the Vietnamese Mekong Delta

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Abstract
Alternate wetting and drying (AWD) irrigation can save water in rice production while maintaining yields, but little is known about its influence on phosphorus (P) availability or fertiliser requirements. Plant-available P decreases as soil dries, causing P sorption and precipitation, and increases on rewetting, as P is released into plant-available soil fractions. This study examined how extent and frequency of wetting and drying cycles affect P availability in paddy soils. A pot trial showed dissolved inorganic P (DIP) concentrations in the soil increased with intensity of drying (continuously flooded: 1.1 mg P kg^{-1}, re-flooded after drying to 66% moisture content: 2.2 mg P kg^{-1} and after drying to 5%: 5.1 mg P kg^{-1}). In a field trial, DIP was higher following a double AWD cycle over a 30 day period (0.30 mg P kg^{-1}) than following a single AWD cycle over the same period (0.1 mg P kg^{-1}; $P<0.05$). However, Olsen P analysis detected no differences between treatments; and no differences were found in grain yields when these AWD frequencies were continued through to harvest, probably because soil P concentrations were already at an agronomic optimum for rice. Five farmers interviewed reported using P fertiliser application rates in their AWD irrigation management that varied greatly from recommended levels. The study highlighted that AWD frequency could be managed to capture increases in DIP where P is limiting. Improvement in matching P fertiliser application to crop needs is more likely to produce significant savings regardless of irrigation method.

Key words
Rice, water efficiency, irrigation, phosphorus, fertiliser application, Mekong

Introduction
Rice is conventionally flooded throughout the growing season. Climate change, inter-industry water competition, population increase and upstream damming are expected to cause water shortages for irrigated rice in the Vietnamese Mekong Delta (VMD). Therefore, rice growers are adopting AWD irrigation to lower water use. Alternate wetting and drying involves allowing water to recede below the soil surface before re-irrigation, lowering total water use (Bouman & Tuong 2001). Regimes vary in the frequency and severity of drying. When adapted varieties are used and drying is not too severe (i.e. does not exceed 30 kPa at a 15-20 cm depth), AWD can produce yields comparable to those achieved under continuous flooding (Bueno 2010). Optimum grain yield requires Olsen P concentration between 10 and 20 mg P kg^{-1} soil (Bai *et al*. 2013) and DIP greater than 0.1 mg P L^{-1} (Hossner *et al*. 1973). Cost-effective fertiliser use brings soil P concentrations to these optimal concentrations. However, little is known of the extent to which AWD irrigation influences P availability in irrigation systems or to what extent P fertiliser requirements are affected. The aim of this study was therefore to determine the influence of severity and frequency of AWD cycles on available P concentrations and rice yield in order to develop recommendations for P management practices in AWD systems in the VMD. In addition, this study evaluated P management in AWD systems in the VMD in order to adapt current P fertiliser recommendations to AWD management.

Materials and Method
Selection of phosphorus analytical methods
Phosphorus exists in in several different forms, each with a different level of availability to the rice plant. Plant-available P decreases as soil dries – causing P sorption and precipitation – and increases on rewetting, as P is released into plant-available soil fractions (Shen *et al*. 2011, Bünemann *et al*. 2013). Olsen P (Olsen *et al*. 1954) is commonly used to measure plant-available P, including both DIP, which is immediately available to the plant, and labile P, which is readily desorbed into soil solution over time. Measuring DIP in isolation gives a more accurate indication of instantaneous P availability. Therefore, this study assessed both Olsen P to measure P-availability over the life of the crop and DIP to identify fluctuations in time.

Pot Trial
A pot trial was conducted to assess the impact of AWD management on plant-available P with three irrigation treatments: continuously flooded (CF), moderate drying and rewetting (MDR) and severe drying and rewetting (SDR) (Figure 1a), using three replicates. Each replicate comprised of 15 g of homogenised moist soil packed at a 5 mm depth into 250 mL sterile plastic jars. All treatments were initially irrigated to 3 cm above the soil surface with 105 mL of deionised water. In the CF treatment, water was maintained at this level throughout the experiment. After the initial irrigation, the MDR treatment was air dried to a gravimetric water content of approximately 66%, representing a visually moist condition and a water potential of approximately -20 kPa, measured by pressure plate analysis (Cresswell 2002) then re-irrigated to 3 cm. The SDR treatment was dried to a gravimetric water content of approximately 5% before re-irrigated to 3 cm. All samples were kept in a dehydrator oven at 40^{0}C to maintain a constant temperature while drying. Concentrations of DIP were analysed using the calcium chloride method (Rayment & Lyons 2011) 14 days after initial flooding.

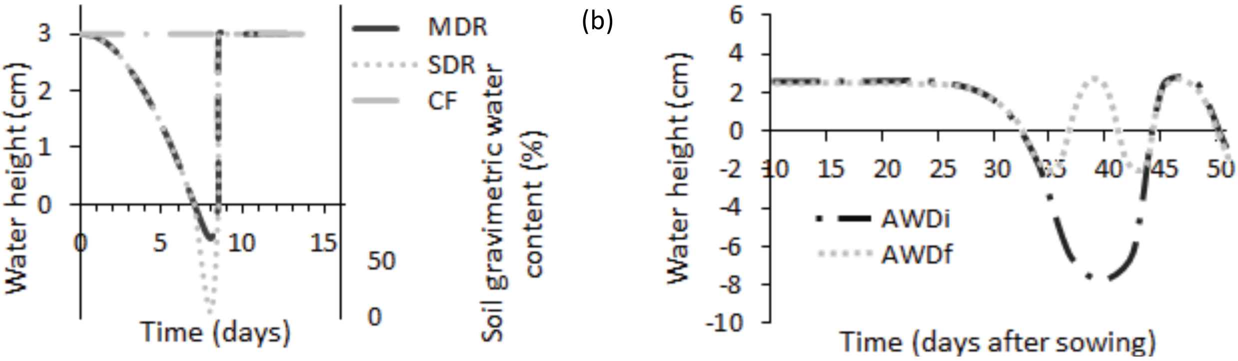

Figure 1: Schematic diagrams showing (a) severity of drying in a pot trial treatments (b) frequency of drying in field trial treatments. See text for explanation of abbreviations.

Field trial
A field trial was conducted in the 2013-14 dry season of the annual three-crop rice growing system in Bac Lieu, Vietnam. Two AWD irrigation treatments were applied at 20 days after sowing: a single AWD cycle in a 30 day period (AWD_i) a double AWD cycle over the same period (AWD_f) (Figure 1b). In AWDi, the perched water table was allowed to recede to -2 cm below the soil surface on average before re-irrigation to 1-5 cm above the soil surface, and in the AWD_f to -8 cm. Soil P was assessed 47 days after sowing but AWD cycles were then repeated at approximately 10- and 20-day intervals until harvest at physiological maturity (112 days after sowing), so that over the life of the crop AWD_i and AWD_f were irrigated 5 and 9 times, respectively.

Three soil cores were taken from the top 15 cm of soil in each treatment and combined to form a composite sample. Samples were analysed for plant-available P using the Olsen method. The soil was kept moist on analysis of Olsen P to prevent any change in available P on soil drying and results were expressed as concentrations of equivalent oven dry soil based on gravimetric water content at the sampling time. At the same time, solution samples were taken from piezometers under vacuum, which were installed 15 cm deep to collect soil water within the root zone. Solution samples were filtered through 0.45 µm filters and DIP was measured using the Phospher®3 Method (Hach Company 1998). Grain yield was measured from a 5 m^2 quadrat within each plot at harvest.

Farmer interviews
To gain an indication of fertiliser practices, interviews were conducted with five farmers practising AWD in Bac Lieu Province, Vietnam in collaboration with staff from the Can Tho University Department of Soil Science, under government approval. The interview included questions regarding current P fertiliser management practise and crop yields.

Results
Pot Trial
Irrigation had a significant influence on DIP concentration, which was 2.3 times higher under SDR (5.1 mg P kg^{-1} soil) than under MDR, and 5.1 times higher than under CF (Figure 2a).

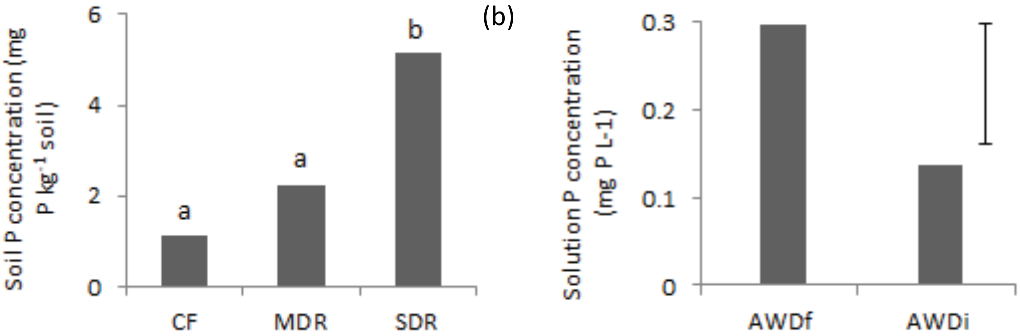

Figure 2: Dissolved inorganic P concentrations in the (a) pot trial assessing severity of drying (columns with different letters are not significantly different at P < 0.05), and (b) field trial assessing drying frequency, where the bar denotes the l.s.d (P < 0.05). See text for explanations of abbreviations.

Field trial

Irrigation treatment did not significantly affect Olsen P concentration, which averaged 10 mg kg^{-1}. However, AWD frequency did significantly affect DIP concentration in water samples (Figure 2b). DIP under AWD_f was 0.30 mg P L^{-1}, 2.1 times that under AWD_i. Irrigation treatment did not significantly affect grain yield, which averaged 5.0 t ha^{-1}.

Farmer interviews

Farmers interviewed reported a 54% variation in grain yields, and a 1266% variation in P-application rates (Table 1). Based on a P removal rate of 2.4 kg P t^{-1} (Reuter & Robinson 1997), application rates ranged from a deficit of 15 kg P ha^{-1} to an excess of 30 kg P ha^{-1}.

Table 1: Grain yield and phosphorus application under AWD irrigated rice management in Bac Lieu Province, Vietnam.

Factor	Range
Rice grain yield (t ha^{-1})	5.5-8.5
P input (kg ha^{-1})	3-42
Crop P removal (kg ha^{-1})*	13-20
Excess P applied (kg ha^{-1})	-15-30

* Assuming 2.4 kg P t-1 rice grain yield is removed at harvest (Reuter & Robinson 1997).

Discussion

The study revealed that irrigation regime affects P dynamics. The positive response of DIP to severe drying and rewetting in laboratory conditions is consistent with other research showing pulses of DIP release following remoistening of pasture soil dried to a 5% gravimetric water content or less, but not when drying has been limited to 15% (Bünemann *et al*. 2013). In the field, this pulse is most likely to occur at the very surface of the soil where drying is likely to be most severe even when soil water does not drop below the root zone (Hasegawa & Yoshida 1982). As most soluble and labile P is present in the top soil (Sims *et al*. 1998), any form of AWD may release significant P after re-irrigation where the surface soil is allowed to dry out severely.

The response of DIP to increased frequency of AWD cycles is also consistent with previous studies showing repeated cycles of drying and remoistening having a cumulative effect on available P in dryland situations. In a study of top soil from a long term pasture system over three weeks, Butterly *et al*. (2009) found an increase in up to approximately 3 mg P kg-1 between the first and third rewetting events. The current study therefore provides evidence that wetting and drying dynamics of P availability in soil under AWD irrigation are similar to those reported under dryland conditions.

However, even though DIP accumulation occurs with severe and frequent AWD, it appears this process may not influence plant-available P through the life of the crop, as AWD regime has not been found to influence the total pool of plant-available P in this or other studies (Butterly *et al.* 2011). Sensitivity of DIP, but not of Olsen P, to irrigation treatment may be a result of the scale between the two measures. Average DIP concentrations found in the present study were a minor component (0.7%) of Olsen P (calculated with a bulk density of 1.2 and gravimetric water content of 65%). Therefore, a small change in available P concentration is more likely to be detectable in measures of DIP than in the combined fractions measured using Olsen P.

Alternatively, failure to detect a change using Olsen P may indicate that any increase in DIP is provided by a corresponding decrease in labile P. The dynamics between the P fractions measured by Olsen P are worthy of further examination.

The lack of yield response from different frequencies of AWD applied in the field indicated that the tested frequencies did not create yield-limiting water stress and that any influence on DIP due to AWD was not limiting to yield. Even though only a small number of farmers were interviewed, the high variability P fertiliser management highlights the need to improve farmer understanding of crop nutrient needs and fertiliser management in the VMD as well as the potential for improvements in P fertiliser application to improve profitability. This conclusion is supported by Tan *et al*. (2004), who revealed similar variation in P application in the VMD (6-61 kg P ha-1 crop-1), regardless of plant and crop needs.

Conclusion

This study demonstrated that DIP in paddy soils can be cumulatively increased through frequent and/ or severe AWD cycles, but further investigation is required to determine whether this will benefit grain in situations where P is limiting. More research is also required on the mechanism responsible for DIP release. The study also highlighted that there is potential to increase efficiency of P fertiliser management in the VMD and the need to improve farmer understanding of the P needs of rice crops. Matching plant P requirements with P fertiliser application should improve farm profit by decreasing input costs and improving crop responses to fertiliser where P is required. These changes are likely to have much greater impact on farm profitability than are relatively small changes to P-availability induced by management of AWD.

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