Aerobic and Alternate-Wet-and-Dry (AWD) Rice Systems

A report for NUFFIELD AUSTRALIA FARMING SCHOLARS

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2005 Nuffield Scholar

Completed: February 2007

Nuffield Australia Project No: RABO 090

Sponsored by: Rabobank

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Executive Summary

This study intends to overview the efforts to adopt aerobic and alternate-wet-and-dry (AWD) rice systems to increase water use efficiency. It then assesses the possible value to the Australian rice industry.

Aerobic rice is defined as receiving no irrigation water, whilst AWD rice receives sufficient irrigation to meet crop requirements without permanently applying floodwater.

Aerobic and AWD systems have significantly increased water use efficiency in more permeable soils (such as northern China), because up to 60 per cent of ponded water was leached from the soil. On low percolation soils (such as Australia), water use efficiency is much less responsive; less water means less transpiration and hence less yield.

Weed control revolves around grass weeds, particularly *Echinachloa* spp., and is heavily reliant on herbicides. There is an adequate diversity in available modes of action, with herbicide groups A,B, D, E and F represented. By comparison, Australia probably makes insufficient use of group B (Clearfield™) and group D (pendalmethalin), especially considering that group E is becoming less available.

Aerobic germplasm, be it inbred or hybrid, is clearly more drought tolerant than lowland varieties. It generally stems from increased early vigour and root volume, greater osmoregulation and better use of nitrate nitrogen. No observed germplasm, however, displayed increased yield per unit transpiration, confining its value to reducing water losses, rather than increasing the conversion of water to yield. C_4 rice (or less temperature responsive germplasm) may be the only possible way of achieving this.

Aerobic and AWD rice systems have greater potential for nitrogen losses; often recording less than half the nitrogen use efficiency of flooded systems (Australian flooded systems typically have 60-80 per cent nitrogen use efficiency). Low soil nitrate levels at sowing, conservative nitrogen strategies until permanent flood and particularly controlled release nitrogen can reduce losses and increase efficiency. Controlled release nitrogen formulations have become much cheaper in recent years with increased manufacturing volumes. They may well become part of mainstream Australian crop management in the near future.

AWD rice systems may well reduce the Australian rice industry's field emissions by about half – provided denitrification (NO_x production) is controlled – by confining the major decomposition of organic carbon to produce CO_2 rather than CH_4.

Only some Australian rice soils will be truly suited to AWD systems, as they may have insufficient ability to store and then deliver water between rainfall/irrigation events. Rice soil suitability assessment may need to be refined for AWD systems, to account for a soil's water relations as opposed to simply its percolation rates. EM38 soil survey techniques may well be a part of this refinement.

An AWD regime for the first half of the growing season will be of great value to the Australian rice industry, but it would only yield marginal water savings. It will be of great value, however, in managing broadleaf weed herbicide resistance, establishment costs, wildlife problems and low initial water allocations. As such, this report recommends adopting some aerobic germplasm, refining AWD nitrogen management, considering Clearfield™ technology and redefining rice soil suitability.

Acknowledgments

Like most Nuffield scholars, I have been humbled be the assistance many folk have rendered to me in planning and executing my studies.

Firstly, I would particularly like to thank Dr Shu Fukai of University of Queensland. He helped me better refine the work and gave me the valuable first introductions to key workers in aerobic rice.

The staff at the International Rice Research Institute (IRRI) – especially Drs Melissa Fitzgerald, Yas Hosen, Sarah Johnson and Fengming Xie - were invariably helpful in helping me skip from germplasm, to irrigation, to physiology, to pathology and elsewhere in looking at the aerobic/AWD question.

Dr Nathan Slaton and Keith and Sandie Thomas did much to make me feel at home in Arkansas – much of it at very short notice.

The staff at RiceTec in Alvin, Texas were very helpful in helping me to quickly come to grips with hybrids, micro satellite markers, QTL's and especially finding the right airport!

Dr Wang Huaqi and his students at China Agricultural University (CAU) helped me to understand the aerobic rice system in northern China. They struggled long and hard to bridge our language barriers and also gave me access to other departments at CAU.

Dr Russell Reinke, Dr Peter Snell and Dr Laurie Lewin all helped me enormously in arriving in the all-important Australian context for considering aerobic and AWD rice.

Finally, I sincerely thank my poor suffering wife, Sue for enduring my absence, especially whilst expecting our second child. Similarly, both my sister Robin and employee Macca both went the extra yard in keeping the farm moving without me.

Aims\Objectives\Study Goals

The aim of this study is to investigate the major agronomic issues of aerobic and alternate-wet-and-dry (AWD) rice growing systems. The primary question of this study is: can a move to more AWD rice systems offer significant water use efficiency improvements for the Australian rice industry? The issues of breeding, weed control and nitrogen nutrition are central to this question.

Introduction

Water is the most limiting factor to Australian rice industry. The Murray and Murrumbidgee catchments appear to face a future of reduced supplies and increased competing interests. Hence, water use efficiency (yield per unit water used) is an important factor upon which to focus.

One strategy that the industry wants to explore, is expanding the area of AWD (also known as drill-sown in Australia) rice and extending the period of aerobic culture, without extending the season or sacrificing yield and hence increasing water productivity. This will require altered management techniques and importantly germplasm better adapted to this situation.

Strictly speaking, aerobic rice is grown purely on rainfall and is not irrigated. This is generally not suitable for the temperate Australian industry as rainfall is generally insufficient to meet crop requirements. Alternate-wet-and-dry (AWD) systems use flush irrigation to supplement rainfall as required. This may be for the whole growing season, or strategically for part of the season.

AWD establishment lends other advantages to the Australian system, namely reduced broadleaf weed pressure, less water applied early in the season to cope with low initial water allocation announcements, lodging resistance and reduced establishment cost. The major disadvantages are an extended growing season and increased grass weed pressure. Hence, although water efficiencies are the main thrust of this study, the diversity of benefits makes us doubly sure of the need to improve our AWD establishment systems.

Water Use Efficiency

It is helpful to define the issue of water use efficiency in rice systems. Overall, the water use efficiency of the rice production system is best defined as the mass of product produced per unit water applied to the system. Seeing that rainfall is generally very limited in Australian temperate rice systems, I will not indulge in the semantics of differentiating irrigation versus rainfall water supply, except to refer to many growers' ability to harvest and reuse rainfall runoff, maximising its value. Likewise, I will only refer to the rice produced in a rice system. Often moisture synergies are achieved with following crops. After rice harvest, the heavy clay rice soils often hold 150 mm of residual available water, for a winter crop sown into the rice residue within weeks of harvest, or after a year of fallow. Hence, 10-15 per cent of the rice's water use is utilised by the following crop. This aspect is not the concern of this study.

$$WUE = Y/(E+T+P+L)$$

WUE = crop water use efficiency(g/kg);

Y = rice yield (kg/ha)

E = seasonal evaporation (kg/ha);

T = seasonal transpiration (kg/ha);

P = seasonal percolation (kg/ha);

L = seasonal runoff (kg/ha).

Initiatives to increase water use efficiency can be broadly split into two areas; reducing non-transpiration fluxes of water (let's call them losses) from the system and increasing the transpiration efficiency of the rice plant. The former is a much easier and hence more popular target than the latter. These two strategies, and their applicability to the Australian Rice Industry, form the context to most of the initiatives described in this report.

Reducing losses from the system

Water losses from the rice system are evaporation (both from soil and free water), percolation and runoff.

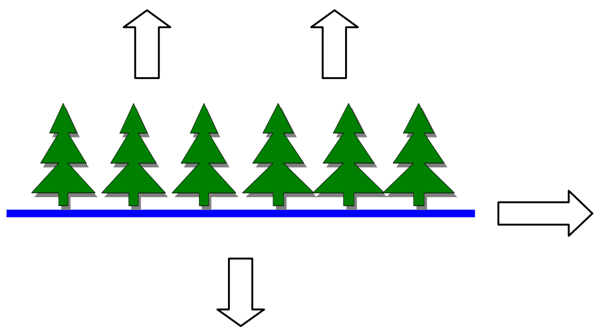


Figure 1: Water fluxes in a rice crop

Evaporation occurs from any crop whenever there is less than full leaf canopy cover of the soil/water. Free surface water evaporates the most in any weather condition, followed by bare soil, and then mulched soil (the mulch may be loose soil, residues or even plastic film). Tao *et.al.* (2005) found water use efficiency increased by 50 per cent by adding plastic mulch, most of which is attributable to eliminating soil evaporation (see Table 1). The biggest evaporation savings are possible on better water holding soils, because the soil surface can be kept dry whilst supplying adequate water to the crop at depth. Whilst in theory, some evaporation will occur throughout the crop season because canopy cover is never complete, for practical purposes intensive rice systems see little evaporation after the latter vegetative stages.

Table 1: A summary of relative evaporation coefficients of common surfaces. The coefficient is relative to well-watered, closely-mown grass being 1.0. Source: Allen et.al. (1998)

Surface	**Evaporation Coefficient (Ke)**
Water	1.05
Wet soil	1.05
Dry soil	0-1.05
50% straw mulch cover	0.75
100% straw mulch cover	0.50
Plastic film	0.20-0.50

Figure 2: A plastic mulch being used experimentally in Hebei Province, China, to reduce soil evaporation losses.

Percolation can be the dominant form of water loss. In lighter textured soils (such as China for example), it often represents around 50 per cent of water use (Tao *et.al*., 2005). Thus, a move away from ponded water has yielded great savings. Heavier textured soils, especially those with sodic horizons (such as Australian approved rice soils) by comparison, have much lower percolation rates, typically less than 10 per cent of water use (Beecher, *pers.comm.*). This is a distinction to remember when considering water loss reduction strategies.

In summary, the main strategies employed to reduce losses are to reduce the period of water ponding within a given growing season, reduce crop duration (provided yield is maintained), cover the soil surface with some form of mulch and establish canopy cover as quickly as possible.

Increasing water productivity

Drought tolerance aims to preserve yield against loss from drought episodes. Increasing water productivity aims to enhance the yield generated from a given transpiration through the plant. Although they are related in the field (drought tolerance facilitates water-saving techniques), they are independent traits to pursue in any research program.

Mechanisms that control stomatal aperture, increase root depth and density or otherwise regulate transpiration are encouraged in drought tolerance screening. Of most interest to Australia are drought tolerance mechanisms that are expressed early in the season, when we want better adaptation to aerobic conditions.

Water productivity can be expressed as the biomass (and by inference rice yield) fixed per unit water transpired.

$$WP_T = Y_{grain}/T$$

$$Where\ Y_{grain} = Y_{biomass}\ x\ HI$$

WP_T (g/kg) is the water productivity;

Y_{grain} (g/ha) is the rice grain yield;

T (kg/ha) is the rice crop's seasonal transpiration;

$Y_{biomass}$ (h/ha) is the rice biomass production;

HI is the crop's harvest index.

A simple strategy is to grow the rice in a less evaporative condition, by altering sowing times. There is a fundamental compromise, however, between sourcing adequate heat for growth and development of (especially lowland) rices (optimum growth occurs at around 30°C) and reducing evaporative demand. Maximum growth and development occurs at about 30-35°C, depending on genotype. Evapotranspiration increases linearly with temperature, so the optimum temperature for growth per unit water will be somewhere slightly less than the 30-35°C (Bouman *et.al.*, 2001). Is there an opportunity to pursue germplasm that has a lower optimum growth and development temperature, to allow similar biomass accumulation at lower temperatures?

The semi-dwarf habit has been a great advance in water productivity, by increasing harvest index. Semi-dwarf varieties – now dominant in many breeding programs – partition 45-55 per cent of their biomass into grain rather than typically 30 per cent for taller varieties.

Likewise, shorter-season varieties which maintain yields have increased water productivity. Generally, these varieties rely on a high harvest index to compensate for reduced biomass production, rather than a significantly greater rate or efficiency of biomass accumulation. Hence, the primary alteration is a higher harvest index.

More challenging, but potentially more rewarding is to intentionally increase the amount of carbon fixed per unit water transpired in a given evaporative condition. Significant variation exists across the rice family (*Oryza* spp.) in water productivity, which can be targeted by out-crossing and then screening progeny (Peng *et.al*.,1998). Tuong *et.al.* (2004) warn that a certain flux of water is required through the leaf to cool the canopy and maintain function, especially in a hot, arid climate like that of Australia. 10 to 15°C evaporative cooling has been commonly recorded on hot days in Australian rice crops (Lewin, *pers.comm*.)

In theory, converting the rice plant to a C_4 photosynthetic pathway should also increase transpiration efficiency, because CO_2 is actively harvested from the wet membrane where gaseous exchange and water loss occurs.

Water use efficiency in Australian rice systems

Australia grows the vast bulk of its rice in flooded culture; water is ponded from sowing until just before harvest. This yields high nitrogen efficiency, robust weed control (whilst herbicide efficacy persists), labour-efficient water management and ensures adequate water supplies in a hot, dry environment. It does come at the cost of evaporative losses until canopy closure (approximately 2-3 ML/ha), higher percolation rates (approximately 1-2 ML/ha) and some more lodging susceptibility.

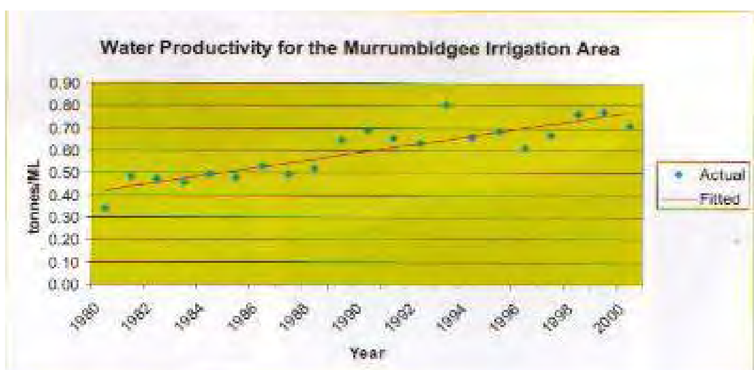


Figure 2: Water productivity in the Murrumbidgee Irrigation Area. Note that the units of tonnes/ML are equivalent to g/kg. Source: Rural Industries Research and Development Corporation (2006)

A move to alternate wet and dry (AWD) culture, therefore, has the potential to save about 3-5 ML/ha from a total water use of 10-15 ML/ha; about 15-30 per cent. This assumes that yield is maintained and that the season length is not extended as compared to flooded culture, as is currently the case.

Experiments to date have shown little improvement in water use efficiency from AWD, as yield has declined in line with water use (Thompson, *pers.comm.*). Notwithstanding the need in some years to have deep water for cold protection, we can infer that in addition to reducing evaporation and percolation, transpiration was also reduced. This is especially in the heavy textured sodic soils typical of our rice industry, where moisture relations can quickly become limiting as moisture drops below field capacity in evaporative conditions. Many of our heavy clay soils have a limited ability to deliver large fluxes of water in an aerobic state. Hence, the realistic place for AWD is in the first (say) 8-10 weeks of the season, where evaporative demand and leaf area is lower. At best (best practice techniques, adapted germplasm) it will yield a 15-30 per cent water use efficiency gain. This observation explains why to date, the Australian breeding program has instead focused on improving yield and reducing crop duration, but retaining flooded culture.

Even with the losses associated with flooded culture, Australia ranks as one of the more water-use efficient industries in the world (rainfall plus irrigation). Our major weakness is that rainfall contributes little.

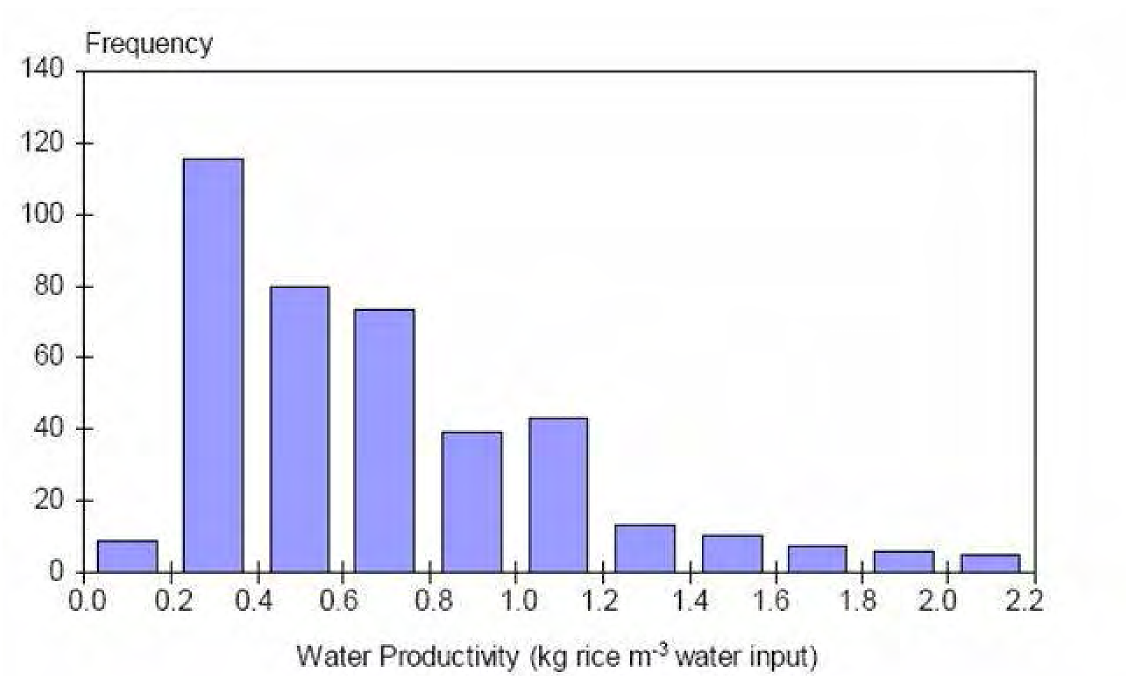


Figure 3: Rice water productivity in India, China and Malaysia (Source: Tuong et.al., 2004)

Breeding

Conventional (inbred) breeding

Germplasm has been screened, either intentionally or deliberately, for drought tolerance in many conventional breeding programs for many years. It comes from a range of physiological characteristics and is a quantitative trait (determined at many loci in the genome) that can be expressed at different times in the crop season. Our main task in Australia is to produce germplasm that can be exposed to mild early drought stress (transient exposure to, say, -25 kPa soil tension) without sacrificing yield or reducing development rate, as is currently the case. Dr T.P. Tuong, a senior crop researcher at IRRI, suggests that because of its root adaptations to retain oxygen in flooded culture, unadapted lowland rice roots do have an impaired ability to absorb water even from (especially heavy clay) soil that is quite close to field capacity. This slows biomass accumulation and development rate. He suggests that even high-yielding lowland rices can be better adapted to early drought through conventional screening, without losing yield potential.

The University of Arkansas rice breeding program, for example, selects varieties according to early season vigour in an aerobic environment. One component of this is early tolerance to (mild, transient) drought (although the researchers seem to give little credence to this). Hence, they have been *de facto* selecting for early drought tolerance for some time.

Figure 4: Typical early conditions in a breeder's plot in Arkansas. Mild drought stress can be a factor, but is not targeted specifically.

Interestingly, because a lack of awareness of the amount of water applied to fields in Arkansas, measures of water use efficiency are lacking amongst farmers and researchers. Productivity per unit land area is currently still the main focus, although high pumping costs may soon change this.

The breeding program at China Agricultural University (CAU) has more aggressively targeted drought tolerance mechanisms by crossing lowland rices (high yield, poor drought tolerance) with upland rices (low yield, more drought tolerance). The outcross and resultant screening has produced the Han Dao ("Dry Rice") varieties that are now gaining popularity in water-scarce northern China. The Han Dao varieties do seem better adapted to drought through a combination of increased stomatal control and denser, deeper roots. Bouman *et.al.* (2006) showed that the vast bulk of the yield advantage of these lines in water-limited conditions came in better drought tolerance in the reproductive phase; ensuring a higher percentage of grains are filled even with reproductive drought. This raises serious questions as to Han Dao's value to the Australian industry, given that we see little motivation for aerobic culture in the reproductive phases.

John Thompson, NSW DPI, has demonstrated that our current varieties do respond to aerobic culture by searching deeper in the soil, but a genetic shift in this direction would be helpful. A deeper root zone in the establishment period should make a drill-sown system more vigorous by accessing more water between irrigation events. Plant water tension is moderated by finding more water between irrigations. A greater rooting depth will allow nutrients to be absorbed from a greater soil volume, which could well increase the potential nutrient flux at peak growth periods. A greater root depth would also increase the moisture store at the end of the season, making the drainage timing not quite as critical and improving grain quality by reducing the 'haying-off' risk. The extent of greater rooting depth in Australian soils by adapted germplasm is uncertain, as they are generally shallow and have poor water relations.

Figure 5: The greater root density and root depth achieved by the Han Dao varieties (on the right in each photo), albeit on a well-structured sandy-loam soil. Source: Dr Wang Huaqi, CAU.

IRRI has been screening a range of germplasm for drought tolerance – both early and late – by exposing it to varying intensities of drought; typically -20, -40 and -70 kPa. Their focus is on preservation of yield in the face of drought stress (even just survival under severe stress!), rather than water use efficiency *per se*.

Figure 6: IRRI breeder Dr. Gary Atlin reading a tensiometer amongst drought tolerance screening plots.

Dr. Gary Atlin, a breeder at IRRI, did suggest, however, that tolerance to severe stress did seem to correlate fairly well to tolerance to mild drought stresses. Hence, drought tolerant germplasm probably is of value to Australia, provided it can be exploited with an appropriate screen. He was finding consistent, useful drought tolerance from *Apo*, an Indian indica line, and crosses with *Apo*. Similarly with *Aus*.

Likewise, many breeding programs have been indirectly targeting faster canopy closure in aerobic conditions by selecting for early vigour.

Hybrids

Heterosis is a significant source of plant vigour. It is also a source of resistance to abiotic stresses, such as cold, heat or drought.

Hybrid rice production is relatively recent art, having been developed and refined in the last few decades. Dr Yuan Longping, based on Hainan Island to the south of China, is the accepted father of hybrid rice. In the early 1990's, the Prince of Lichtenstein established Rice Tec Ltd. in the USA to develop hybrid seed production for all of the Americas. Now, 50 per cent of (indica) rice in southern China is hybrid, 10-20 per cent (and growing) of rice in southern USA is hybrid and similar in South America.

Seed costs are typically four-fold that of inbred seed, because hybrid seed must be regenerated anew from parents each season. Needless to say, any Australian system using hybrid seed would need to use it efficiently. Hybrid japonica rices seem to be harder to produce, because the yield from the final cross is lower. The Tianjin Tianlong Agricultural Science Co., Ltd., Teda now produces about 3 t/ha of hybrid rice, as compared to 4-5 t/ha for indica hybrids at Ricetec, Houston. This seems to be the limiting factor in reducing the price of hybrid seed, as most aspects can be mechanized to accommodate variations in labour costs.

I saw many hybrid rice crops in Arkansas and Texas. They were definitely thinner stands, as they are typically sown at about 35 kg/ha. The grain quality of the Rice Tec hybrids (higher chalk content because of tiller asynchrony) seems to be improving relative to that of the inbreds, but they are still acknowledged as inferior quality. This is a big consideration for these growers, as the premium/discount for quality is greater than those Sunrice offers.

Figure 7: A best-practice (no-till) stand of hybrid rice near Wynne, Arkansas. The target population is 50-60 plants per square metre.

There is clear evidence at a farm level in Arkansas that hybrid rice has a more vigorous root habit than the inbreds, again remembering that the soil type was typically a stratified silt-loam.

Figure 8: A Rice Tec hybrid (Clearfield XL8) on the left, an inbred (variety Wells) on the right. Note the hybrids greater root density, notwithstanding root damage when extracting them from the soil.

At IRRI, this translated into greater drought tolerance and hence greater biomass production than inbreds under consistent drought conditions. Gary Atlin believes that this is due to accessing more water in the soil profile, rather than any greater transpiration efficiency. Gary was also finding little interaction between genotype and degree of drought stress; response to mild drought stress was similar to severe drought stress.

Figure 9: Under severe drought stress (-70 kPa), hybrids such as that on the right, generated more biomass than inbreds such as that on the left, primarily through accessing more moisture rather than increasing transpiration efficiency.

The Tianjin japonica hybrids seem to be bred for flooded culture, so do not have tolerance to drought *per se*.

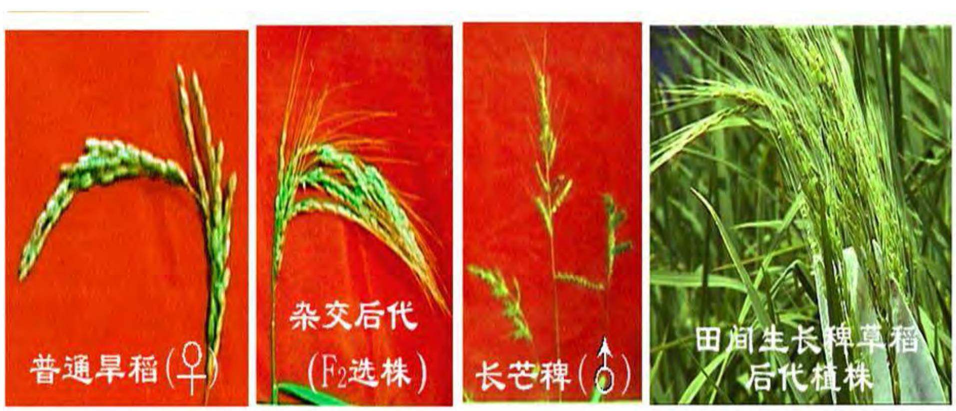
Figure 10: Hybrid seed production at Tianjin. Five female rows between each male row. They still seem to be bred for flooded culture.

Transgenics

Whilst I expected to see clear mention of transgenic rice in increasing water use efficiency, I found very little reference to it until late in my time in China.

Transgenic rice may prove of value if the genes of interest are only at one or a few loci. Quantitative traits, such as drought tolerance, would be difficult to achieve with transgenics.

One tentative ray of light did appear at CAU, however. Dr Wang Huaqi showed me photographic evidence of an apparently-successful transgenic cross between *Oryza sativa* spp *japonica* (rice) and *Echinachloa caudata* (barnyard grass). It had been achieved by scientists under Dr Ming Zhao at the Chinese Academy of Agriculture. The resultant photosynthetic efficiency of the F2 population was claimed to be 30 per cent greater than that of the rice parent. This implies that the F2 population probably has some degree of C_4 metabolism. It also seems to imply that the genes governing the C_4 metabolism are on a small number of loci (a qualitative trait). As mentioned above, this may open up a significant improvement in transpiration efficiency.



(a) (b) (c) (d)

Figure 11: Han Dao 65 (a) was crossed with Echinachloa caudata (c) to produce an F2 population (b). Plants were selected from this population (d), which had 30% higher photosynthetic efficiency than the parents.

IRRI has recently initiated a project – the Frontier Project – to pursue C_4 metabolism in rice. They plan to screen wild rices for C_4 metabolism, but also plan to introduce C_4 metabolism with transgenic crosses. Many traditional scientists do roll-back their eyes at the mention of C_4 rice, as it has been speculated upon for some time. It is no small ask to marry C_3 rice, with its macro- and micro-architecture and other physiological traits, with the C_4 metabolism. It does seem, however, to be the only clear path to greater transpiration efficiency.

Nutrition

Nitrogen

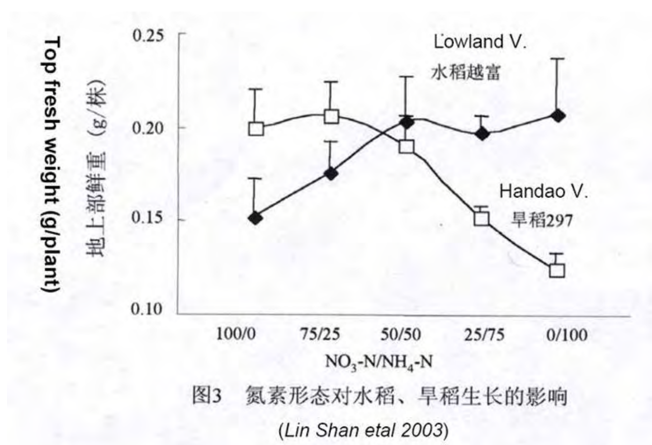
Reduced nitrogen in a ponded soil remains in the reduced state (NH_4^+). Oxygenation of the soil (non-ponded culture) allows nitrification (NH_4^+ => NO_3^-) to occur. Subsequent re-flooding and oxygen depletion promotes denitrification (NO_3^- => N_2O, NO_2). AWD systems are inherently less nitrogen efficient than flooded systems. AWD systems will require more energy in the form of nitrogen; we will substitute nitrogen for water, to a degree. To frame it colloquially, there is no such thing as a free lunch.

The dominant methodology in Arkansas to minimize nitrogen losses is to apply no nitrogen fertilizer until just before permanent water is applied; identical to Australia, where drill-sowing is used. This can achieve nitrogen use efficiency (NUE) of over 80 per cent (Wilson *et.al*., 2000). Interestingly, this improvement has only been made in the last ten years through the advocacy of Dr Nathan Slaton and Dr Rick Norman, University of Arkansas. It is amazing what changes rising nitrogen costs can induce!

Professor Lin Shao, at China Agricultural University (CAU) has been studying interactions between irrigated rice regime and nitrogen dynamics. Typically the aerobic and AWD systems in northern China are achieving 35-40% nitrogen use efficiency (NUE), primarily because of ammonia volatilization after urea application, but also denitrification after irrigation or heavy rainfall. Placement of urea in the soil increased the NUE to about 50%, by eliminating most of the volatilisation (Limeng and Liu, *pers.comm.*).

There is strong evidence that a mixture of nitrate and ammonium nitrogen gives superior nitrogen nutrition in aerobic/AWD culture. Professor Lin Shan at CAU found this is especially true for Han Dao varieties. Qian *et.al.* (2004) found similar using Shanyou63, a Chinese drought resistant cultivar.

Figure 12: The interaction of mix of nitrogen form and variety and their effect on growth rate.



Nitrification inhibitors

Nitrification inhibitors do not seem to be as commercially developed. They are limited to experimental and specialty situations. In theory, they should retard nitrate formation and hence reduce subsequent denitrification when a soil is flooded, but they seem to be quite unreliable, at the least site-specific. The efficacy of trial compounds seemed to vary between studies. For example, Pathak and Nedwell (2001) found nitrapyrin on urea gave 88% reduction in denitrification, but Keerthisinghe (1993) found it gave no reduction at all. Boeckx *et.al.* (2005) found dicyandiamide on urea reduced denitrification by 47%, whereas Malla *et.al.* (2005) found it gave little efficacy.

The most practical nitrification inhibitor appears to be a high ammonium concentration such as when anhydrous ammonia or urea is banded at high rates. The high NH_4^+ concentration inhibits the nitrifying bacteria (Angus, *pers.comm.*).

Slow release nitrogen

Slow release formulations of nitrogen may be well suited to increasing NUE in AWD culture. To increase NUE in an AWD culture, George *et.al.* (1995) recommend avoiding nitrate accumulation by whatever means. Slow release nitrogen formulations will make nitrate available, but never in large pulses that are vulnerable to denitrification.

The use of slow release nitrogen is being investigated at IRRI, in Arkansas and at CAU. The key driver for this research is a recent sharp reduction in its price; it has fallen from a 200 per cent premium ('Meister', that Japanese rice farmers have been using for some time) to about 40 per cent (a range of products from Agrium, Canada and Chinese product).

For the 'Meister' range of products in Japan, the nutrient release is controlled by a coating of a mixture of ethylene vinyl acetate and polyethylene. The ratio of the EVA to polyethylene determines the rate that water penetrates the polymer coating and hence the rate of nutrient release. Organic surfactants can be added to make the release pattern sigmoidal (see Figure 13 for an illustration) (Fujita and Shoji, 1999). Both Agrium and CAU appear to be using very similar technology to this.

CAU trials have found that controlled release nitrogen increased NUE from 35-40 per cent to about 80 per cent by reducing ammonia volatilisation after topdressing and denitrification from an AWD system (Limeng and Liu, pers.comm.). IRRI work is still in progress.

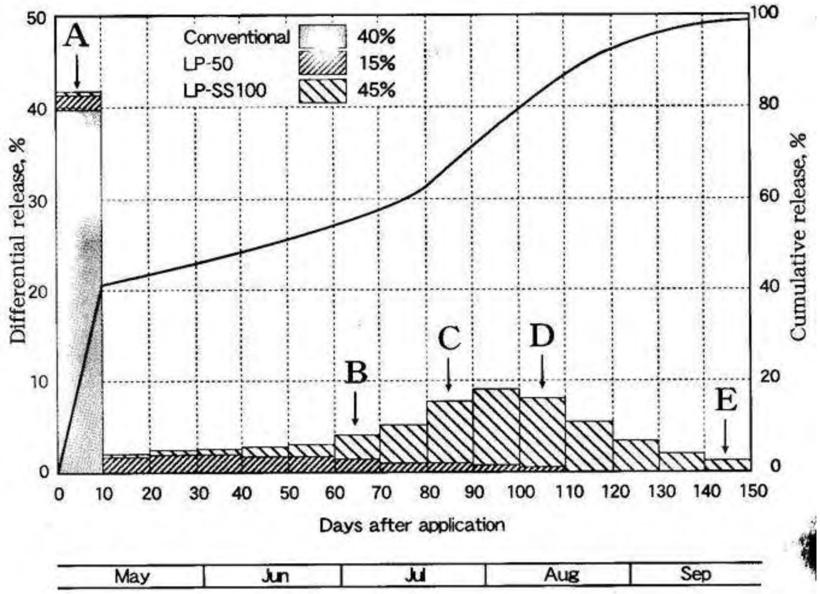


Figure 13: Nitrogen release pattern of mixed conventional, linear (LP-50) and sigmoidal release (LP-SS100) Meister fertilisers. Source: Fujita and Shoji (1999)

Other macronutrients

Many of the macronutrient concerns with aerobic culture stem not primarily from chemical considerations, but physical and even biological constraints imposed on root absorption by soils at less than field capacity (Johnson, *pers.comm.*). Hence, many macronutrient deficiencies (including nitrogen) are associated with poor root exploration from moisture deficit, soil constraints and/or root pathogens. That being said, there are some nutrient nuances that should be noted.

Phosphorus will not be as readily available, because in aerobic culture it is present in the Fe^{3+} form. This does represent a problem for many previously-paddy soils, as greater availability (Fe^{2+} form) has led to greater phosphorus extraction and hence more intense deficiency in its new, aerobic state. In a similar vain, a soil that has been in flood the previous season (which includes even previous drill-sown crops in an Australian context) will have phosphorus present in the crystalline Fe^{3+} form. This is less available than the non-crystalline Fe^{3+} form of P. Hence, higher phosphorus rates will probably be required in many of our rice soils.

Sulphur should be more available, as rice uses the oxidised $SO4^{2-}$ form. Likewise there should be no additional issues with potassium.

Micronutrients

Only two micronutrients get a significant mention with regard to aerobic culture; zinc and iron.

Zinc is more available in aerobic culture. In anaerobic conditions as it bound up with S^{2-} ions generated by the reduced state. Interestingly, zinc deficiency is expressed as incomplete vascular development in rice, so the main symptoms are generally observed *after* permanent water is applied (and it is too late to ameliorate).

Zinc deficiencies can be induced by high pH, such as in Arkansas, for example, because of carbonate-rich bore water elevating soil pH. Our approved rice soils do have some areas of high pH and these are generally given zinc supplements already, but as far as I am aware, carbonates are the last of our problems in Australia from surface or bore water!

Iron will be less available to the rice plant in aerobic soil. Fe^{3+}, especially the aforementioned crystalline state, is less available to the rice than Fe^{2+}.

Pests and Pathology

Research at IRRI has found that root pathogens (nematodes especially) have become a limiting factor with the transition from flooded to fully aerobic rice. It appears that the old ponding regime was having previously-unappreciated advantages. The effects on growth and subsequent yield can be very significant.

Figure 14: The plot on the left (surrounded by plastic) has been fumigated. Aerobic rice growth is increased in the absence of pathogens.

Virulent root pathogens should not be an issue in an Australian context, as flooding for at least the last half of the season should eliminate any pathogens. Nonetheless, it is worth bearing in mind should such 'unexpected surprises' occur.

Weed management

Weed management in aerobic and AWD systems revolves around grass weeds, predominantly *Echinachloa* spp (barnyard grass). They are well adapted to alternating aerobic/anaerobic regimes, they have greater nitrogen response than rice and, interestingly, they are generally C_4 plants.

Of my travels, only Arkansas, Texas and California revealed anything of interest. Both China and IRRI are taking much of their herbicide direction from the USA.

Both Arkansas and Texas are making increasing use of Clearfield ™ technology (imidazolinone tolerant varieties), often in association with the Ricetec™ hybrids. It does make weed control remarkably simple, especially for red rice. Most rice systems there involve a rice-soybean rotation which allows alternative modes of action (generally glyphosate) to be employed in the soybeans. This will dramatically extend the efficacy of imidazolinone herbicides, especially with the restrictions forbidding Clearfield™ to be used in consecutive seasons.

Away from hybrids, Arkansas is very reliant on clomazone (Command®, Magister®) for grass control. Significant crop damage can occur in their loamy soils, especially if it is applied straight after sowing and rain falls soon after application. Clomazone damage can combine with cooler weather to promote insect (Grape Colaspis) and/or Fusarium (‘seedling disease’) infestation. This logic probably holds for other herbicide damage. The University of Arkansas is encouraging more use of pendalmethalin (Prowl®, Stomp®), cyhalofop (Clincher®, Barnstorm®) and quinclorac (Facet®), especially subsequent to reduced rates of clomazone, to reduce the phyto-toxicity risk. *Echinachloa* spp. now have widespread resistance to propanil (SuperWham®, Stam®) and subsequent cross-resistance to bispyribac-sodium (Regiment®). The complete list of herbicides in use in Arkansas appears in Appendix 1.

California makes little use of clomazone in their AWD rice as yet (although they are in the early days of drill-sowing), relying more on pendalmethalin. Similarly, California has widespread populations of *Echinachloa* spp. with cross-resistance to molinate, propanil and cyhalofop. Both states have now lost molinate.

Figure 15: Severe clomazone damage in Arkansas, caused by rainfall immediately after application post-sowing, pre-emergence

Figure 16: Excellent weed control in California achieved primarily with pendalmethalin

It would seem wise to broaden the modes of action available to Australian growers. Clomazone, fenoxaprop, propanil and pendalmethalin are available, but quinclorac and cyhalofop would be helpful additions.

Irrigation techniques

In-field distribution

Only one genuine innovation was observed distributing irrigation water within the field. The rice farmers in Arkansas are rapidly adopting temporary plastic pipe to directly supply water to each bay in the field, as opposed to letting water cascade through bays. The pipe typically carries water for a few hundred metres.

They claim significant water savings and the ability to irrigate their fields quicker. I do struggle to reconcile how this is so, other than perhaps inferring that percolation losses rise rapidly once flood is achieved. Given that the supply is generally pressurised, is does give a distribution method that provides a minimum of obstacles for field operations.

Figure 17: In Arkansas, temporary plastic pipe conveys water directly from the pressurised riser to each individual bay in the field.

Figure 18: Temporary plastic pipe travelling down the field

The manufacturer has introduced a recycle program in conjunction with the introduction of the temporary plastic pipes.

Drainage

In both Arkansas and California, rice farmers are making widespread use of drainage ditches to facilitate drainage. In non-landformed fields, the placement of the ditches is something of an art-form, connecting low areas to drainage. Four-wheelers are often used to form the ditches. Even in the landformed fields, the drainage ditches were seen as the primary drainage tool, rather than a slope in the field. Most landformed fields were landformed to a zero grade (no slope in each bay).

Figure 19: Typical drainage ditches in a Californian rice field. Note the two ditches; one parallel to the bank and one diagonally across the bay.

Greenhouse Gas Emissions

Rice cultivation has a significant greenhouse footprint. The most commonly cited issue is methane emissions through the anaerobic decomposition of labile soil carbon pools. Other significant parts of the footprint are soil carbon losses as carbon dioxide, nitrogen losses in the form of nitrous oxides and fossil fuel usage for fertiliser manufacture, other inputs, field operations and transport and processing of the paddy rice.

The most important angle to consider in this report is the interaction between water regimes and greenhouse gas emissions.

Gas	**Greenhouse potential (CO2 equivalents)**
CO2	1
CH4	21
NOx	310

Table 2: The relative greenhouse potential of common greenhouse gases, with CO2 set at 1.

IRRI have commissioned a coordinated set of trials to assess the effects of residue, nitrogen fertilisation and irrigation regime on emissions of CH_4, CO_2, NO_x and NH_3. The trials are being done at IRRI, in India and China. These trials have just begun.

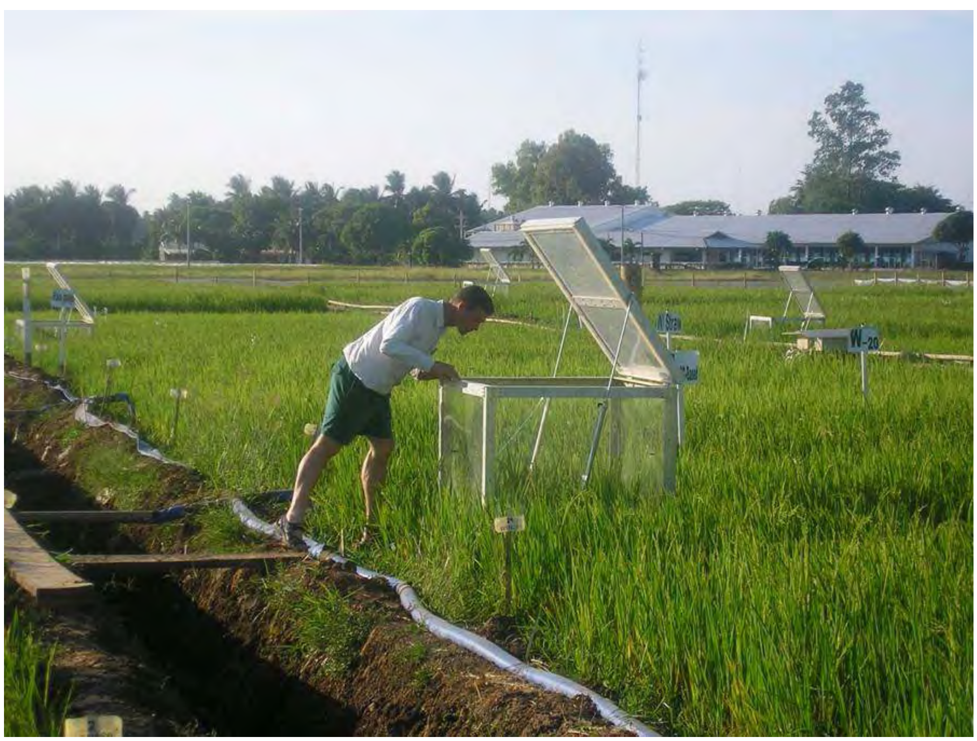


Figure 20: The automated gas analysis chambers in the greenhouse emissions trials at IRRI.

Soil Carbon

Moving the crop water management towards a more aerobic regime will increase both the average and the minimum soil redox potential. This will ensure that more of the decomposing soil organic matter (SOM) will decompose to CO_2, rather than CH_4. In a fully-flooded regime, SOM decomposition into CH_4 seems to occur in two major pulses; for the first week after flooding (as the soil redox potential drops and alternate electron acceptors are exhausted), then during grain-filling (as fine roots and root exudates decompose). Grace (2003) details that methane emissions only commence once several other redox reactions have taken place, that consume NO_3^-, N_2O, Mn^{4+}, Fe^{3+}, and SO_4^{2-} respectively. Large reservoirs of any of these alternate electron acceptors delay methane production making mitigation easier.

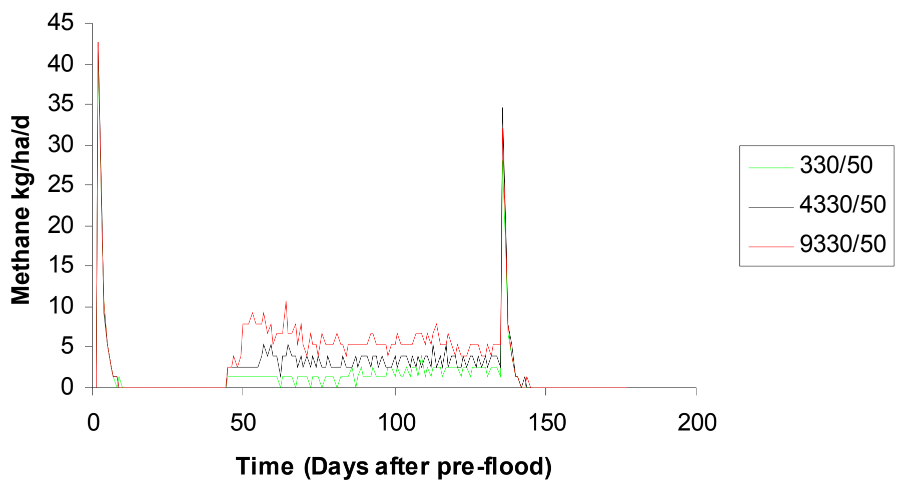


Figure 21: A typical methane release pattern in flooded rice, as modelled by MERES, for heavy (red), moderate (black) and light (green) stubble loads in the seedbed. Source: Grace (2003)

Our industry would seem to able to reduce CH_4 emissions greatly by drill-sowing and flush irrigating (AWD) for the first 50 days, applying full flood, then reverting back to AWD for the last 30 days of the season. Initial RGA-sponsored trials in the 2005/06 season suggest an approximate 50% reduction in methane emissions.

A mid-season drainage event, which dries the soil out to about 80 mm deficit in the late tillering phase (about 70 days), appears to give CH_4 reductions by increasing soil redox not long after the suggested 50 day commencement of methane emissions. Initial RGA-sponsored trials are inconclusive.

The presence of fresh crop residues in the soil upon flooding of the soil increases CH_4 production, as it makes a large pool of labile SOM to decompose. Likewise, heavy cultivation before flood would achieve the same. Modelling suggests this (Grace, 2003) and initial trials support it.

Hence, allowing residues to largely decompose and using reduced cultivation techniques both reduce CH4 emissions.

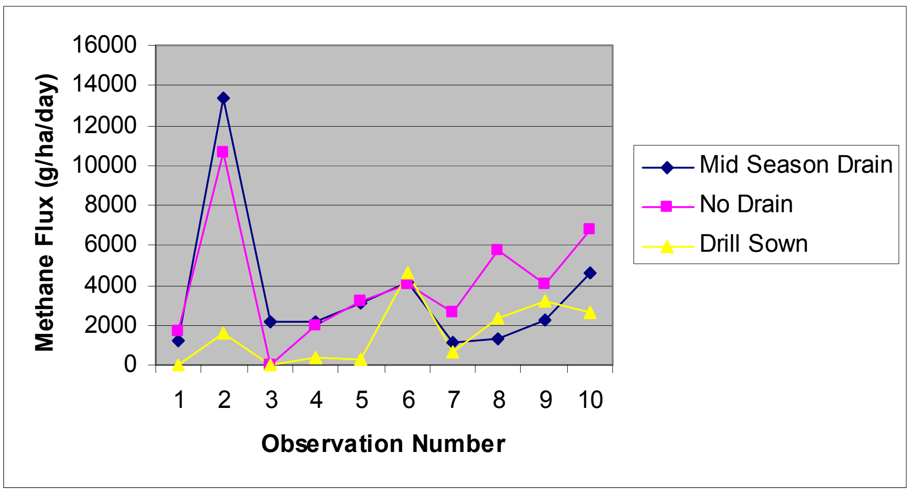


Figure 22: A summary of a limited trial at Moulamein in late 2005, comparing the methane flux from a fully-flooded, a mid-season drain and a drill-sown regime. The first observation was made on 16th November, with observations roughly weekly until 19th January.

Nitrogen

Nitrous oxides (NO_x) have a greenhouse potential 310 times that of CO2. Hence, even small losses of nitrogen in the form of NO_x can have a significant greenhouse impact.

NO_x is commonly produced when a soil transitions from aerobic to anaerobic states, as occurs in AWD systems. Mineralised N is nitrified to NO_3^- in the aerobic phase, then denitrified into NO_x (by bacteria using nitrate as an alternate electron acceptor in the absence of oxygen).

Researchers at China Agricultural University have found that their AWD systems can lose large amounts of nitrogen, much of it as NOx. A typical AWD rice crop in northern China currently has nitrogen use efficiency (NUE) of 35-50 per cent. This compares to about 70-85 per cent in Australia and similar in Arkansas (provided urea is spread before permanent flood). Most of these losses are lost as NH_3 gas (from surface urea volatilisation), but some of the losses are lost as NOx (Limeng, *pers.comm.*). Controlled release formulations lift NUE to about 80 per cent; only small quantities of nitrate are present at any point in time to be denitrified.

Fertiliser nitrogen is an energy intense product. The equivalent of about 1.5 litres of diesel – and the carbon generated in burning it - is required to fix a kilogram of nitrogen (McKague, 2006, USA EPA, 2006) Nitrogen can form a good 20-30 per cent of a typical Australian rice farmer's greenhouse emissions. Hence, efficient use of nitrogen is paramount in any effective greenhouse strategy for a cropping system.

Controlled release (CR) nitrogen formulations will become more important over time, as the cost of nitrogen increases, the cost of the controlled release technology decreases and the greenhouse consequence of its production and loss becomes better accounted for. CR nitrogen will be very important in the move to more aerobic rice regimes. With conventional nitrogen fertiliser and strategies, any water and methane savings will be accompanied by sharp increases in nitrogen losses; an uncomfortable trade-off.

Soil suitability

To date, Australian rice soils have been approved on their ability to retard percolation. This saves water and reduces acidification from nitrate leaching and ferrolysis. AWD systems may require a refinement of soil requirements to consider a soil's ability to hold and deliver water to the crop. This becomes of primary importance in the absence of floodwater, to provide sufficient water between irrigation and rainfall events.

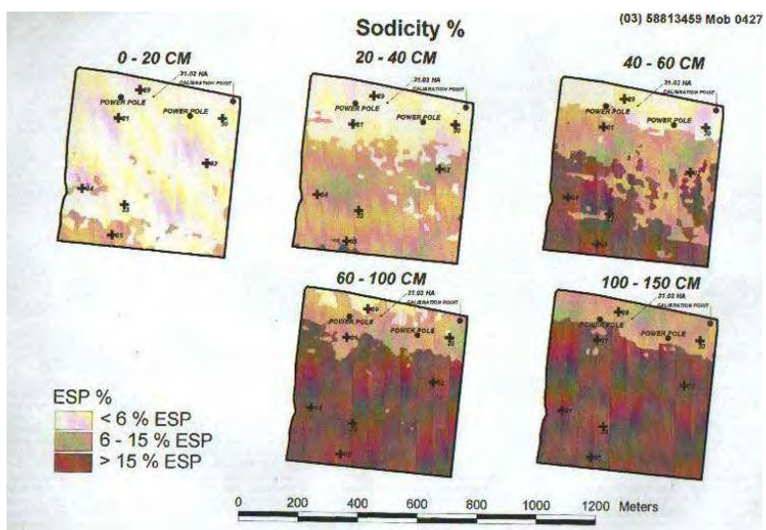
China's aerobic rice is generally grown on deep, silty loess soils which allow free root exploration to depth and hence allows the soil to deliver more moisture between rainfall/irrigation events.

In Arkansas, there is a differentiation between soils that can deliver more or less moisture, corresponding to the crop's rooting depth. Soils with restricted rooting depths, be it naturally or from topsoil removal during landforming, are generally identified and targeted for early application of permanent flood, in lieu of their poor moisture relations.

Figure 23: A shallow topsoil in Arkansas. Soil pH and salinity increase sharply at 10-15 cm depth. Consequently, permanent water is applied after 3-4 weeks, weather permitting.

EM38 survey techniques are now inferring soils' moisture relations and may be of great value in both determining suitability for AWD systems and guiding crop management each season. This is especially so due to many Australian rice soils' poor moisture relations. 'Poor' soils will need permanent water earlier.

Figure 24: Sodicity maps deduced from an EM38 soil electro-conductivity survey, taken in the Moulamein area. Sodicity is the primary factor determining root depth in those soils, so available water holding capacity can be inferred from sodicity distribution. Source: Advanced Soil Mapping, Deniliquin, NSW, 2006.



Soil Acidification

Many of Australia's rice soils are acidifying (Beecher and Lake, 2004). Familiar processes are causing the problem; nitrate leaching, product removal, organic matter accumulation and use of acidifying nitrogenous fertilisers. The flooded phase in an Australian rice system induces one further acidifying process. Flooding of the soil converts Fe^{3+} ions to the more soluble Fe^{2+} (a process that captures an electron) once the soils redox potential drops to a certain level. The increased availability of Fe^{2+} may also increase displacement of bases (Ca^{2+},Mg^{2+}, K^{+} and Na^{+}), all of which can then be leached from the root zone causing acidification or ferrolysis. The importance of nitrate leaching and ferrolysis is illustrated by the higher percolation rice soils generally being the more acidified (Beecher and Lake, 2004).

Would an AWD rice system reduce soil acidification?

It is safe to assume that product removal and organic matter accumulation rates would be similar. Nitrate leaching may well increase, as nitrification forms nitrates between irrigation events, then leaches them during the events. This process should not be too pronounced on approved Australian rice soils, as percolation rates are low.

An AWD rice system should avoid increased availability of Fe2+ and subsequent ferrolysis (a long term process), until such time as permanent water is applied. After permanent water, Fe2+ reaches peak after about 1-3 weeks. The subsequent acidification rate will be controlled by the percolation rate of water from the profile.

A broad conclusion would seem to be that an AWD phase in the growing season will reduce ferrolysis-induced acidification in higher percolation soils (> 1 mm/day) by reducing the period of flooding, but will probably exacerbate nitrate leaching. On low percolation soils, it will probably only have marginal impact on ferrolysis or nitrate leaching, as their rate is driven by the leaching fraction.

Water policy

Whilst it is not strictly the brief of this report, it is difficult not to observe some case studies of the current approach to water supply and the changes in response to increased competition for water.

In Arkansas there is a complete lack of any formal water allocation mechanism, both for groundwater and surface water. Pumping costs are becoming a proxy allocation mechanism, as the groundwater pressure appears to be declining by about a foot (300 mm) each year. Those who can are moving to exploit surface water supplies to reduce pumping heads, both direct from water courses and by storing stormwater runoff. Indeed, in Arkansas, there is a large state government subsidy available to build such storages. A large surface water diversion scheme has been proposed for the White River in east Arkansas to improve access to surface water supplies. Much debate has ensued from vested interests on both sides. There seems to be a poor acknowledgement of the strong linkage between surface and groundwater supplies. Groundwater and surface water are linked and substitutable; the overall resource is finite.

The Ogallala Aquifer is a similar case study. It is an enormous water resource, but like most groundwater resources in the world, it is being overdrawn. It supports a total of 5.5 million hectares of irrigation, predominantly in Nebraska, Kansas and Texas. In 1990 it had a usable volume of 3.9 billion megalitres (Guru and Horne, 2000).

Figure 25: The Ogallala Aquifer, which underlies eight US States.

Overall recharge and extraction rates seem to be very hard to find, but average water heads appear to be falling by about 80 cm/year (Kromm, 2006). The fall in water levels seems to be more pronounced in the southern areas of the aquifer, promoting inter-state tensions. The state of Kansas has recently successfully sued the state of Nebraska for the drying up of their Republican River, a direct consequence of their overdraft of the Ogalalla aquifer. This has forced the state of Nebraska to limit pumpers' extractions near the Republican. One suspects this is the first step to all groundwater users being limited.

Most states now monitor water extractions and forbid drilling of new bores, but the debate seems to be slowly swinging towards volumetric restrictions. Kansas, for example, has monitored extractions since the late 1980's. Volumetric limits on water extractions appear to be rare, although an energy limit appears to be looming as pumping costs increase (increased head and more expensive fuel).

Figure 26: Surface water is currently available - unmetered and uncharged - in Arkansas. Competition for surface water supplies appears to be increasing.

California, whilst certainly more advanced in forming market mechanisms, is decidedly schizophrenic in its approach to water, largely as an accident of history. Policy is now evolving quickly in the face of increased demand for water.

In the north of the Valley (close to the major reservoirs), water is cheap and plentiful. Sacramento rice farmers pay between US$1.60 and US$16 per megalitre for as many megalitres as their land requires. These terms appear to be the relic of a 40 year contract with the Bureau of Inland Reclamation. This contract expired a few years ago and is now up for renegotiation. They seem to have the benefit of the previous terms in the meantime. A concept that seems to be gaining traction in these negotiations is pricing water according to the "value of its use", rather than its highest value use. This implies that a rice grower will obtain water cheaper than the plum grower next door to them. There appears to be a desire to preserve some diversity of production by differentially pricing water.

The San Joaquin Valley further south does appear to have variable water supply and does pay significantly more for its water. The price seems to be a function of the pumping costs; the bulk of the water has to be pumped at the Sacramento Delta and conveyed (and pumped again) along the California Aqueduct (the bulk of its capacity services Los Angeles) to reach districts and farms. They pay about US$100/ML at present, but supply is not assured. They seem to have a lower grade of security than the irrigators in the Sacramento Valley. Will this persist? There does not appear to be any scarcity rent at this point.

"Water flows uphill towards money", a common Californian saying.

China offers a different model. In response to water shortage they have arbitrarily forbidden some uses of water and are engineering huge shifts of water across the country.

In the Yellow River Basin and especially in the Beijing area, where water shortages are most acute, ponded rice will be banned from 2007. There seemed to be little consultation (then again, how genuine is Australia's consultation process?) before this policy change. Perhaps this undiluted policy change is a superior method to address a perceived problem, especially when it was also accompanied by significant research resources to develop adapted rice varieties. This is how the *Han Dao* varieties were born.

The *Han Dao* process touches on an important philosophy in China, that is instructive considered in context. China has clear policies to feed its population. The most efficient means to feed a population (considering water, energy and labour) is carbohydrate crops; predominantly rice and wheat. China considers carbohydrate crops a high value use of water, energy and labour and promotes their production with infrastructure, research, extension, etc. Whilst Australia is far from the food supply pressures that 1.3 billion people bring, the point is still valid: carbohydrate production is *not* a low value use of resource in a global sense, as our national media would have us believe.

Other than incurring pumping costs (quite significant when groundwater depths are more than 100 metres in places), water is not metered or charged. It is not much different to Arkansas, really, although the latter resides in the country that supposedly sets the pace in competitive capitalist economics! Essentially water is accessed freely by those who have the location or resources to get it.

China is engineering a solution to water shortages in the Yellow River Basin. Water from the Yangtze River will be conveyed north in two canals, syphoned under the Yellow River and service the urban needs of Beijing and nearby Tianjin. There appears to be no concept of an environmental flow for the Yellow River as yet.

Figure 27: The Yellow River near ZhengZhou. It is only a foot or two deep here and frequently ceases flowing during the irrigation season.

The Yellow River Conservation Commission (YRCC) now exists to oversee the monitoring and regulation of flows and extractions from the Yellow River. Its role is much like that of the Murray Darling Basin Commission. It has seen the installation of sophisticated monitoring and regulation infrastructure to target equitable flow-sharing along the Yellow River basin. It is something of a micro-cosm of the divide between national and local government, however, as local authorities currently pay little attention to the YRCC. Excessive flows are still diverted from higher reaches of the Yellow River, leaving little for the lower reaches. Increased pressure on water supplies, and international attention from the upcoming Beijing Olympics, may see this situation revisited.

Anthropocentrism **(regarding humans as the central factor in the universe)**

An overall philosophy that I observed in my studies, was that increased human population is taken as a given (the IRRI website even counts it for us), an individual desire for more goods and services is taken as a given, as is the need to continue increasing our demands on the earth's photosynthetic abilities.

Whilst I will not launch into a detailed treatise, I cannot help but reach the conclusion that not-directly-useful-to-humans parts of the world's ecosystems will continue to be converted to more useful forms, to exhaustion where required. Whilst much research and development is now focused upon being more efficient with our resources, everywhere from California to northern China a far greater amount of energy is being devoted to procuring more resource *from somewhere*. As the most populous nation, the growth targets of the Chinese government and the anthropocentric attitude of the average Chinese to the environment can be taken as a serious warning. Certainly, many prominent agricultural researchers in China are gravely worried at the decline in China's natural capital.

Global warming will probably be the first of many pressing environmental issues that must be dealt with, well, globally. With concurrent increasing population, declining agricultural resources and diminishing fossil fuel supplies, the Westphalian model of sovereign states overlain with multilateral institutions may well prove useless. In the face of powerful vested interest, it has been less than potent to date. It is yet to deliver a basic and universal set of standards to humans. How on earth can it deliver a viable future for the other 99 per cent of the world's beings? Democracy is based on compromise; it is found wanting when faced with uncompromising issues. 2000 years ago, Plato scorned democracy as imperfect, because it becomes obsessed with liberty and greed at the expense of responsibility. Governments and oppositions of democratic nations are focussing on greenhouse abatement strategies, whilst not breathing a word that their constituents' consumptions patterns will be curtailed. It is a nonsense, but a necessary nonsense if they want to win government.

At some point humans, especially in the developed world, will learn to live with less. Alas, the concept of restraint cuts right across the much sought after concept of growth as progress. We need to accept the idea that restraint *is* progress. It will probably not be a pleasant process, but Chairman Mao warned us that '…the Revolution is not a picnic'. In the words of my mother, this will end in tears.

Energy

One can make a similar side-study of our approach to energy. In my travels, I often observed farmers and researchers faced with substitution decisions between resources; particularly natural resources for energy. The groundwater users in the USA and China must use more fuel to extract their required water. Some Arkansas farmers are substituting surface water for ground water to reduce fuel costs. Generally, aerobic and AWD rice systems require more nitrogen (hence energy) per unit yield in order to realise water savings. Many AWD systems require more labour and irrigation infrastructure to manage water more precisely.

It was very interesting to observe energy costs emerging as a water rationing mechanism in itself, giving us an insight into acceptable substitution ratios between the two.

Whilst I observed innovative approaches to saving water, I saw less focus upon saving energy (in particular fossil-fuel derived energy) in producing rice. Whilst water is a crucial component of crop production, it is a function of several variables, most notably water, energy and labour. Many ‘savings’ in one variable are in fact substitutions for another.

It will be heartening when popular debate truly links all natural resources when debating the need for greater efficiencies, then develops accepted substitution ratios between them.

Conclusions

The central conclusion from my study is that although aerobic germplasm will lend helpful drought tolerance, to allow un-retarded and high-yielding AWD crops, it offers no significant increase in transpiration efficiency – the probable source of Australia's next jump in water use efficiency. C_4 rice offers such an increase, but will be some time coming. In the meantime, breeders will focus on developing higher yields in less time, as they have done over the last 20 years.

A full-season AWD culture offers Australia little, as it will be impossible to satisfy the exceedingly high evaporative demand of a full crop canopy. A more aerobic regime will prove useful in reducing evaporative losses (providing a helpful increment of 20-30 per cent water savings), reduce greenhouse gas emissions (provided denitrification is limited), rotating weed control options, avoiding algae, ducks and other afflictions of flooded establishment.

Controlled release nitrogen formulations will become much more popular, as their price premium declines and their efficiency gains are appreciated.

Successful AWD and aerobic systems are generally conducted on relatively deep soils that can supply water to the crop between irrigation/rainfall events. The Australian definition of rice-suitable soils will need to be refined to account for a soil's available water holding capacity, as well as its ability to restrict percolation.

Recommendations

1. The Australian rice breeding program should breed germplasm adapted to AWD culture for the first 10 weeks of the growing season;
2. AWD culture for the first 10 weeks of the growing season could save 20-30 per cent of water use, as compared to fully-flooded culture;
3. Controlled release nitrogen formulations should be investigated for their ability to restrict denitrification and nitrate leaching, hence increase nitrogen use efficiency, in the AWD culture;
4. Imidizolinone tolerant (Clearfield™) rice should be introduced to offer alternate mode of action for grass weed control;
5. The greenhouse gas emissions of AWD culture needs to be further investigated, to add more resolution to methane measurements and to measure NOx emissions;
6. Rice soil suitability may need to be redefined to account for variations in moisture relations and subsequent ability to supply water in the aerobic phase.
7. The ability of AWD culture to reduce soil acidification in Australian rice soils needs to be quantified;
8. Within the current quarantine constraints, the value of hybrids in increasing yield and water use efficiency should be investigated;
9. The adoption of a C4 metabolism in rice – which will only be achieved via transgenics - offers the next significant jump in water use efficiency.

References

Allen, R., Pereira, L., Raes, D. and Smith, M. (1998) Crop evapotranspiration – guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No.56, Food and Agriculture Organization of the United Nations, Rome

Beecher, G. and Lake, B. (2004) Soil Acidity in Irrigated farming systems of Southern NSW, NSW Agriculture, RIRDC Publication No 04/007 RIRDC Project No DAN-161A

Boeckx, P., Xu, X. and Van Cleemput, O. (2005) Mitigation of N2O and CH4 emission from rice and wheat cropping systems using dicyandiamide and hydroquinone. Nutrient Cycling in Agroecosystems 72(1): 42-49

Bouman, BAM, Xiaoguang, Y, Huaqi, W, Zhimin, W, Junfang, Z and Bin, C. (2006) Performance of aerobic rice varieties under irrigated conditions in North China, *Field Crops Research 97: 53-65*

Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., ten Berge, H.F.M. and van Laar, H.H. (2001) ORYZA2000: modelling lowland rice, Chapter 3: Crop Growth and Development, International Rice Research Institute, Las Banos, Phillippines, pp.23-78.

Fujita, T. and Shoji, S. (1999) *Kinds and properties of Meister fertilizers*. In: Meister Controlled Release Fertiliser, Ed. Shoji, S., Chapter 2, pp.13-33

George,T, Ladha, J.K., Buresh, R.J. and Garrity, D.P. (1993) Nitrate dynamics during the aerobic soil phase in lowland rice-based cropping systems. Soil Science Society of America Journal 57(6): 1526-1532

Grace, P. (2003) The simulation of methane emissions from rice growing soils in South-Eastern Australia, SMEC Australia Pty. Ltd/Ricegrowers' Association of Australia.

Guru, M. and Horne, J. (2000) The Ogallala Aquifer. The Kerr Centre for Sustainable Agriculture, Poteau, Oklahoma.

Johnson, S., Soil scientist, International Rice Research Institute, Las Banos, Philippines

Keerthisinghe, D.G., Freney, J.R. and Mosier, A.R. (1993) Effect of wax-coated calcium carbide and nitrapyrin on nitrogen loss and methane emission from dry-seeded flooded rice. Biology and Fertility of Soils 16(1): 71-75

Kromm, D. (2006) Ogallala Aquifer. In waterencyclopedia.com

Lewin, L., Retired rice breeder and Rice CRC Director, NSW DPI.

Limeng, Z. and Liu, P., Department of Plant Nutrition, China Agricultural University, Beijing.

McKague, K. (2006) Energy opportunities: nutrient management – can it play a role in conserving fossil fuels? Ontario Ministry for Agriculture, Food and Rural Affairs, Factsheet 768/538

Malla, G., Bhatia, A., Pathak, H., Prasad, S., Jain, N. and Singh, J. (2005) Mitigating nitrous oxide and methane emissions from soil in rice-wheat systems of the Indo-Gangetic plain with nitrification and urease inhibitors. Chemosphere 58(2): 141-147

Pathak, H. and Nedwell, D.B. (2001) Nitrous oxide emission from soil with different fertilizers, water levels and nitrification inhibitors. Water, Air and Soil Pollution 129(1-4): 217-228

Peng, S, Laza, RC, Khush, GS, Sanico, AL, Visperas, RM and Garcia, FV (1998). Transpiration efficiencies of indica and improved tropical japonica rice grown under irrigated conditions. Euphytica 103: 103-108.

Rural Industries Research and Development Corporation (2006) Rice. Reaping the rewards of innovation, Publication No. 06/017

Scott, R., Boyd, J. and Smith, K. (2006) Recommended chemicals for weed and brush control, Cooperative Extension Service, University of Arkansas, USDA and County Governments, pp.75-89.

Tao, H, Brueck, H, Dittert, K, Kreye, C, Lin, S and Sattelmacher, B (2005) Growth and Yield Formation of Rice (*Oryza sativa* L.) in the water-saving ground-cover rice production system (GCRPS), Field Crops Research, xxx: xxx – xxx

Thompson, J. , Senior Scientist, NSW DPI, Deniliquin, NSW

Tuong, TP, Bouman, BAM and Mortimer, M (2004) More Rice, Less Water – Integrated Approaches for Increasing Water Productivity in Irrigated Rice-Based Systems in Asia. In: Proc. 4th International Crop Science Congress, 26th Sept – 1st Oct 2004, Brisbane Australia.

USA Environment Protection Agency (2006) Agriculture and forestry sector: nitrogen reduction (information by Craig Stark, Iowa Department of Natural Resources).

Wilson, C., Slaton, N., Norman, R. and Miller, D. (2000) *Efficient Use of Fertiliser*. In: Rice Production Handbook, University of Arkansas, Division of Agriculture, Cooperative Extension Service, Chapter 8, pp. 51-74

Yu, L.U., Ray, J.D., O'Toole, J.C. and Nguyen, H.T. (1995) Use of wax-petrolatum layers for screening rice root penetration. Crop Sci. 35, 684-687.

Appendices

Appendix 1: A summary of herbicide options for drill-sown rice in Arkansas. Source: Cooperative Extension Service, 2006

Active Ingredient	**Trade Names**	**Weeds controlled**	**Notes**
Clomazone	Command, Magister	*Echinachloa* spp.	Tank mix with glyphosate, paraquat, cyhalofop Sig. damage possible on poor soils at full rates
Pendimethalin	Prowl, Stomp	*Echinachloa* spp.	Can tank mix with quinclorac, thiobencarb Apply after seed has imbibed water No incorporation required.
Quinclorac	Facet	*Echinachloa* spp., selected broadleaf weeds	Flexible application window
Cyhalofop	Clincher	*Echinachloa* spp.	Tank mix with clomazone, quinclorac
Fenoxaprop	Ricestar	Grasses	Post emergent
Imidizolinone group	Clearfield system	Grasses and broad leafs. Some minor exceptions.	
Propanil	Stam M-4, Super Wham, Ronacil	Grasses, most aquatics	Post emergent, tank mix with molinate, halosulfuron, pendimethalin, quinclorac, bensulfuron methyl, thiobencarb, bentazon
Halosulfuron	Permit	Sedges especially	Post emergence, tank mix with propanil, beware resistance risk
Bensulfuron-methyl	Londax	Sedges especially	Post emergence, only as tank mix with propanil
Bentazon	Basagran	Aquatics	Mostly tank-mixed with propanil
Carfentrazone-ethyl	Aim 2 EC	Some broad leafs	Mostly tank-mixed with quinclorac
Bentazon/acifluorfen	Storm	Some broad leafs	Mostly tank-mixed with propanil