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A strategic soil nitrogen test for flooded rice

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A STRATEGIC SOIL NITROGEN TEST FOR FLOODED RICE

1. Summary

From 1998 until 2002 a project to develop a soil nitrogen (N) test for flooded rice was conducted in the Rice CRC. The reason for wanting such a test for the Australian rice industry is that N fertiliser is used more efficiently when applied before sowing so it is economically and environmentally preferable for as much as possible of the optimum amount of N fertiliser to be applied at that time. However excessive N applied before sowing leads to a high risk of yield loss due to cold damage. The aim was to develop a system to forecast the optimum N supply for pre-flood application and minimize the amount being topdressed which has been a safe, but inefficient system.

The method of developing the test was first to compare the near infrared reflectance (NIR) spectra with crop productivity and N mineralisation measured by wet chemistry. These measurements were made with soil from 22 previous experiments measuring yield response to N applied at sowing. There were close relationships of the NIR spectra with crop productivity and N mineralisation but because of the small data set the relationships had little predictive value. However the close relationships found between NIRS, N mineralisation measured in the laboratory and crop performance encouraged us to proceed with further studies.

A more detailed study related soil mineralisation across farms to crop performance. Seventeen methods of mineralisation were tested and the most reliable was found to be anaerobic incubation at 40°C for 21 days. This method predicted the optimum N requirement with a standard error of about 75 kgN/ha, which is clearly unsatisfactory for an industry where the average amount of N fertiliser applied is 145 kgN/ha. A possible reason for the low correlation between mineralisation and crop performance was that other factors were limiting N response. There was some evidence that sowing date and deficiencies of other nutrients were partly responsible for the variability of the N response. However it is unlikely that including information about these factors would lift the soil-N test to acceptable accuracy for commercial use. The most likely reason for the low correlation was that the soil depth used for mineralisation measurements was poorly defined because of the widespread levelling of rice fields which led to different depths of topsoil.

Two options are proposed for more reliable application of N fertiliser at the time of sowing. Both require further research. One is to use the existing soil test only to identify soils with large amounts of potentially mineralisable N. Such a test could be the basis of a recommendation to apply little or no N fertiliser before sowing. Rice growers would still have the option of topdressing N fertiliser at the panicle initiation stage. The advantage of using a test in this way is that it is most unlikely to result in ‘false positives’, i.e. - recommendations for excessive N fertiliser leading to yield reductions.

The other option is to set up a system of zone management for N fertiliser based on the likely N mineralisation in different parts of a rice field. The results in this project suggest that yield responses are more accurately predicted by sodicity than by the soil N test. It is likely that sodicity is a good indication of the depth of topsoil cut in the process of levelling. If this result is shown to be general, maps of ‘cut and fill’ areas may help in deciding the optimum amount of N fertiliser.

Evidence from the Ricecheck database shows that about 10% of rice paddocks receive too much N fertiliser at sowing and suffer a large yield reduction. This leads to an annual loss of about $18 m. While this project has not led to a solution to this problem, the two suggestions arising from the project offer methods to reduce the problem.

2. Background

The Australian rice industry started in the Murrumbidgee valley of southern New South Wales in the 1920s and from then until the 1960s the only significant sources of nitrogen (N) were mineralisation of soil organic matter and the residues of legume-based pasture of up to 8 years duration (Boerema and McDonald, 1965). The use of N fertiliser increased as the rotations narrowed, so that by 2001 the average N-fertiliser rate was 145 kg ha^{-1}, with a range from 0 to 400 kg ha^{-1} (J. Lacy, pers. comm. 2003). On average, 95 kg N ha^{-1} is incorporated into the soil in the form of urea or anhydrous ammonia in mid-October, a few days before the field is flooded to a depth of 1-5 cm and seeded by aircraft. The remaining 50 kgN ha^{-1} is topdressed as urea at the panicle initiation stage, which normally occurs in early January, about 80 days into the 150-day life cycle of the crop. Soil N-supply depends on previous land use, which varies considerably from field to field (Beecher et al., 1994). For example some rice crops which are grown after many years of legume-based pasture require little or no N fertiliser to achieve the economic optimum yield. At the other extreme, many continuously cropped rice crops require a large amount of N fertiliser to achieve optimum yield. Farmers currently base decisions about the amount of N fertiliser to apply before sowing on the productivity of previous rice crops and the sequence of previous pastures and crops.

The greatest cause of year-to-year variation in yield is cold damage to the developing pollen cells, when minimum temperatures fall below 10-15°C about two weeks before anthesis, which generally occurs in early February. The risk of cold damage increases with high plant-N status, which can result from large fertiliser N applications at sowing (Heenan and Lewin, 1982). However, when there is no cold damage, a given rate of N fertiliser applied at sowing raises crop yields twice as much as when it is topdressed (Angus et al., 1994). Until 1985-90, most of the N fertiliser was topdressed by aircraft at the panicle initiation stage, with the amount guided by a field test of biomass and tissue-N status (Batten et al., 2004). At the time, topdressing was the most effective means of supplying fertiliser N because the tall varieties then available were less prone to lodge when N fertiliser was broadcast with than when the same amount was applied at sowing (Heenan and Lewin, 1982). The risk of lodging was reduced with the release of semi-dwarf varieties after the mid 1980s (Hartley and Milthorpe, 1982). There is usually less cold damage to semi-dwarf than to tall varieties, provided the depth of floodwater is raised to about 20 cm, a level that provides thermal insulation to the crop (Williams and Angus, 1994). Topdressing high rates of N does induce yield loss due to lodging and cold damage, unlike application before flooding (Heenan and Lewin, 1982). The combination of semi-dwarf varieties and deep floodwater therefore provides an opportunity for the rice industry to benefit from the low application cost and higher efficiency of N fertiliser applied at or before sowing. Rice growers persist with topdressing, despite its inefficiency, because there is no soil test to predict soil N supply and minimize the risks of over-fertilisation (Angus et al., 1996). The requirements of a N test for flooded soil are different from those used for upland crops where the accumulated mineral N at sowing represents a large part of the N used by the plant.

In a preliminary study, Russell et al. (2002) reported correlations between N mineralisation measured under anaerobic conditions and near infrared reflectance spectra of the soil. These spectra were in turn well correlated with growth of rice plants in a glasshouse. However neither near infrared spectra nor wet-chemistry measures of mineralisation offered a basis for a commercial soil test for rice. The preliminary study was sufficiently encouraging to justify further study to identify the most accurate and repeatable test, sampling protocol and the relationship between the soil test and crop growth in the field. The approach taken in this study was to sample commercial fields managed with best practice, over a wide geographical range and with diverse cropping systems, with the aim of developing a robust soil-N test for the region.

3. Objectives.

The overall objective is to develop a commercial test to predict soil N supply to rice. The first stage of the project leading to this objective is to evaluate near infrared reflectance spectroscopy (NIRS) as (1) a predictor of crop yield and (2) predictor of mineralisation in controlled conditions. Selection of NIRS as the primary soil-test method was based on its low cost and high throughput.

In addition to testing NIRS, the objectives of the project were to identify the best test of N mineralisation in soil and the factors affecting the relationship between N mineralisation and crop productivity.

Lastly the project aimed at investigating how well rice growers selected an optimum pre-sowing application of N fertiliser.

4. Introduction

Prediction of the supply of N by the soil is needed to specify the optimum amount of fertiliser N, and to minimise environmental degradation from excess N. There are many tests of plant-available N from the soil, as well as direct and indirect measures of plant N uptake (Bundy and Meiseinger, 1994; Drinkwater et al., 1996). Most N tests apply to upland crops and aerobic soils, which differ in critical respects from flooded soils used for growing lowland rice. For upland crops, mineral N accumulated before sowing is mostly available for plant uptake, either directly from the topsoil or from the subsoil after leaching. In contrast, for lowland rice, any nitrate accumulated before sowing is lost by denitrification at the time of flooding. Furthermore, mineral N in the subsoil is mostly unavailable because of the shallow roots of lowland rice (Heenan and Thompson, 1984).

The most appropriate soil N tests for lowland rice are therefore those that predict the supply of mineral N during crop growth. These include measures of potentially mineralisable N, as defined by Stanford and Smith (1972), and by aerobic or anaerobic incubations. The limitations of soil mineralisation for a commercial test are the time and cost of measurement, even for short-duration incubations such as the 2-day test proposed by Sahrawat (1998). Alternatively, promising results have been obtained with chemical extractants and the use of hot 2M KCl for releasing ammonium has been promoted by Jalil et al. (1996) and Campbell et al. (1997).

There has been less attention to the use of near infrared reflectance (NIR) techniques as tests of soil-N supply. NIR spectroscopy offers the advantages of rapid and low-cost analysis, and is currently used for the routine analysis of grain, stockfeed, food and pharmaceutical products (Batten 1998). NIR spectroscopy has been evaluated for soil testing by Meyer (1989) who found a high correlation with mineralisable N, defined as the ammonium-N liberated upon Walkely-Black digestion. NIR spectra have also been correlated with N uptake by wheat (Börjesson et al., 1999) and rice (Dunn et al., 2002), in both cases for soils collected from a small area.

5. Methodology

The project was conducted in 5 parts:

(a) Preliminary analysis of relationships between NIRS and (1) productivity of 22 rice crops, using an existing set of data (2) analysis of relationships between NIRS and N mineralisation, measured by wet chemistry.

(b) Field measurements of soil tests and N response in 84 commercial crops over two years. This part of the project included examination of factors affecting the relationship between soil tests and crop response to N fertiliser

(c) Comparison of NIRS with mineralisation for a set of 807 soils, so as assess NIR with a large enough data set to avoid spurious results.

(d) Evaluation of soil tests to predict yield response to N fertiliser in different parts of a paddock.

(e) Evaluation of rice growers' ability to select optimum N fertiliser rate without access to a soil test.

6. Results

6.1 Initial tests of near infrared reflectance spectroscopy of soil N supply

Prediction of N mineralisation is important for specifying the optimum rate of N fertiliser for flooded rice at the time of sowing. To develop a predictive test, soils (0-0.1 m) were sampled from 22 farms throughout the rice-growing region of southern Australia over a 4-year period. Near infrared reflectance (NIR) spectra of the soils were compared with sixteen biological and chemical soil tests for the prediction of N-uptake by rice plants from
Analysis of the soil spectra showed that similar wavelengths were correlated with both plant-N uptake and mineralisation (Fig.).

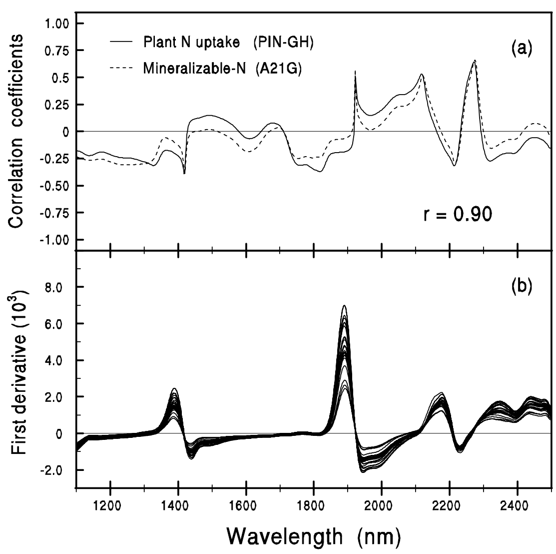

Fig. 1. Correlation coefficients (a) for the first derivatives of the 22 soil NIR spectra (b) in relation to the N uptake of rice grown in the glasshouse (PIN-GH) and the mineralisable-N from an anaerobic incubation at 40 C for 21 days (A21G).

Since the data set was small and N uptake by rice in the field was affected by varying weather and management, the field calibration is probably spurious. The calibration of soil NIR spectra with N uptake by glasshouse plants was satisfactory, with a standard error (SE) of 13 kg ha^{-1} over a range of 11 – 95 kg ha^{-1}, and a correlation between calculated and measured N uptake (r = 0.87, P<0.001). An even better soil-NIR calibration was found with N-mineralisation after 21 days of anaerobic incubation (SE 16 mg kg^{-1}, range 52 - 175 mg kg^{-1}) (Fig. 2).

Analysis of the soil spectra showed that similar wavelengths were correlated with both plant-N uptake and mineralisation. The accuracy of this test suggests that NIR spectroscopy may adequately predict the N mineralisation of flooded rice soil, and therefore has the potential as a commercial test to specify optimum rates of pre-flood N fertiliser.

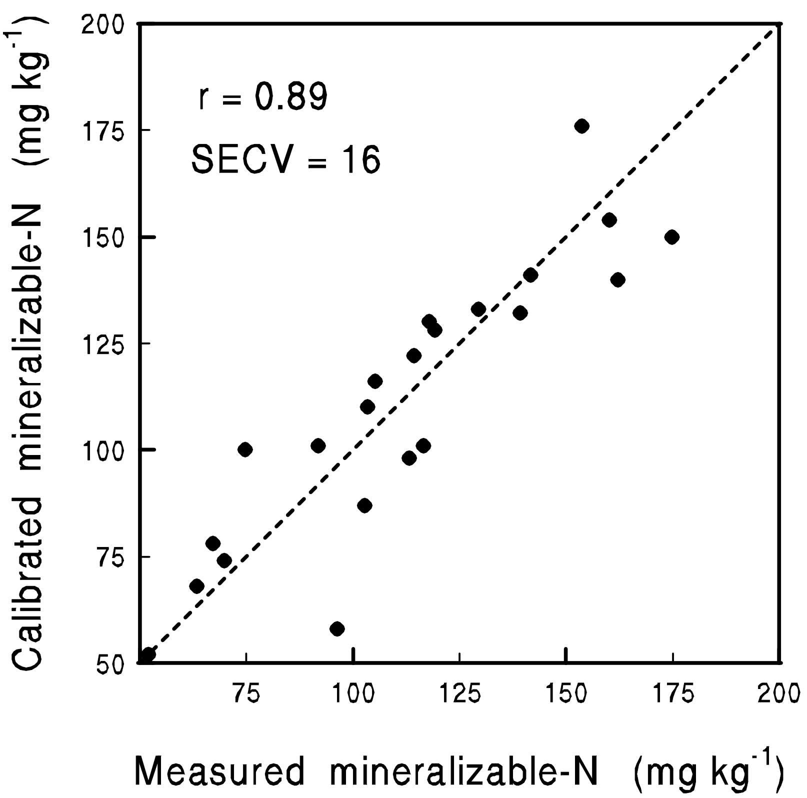

Fig. 2. Calibration of soil NIR spectra with mineralisable-N, measured by anaerobic incubation at 40°C for 21 days, using a one-out cross-validation routine. The broken line shows the 1:1 relationship, SECV = standard error of cross validation.

6.2 Precision of field soil sampling and repeatability of soil analysis

The variability of soil-N supply in field plots and the repeatability of the analysis were studied for anaerobic incubation at 40°C for 21 days. First, the 36 m^2 plots in eight of the survey fields were sampled to estimate the number of samples needed to specify the mean value within a specified percentage range (Table 1). On average, to estimate the population mean within 10% required a composite of 46 cores (range = 2 to 90), within 20% 12 cores (range = 1 to 23), and within 30% 8 cores (range = 1 to 21). Two of the uncultivated plots were surprisingly uniform, requiring fewer than 10 cores to be within 10% of the population mean 95% of the time. Regardless of the level of approximation to the population mean, undisturbed sites required about half the number of cores to represent the mean compared with disturbed sites.

Table 1. Variability of soil N mineralisation in a selection of unfertilised plots and the estimated number of samples needed to estimate mean mineralisation for specified accuracy

Cultivation and previous crop	N mineralisation ($mg\ kg^{-1}$ at 40° C for 21 days)		Number of samples required for specified accuracy		
	mean	cv(%)	10%	20%	30%
Uncultivated					
Pasture	126	10	6	2	1
Rice	128	5	2	1	1
Fallow/pasture	36	20	22	6	5
Fallow/wheat	118	31	51	13	6
Mean			21	6	4
Cultivated					
Rice	44	35	64	16	12
Rice	114	33	59	15	8
Rice	107	39	79	20	9
Wheat	96	41	90	23	21
Mean			73	19	13

Repeatability of the measurement of N mineralisation was investigated by incubating 25 samples of dried soil, selected from the 125 fields sampled in the first season. These samples were subsampled, incubated and analysed for NH_4^+-N on five occasions during the two years after sampling (Table 2). The mean values of N mineralisation on each occasion were within 5% of the mean for all batches and the individual values for each batch were closely correlated with the mean for all batches. The probable reason for fluctuations in values for each batch was variation in temperature of the incubation cabinet of about 1°C. For all mineralisation measurements for the rest of this study we compensated for between-batch variation with an offset correction based on measurements with the same 5 check samples.

Table 2. N mineralisation ($mg\ kg^{-1}$ at 40°C for 21 days) measured repeatedly on samples of the same 25 soils on 5 occasions over a 2-year period and the correlation coefficient between values at each occasion and the mean

	Analysis occasion					Mean	Standard deviation
	1	2	3	4	5		
Mean	108	111	118	114	120	114	15
Min	17	26	5	29	29	28	
Max	187	185	204	204	209	197	
Correlation with mean	0.98	0.96	0.85	0.97	0.95	1.00	

6.3 Crop productivity and responses to pre-flood nitrogen.

The measures of crop productivity used to evaluate the soil tests were yield, biomass at panicle initiation and maturity, and N-uptake at panicle initiation and maturity. The reason for considering samples collected at maturity is that they integrate the N supply over the life of the crop and are less variable than samples at panicle initiation. The earlier samples were also considered because they are available in time to assist decisions about topdressing.

Yield of dry grain was about 50% of maturity biomass for most crops (Fig. 3). This value of harvest index is normal for well-managed semi-dwarf rice crops (Evans, 1993). There are several outliers in Fig. 3, for which yield was much less than 50% of maturity biomass, apparently because of low grain yield due to cold damage at the microspore stage. All the outliers were supplied with fertiliser N. Low temperatures have less effect on biomass production than grain yield, so to avoid the complexity of cold damage in this analysis, we focussed on biomass and N uptake at maturity and panicle initiation to assess the soil tests.

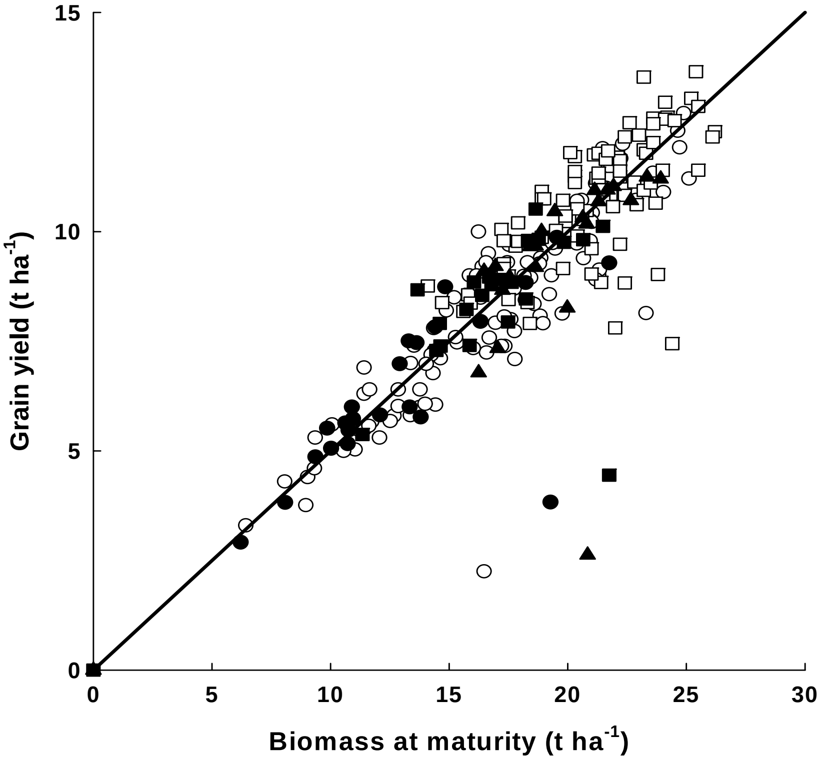

Fig. 3. Yield of dry grain in relation to biomass at maturity. 1999 survey: ○,nil-N; □, Farm Crops; 2000 experiments: ●, nil-N; ■, 75 kgN ha^{-1}; ▲,150 kgN ha^{-1}. The solid line represents a harvest index of 0.5.

Mean yield of dry grain for the farm crops in 1999 was 10.7 t ha^{-}1, equivalent to a commercial yield of 12.4 t ha^{-1} of grain containing 14% water. In comparison, mean industry yield in that season was 9.8 t ha^{-1} for the main variety, Amaroo (Table 3). In the following season, when low temperatures restricted yield, the mean yield of crops (grain containing 14% water) that received 150 kgN ha^{-1} was 10.8 t ha^{-1}(adjusted from 9.5 t ha^{-1} for dry paddy), compared to the mean industry yield of 8.8 t ha^{-1}. The comparison between experiments and industry yield is made for this treatment because it is close to the industry average of 145 kgN ha^{-1}. The probable reasons that the survey and experimental crops were unrepresentative was because of the exclusion of data from some fields and because the plots were harvested by hand (1999) or small-plot harvester (2000).

In both seasons average yields increased in response to applied N. The yields and N responses were larger in the 1999 season. The crops managed by rice growers in that season received an average of 100 kg N ha^{-1} applied pre-flood, almost exactly the industry average. The apparent recovery of the applied N in 1999 was 50 % at panicle initiation and 58 % at maturity. In the cooler 2000 season the equivalent recoveries were 35-37% and 51-54%. For crops that received commercial levels of N fertiliser, the contribution of N from the soil represented 70 % of the N contained in the above-ground tissue at maturity in 1999 and 60 % in 2000.

Table 3. Productivity and N relations of rice crops on Riverina farms (mean ± standard deviation)

Season 1, 63 survey fields				
		nil-N crops	*Farm crops*	
Above-ground biomass at PI	t ha^{-1}	4.3 ± 1.6	6.5 ± 1.4	
Above-ground N at PI	kg ha^{-1}	53 ± 28	106 ± 17	
Above-ground biomass at maturity	t ha^{-1}	16.6 ±4.5	20.8 ± 2.0	
Above-ground N at maturity	kg ha^{-1}	147 ±57	208 ± 30	
Dry grain	t ha^{-1}	8.2 ± 2.4	10.7 ± 1.0	
Biomass response to N at PI	kg kg^{-1}		25.1 ± 11.3	
Apparent N-fertiliser recovery at PI	kg kg^{-1}		0.50 ± 0.15	
Biomass response to N at maturity	kg kg^{-1}		43.5 ± 27.9	
Apparent N-fertiliser recovery at maturity	kg kg^{-1}		0.58 ±0.27	
Season 2, 23 experiments				
		nil-N	*75kg N ha^{-1}*	*150kg Nha^{-1}*
Above-ground biomass at PI	t ha^{-1}	3.4 ± 1.3	4.9 ± 1.1	5.9 ± 1.2
Above-ground N at PI	kg ha^{-1}	43 ± 20	69 ± 22	99 ± 26
Above-ground biomass at maturity	t ha^{-1}	13.4 ± 3.9	17.1 ± 2.7	20.0 ± 2.0
Above-ground N at maturity	kg ha^{-1}	119 ± 40	159 ± 28	196 ± 33
Dry grain	t ha^{-1}	6.5 ± 1.9	8.3 ± 1.6	9.5 ± 1.9
Biomass response to N at PI	kg kg^{-1}		19.8 ± 7.1	16.6 ± 6.3
Apparent N-fertiliser recovery at PI	kg kg^{-1}		0.35 ± 0.14	0.37 ± 0.11
Biomass response to N at maturity	kg kg^{-1}		50.5 ± 24.5	44.0 ± 17.4
Apparent N-fertiliser recovery at maturity	kg kg^{-1}		0.54 ± 0.28	0.51 ± 0.16

N uptake by nil-N crops at panicle initiation was 35-40 % of uptake at maturity in both seasons. For crops supplied with commercial levels of N fertiliser, N uptake at panicle initiation was 45-50% of N-uptake at maturity, and of the apparent recovery of the fertiliser, 56-71% was taken up at panicle initiation. Biomass production at panicle initiation was 24-30% of the amount at maturity.

Crop productivity and response to N varied widely between fields (Table 3). There was a tendency for less variable productivity and N uptake of crops that received N fertiliser than for those that received none, and for less variability of productivity and N uptake at maturity than at panicle initiation.

6.4 Soil nitrogen tests

Of the four types of soil N availability tests investigated, anaerobic incubation of soils at 40°C liberated the greatest amount of NH_4^+-N. The amino-sugar test released less N, followed by incubation at 25°C and hot KCl extraction (Table 4). The NH_4^+-N measured after anaerobic incubation at 40°C for 21 days was almost an order of magnitude greater than the initial NH_4^+-N content. For soils containing the average total-N concentration, 1.4 g N kg $^{-1}$, mineralisation under these conditions represents about 8% of the total N present.

Table 4. Tests of soil nitrogen supply

Property	Units	Mean	Range	
			Minimum	Maximum
Survey fields – soil total C and N				
Total C	$g\ kg^{-1}$	17.0	9.5	26.0
Total N	$g\ kg^{-1}$	1.4	0.90	2.0
NH_4^+-N	$mg\ kg^{-1}$	17	5	40
NO3--N	$mg\ kg^{-1}$	7	0	72
Inorganic nitrogen	$mg\ kg^{-1}$	24	8	96
Survey fields – anaerobic incubation and extraction				
Gross NH_4^+-N (21 days at 40^{o}C)	$mg\ kg^{-1}$	120	34	215
Net NH_4^+-N (21 days at 40^{o}C)	$mg\ kg^{-1}$	103	13	206
Gross NH_4^+-N (21 days at 25^{o}C)	$mg\ kg^{-1}$	61	7	129
Net NH_4^+-N (21 days at 25^{o}C)	$mg\ kg^{-1}$	45	-5	115
Gross NH_4^+-N (4 hours hot KCl)	$mg\ kg^{-1}$	38	17	69
Net NH_4^+-N after (4 hours hot KCl)	mg kg-1	22	9	39
Gross NH_4^+-N (amino sugar)	$mg\ kg^{-1}$	76	45	117
Net NH_4^+-N (amino sugar)	$mg\ kg^{-1}$	59	34	101
Survey fields – partial anaerobic incubation				
Gross NH_4^+-N (2 days at 40^{o}C)	$mg\ kg^{-1}$	44	6	86
Gross NH_4^+-N (7 days at 40^{o}C)	$mg\ kg^{-1}$	66	6	163
NH_4^+ -N (2 - 21 days at 40^{o}C)	$mg\ kg^{-1}$	76	10	141
NH_4^+ -N (7 and 21 days at 40^{o}C	$mg\ kg^{-1}$	53	-2	113
Experimental fields – anaerobic incubation				
Gross NH_4^+-N (21 days at 40^{o}C)	$mg\ kg^{-1}$	148	70	293
Glasshouse bioassays of soils from survey sites				
Above-ground weight	$g\ pot^{-1}$	2.6	0.8	4.8
Above-ground N-content	$mg\ pot^{-1}$	13.7	4.1	31.5

The seventeen soil tests for the survey sites were compared against measurements of productivity and response to pre-flood N for crops growing at the sites (Table 5). Almost all the soil tests were positively correlated with the measurements of crop productivity. The highest correlations with all crop properties were with the incubation tests. Of these, incubations at 40^{o}C were more closely correlated to all crop properties than incubations at 25^{o}C, and incubations for 21 days had higher correlations than incubations for shorter periods. The correlations with the soil tests were generally greater for crop properties measured at maturity than at panicle initiation, and generally greater for crop properties than for N responses. The largest correlations were found between the soil tests and the production and N content of plants growing in those soils in a glasshouse. Some of the tests were negatively correlated with responses of biomass at maturity to applied N. There were no significant correlations between any of the soil tests and the response of biomass at panicle initiation to applied N. For all measures of crop productivity, the most effective test was gross incubation at 40^{o}C for 21 days. This test was also found to be the most effective in a previous comparison involving fewer tests and fewer samples (Russell et al., 2002).

Table 5. Correlation coefficients between soil tests and crop productivity of crops that received no N fertiliser and biomass response to fertiliser N. The subscripts refer to productivity or N-response at panicle initiation (PI), maturity (M) or for glasshouse plants (GH). The correlations shown are those that are significant at P<0.05 (r>0.24 for 63 observations)

	Crop productivity			Biomass response to N at:	
	$N\text{-uptake}_{PI}$	$N\text{-uptake}_{M}$	$Biomass_{GH}$	PI	Maturity
Survey fields – soil total C and N					
Total C	0.33	0.42	0.48		
Total N	0.35	0.47	0.63		
NH_4^+-N	-	-	0.25		-0.26
NO_3^- nitrogen	0.30	-	-		
Inorganic nitrogen	0.30	-	-		
Survey fields – anaerobic incubation and extraction					
Gross NH_4^+-N (21 days at 40°C)	0.59	0.61	0.80	-	-0.38
Net NH_4^+-N (21 days at 40°C)	0.58	0.61	0.77	-	-0.37
Gross NH_4^+-N (21 days at 25°C)	0.51	0.55	0.75	-	-0.36
Net NH_4^+-N (21 days at 25°C)	0.51	0.54	0.71	-	-0.35
Gross NH_4^+-N (4 hours hot KCl)	-	0.30	0.54	-	-
Net NH_4^+-N (4 hours hot KCl)	-	0.32	0.50	-	-
Gross NH_4^+-N (amino sugar)	0.37	0.47	0.69	-	-0.26
Net NH_4^+-N (amino sugar)	0.37	0.48	0.68	-	-0.34
Survey fields – partial anaerobic incubation					
Gross NH_4^+-N (2 days at 40°C)	0.45	0.47	0.68	-	-0.33
Gross NH_4^+-N (7 days at 40°C)	0.49	0.50	0.75	-	-0.31
NH_4^+ -N (2 - 21 days at 40°C)	0.57	0.58	0.72	-	-0.34
NH_4^+ -N (7 - 21 days at 40°C)	0.37	0.39	0.36	-	-0.34
Experiment fields – anaerobic incubation					
Gross NH_4^+-N (21 days at 40°C)	0.53				

6.5 Comparison of soil and plant tests

The best soil-N test was then compared with the existing test of crop-N status, which is widely used by Australian rice growers (Batten et al., 2004). It involves sampling biomass at the panicle initiation stage and measuring N% of a dried sample using NIR. The comparison of the soil and plant tests shows linear relationships between crop biomass at maturity and the soil test and non-linear relationships with the plant tests (Fig. 4). The open points on the soil-test graphs (Figs. 3a-d) each represent a sample of an unfertilised plot in a field, while the open points in the plant-test graphs (Fig. 3e and f) represent these same unfertilised plots and the closed points represent fertilised plots in the same fields.

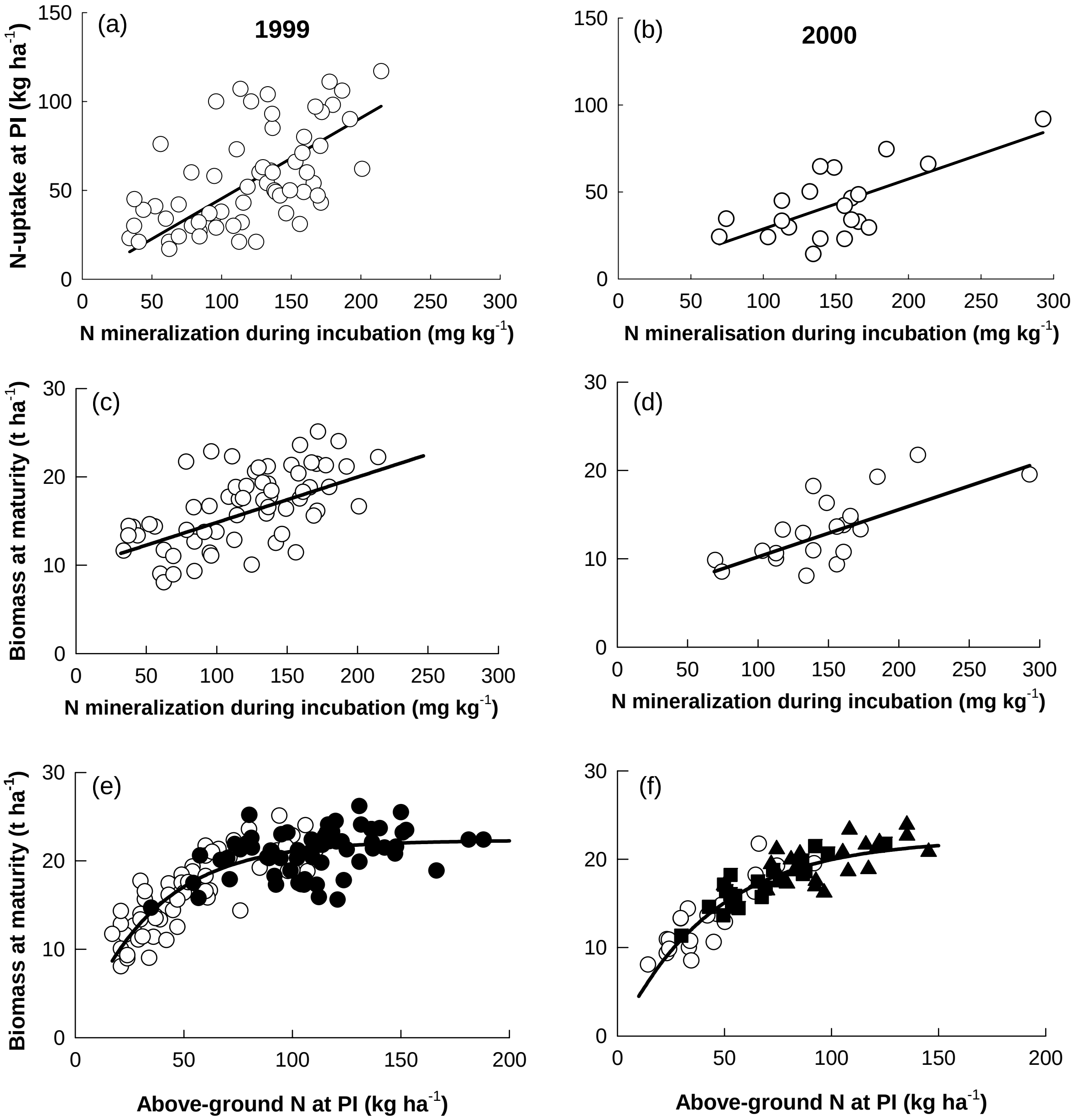

Fig. 4. Above-ground crop biomass at panicle initiation (PI) in relation to soil N mineralisation measured by anaerobic soil incubation at 40°C for 21 days (a and b), crop biomass at maturity in relation to the same soil test (c and d) and crop biomass at maturity in relation to above-ground N at PI (e and f) for 1999 survey crops (a, c and e) and 2000 experiments (b, d and f). Open symbols represent unfertilised crops and solid symbols represent fertilised crops as in Fig. 2.

Soil mineralisation was linearly related to above-ground N uptake at panicle initiation in both seasons (Fig. 4a and b). The slope of the line for 1999 was steeper than for 2000, which is consistent with the higher temperatures in 1999. The model fit for the 1999 data was R^2=37 % and SE_{obs}=22 kgN ha^{-1} and for the 2000 data, R^2=45 % and SE_{obs}=15 kgN ha^{-1}.

The soil mineralisation test and plant test are shown in relation to crop biomass at maturity in Fig. 4c-f. For both seasons, the relationship between biomass and the soil test appears linear but the relationship with the plant test appears non-linear. The difference is because the data for the plant tests included fertilised crops while the soil test data was only for unfertilised crops. For the 1999 relationship between the soil data and crop biomass at maturity, R^2=36 % and SE_{obs}=3.34 t ha^{-1} and for the 2000 relationship, R^2=0.37 % and SE_{obs}=3.07 t ha^{-1}. For exponential regressions fitted to the plant test in 1999, R^2=88 % and SE_{obs}=1.96 t ha^{-1} and for 2000, R^2=89 % and SE_{obs}=1.64 t ha^{-1}. The relative sizes of the standard errors suggest that the plant test is more accurate than the soil test.

6.6 Recovery of N by crops from soil and fertiliser

The recovery of N by rice crops at panicle initiation and maturity was related to mineralised soil N and fertiliser N, where the supply of soil N is calculated from the amount mineralised at 40°C for 21 days and a bulk density of 1.3 g cm^{-3} for the top 10 cm of soil (Angus et al. 2004). Initially the N mineralised during anaerobic incubation was added to the amount of fertiliser N, all expressed in kg ha^{-1} (Fig. 5).

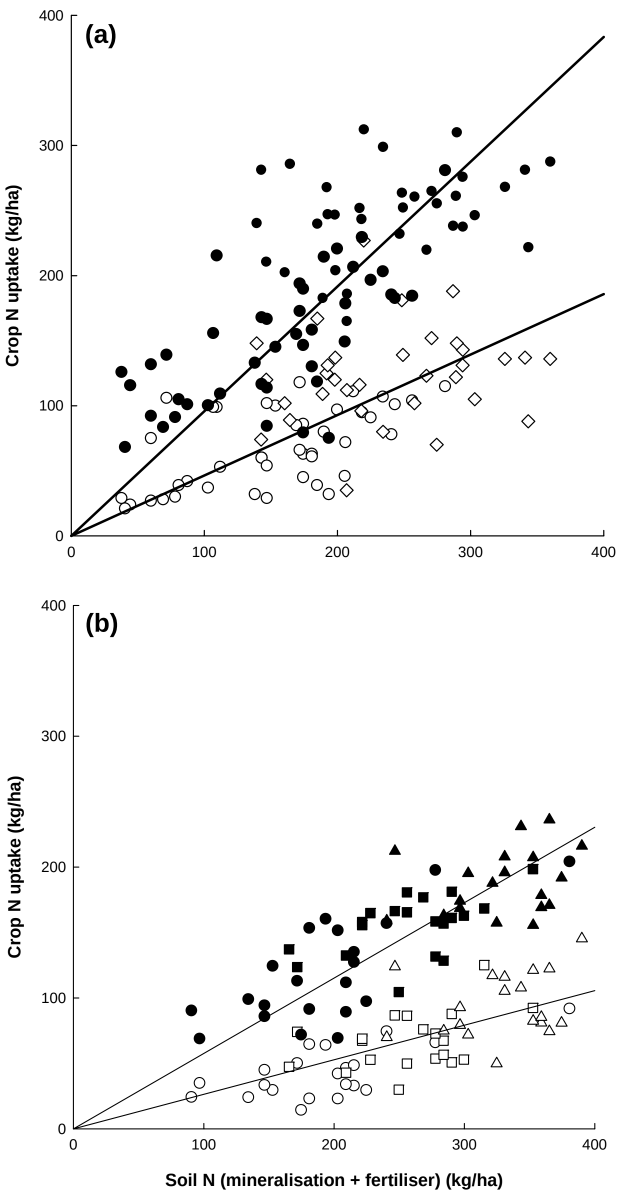

Fig. 5. Above-ground N uptake at panicle initiation (open symbols) and maturity (closed symbols) of rice crops in relation to plant-available soil N (a) by 1999 survey crops: O, no added N; Δ, N applied by rice growers (b) by 2000 experimental crops: O, no added N; □, 75 kg N ha^{-1}; ▲, 150 kg N ha^{-1})

In 1999, mean above-ground N uptake at panicle initiation was 46.4±2.0 % of the combined N supply and 95.9±2.9 % at maturity. In the cooler 2000 season, the equivalent recoveries were 26.4±0.9 % at panicle initiation and 56.7±2.0% at maturity. The amount of N in crops at panicle initiation was 46±14 % of the amount at maturity in 1999 and 44±11 % in 2000.

These expressions of N recovery imply that the data fit through the origin. Regressions relating N-uptake at maturity and available N were then computed with an intercept for 1999 and 2000 respectively:

$$N_{uptake} = \underset{(\pm 14.3)}{73.1} + \underset{(\pm 0.07)}{0.62}\, N_{incub+fert} \quad , \qquad R^2=51\ \%,\ SE=45.9\ \text{kg ha}^{-1}$$

$$N_{uptake} = \underset{(\pm 10.4)}{39.3} + \underset{(\pm 0.04)}{0.44}\, N_{incub+fert} \quad , \qquad R^2=69\ \%,\ SE=25.2\ \text{kg ha}^{-1} \tag{1}$$

The relationship is clearly closer for the experiments in 2000 than for the survey in 1999, possibly because the fertiliser amounts were measured directly rather than reported by rice growers. Both equations imply significant positive intercepts and higher values for both intercept and recovery in the warmer 1999 season.

Possible differences in efficiencies of recovery of soil and fertiliser N were studied by a multiple regression of the two sources for 1999 and 2000 respectively:

$$N_{uptake} = \underset{(\pm 13.6)}{87.6} + \underset{(\pm 0.08)}{0.46}\, N_{incub} + \underset{(\pm 0.10)}{0.92}\, N_{fert}, \qquad R^2=59\ \%,\ SE_{obs}\ 42.0\ \text{kg ha}^{-1}$$

$$N_{uptake} = \underset{(\pm 9.4)}{47.6} + \underset{(\pm 0.05)}{0.37}\, N_{incub} + \underset{(\pm 0.05)}{0.51}\, N_{fert}, \qquad R^2=71\ \%,\ SE_{obs}\ 24.7\ \text{kg ha}^{-1} \tag{2}$$

For both seasons, separating fertiliser from mineralised organic matter led to improved explanation of N_{uptake}. The values of the coefficients suggest that crop recovery of the mineralised organic matter is lower than recovery of fertiliser N.

The large positive values of the intercepts in equations 1 and 2 are surprising because low mineralisation is expected to lead to low crop N uptake. It is possible that a linear model of mineralisation does not adequately reflect the relationship at low values of N supply. Exponential models for mineralised N combined with linear models for fertiliser N (eq 3) were fitted to data for 1999 and 2000 respectively, and showed close relationships:

$$N_{uptake} = \underset{(\pm 15)}{193}\,[1 - e^{\underset{(\pm 0.0028)}{-0.0125} N_{incub})}] + \underset{(\pm 0.105)}{0.95}\, N_{fert} \qquad R^2=86.2,\quad SE_{obs}=36.6\ \text{kg ha}^{-1}$$

$$N_{uptake} = \underset{(\pm 49)}{256}\,[1 - e^{\underset{(\pm 0.00113)}{-0.0033} N_{incub})}] + \underset{(\pm 0.053)}{0.53}\, N_{fert} \qquad R^2=85.9,\quad SE_{obs}=23.3\ \text{kg ha}^{-1} \tag{3}$$

The large difference in crop-N uptake in the two seasons may reflect the different temperatures. The mineralisation equation (4) of Angus et al. (1994) was used to test the effect of seasonal temperature. In this model, daily mineralisation, dN/dt, is calculated in relation to an initial pool of mineralisable nitrogen, N_0, a daily mean temperature, T, above a base, T_b and a first-order decomposition rate, b. The parameters of the equation were derived from laboratory incubations at different temperatures for a single soil.

$$dN/dt = b(N_0 - N)(T - T_b) \qquad T > T_b \qquad (4)$$

This model was used to calculate mineralisation during the two seasons of this project, using mean daily screen temperatures of four locations the Riverina (Fig. 5). In early January at the panicle initiation stage, calculated mineralisation was 50% greater in 1999 than in 2000, but the margin decreased to 7% at maturity in late March. N uptake in the above-ground parts of the crops was also greater in 1999 than 2000; 34% more at panicle initiation and 25% more at maturity (Table 3).

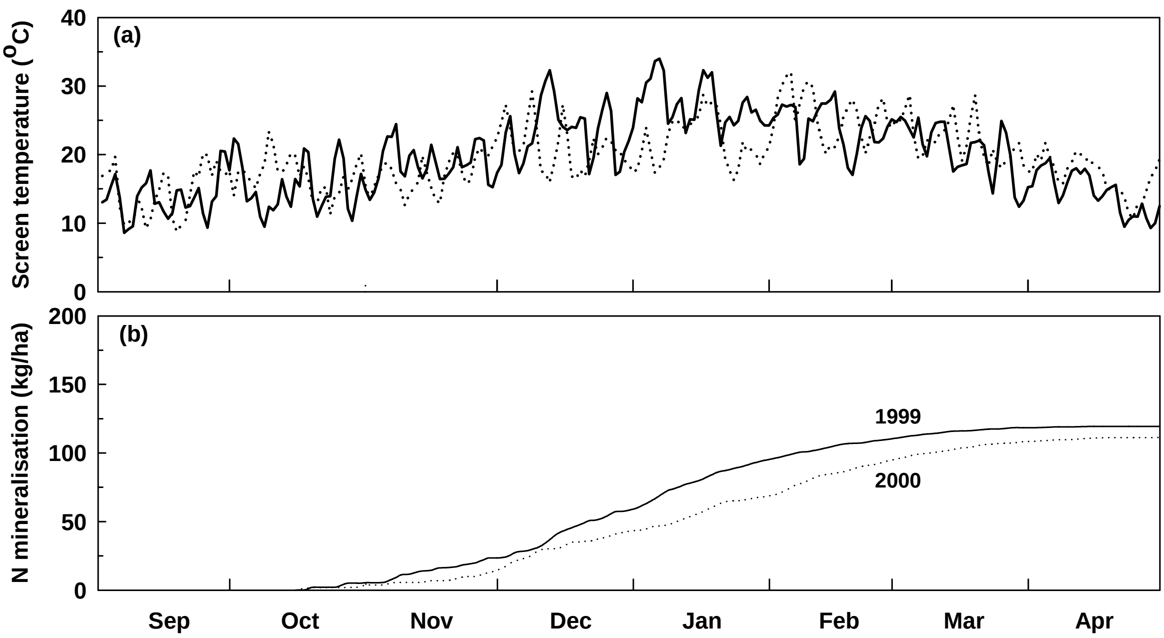

Fig. 5. Simulated effect of temperature on N mineralisation (a) mean daily screen temperatures for the rice-growing region (mean of Coleambally, Deniliquin, Griffith and Hay) for the 1998/99 and 1999/2000 seasons (b) N mineralisation calculated from these temperatures using eq. 4.

The seasonal variation in mineralisation was investigated further using equation 4 with daily temperatures for 46 growing seasons. The mean and standard deviation of mineralisation up to the end of December was 57.0 ± 9.5 kg N ha^{-1}, indicating that the difference between the 1999 and 2000 seasons was at the upper end of seasonal variation.

6.7 Optimum N supply

The optimum supply of N fertiliser depends not only on the crop response to available N, but also on the relative cost of N fertiliser and the price of grain. When a Mitscherlich equation is expressed in the differential form (equation 5), the optimum level of N uptake is estimated when the increment of yield per unit of additional N is sufficient to pay for the marginal cost of fertiliser and application. Equation 5 identifies the optimum biomass, B, in relation to nitrogen uptake at panicle initiation, N, using two fitted parameters, *A* and *c*. The value of *A* is the asymptote of B and *c* defines the shape of the curve. The constant 0.5 represents harvest index (Fig. 3) to convert the units from biomass to yield. The constant *t* is the target marginal return, set at 2 in this example, meaning that the required gross return from additional grain is twice the additional N cost.

$$\frac{t \text{ N cost}}{\text{Grain price}} = 0.5\text{dB/dN} = (A - \text{B})\, c \qquad (5)$$

In the period 1994-2003, the farm-gate price of grain varied from about \$A150 to \$A300 t^{-1}, depending mostly on world supply and demand. Over the same time, the cost of fertiliser N, as urea, has fluctuated from about \$A500 to \$A1000 t^{-1}. The average ratio of N cost to grain price over the period has been about 3.5, with extremes of 1.7 and 6.0. These values are used to estimate the economic optimum yield and corresponding N content of the biomass at panicle initiation using the data in Figs 3e-f. The values of *A* and *c* were estimated using the parameter estimation routine of Miller (1979). The soil N mineralised during anaerobic incubation corresponding to the N content of biomass was estimated from the data in Fig. 5.

Optimum yield varied by 5-10% in relation to price ratio and by a similar amount in relation to the contrasting seasons. However the optimum values of potential soil mineralisation and optimum plant-N uptake at panicle initiation varied by 40-60% in relation to both price ratio and season (Table 6). This amplified variation was because of the shape of the response curves. The variation in optimum N due to costs and prices was less than variation due to soil mineralisation.

Table 6. Optimum yield, N-uptake at panicle initiation and soil N mineralisation estimated from eq. 4 and the data in Fig. 3

Season	1999			2000		
Parameters in eq. 3	*A*=23.13±0.523,	*c*=0.0249±0.0019		*A*=22.39±0.729,	*c*=0.0228±0.0018	
	Optimum:			Optimum:		
N cost: grain price	Yield ($t\ ha^{-1}$)	N uptake at PI ($kg\ ha^{-1}$)	N-mineralisation ($kg\ ha^{-1}$)	Yield ($t\ ha^{-1}$)	N uptake at PI ($kg\ ha^{-1}$)	N-mineralisation ($kg\ ha^{-1}$)
6.6	10.6	99	183	9.6	84	256
3.5	11.1	123	227	10.4	112	317
1.7	11.3	152	281	10.8	142	406

6.8 Rice growers' skill in selecting optimum N applications

The survey of 63 crops provides an indication of rice growers' ability to judge the optimum amount of pre-sowing N fertiliser, based on their experience. As a first step, the biomass of crops fertilised by rice growers is compared with the biomass of the matched crops that received no N fertiliser (Fig. 6a). N fertiliser clearly increased biomass of the least productive crops but had less effect for the most productive crops. The biomass at which N fertiliser had no effect was estimated to be 25 t ha^{-1}, represented by the intersection of the solid (fitted) line with the dashed 1/1 line. This value agrees well with the biomass of crops grown under the best experimental conditions, and is shown as the horizontal line representing maximum biomass in Fig. 6a. For unfertilised crops with biomass less than 25 t ha^{-1}, addition of N fertiliser did not lift biomass to the maximum. For example, where average –N crops had a biomass of 10 t ha^{-1} the corresponding biomass for +N crops was 17 t ha^{-1}, showing that whatever fertiliser was applied did not raise yield to the maximum. From these data it is impossible to conclude whether the reason was insufficient N or other limiting factors.

Fig. 6b shows the amounts of N fertiliser applied by rice growers before flooding, based on their experience. The data show a trend for more N applied to fields where biomass production by –N crops was low, i.e. - where it was needed. The N requirement is estimated ex post from an optimum biomass of 21.5 t ha^{-1}, based on the mean of the two seasons in Table 6, and the reported N-use efficiencies for biomass production (Table 3), and is shown as the dashed line in Fig. 6b.

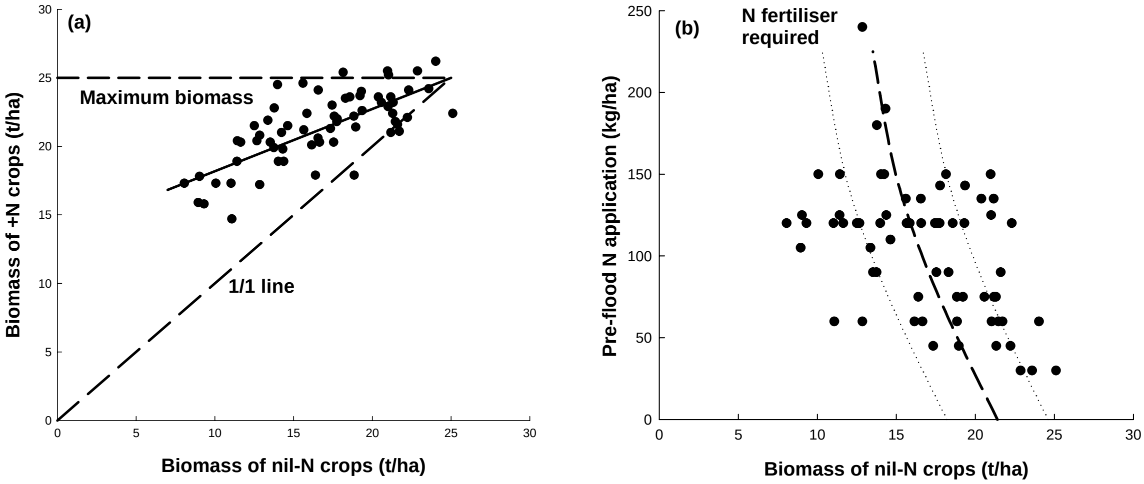

Fig. 6. Biomass production of survey crops in parts of the fields supplied with no N fertiliser in comparison with (a) biomass from the surrounding fields that received N fertiliser applied by rice growers and (b) the rate of N fertiliser applied by rice growers relative to the N-fertiliser required for optimum yield. In (b), the dashed line represents the fertiliser required, estimated from the economic optimum in Table 6, and the average N-use efficiency in Table 3. The dotted lines represent the standard error of the estimated N-requirement.

6.9 Factors affecting yield response to N

The reason for the inaccuracy of the soil-N test may be the inherent problems of soil sampling and that factors other than N are limiting both yield and crop response to soil N. There is evidence for both sampling inaccuracy and other limiting factors. The aim of this part of the study was to investigate the importance of other limiting factors,

Yield of farm crops in 1999 decreased by 121±58 kg/ha with each day's delay in sowing (Fig. 7a). These crops had been supplied with N fertiliser at a rate decided by the rice growers and the yield response to N was evaluated from hand harvests of the fertilised crop and the reference area where no N fertiliser had been supplied. However yield response to N fertiliser was not significantly related to sowing date for the same set of farm crops (Fig.7b).

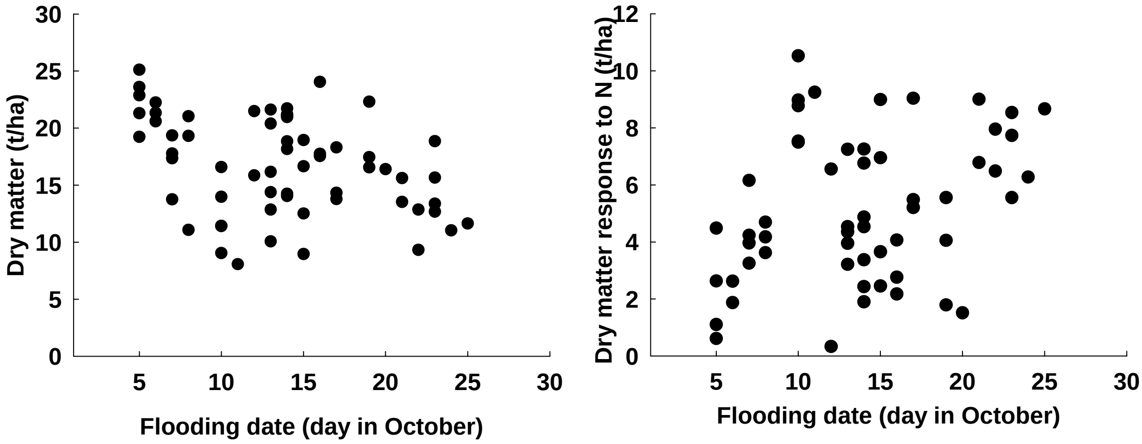

Fig. 7.(a)Relationships between (a) dry matter at maturity for 63 farm crops and sowing date (b) dry matter response to N fertiliser and sowing date for the same crops.

Some evidence that yields are limited by factors other than N come from the previous section where a survey of farm yields suggested that N-fertiliser management on low-yielding fields was inadequate to bring biomass production up to that season's potential. While this failure may have been due to insufficient N fertiliser, it is possible that other factors limited the plant utilisation of applied N. There are four possible explanations for this observation; (1) land managers grossly under-fertilised soils of low organic N supply, (2) substantial amounts of fertiliser N were lost from the system before crop establishment – the impact of this being greatest on low N fertility sites, (3) rice productivity from these soils was limited by nutrients other than N, and (4) various combinations of these three scenarios.

N has normally been the only fertiliser applied to rice, although phosphorus and zinc have been applied in some circumstances. While phosphorus is applied to some crops, recent observations of responses to applied P are widespread (Y. Dang and C.N Walker pers comm. 2002). In recent years, rice farming has both increased and intensified across the Riverina, its intensification a result of the enforced restriction to less permeable soils. The result of this has been longer phases of rice, with three or more years of continuous rice not an uncommon management practice. Furthermore, the introduction of semi-dwarf varieties has caused a marked increase in rice yields with the net result being greater export of nutrients from these soils in the last 15 years. Little is known of the quantities of nutrients removed in rice paddy throughout the Riverina, even less is known of the current effect of soil properties on rice productivity, yield and nutrient status. Due to the complexity of plant growth, soil nutrient availability, and plant nutrient acquisition, soil tests are considered to be at best general guides to the availability of soil minerals. Therefore, soil tests are likely to be poor tools to investigate possible crop responses to soil mineral acquisition. Plant mineral status however, might be a better measure of the availability of individual nutrients when a major nutrient such as N is in good supply. In this study, we have undertaken a comprehensive analysis of soil properties and plant mineral status of N amended rice crops for the purpose of predicting rice productivity from nil-N crops.

Results of soil concentrations and crop uptake are shown in Table 7. They are shown in relation to published estimates of critical upper and lower soil levels compiled by Dobermann and Fairhurst (2000). N was the only nutrient which is generally present at a concentration less than the critical level. Al was generally at levels greater than the level for toxicity. There are few if any symptoms of Al toxicity in Riverina rice and it is likely that the Al level were measured when soils were generally dry and had a low pH. The buffering of soil pH when flooded presumably leads to a reduction of the Al concentration. The high general level of soil Al is a matter of long-term concern, although it may not be relevant to rice yield responses to N fertiliser.

Table 8 shows correlations between soil nutrient concentrations and the concentrations and amounts of the nutrients in rice tissue. Data are presented only when the correlations are statistically significant. Two of the nutrients, B and Mg, are related only to tissue levels at panicle initiation, so presumably nutrient uptake later in crop development compensated for early variation. Four other nutrients, Mn, K, Na and S are related to tissue levels at other times but there is no supporting evidence that deficiencies of these nutrients generally cause problems for Riverina rice. However the soil concentrations of P and Zn are significantly correlated with levels in the grain so that they may be considered as deficient in some circumstances.

Accuracy of a soil N test may be improved if levels of soil P and Zn are known or if rice growers ensure that levels of these nutrients are adequate if high levels of N fertiliser are applied before sowing.

Table 7. Soil concentrations and critical levels of extractable elements and uptake in the shoots of 63 farm crops at the panicle initiation stage

	Al	B	Ca	Cu	Fe	Mg	Mn	Mo	Ni	N	P	K	Na	S	Zn
Soil concentrations (g/kg)															
Mean	0.259	0.009	2.23	0.004	0.374	1.80	0.489	0.004	0.008	17.3	2.95	25.3	1.81	1.59	0.022
c.v. (%)	61	22	17	37	49	11	34	58	26	20	17	13	77	17	20
Min	0.048	0.005	1.22	0.001	0.168	1.45	0.245	0.001	0.004	8.5	1.86	17.0	0.28	1.02	0.015
Max	0.710	0.014	3.35	0.007	1.000	2.50	0.945	0.013	0.015	26.5	4.45	38.5	7.75	2.55	0.034
Ratio	15	3	3	5	6	2	4	10	3	3	2	2	28	3	2
Soil critical levels[A]															
Deficiency					0.05	1.3	0.02			25				1.1	0.01
(%)					0	0	0			98				2	0
Toxicity	0.10	0.035	7.0			5.0				30	5.0	30			0.05
(%)	83	0	0			0				0	0	10			0
Crop uptake (kg/ha)															
Mean	1.69	0.06	14	0.02	2.4	12	3.2	0.03	0.05	112	19	165	12	10	0.15
c.v. (%)	63	33	29	48	50	25	41	52	33	30	32	26	75	30	27
Min	0.27	0.02	6	0.01	0.9	4	0.8	0.01	0.02	35	9	58	2	2	0.06
Max	4.47	0.10	24	0.06	6.5	21	6.9	0.06	0.10	226	34	308	52	19	0.27
Ratio	17	5	4	10	7	5	9	9	4	6	4	5	26	10	5

[A]Dobermann and Fairhurst (2000).

Ratio = maximum / minimum

Table 8. Correlations of significant ($P<0.05$) relationships between the soil analyses and their respective mineral concentrations and mineral yields in PI shoots, straw, brown grain and mature shoots of the N fertilised crops. Elements are only presented where there was at least one significant correlation.

Soil	PI Shoots		Straw		Grain		Mature Shoots	
	Conc.	Yield	Conc.	Yield	Conc.	Yield	Conc.	Yield
B[A]	0.40	---	---	---	---	---	---	---
Mg	0.44	---	---	---	---	---	---	---
Mn	0.45	0.38	0.27	---	0.37	0.33	0.30	0.26
N[B]	0.40	0.39	0.26	0.32	---	0.35	0.25	0.42
P	0.52	---	0.42	0.34	---	0.28	0.42	0.47
K	0.32	---	---	---	---	---	---	---
Na	0.76	0.74	0.65	0.73	---	---	0.66	0.73
S	0.25	0.27	0.38	0.33	---	---	0.38	0.28
Zn	---	---	---	---	0.30	0.25	---	---

df=62, $P<0.05$ $r=0.25$; $P<0.01$ $r=0.33$

6.10 NIR test on an extensive data set

Near infrared reflectance (NIR) spectra of 807 soils from the Riverina region were calibrated with ammonium released during anaerobic incubation. The aim was to evaluate a soil test to recommend optimum N fertiliser applied at the time of sowing flooded rice. The most accurate calibration was obtained using the first derivative of the spectra using partial least squares. This calibration had a standard error of prediction of 25 mgN/kg for soils ranging in concentration of mineralised-N from 25 to 250 mgN/kg (Fig. 8). The accuracy of this NIR calibration was comparable with the small data set in Fig. 2.

When tested on an independent set of 63 soils the standard error of prediction was similar. The residuals from these predictions were then correlated with a range of soil chemical properties. Soil Fe was the most strongly correlated property, and the only soil property that was significantly positively related to the residuals. Multiple linear regression analysis of these properties in relation to the residuals showed that Fe and TSN could explain 26%, Fe and NO_3-N 27%, while Fe, NO_3-N and TSN (total soil nitrogen) could explain 35% of the variation in the residuals. These properties cannot be detected by NIR so any additional information that could be gained from them would require a separate analysis. We conclude that the additional information would not be justified by the cost of analysis in a commercial soil-N test.

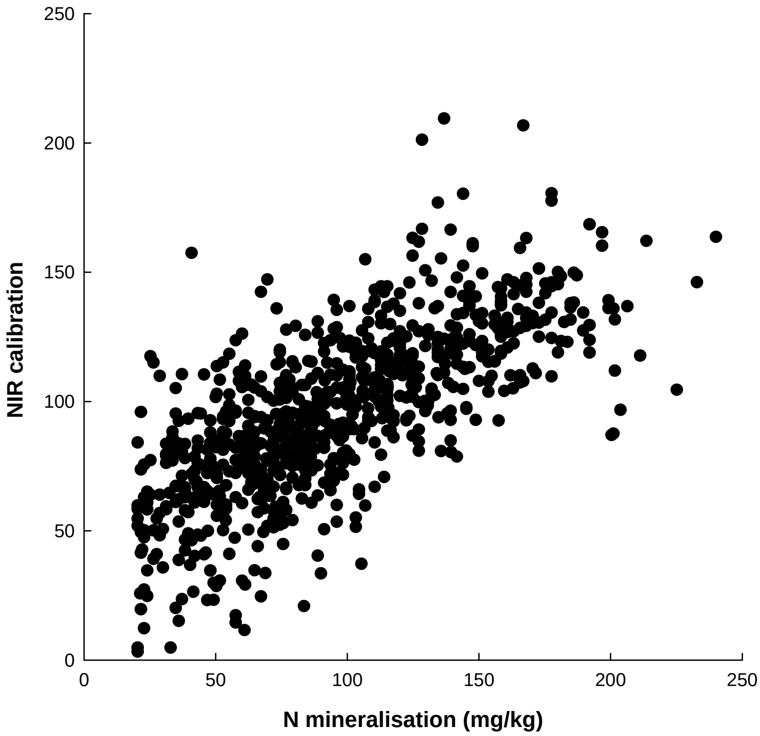

Fig. 8. NIRS calibration of N mineralisation measured by anaerobic incubation at 40°C for 21 days. The data were calibrated using partial least squares. The correlation coefficient was 0.71 and the standard error of prediction was 25 mg/kg.

6.11 Zone management of nitrogen fertiliser

The parts of the projects described previously dealt with measurements made in rice fields with the implicit assumption that the sampled areas were representative of the field as a whole. This simple assumption is obviously false so as part of the project we investigated the response to pre-flood N fertiliser in different parts of a paddock where the soil properties had been measured. The experiment was conducted on a commercial crop of Amaroo near Jerilderie in the 2001-2002 season.

The paddock selected for observations had been laser-levelled in 1995. Up to 40 cm of soil had been cut from part of the paddock. Prior to sowing the crop in mid-October 2001, samples of soil were collected from 25 locations in the cut and filled areas of the field. The locations of the sampled areas were recorded using a global positioning system (GPS) receiver. The samples from each location were analysed for standard soil properties by a commercial laboratory and were also incubated to detect the amount of potentially mineralisable N.

At each of the 25 locations on the field, the yield response to pre-drilled N fertiliser was measured by comparing yields of parts of the crop that had received either no N fertiliser or 120 kg N/ha predrilled as urea. The treatment consisted of applying no N fertiliser in small plots of a paddock where a blanket application of 120 kgN/ha was applied as urea drilled into the soil before sowing. The size of these plots was the width of the drill used inject the urea (3m) and a length of about 10 m. The locations of these areas are shown as the small rectangular areas in Fig. 9. As well as the GPS record of the location, each plot was identified with a post hammered into the soil. Just before commercial harvest, crop biomass was measured in 1 m^2 quadrats within in each zero-N plot and the adjacent fertilised area. The two quadrats were located within 5 m of each other.

Fig. 9. False infrared colour image of a rice paddock at Jerilderie in February 2002. N fertiliser was applied at sowing at the rate of 120 kgN/ha across the paddock, except in small areas shown as dark strips in the image. The large generally dark area in the right-central part of the paddock is a low-growth area where the topsoil was cut during levelling.

Biomass in the different parts of the field is shown in relation to exchangeable sodium percentage (ESP) in Fig 10a and in relation to potentially mineralisable N in Fig 10b. The method used to measure potentially mineralisable N was anaerobic incubation at 40°C for 21 days. The relationship between biomass and ESP was clearly closer than the relationship with potentially mineralisable N. The biomass response to N fertiliser was clearly greater at low values of ESP than at high values. From Fig 10a, allowing for the likely proportion of biomass in grain, it appears that the efficiency of N fertiliser was 33 kg of grain per kg of N of in parts of the field where ESP was lowest, but 55 kg of grain per kg of N where the ESP was highest. The close relationships between N response and ESP and the poor relationship between N response and the soil test suggests that factors related to ESP could provide a basis for zone application of N fertiliser. ESP normally increases with depth in many soil and it is likely that in this case it reflected the amounts of cut and fill during levelling. A map of cut and fill is normally cheaper and easier to obtain than a map of ESP, although it was not available for the paddock used in this study. Further research is needed to show whether cut and fill maps are a reliable indicator of yield response to N fertiliser.

This approach could be combined with a soil N test of low-ESP parts of a paddock to provide a recommendation of the amount and distribution of N fertiliser.

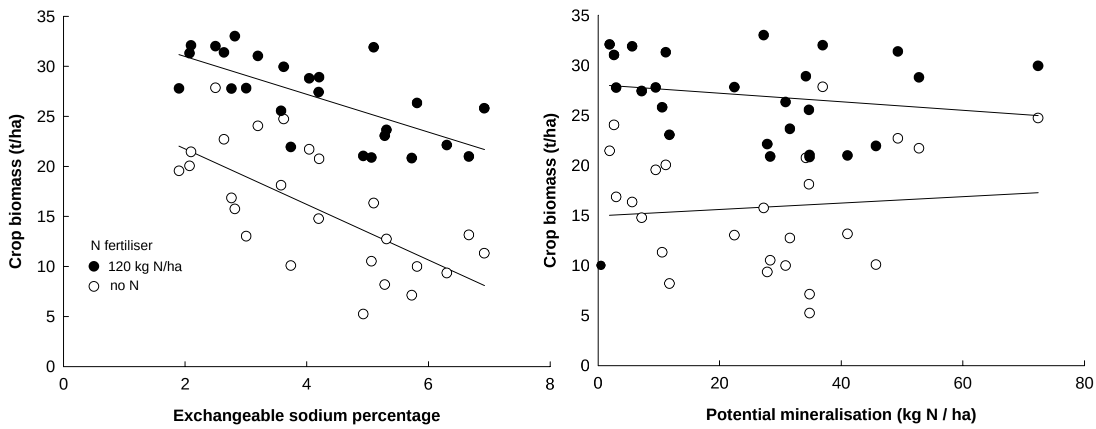

Fig 10. Change in biomass in response to N fertiliser applied at the time of sowing at each of the locations in the paddock in Fig, 9. The biomass at each point was measured by cutting a 1 m2 quadrat.

6.12 Farm yields classified by deciles

Yields of all Amaroo crops in the Ricecheck database were analysed for the period from 1994 to 2004, a total of 3300 crops (Fig.11). The first stage of this analysis was to classify them into ten classes or deciles (Fig.11a). This shows that yield in the lowest decile is less than 6 t/ha while yield in the highest decile is almost 12 t/ha. There is a particularly large yield gap between the lowest and second-lowest decile. There was almost no difference between these deciles in the amount of N fertiliser applied before sowing (Fig. 11b). However the N uptake at the time of panicle initiation was greatest for the lowest decile (Fig.11c). The likely reason for this is that rice growers applied the average amount of N fertiliser (about 75 kgN /ha) to paddock that were already high in mineralisable N. There is no evidence that particular rice growers or rice fields regularly contribute to this lowest decile. Rice growers report great difficulty of selecting the amount of preflood N fertiliser, based on the only information available to them at the time – paddock history. The evidence is that many overfertilise occasionally rather than a few overfertilise regularly.

The consequence of high levels of N in rice crops at the time of panicle initiation is that less N fertiliser is applied at that time (Fig.11d). Crops in the lowest yield decile contained about 140 kgN/ha, far in excess of the target of 100 kgN/ha at that stage.

The characteristics of these paddocks should be examined more closely. It is possible that mineralisation levels are greater than expected, as suggested by the estimated level in Fig.11e, which was back-estimated from the amount of N in the crop at panicle initiation, and the relationships in Fig. 4a and b. These calculations should be treated with care since the relationships were collected on individual paddocks and the inference applies to averages.

This analysis suggests that the issue of preflood N application should be reconsidered as avoiding overfertilisation rather than attempting to predict the optimum amount of N for all fields. Even with the errors in the NIR soil test it would be possible to identify most of these fields. Fig. 12 presents the distribution of mineralisations, ranging from 30 to 250 kgN/ha. The 10% of paddocks with the highest rates of mineralisation extend to 160 kgN/ha. A soil test could identify paddocks such as these with large potential mineralisations.

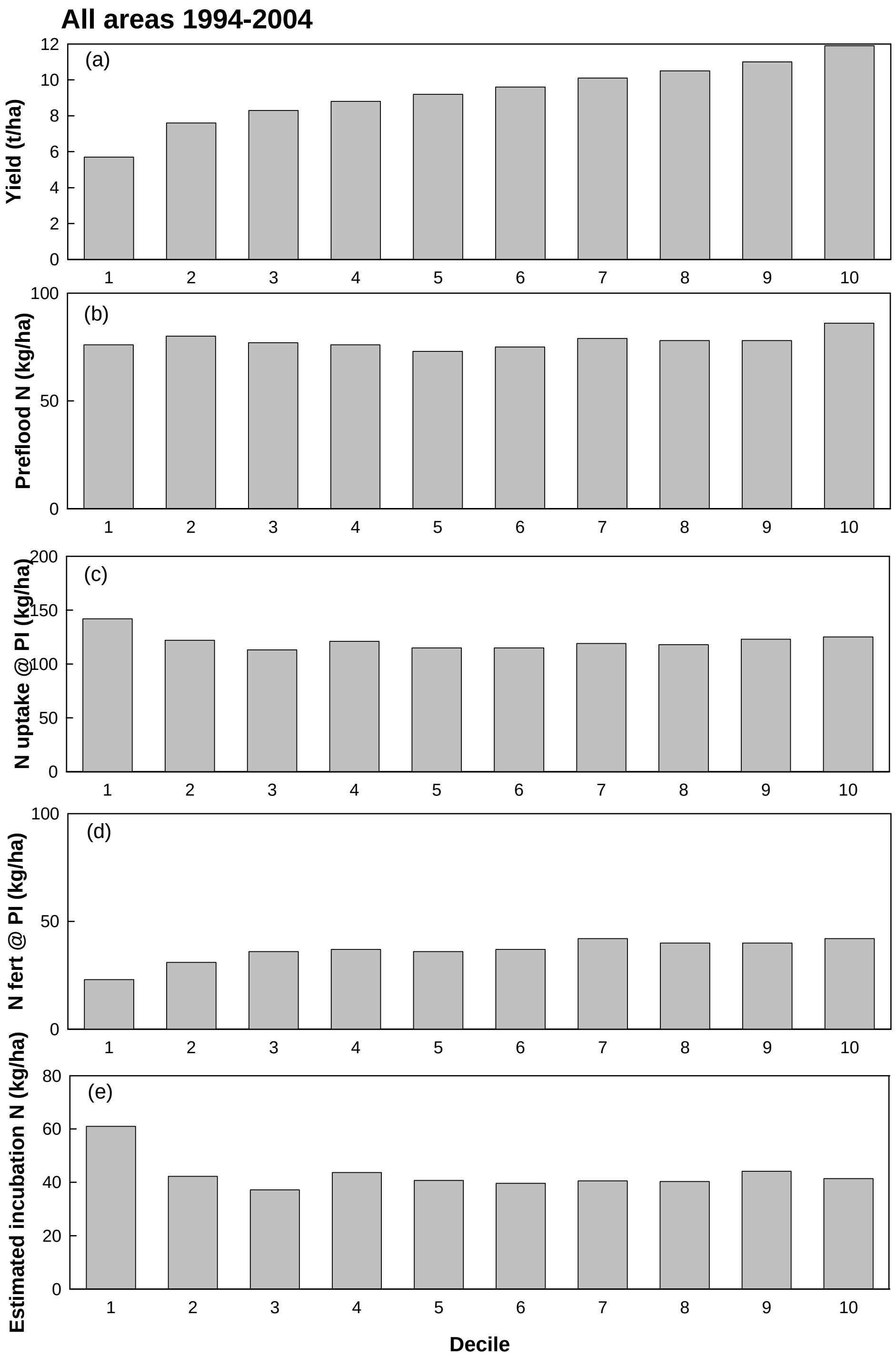

Fig. 11. Yield and N relations of 3300 commercial crops of Amaroo in the Riverina from 1994 classified into deciles based on yield. Data for (a)-(d) were obtained from the Ricecheck database and data in (e) were back calculated using Fig 4 a and b and the data in Fig. 11(c) and (d).

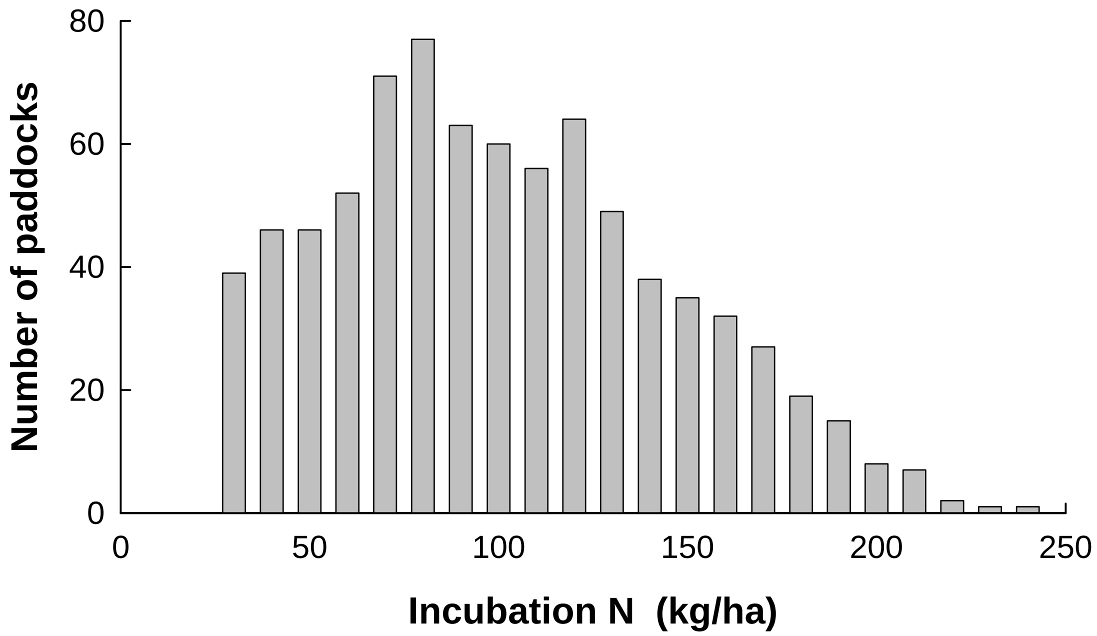

Fig. 12. Distribution of potential mineralisation across 807 Riverina fields, estimated from the anaerobic incubations reported in Fig. 8.

7. Discussion

The project did not lead to a commercial soil-N test. A total of 17 currently available tests were evaluated and NIR was evaluated against these and against crop performance While several tests produced significant correlations with the supply of N to commercial crops, the errors associated with these tests were unacceptable for commercial use. The reason for the poor performance of the tests was probably the heterogeneity of rice soils because of the pattern of cut and fill associated with land levelling.

While the soil test cannot be implemented in full there are two options proposed for more reliable application of N fertiliser at the time of sowing. Both require further research. One is to use the existing soil test only to identify soils with large amounts of potentially mineralisable N. Such a test could be the basis of a recommendation to apply little or no N fertiliser before sowing. Rice growers would still have the option of topdressing N fertiliser at the panicle initiation stage. The advantage of using a test in this way is that it is most unlikely to result in 'false positives', that is, recommendations for excessive N fertiliser leading to yield reductions.

The other option is to set up a system of zone management for N fertiliser based on the likely N mineralisation in different parts of a rice field. The results in this project suggest that yield responses are more accurately predicted by sodicity than by the soil N test. It is likely that sodicity is a good indication of the depth of topsoil cut in the process of levelling. If this result is shown to be general, maps of 'cut and fill' areas may be an important source of information in deciding the optimum amount of N fertiliser.

As part of a zone-management system, a soil test should be used on the fill areas of the paddock to avoid overfertilisation with preflood N.

8. Implications

Data collected during the course of this project shows the importance of avoiding overfertilising at sowing. From the results of the Ricecheck database, there are about 10% of paddocks in which excessive N fertiliser is applied before sowing to fields that have the capacity for high rates of mineralisation.

It is unlikely that all crops in the lowest yielding decile are overfertilised. Other reasons for low yields are weeds, poor stands and lack of water. However it is likely that most of the lowest-decile crops are overfertilised. We here assume that half the lowest decile of rice yields are low because of N overfertilisation and that otherwise their yields would not be 6 t/ha, but 12 t/ha, similar to the yields of the highest decile. So the yields of 5% of rice paddocks could be increased from 6 to 12 t/ha if overfertilisation could be avoided. Assuming a rice area of 100,000 ha, 5% of paddocks represent 5,000 ha and the additional production would be 30,000 tonnes, worth $9m at the farm gate
This calculation suggests that it is worth the effort to use the results of this project to prevent overfertilisation.

The intellectual property of the project rests in the relationship between NIRS and soil mineralisation. This information is contained in two forms. On is contained in equations held in computer files. The limitation of this information is that it relates to a particular NIR spectroscope, the calibration of which may not remain stable. The other form of the combination of the physical soil samples and the records of mineralisation measured during the project. These soil samples are archived at Yanco Agricultural Institute. These samples are available to develop a commercial soil N test, as recommended below, for different NIR or MIR spectroscopes.

9. Recommendations

There are two opportunities for improved efficiency of rice production based on this project. One is to make the soil test available to rice growers on a limited basis: only to provide recommendations *not* to add N fertiliser at sowing. The errors inherent in the soil test are such that is should not be used to make recommendations to apply N at sowing.

The other recommendation is to follow up the finding of greater responses to N on the cut parts of a levelled paddock. The evidence that the sodicity was a better indicator of N response than the soil-N test should be followed up because it leads to the possibility that cut and fill maps could be the basis of zone management of N.

A combination of zone management and a soil test to avoid overfertilisation on the cut areas may provide a basis for preflood N fertiliser application.

A possible commercial operator of a soil test could be SunRice Ltd., which already runs an NIR-based test for plant-N status

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