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Season and plant type affect the response of rice yield to nitrogen fertilisation in a semi-arid tropical environment

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Abstract. Production of flooded direct-seeded rice (*Oryza sativa* L.) in semi-arid tropical regions of northern Australia would be enhanced by increasing the efficiency of fertiliser nitrogen (N) use. Short-statured and early-maturing genotypes have replaced the taller and later genotypes in northern Australia, and they may respond differently to N. This paper reports the results of 4 experiments comparing the response of 3 rice genotypes differing in maturity and stature to 5 rates of applied nitrogen (0, 70, 140, 210, and 280 kg/ha) over 4 seasons (2 wet and 2 dry seasons) in the Burdekin River Irrigation Area, northern Australia.

Grain yield varied among seasons and was negatively correlated with average daily mean temperature during the 30-day period before anthesis. The response of yield to N fertilisation was generally higher in the dry season. Panicle number was correlated with grain yield in both seasons, yet responded to N fertilisation only in the dry season. In 3 of 4 experiments, grain yield responded to the application of up to 70 kg N/ha, yielding about 750 g/m^2. In only 1 dry season experiment did grain yield respond to the application of 140 kg N/ha, yielding about 930 g/m^2. In this experiment, the response of grain yield to N rate also varied among genotypes such that yield in the early-maturing genotypes (Newbonnet and Lemont) was more responsive to N rates above 70 kg/ha than in the late-maturing genotype (Starbonnet).

Of the 3 genotypes examined, highest yields were attained in Newbonnet (early-maturing, medium-statured) by combining high total dry matter production with high harvest index, indicating that this plant type may have an advantage in northern Australia. Yields in Lemont (early-maturing, short-statured) and Starbonnet (late-maturing, tall-statured) were limited by dry matter production and harvest index, respectively. There is some evidence that increased dry matter production in Newbonnet compared with Lemont was related to increased stem length. The evidence linking high harvest index with increased earliness in Newbonnet compared with Starbonnet is less compelling.

Additional keywords: Oryza sativa, nitrogen application, semi-arid tropics, genotypes, plant height, maturity.

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Introduction

Nitrogen (N) fertiliser accounts for about 20% of the total variable cost of rice production in the Burdekin River Irrigation Area (BRIA) of northern Australia (Bourne and Norman 1990). In addition, there is increasing pressure for N fertiliser inputs to be reduced to prevent drainage of excess nitrate from agricultural enterprises into coastal rivers, and eventually the Great Barrier Reef (Prove *et al.* 1990). Therefore, it is important to improve the efficiency with which N fertiliser is used to produce crops in coastal areas of North Queensland such as the BRIA. (Rice was grown commercially in North Queensland for a 25-year period between 1968 and 1993.)

Variation in yield response of rice to N fertilisation is influenced by differences in solar radiation during the reproductive and grain-filling periods (Stansel 1967; De Datta and Zarate 1970). Solar radiation patterns in the semi-arid tropics differ markedly from those in wet tropical regions (e.g. 10 *v.* 18 $\mathrm{MJ/m^2 \cdot day}$ in the wet and dry seasons, respectively, within the Philippines, De Datta and Malabuyoc 1976) and temperate regions. The response of grain yield to N fertiliser in wet tropical Asia is substantially higher in the dry than the wet season (De Datta and Malabuyoc 1976). This may not be the case, however, in semi-arid tropical Australia where seasonal differences in solar radiation are often small (about 21 $\mathrm{MJ/m^2 \cdot day}$ in both the wet and dry seasons for the current experiments in the BRIA), depending on the extent of the wet season.

Plant type also affects the response of grain yield to N fertiliser. Generally, short-statured and early-maturing genotypes are more responsive to N than tall-statured and late-maturing genotypes (De Datta *et al.* 1968; Sanchez *et al.* 1973; De Datta and Malabuyoc 1976). At the time of this study in northern Australia, a short-statured and early-maturing genotype (cv. Lemont) had replaced taller and later genotypes (e.g. cv. Starbonnet) and it was considered that Lemont may respond differently to N.

This paper examines how season and plant type affect the response of grain yield in rice to 5 rates of N fertilisation in a semi-arid tropical environment.

Materials and methods

Location and soil details

Four experiments were conducted in 4 consecutive seasons at Millaroo Research Station, BRIA (20°03′S, 147°16′E): Experiment 1 (1986 dry season), Experiment 2 (1987 wet season), Experiment 3 (1987 dry season), and Experiment 4 (1988 wet season). Soil type was a grey clay (Ug5·29; Northcote 1974) (Entic Chromustert; Soil Survey Staff 1975) and, according to Reid and Baker (1984), lies on a major flood plain, and is moderately self mulching and seasonally cracking, with a pH range from 6·0–8·5 at the surface to 8·5–9·2 at 1·5 m. Selected chemical properties of the experimental site are presented in Table 1.

Treatments

A randomised split plot design with 5 rates of N fertiliser (0, 70, 140, 210, and 280 kg/ha) split for 3 genotypes (cv. Lemont, early-maturing short-statured; cv. Newbonnet, early-maturing medium-statured; and cv. Starbonnet, late-maturing tall-statured) was used. There were 4 replications and each was enclosed within a separate bay to control water levels adequately. Compacted earth banks (0·5 m high, 2 m wide) bordered all bays.

For a given N rate, genotypes were enclosed within mini-bays preventing the movement of N in the floodwater between N treatments. Compacted earth banks (0·5 m high, 1 m wide) bordered all mini-bays and in constructing the banks, soil was taken from the inside perimeter of each bay, creating a trench of depth 0·4 m. Therefore topsoil from the experimental plots was not used to construct the banks. Water depth in the mini-bays was maintained at 0·1 m until draining prior to harvest.

Starbonnet was bred in Arkansas and released in North Queensland in the mid 1970s. Lemont was bred in Texas (Bollich *et al.* 1985) and released in North Queensland in 1987. Newbonnet was bred in Arkansas, but has not been released in Australia.

All N was applied as urea. Half of the N was applied to the soil surface immediately prior to permanent flood, and the remaining half was applied into floodwater around panicle initiation (48 and 66 days after sowing in the wet and dry seasons, respectively), since previous research in northern Australia found that this method resulted in the highest grain yields (Maltby and Barnes 1986). The time for topdressing N at panicle initiation was estimated for a mean rate of N (140 kg/ha) and was intermediate between early- and late-maturing genotypes i.e. fertiliser was applied 3–5 days before initiation in the late-maturing genotype and 3–5 days after initiation in the early-maturing genotypes.

Panicle initiation was determined by randomly selecting 10 plants from each plot 3 times a week after the emergence of

Table 1. Selected chemical properties (with standard deviations) of the surface (0–0·2 m) of Barratta soils used in the wet and dry season nitrogen fertilisation studies in rice at Millaroo Research Station

Depth (m)	pH	EC (dS/m) (1 : 5 soil : water)	Cl (mg/kg)	Organic C (%)	$\mathrm{P_B}$ (mg/kg)	Repl. K[A] (cmol(+)/kg)	Aqueous $\mathrm{NO_3^-}$-N (mg/kg)
0·0–0·1	6·9	0·9	46·8	0·72	11·2	0·40	7·8
	(0·1)	(0·01)	(10·5)	(0·11)	(1·3)	(0·01)	(1·6)
0·1–0·2	6·6	0·9	52·0	0·70	9·4	0·40	7·4
	(0·6)	(0·01)	(9·9)	(0·01)	(1·5)	(0·01)	(1·1)

[A] Replaceable K using HCl extractant.

6 leaves in Lemont. The mainstems were sliced in half, and the commencement of stem elongation was noted. Preliminary experiments at Millaroo Research Station immediately prior to these N studies found that initiation in rice coincided with a stem internode length of about 2 mm in Lemont and Starbonnet.

Agronomy

All experiments were sown into dry soil with a cone-seeder to a depth of 10–20 mm in rows 0·175 m apart at a seeding rate of 130 kg/ha and immediately irrigated. Each plot was 9·45 m^2, 6 rows wide (1·05 m) by 9 m long. Experiments were sown consecutively at the following times over a 2-year period: Experiment 1 (22 July), Experiment 2 (16 December), Experiment 3 (21 August), and Experiment 4 (16 December). The site of the experiments was different each year, being conducted on adjacent land. In all cases, the land was fallow for at least 1 year prior to experimentation. The sowing times used in these experiments were representative of commercial sowing times in the dry (July–August) and wet (December–January) seasons.

All experiments were fertilised prior to sowing with a mixture containing (kg/ha) P, 18; K, 13; S, 23; Ca, 40; and Zn, 6. Propanil (a.i. 3′,4′-dichloropropionanilide) was applied aerially to all treatments immediately prior to permanent flood to control barnyard grass (*Echinochloa colonum*) and sedges (*Cyperus iria* and *C. difformis*). A second application of Propanil was required in Experiments 2 and 3.

Harvests

Dry matter was determined at maturity in all seasons from a 0·7-m^2 quadrat (4 rows of 1 m) cut at ground level in each plot and dried at 80°C for 48 h. Physiological maturity was defined as the time when 90% of the florets were yellow. Panicle number per quadrat was determined prior to drying and 500-grain weight was determined from subsamples within each quadrat.

In Experiments 1, 2, and 4 quadrats were cut from all genotypes on the same day after the attainment of physiological maturity in the late-maturing genotypes. No yield loss was observed in the early-maturing types due to this harvesting procedure. In Experiment 3, however, Lemont, Newbonnet, and Starbonnet were harvested at 123, 130, and 137 days after sowing (DAS), respectively, as yield loss from birds was considered a potential problem in this season.

In Experiments 2 and 3, at both panicle initiation and anthesis, an additional sample of a 0·5-m length of row, selected from the centre 4 rows of the 6-row plot, was cut at ground level. Anthesis was considered to have occurred when anthers had extruded from the mainstem panicle of 50% of the plants within a plot. Senesced tissue was included in the samples. Adjacent rows were not harvested, and when samples were taken from the same row, a 1-m border remained between samples. All plants were partitioned into stem and leaf at panicle initiation, and into stem, leaf, and panicle at anthesis. Samples were dried at 80°C for 48 h in a forced-draft oven before weighing.

Statistical analysis

Data were analysed by standard analysis of variance and pairwise comparisons of means were performed using the protected l.s.d. procedure at $P = 0{\cdot}05$. Pooled analyses were performed across experiments for grain yield, above-ground dry mass, harvest index, days to anthesis, and plant height. Harvest index was derived by dividing grain yield by above-ground dry mass (AGDM), and grain number per m^2 was calculated from the product of panicle number per m^2 and grain number per panicle. Correlations were calculated between grain yield and grain number per m^2, panicle number per m^2, spikelet number per panicle, and mass per grain. Correlations were also calculated between average daily mean temperature during the 30-day period before anthesis and grain yield, above-ground dry mass, and harvest index.

Results

Meteorology

Rainfall was higher in the wet (334 and 630 mm in Experiments 2 and 4) than dry (222 and 300 mm in Experiments 1 and 3) season experiments (Table 2). Maximum temperatures averaged 32 and 33°C in the dry and wet seasons, respectively, while minimum temperatures averaged 18 and 22°C in these respective seasons.

Overall, the wet season crop experienced high maximum and minimum temperatures during the vegetative period (December–January) and lower temperatures during the grain-filling period (March–April). In contrast, the dry season crop experienced relatively low maximum and minimum temperatures during the vegetative period (July–August) and higher temperatures during grain filling (November–December). Mean daily solar radiation was not recorded during Experiments 1 and 2. Mean daily solar radiation was similar in Experiments 3 (22·2 $MJ/m^2 \cdot day$, dry season) and 4 (20·2 $MJ/m^2 \cdot day$, wet season), although during the grain-filling period it was considerably higher in the dry (24·1 $MJ/m^2 \cdot day$) than wet (17·7 $MJ/m^2 \cdot day$) season.

Phenology

Time to anthesis was longer in the dry seasons (100 and 92 days for Experiments 1 and 3, respectively) than the wet seasons (80 and 85 days for Experiments 2 and 4, respectively) (Table 3). In the dry season, Experiment 1 was sown 4 weeks earlier than Experiment 3, resulting in a longer pre-anthesis period in Experiment 1 due to lower average daily mean temperatures in this period (22·6°C *v.* 24·9°C).

The effect of N on phenology differed ($P < 0{\cdot}01$) among seasons. Applying 70 kg N/ha reduced the time to anthesis in all experiments by 1–4 days. However, for N rates above 70 kg/ha, time to anthesis increased with N rate for Experiments 2–4, but remained constant in Experiment 1.

The early-maturing genotypes (Lemont and Newbonnet) reached anthesis about 14 and 9 days earlier than Starbonnet in the dry and wet seasons, respectively. A combined analysis across all experiments found a significant ($P < 0{\cdot}01$) response of genotype

Table 2. Mean monthly rainfall (mm), mean daily pan evaporation (mm), mean monthly maximum and minimum temperatures (°C), and mean daily solar radiation ($MJ/m^2 \cdot day$) recorded at Millaroo Research Station during four consecutive rice crops

	Rainfall	Mean daily pan evaporation	Temperature Maximum	Temperature Minimum	Mean daily solar radiation
Experiment 1 (dry season)					
July	41·0	3·1	26·6	13·3	n.r.
August	27·4	4·4	26·0	13·2	n.r.
September	10·4	4·4	31·0	15·0	n.r.
October	117·6	4·8	31·3	20·4	n.r.
November	0·0	7·1	33·8	19·3	n.r.
December	25·6	6·3	35·4	23·3	n.r.
Experiment 2 (wet season)					
December	25·6	6·3	35·4	23·3	n.r.
January	104·1	6·5	34·8	24·5	n.r.
February	93·2	6·0	33·9	22·9	n.r.
March	88·4	6·1	33·3	21·8	n.r.
April	22·4	4·8	30·8	18·9	n.r.
Experiment 3 (dry season)					
August	1·9	4·1	28·4	12·0	n.r.
September	2·2	5·5	29·8	13·6	22·5
October	14·4	7·0	33·9	21·0	21·1
November	57·4	6·4	33·2	23·1	19·7
December	166·6	6·6	34·6	22·1	24·1
January	57·2	7·0	34·0	22·9	23·6
Experiment 4 (wet season)					
December	166·6	6·6	34·6	22·1	24·1
January	57·2	7·0	34·0	22·9	23·6
February	173·0	5·9	33·4	22·9	18·0
March	128·8	4·9	30·0	22·0	19·1
April	104·8	3·7	29·5	19·7	16·3

n.r., not recorded.

Table 3. Time from sowing to anthesis (days) for five rates of applied nitrogen (kg/ha) and three genotypes across four experiments

Means within a column and treatment followed by a common letter are not significantly different at $P = 0{\cdot}05$

Treatment	Experiment 1 (dry season)	Experiment 2 (wet season)	Experiment 3 (dry season)	Experiment 4 (wet season)
Rate of N (kg/ha)				
0	103b	79b	93c	85ab
70	99a	78a	90a	83a
140	99a	79b	92b	84a
210	99a	81c	93c	86bc
280	99a	82d	93c	87c
Genotype				
Lemont	94a	77a	87a	84b
Newbonnet	96b	76a	88b	81a
Starbonnet	109c	86b	101c	90c

to N rate. Time to anthesis was 2 days less for 0 kg N/ha than 280 kg N/ha in Lemont. For Newbonnet and Starbonnet, time to anthesis was the same for the lowest and highest rates of applied N; however, it was 2 days less for 70 kg N/ha than for 280 kg N/ha in these genotypes.

Phenology also affected harvest index (Fig. 1). In a comparison of harvest index in the 2 taller genotypes, early-maturing Newbonnet exceeded ($P < 0{\cdot}01$) late-maturing Starbonnet for all N rates in Experiment 1 (Fig. 1*a*). In the wet seasons, lower harvest indices were observed at the higher rates of N (210 and 280 kg

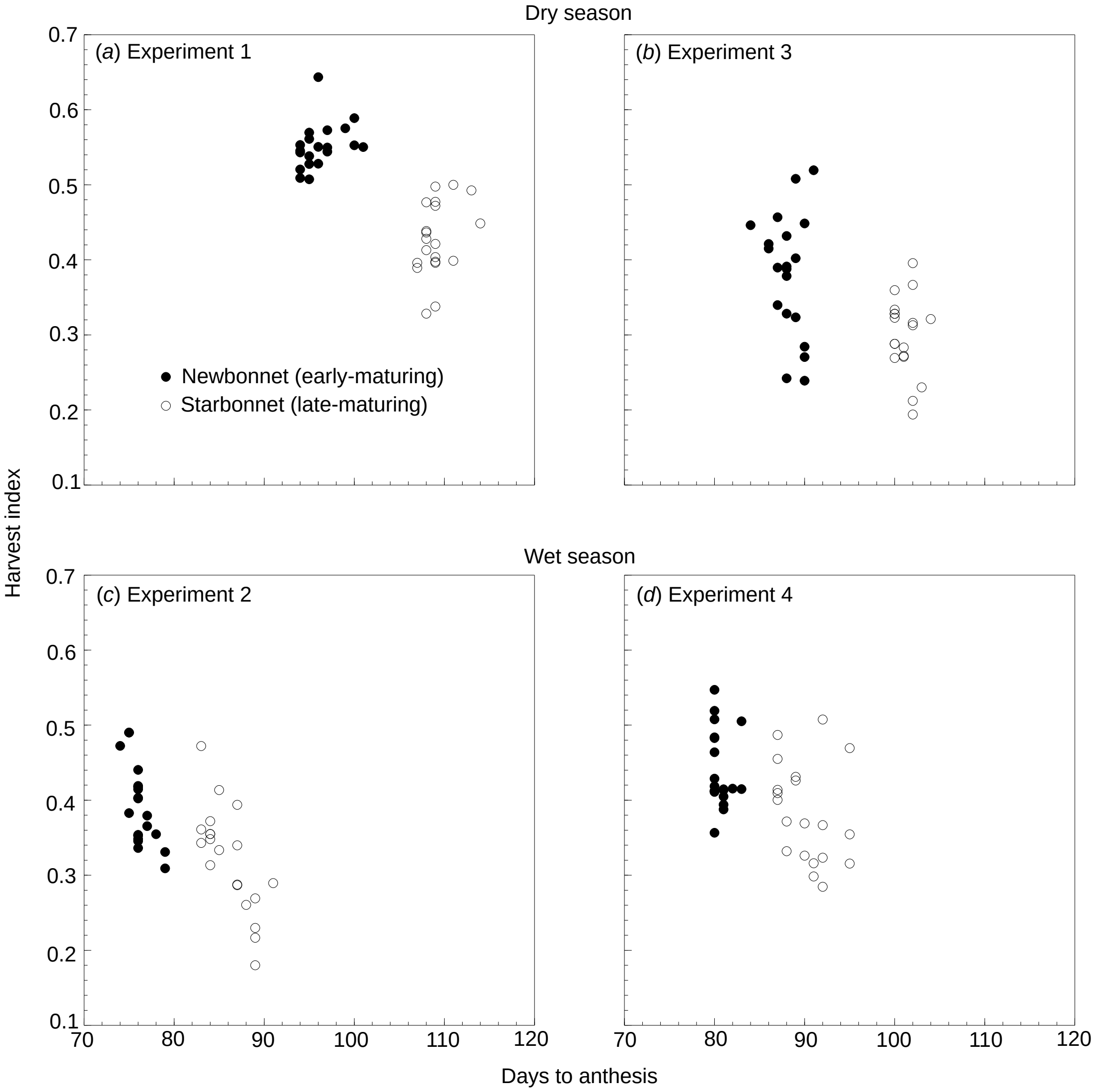

Fig. 1. Relation between days to anthesis and harvest index in 2 dry seasons and 2 wet seasons for rice genotypes differing in maturity: Newbonnet (early-maturing) (●) and Starbonnet (late-maturing) (○).

N/ha) in Starbonnet compared with Newbonnet (Fig. 1*c* and *d*).

Crop growth at panicle initiation and anthesis (Experiments 2 and 3)

At panicle initiation, AGDM responded to the application of up to 210 and 70 kg N/ha in the wet and dry seasons, respectively, reaching maximum values of about 490 and 600 g/m^2 in these respective seasons (Table 4). Lemont and Newbonnet exceeded ($P < 0{\cdot}01$) Starbonnet in AGDM in the dry season but not in the wet season.

At anthesis, AGDM responded to the application of up to 140 and 210 kg N/ha in the wet and dry seasons, attaining maximum values of about 2500 and 1700 g/m^2 in these respective seasons. Starbonnet produced more ($P < 0{\cdot}01$) AGDM than Lemont in the wet season, whereas Newbonnet exceeded ($P < 0{\cdot}05$) Lemont in the dry season.

Crop growth at maturity (Experiments 1–4)

Production of dry matter

AGDM was higher ($P < 0{\cdot}01$) in Experiments 2 and 3 (about 1890 g/m^2) than Experiments 1 (1600 g/m^2) and 4 (1700 g/m^2) (Table 5). AGDM increased with N up to 140 kg N/ha in all experiments, plateauing at masses of about 2000–2100 g/m^2.

In all seasons AGDM was higher ($P < 0{\cdot}01$) in Newbonnet and Starbonnet (about 1900 g/m^2) than in Lemont (about 1500 g/m^2). A significant genotype×N interaction ($P < 0{\cdot}05$) was observed in Experiment 3

Table 4. Above-ground dry mass (g/m^2) at panicle initiation and anthesis for five rates of applied nitrogen (kg/ha) and three genotypes across two seasons

Means within a column and treatment followed by a common letter are not significantly different at $P = 0{\cdot}05$

Treatment	Wet season (Experiment 2)		Dry season (Experiment 3)	
	Panicle initiation	Anthesis	Panicle initiation	Anthesis
		Rate of N (kg/ha)		
0	170a	1303a	141a	632a
70	402b	1780ab	467b	1188b
140	419bc	1951bc	554b	1142b
210	499d	2177bc	598b	1830c
280	485cd	2561c	607b	1635c
		Genotype		
Lemont	388a	1690a	533b	1141a
Newbonnet	377a	1943ab	499b	1439b
Starbonnet	420a	2230b	388a	1276ab

(dry season), as AGDM plateaued at 70 kg N/ha in Lemont and Starbonnet, but continued to increase to the highest N rate in Newbonnet. No interactions occurred for the other experiments.

Grain yield

Grain yield varied ($P < 0{\cdot}01$) between dry (Experiments 1 and 3) and wet (Experiments 2 and 4) seasons, but not consistently: Experiment 1 (801 g/m^2) > Experiment 4 (723 g/m^2) > Experiments 2 (682 g/m^2) and 3 (665 g/m^2) (Table 5). Yoshida and Parao (1976) found rice grain yield in the tropics to be highly negatively correlated with average daily mean temperature (ADMT) during the 25-day period before anthesis, and an analysis of ADMT (°C) during the 30-day period before anthesis in the current study also found it was negatively correlated ($r^2 = 0{\cdot}93^*$) with grain yield (g/m^2) ($y = 2067–49{\cdot}36x$).

The response of grain yield to N fertilisation differed ($P < 0{\cdot}01$) across experiments. While yield increased with N to 70 kg N/ha in all experiments, thereafter it plateaued in Experiments 3 (dry season) and 4 (wet season), increased in Experiment 1 (dry season) to 140 kg N/ha before plateauing, and decreased in Experiment 2 (wet season) such that yield at 280 kg N/ha was less than at 70 kg N/ha.

In 3 of 4 experiments, grain yield was higher ($P < 0{\cdot}05$) in Newbonnet than in Lemont or Starbonnet. There was no significant difference in grain yield among genotypes in Experiment 4, although Newbonnet again had the highest mean yield.

Response of grain yield to N rate varied ($P < 0{\cdot}05$) with genotype in Experiment 1 (dry season). Yield in the early-maturing genotypes (Newbonnet and Lemont) was more responsive to N rates above 70 kg/ha than in the late-maturing genotype (Starbonnet). There was no significant genotype×nitrogen interaction in Experiments 2–4.

Harvest index

Harvest index (HI) varied ($P < 0{\cdot}01$) between dry (Experiments 1 and 3) and wet (Experiments 2 and 4) seasons, but not consistently: Experiment 1 (0·51) > Experiment 4 (0·44) > Experiments 2 and 3 (0·37) (Table 5). As with grain yield, harvest index was also negatively correlated ($r^2 = 0{\cdot}95^*$) with average daily mean temperature (°C) in the 30-day period before anthesis ($y = 2{\cdot}015–0{\cdot}058x$).

Harvest index was always highest without N fertilisation or with an application of 70 kg N/ha, but declined significantly for N rates above 140 and 70 kg/ha in Experiments 2 and 4, respectively.

Harvest index in the early-maturing genotypes (Lemont and Newbonnet) was higher ($P < 0{\cdot}01$) than in the late-maturing Starbonnet in all experiments, and within the early-maturing genotypes, was higher ($P < 0{\cdot}01$) in short-statured Lemont than medium-statured Newbonnet in Experiments 3 and 4.

Nitrogen rate interacted with genotype for HI in both dry seasons (Experiment 1, $P < 0{\cdot}01$; Experiment 3, $P < 0{\cdot}05$). In Experiment 1, HI of the early-maturing genotypes (Lemont and Newbonnet) remained high for all N rates, but declined with increasing rates of N in the late-maturing Starbonnet. In Experiment 3, HI remained relatively constant across N rates for Lemont (about 0·44) and Starbonnet (0·30), while in Newbonnet, it declined from 0·47 to 0·30 with increasing N rate.

Components of yield

Panicle number per m^2 increased with N to 140 kg N/ha in the dry season, plateauing at about 420 in

Table 5. Above-ground dry mass (g/m^2), grain yield (g/m^2), harvest index, panicle number per m^2, grain number per panicle, and mass per grain (mg) for five rates of applied nitrogen and three genotypes across four experiments

Means within a column, experiment, and treatment followed by a common letter are not significantly different at $P = 0{\cdot}05$

Treatment	Above-ground dry mass	Grain yield	Harvest index	Panicle number per m^2	Grain number per panicle	Mass per grain
			Experiment 1 (dry season)			
Rate of N (kg/ha)						
0	853a	440a	0·52a	278a	67a	24·2bc
70	1489b	780b	0·53a	396b	82b	24·9c
140	1854c	928c	0·51a	431bc	92b	24·2bc
210	1964c	963c	0·49a	463c	90b	23·6ab
280	1850c	892c	0·49a	380b	107c	22·9a
Genotype						
Lemont	1350a	735a	0·54b	364a	77a	27·2c
Newbonnet	1696b	927b	0·55b	413a	95b	23·5b
Starbonnet	1760b	740a	0·43a	391a	90b	21·2a
			Experiment 2 (wet season)			
Rate of N (kg/ha)						
0	1106a	467a	0·42b	319a	60a	24·6c
70	1957b	824c	0·42b	347a	101bc	23·9c
140	2073bc	752bc	0·36ab	330a	105c	22·4b
210	2193c	720bc	0·33a	352a	100bc	21·5a
280	2077bc	647b	0·31a	345a	87b	21·2a
			Genotype			
Lemont	1639a	639a	0·38b	340a	75a	25·3c
Newbonnet	1940b	754b	0·40b	354a	98b	22·4b
Starbonnet	2064b	654a	0·32a	322a	99b	20·5a
			Experiment 3 (dry season)			
Rate of N (kg/ha)						
0	1001a	401a	0·40a	233a	70ab	25·9c
70	1779b	689b	0·40a	358b	79bc	25·6c
140	2092bc	704b	0·36a	421c	67a	25·3bc
210	2270c	792b	0·36a	384bc	87c	24·2ab
280	2266c	740b	0·34a	425c	77ab	23·6a
Genotype						
Lemont	1432a	616a	0·43c	374b	59a	28·2c
Newbonnet	2122b	764b	0·38b	420c	75b	24·4b
Starbonnet	2090b	616a	0·30a	299a	94c	22·2a
			Experiment 4 (wet season)			
Rate of N (kg/ha)						
0	978a	482a	0·49b	254a	85a	25·0c
70	1593b	743b	0·47b	326a	99a	23·4b
140	1933c	780b	0·41a	361a	97a	22·5a
210	2064c	816b	0·40a	349a	113a	22·8ab
280	1959c	794b	0·41a	323a	115a	22·1a
Genotype						
Lemont	1536a	739a	0·48c	352b	85a	25·6b
Newbonnet	1736b	743a	0·44b	324ab	106b	21·8a
Starbonnet	1844b	688a	0·38a	294a	114b	22·0a

both experiments (Table 5). The response of grain number per panicle to N rate was variable, responding to an application of up to 70 kg/ha in Experiment 2, 210 kg/ha in Experiment 3, and 280 kg/ha in Experiment 1. Mass per grain generally declined with increasing N rate, such that masses were lower for 210 and 280 kg N/ha than for 0 and 70 kg N/ha, suggesting that as grain number increased with rate

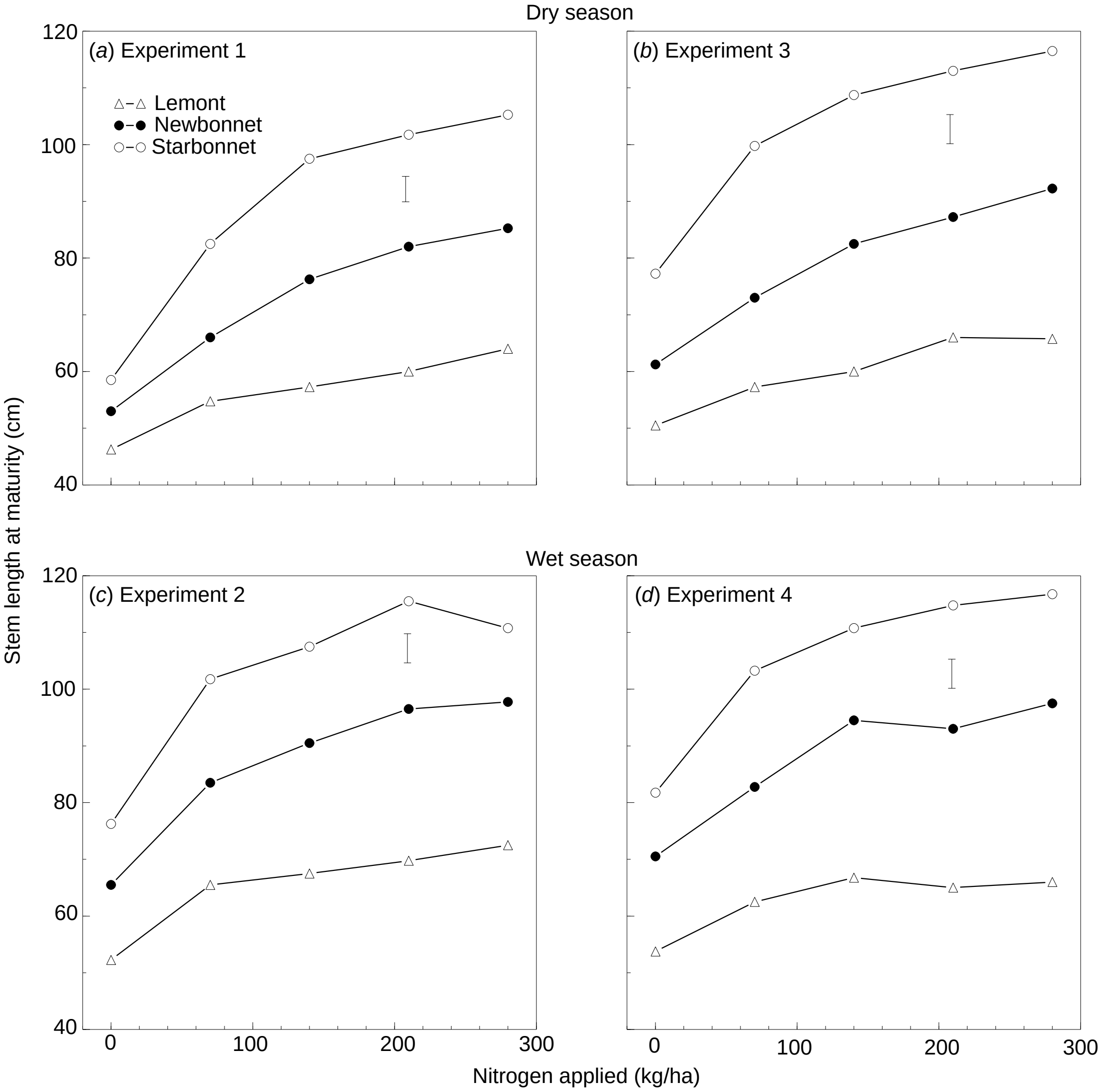

Fig. 2. Relation between nitrogen applied and stem length at maturity in 2 dry seasons and 2 wet seasons for 3 rice genotypes: Lemont (short-statured) (△), Newbonnet (medium-statured) (●), and Starbonnet (tall-statured) (○). Vertical bars denote l.s.d. of interaction ($P = 0{\cdot}05$).

of N, insufficient assimilate was available to fill the grain.

Highest grain yield in Newbonnet was associated with a high number of panicles per m^2 and grains per panicle. Overall, grain number per m^2 was positively correlated with yield in all seasons ($r = 0{\cdot}94^{**}$, $n = 60$), largely due to the positive correlation between yield and panicle number per m^2 in the wet ($r = 0{\cdot}62^{**}$, $n = 30$) and dry ($r = 0{\cdot}84^{**}$, $n = 30$) seasons. Yield was not correlated with grain number per panicle or mass per grain in either season. Although Newbonnet and Starbonnet produced equivalent grain numbers per panicle in most experiments, mass per grain was higher ($P < 0{\cdot}01$) in Newbonnet than Starbonnet in 3 of 4 experiments. Panicle numbers were also lower in Starbonnet than Lemont and Newbonnet in Experiments 3 and 4, particularly for higher rates of N. In Lemont, high masses per grain and moderate panicle numbers compensated for low grain numbers per panicle in all experiments.

Stem length

Stem length at maturity was higher ($P < 0{\cdot}01$) in the wet than dry seasons and, within the dry season, was higher ($P < 0{\cdot}01$) in Experiment 3 than Experiment 1. Experiment 3 was sown 4 weeks later than Experiment 1, and increased stem length in Experiment 3 was probably a result of higher average daily mean temperatures during the pre-anthesis period (24·9°C *v.* 22·6°C).

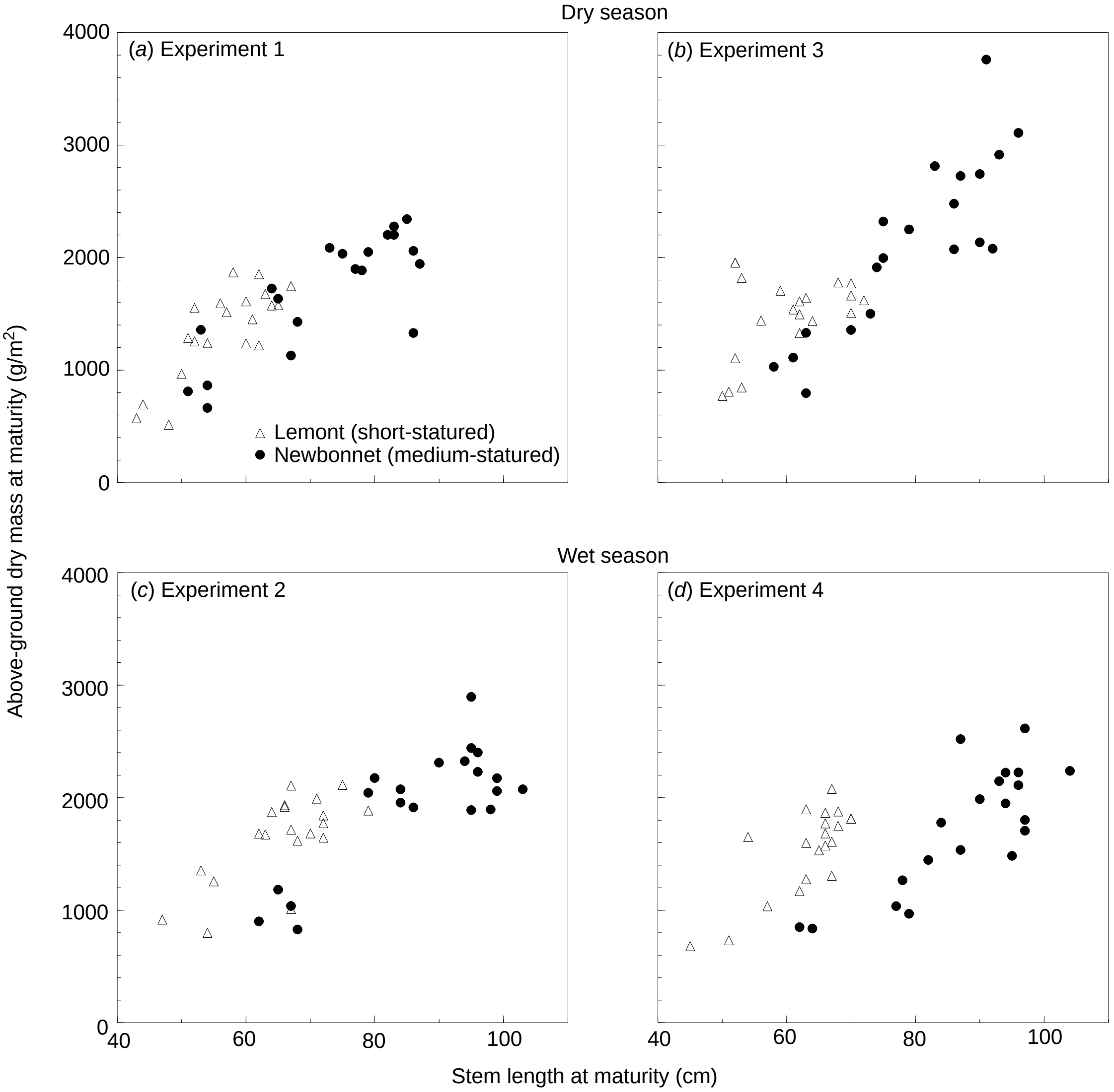

Fig. 3. Relation between stem length at maturity and above-ground dry mass at maturity in 2 dry seasons and 2 wet seasons for rice genotypes differing in plant height: Lemont (short-statured) (△) and Newbonnet (medium-statured) (●).

Stem length at maturity was greatest ($P < 0{\cdot}01$) in Starbonnet (100 cm), intermediate in Newbonnet (82 cm), and least in Lemont (61 cm). The response of stem length to N rate varied ($P < 0{\cdot}01$) among genotypes in all experiments (Fig. 2). The responses of Starbonnet, Newbonnet, and Lemont to N fertilisation were high, intermediate, and low, respectively.

Stem length also affected dry matter production (Fig. 3). In a comparison of the 2 early-maturing genotypes which varied in stem length (i.e. Lemont, 60 cm; Newbonnet, 80 cm), dry matter production increased with stem length in all experiments, although the relation was linear in some cases (i.e. Experiment 3) and curvilinear in others (i.e. Experiments 1 and 2). In turn, dry matter production was positively correlated with grain yield in these genotypes for all experiments (Fig. 4).

Discussion

Effect of season

Variation in grain yield between the dry (Experiments 1 and 3) and wet (Experiments 2 and 4) seasons was not consistent: Experiment 1 (801 g/m^2) > Experiment 4 (723 g/m^2) > Experiment 2 (682 g/m^2) > Experiment 3 (665 g/m^2). Differences in yield between the 2 dry season crops may have been partly associated with differences in time of sowing (22 July and 21 August, respectively). Both wet season crops were sown on 16 December.

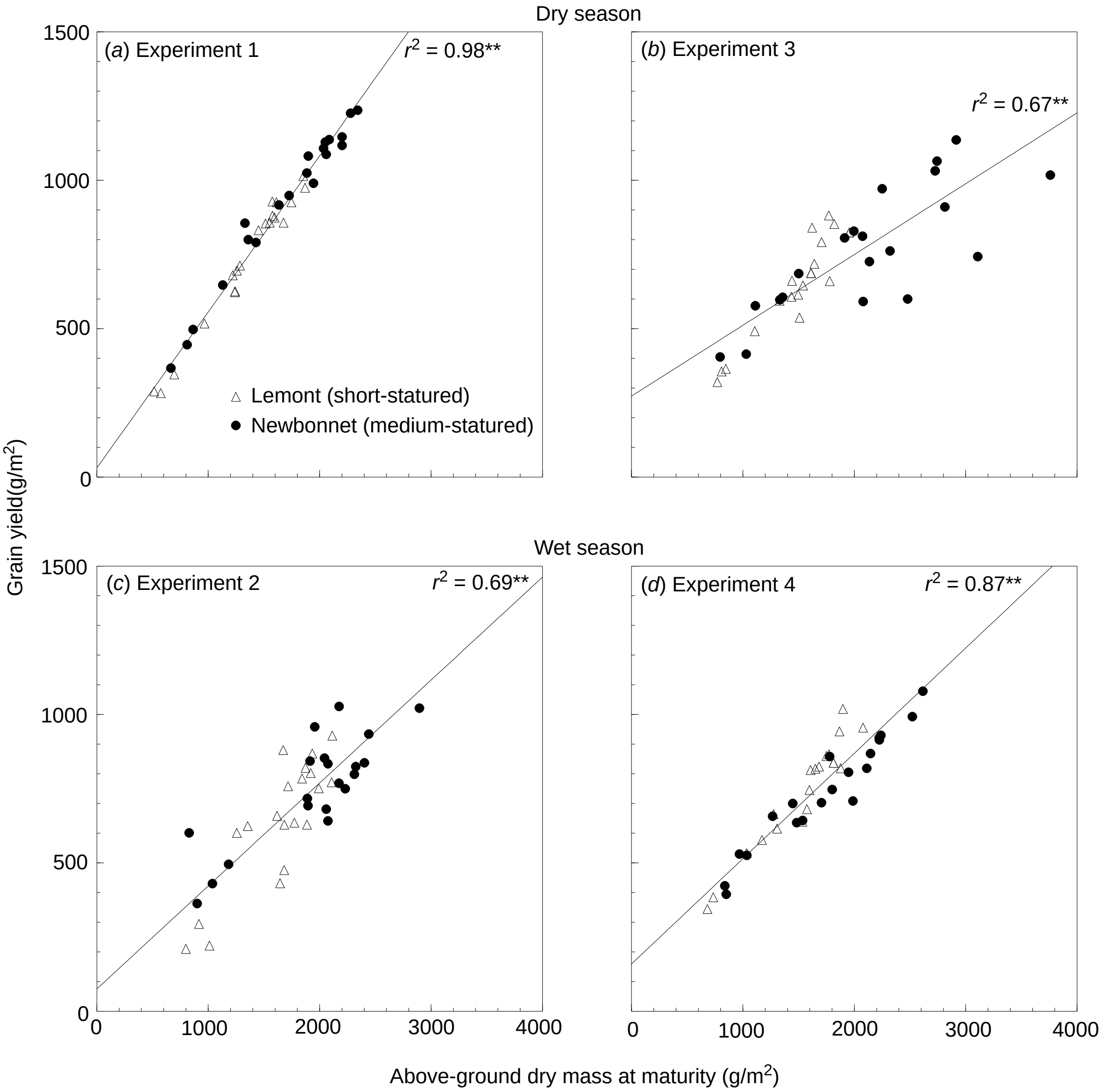

Fig. 4. Relation between above-ground dry mass at maturity and grain yield in 2 dry seasons (Experiment 1, $r^2 = 0\cdot98^{**}$; Experiment 3, $r^2 = 0\cdot67^{**}$) and 2 wet seasons (Experiment 2, $r^2 = 0\cdot69^{**}$; Experiment 4, $r^2 = 0\cdot87^{**}$) for rice genotypes differing in plant height: Lemont (short-statured) (△) and Newbonnet (medium-statured) (●). Linear regressions were fitted to the data.

Earlier studies on the response of rice yield to N fertilisation in southern New South Wales found that solar radiation and temperature were important in explaining seasonal variation in yield (Reinke *et al.* 1994). In the current study, solar radiation was measured only in Experiments 3 and 4, preventing a detailed analysis of the seasonal effects of radiation on yield. However, Yoshida and Parao (1976) found rice grain yield in the tropics to be highly negatively correlated with average daily mean temperature (ADMT) during the 25-day period before anthesis, and an analysis of ADMT during the 30-day period before anthesis in the current study also found it was negatively correlated ($r^2 = 0\cdot95^*$) with grain yield. In fact, ADMT during the 30-day period before anthesis was negatively correlated ($r^2 = 0\cdot93^*$) with harvest index, such that ADMTs below 27·5°C were required to obtain harvest indices $>0\cdot4$. These correlations suggest that ADMT during the reproductive period (panicle initiation to anthesis) had a marked effect on the partitioning of dry matter between grain and non-grain components, explaining some of the seasonal variation in grain yield observed in the current study.

Poor growth during the grain-filling period in the wet season may have been associated with rapid growth to anthesis. Reinke *et al.* (1994) found large biomass at anthesis to be associated with low post-anthesis growth for late-sown rice in southern Australia. Furthermore in a water culture experiment, Akita (1989) found the dark respiration rate for rice at heading was more than 40 $g/m^2 \cdot$day when 2000 g/m^2 biomass was obtained at heading. He reported little increase in biomass after heading. Similarly, biomass at anthesis in the present study was 1954 g/m^2 in the wet season (compared with 1285 g/m^2 in the dry season).

The response of grain yield to N fertilisation also varied among experiments. Yield increased with N rate to 70 kg N/ha in all experiments, but the response of yield to higher N rates was variable. Yield plateaued for N rates >70 kg/ha in Experiments 3 (dry season) and 4 (wet season), responded to the application of up to 140 kg/ha in Experiment 1 (dry season), and decreased with increasing N rate in Experiment 2 (wet season) such that yield at 280 kg N/ha was less than at 70 kg N/ha.

Above-ground dry mass responded to the application of up to 140 kg N/ha applied in all experiments, plateauing at masses of about 2000–2100 g/m^2. However, the response of harvest index to N application differed among experiments, resulting in seasonal variation in the response of grain yield to N application. Harvest index was always highest without N fertilisation or with an application of 70 kg N/ha, but declined more dramatically with increasing N in the wet than dry season. Similar decreases in harvest index with increasing N application were reported for rice in southern Australia by Reinke *et al.* (1994).

Seasonal variation in the response of yield to N in the semi-arid tropics of northern Australia does not appear to be as marked as for the Philippines, a wet tropical region. De Datta and Malabuyoc (1976) reported no response for an N rate of 150 kg N/ha in the wet season but a 78% response in the dry season, and this appears to have been due to differences in daily solar radiation between seasons (10 $MJ/m^2 \cdot$day, wet; 18 $MJ/m^2 \cdot$day, dry; De Datta and Malabuyoc 1976). By contrast, daily solar radiation in the BRIA was similar in the wet and dry seasons (about 22 $MJ/m^2 \cdot$day) between 1990 and 1994 (1990 data from Experiments 3 and 4; 1991–1994 data from R. C. Muchow, pers. comm.).

It should be noted that these studies were conducted over a 2-year period (4 experiments) representing only a small sample of the climatic variability possible at this location. Importantly, the time of onset and the magnitude of the wet season determines the responses of both wet and dry season rice crops to N fertilisation. It is likely that the response of rice grain yield to N fertilisation will be less in those seasons with strong monsoonal activity and therefore lower solar radiation. While such activity will have the greatest impact on wet season crops, the early onset of a monsoon could also significantly affect rice growth during the grain-filling period of a dry season crop. The use of simulation modelling to predict the response of yield to N fertilisation in northern Australia is recommended.

Effect of plant type

In 3 of 4 experiments, Newbonnet outyielded Lemont and Starbonnet by combining high dry matter production with high harvest indices. There is some evidence that increased dry matter production was related to increased plant height. Comparing the 2 early-maturing genotypes which varied in height (i.e. short-statured Lemont and medium-statured Newbonnet) highlights the effect of stem length on dry matter production in the absence of confounding phenological differences. Dry matter production increased with increasing stem length, and in turn, above-ground dry mass was positively correlated with grain yield.

However, evidence linking higher harvest index with increased earliness was less substantial in the current study. Comparing the 2 taller genotypes which varied in phenology (i.e. early-maturing Newbonnet and late-maturing Starbonnet) highlights the effect of maturity on harvest index, while minimising the confounding effect of height. In Experiment 1 (dry season), Newbonnet anthesed after 96 days, attaining harvest indices of 0·5–0·64 (depending on N rate), whereas Starbonnet flowered 13 days later, attaining harvest indices of 0·32–0·5. However, considerable overlap in harvest index occurred between the 2 genotypes in Experiments 2–4, particularly for lower N rates (i.e. 0, 70, and 140 kg/ha). In both wet seasons, Starbonnet flowered 10 days later than Newbonnet, and at the higher rates of N (i.e. 210 and 280 kg/ha), lower harvest indices were observed for Starbonnet (generally <0·3).

Response of grain yield to N rate varied with genotype in Experiment 1 (dry season) such that yield in the early-maturing genotypes (Newbonnet and Lemont) was more responsive to N rates >70 kg/ha than in the late-maturing genotype (Starbonnet). Similarly, Sanchez *et al.* (1973) found that within a specific rice plant type in Peru, the earlier maturing genotype produced a higher grain yield in response to N than its later maturing counterpart, suggesting that early maturity increases the responsiveness of grain yield to N in a high solar radiation environment.

What of components of yield? High grain yield in Newbonnet was associated with high panicle numbers and grains per panicle, and moderate masses per grain. Yields in Lemont and Starbonnet were limited by dry matter production and harvest index, respectively. Component analysis found that yield in Lemont was primarily limited by low grain number per panicle, and that yield in Starbonnet was limited by low panicle numbers and masses per grain.

Conclusions

Seasonal variation in grain yield was evident and yield was negatively correlated with average daily mean temperature between panicle initiation and anthesis. The response of yield to N fertilisation was generally higher in the dry season, and panicle numbers, which were correlated with grain yield in both seasons, only responded to the application of N fertiliser in this season (Experiments 1 and 3). Grain yield responded to the application of up to 70 kg N/ha in 3 of 4 experiments, and up to 140 kg N/ha in Experiment 1 (dry season).

In 3 of 4 experiments, Newbonnet attained the highest yield by combining high dry matter production with high harvest index, suggesting that this plant type (medium-stature and early-maturity) may have an advantage in northern Australia. There is some evidence that the high dry matter production observed in Newbonnet compared with Lemont was linked to increased stem length. The evidence linking high harvest index with increased earliness in Newbonnet compared with Starbonnet is less compelling.

High grain yield in Newbonnet was also associated with high numbers of panicles and grain numbers per panicle and moderate masses per grain.

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