GROWTH AND YIELD OF RICE IN THE MURRUMBIDGEE VALLEY AS INFLUENCED BY CLIMATE, METHOD OF SOWING, PLANT DENSITY AND NITROGEN NUTRITION

by

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Thesis submitted to Macquarie University for the degree of Master of Science with Honours

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Yanco, March 1974

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Certificate of Originality

This thesis contains original work carried out by myself with such assistance as is acknowledged elsewhere. It contains no material that has been submitted for the award of any other degree at this or any other University or Institution.

E. B. Boerema,

March, 1974

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Summary

The climate of the Murrumbidgee Irrigation Areas varies only slightly regionally; the long summer days with high solar radiation allow a growing season of 190-200 days and are conducive to high yields. Nevertheless, appreciable variations in annual yields occur, these being associated with low temperatures at sowing and particularly at flowering. A high proportion of sterile florets are induced with minimum temperatures of less than 15^{o}C, this effect being accentuated by high concentrations of nitrogen.

Two series of field experiments were made at two sowing dates over two seasons. In one series the varieties Calrose, Kulu and Baru were sown either by combine or aerially with three rates of nitrogen fertiliser. In the other the same three varieties were compared at two densities and two rates of nitrogen supply. Detailed growth analyses were made from fortnightly harvests.

Aerial sowing gave the most rapid early growth leading to a large leaf area, especially with high nitrogen. Lodging later in the season was encouraged and the yield was frequently reduced below that of combine-sown rice with an intermediate supply of nitrogen, the yield reduction being reflected by a high degree of floret sterility and low grain weight. These and other differences between the varieties and the treatments explored were analysed in detail throughout the season. One interesting effect was an apparent increase in growth rate late in the season.

Low density resulted in slow early growth but differences between densities narrowed during grain-filling. Nitrogen had a larger effect than density.

Calrose appeared to be the best adapted variety, tillering more profusely than the thick-stemmed Baru with its large panicle. Although Baru had the highest potential for yield, this was rarely realised mainly because of high floret sterility. Kulu tillered too profusely and was also prone to floret sterility.

A reasonable detailed analyses of the nitrogen balance was made. The rate of nitrification during fallow was about 0.46 ppm d^{-1} and after adding sulphate of ammonia this rose to 2.2 ppm d^{-1} during the germinating period prior to permanent flood. Denitrification is extremely rapid after permanent flood. Ammonium ions are not lost when reducing conditions are induced; hence the most effective use of nitrogen is obtained with aerial sowing or applying it just before permanent flood after combine sowing. Then 30.6% of that applied was recovered in the crop compared with 16% when combined in with the seed.

I. INTRODUCTION

Average yields of rice in temperate climates are consistently higher than those obtained in the tropics. Many factors contribute to these differences. Most indica varieties, which are adapted to high temperatures, are tall, weak-strawed and usually low-yielding, long-grained and grown under poorly developed agronomy. They are mainly grown during the wet season with relatively low levels of solar radiation. High quality is generally associated with long grain. Most varieties grown in temperate regions are of the stronger-strawed, short-grained japonica type of low cooking quality. They are grown under irrigation and at high levels of solar radiation. These are the varieties which have been traditionally grown in countries which feature at the top of the yield table, when coupled with a highly developed agronomy (Table 1).

Australia has enjoyed the reputation of achieving high yields since rice was first introduced in the Murrumbidgee Irrigation Area in 1924. At present some 95% of the Australian acreage is located in southern New South Wales where the average yield from some 42000 ha is 7.5 t/ha^{-1}. In the Burdekin Valley of Queensland where some 2500 ha of long-grain rice is grown, yields average about 4.8 t/ha^{-1}. Commercial rice ventures in tropical Western Australia and the Northern Territory have failed to survive.

The Murrumbidgee Irrigation Areas (Fig. 1) are located in southern New South Wales (lat. 34-35^{o}S) and comprise three main areas, the

Table 1

Average area and production of rice of some selected countries over a four-year period 1969/70 to 1971/72 (Rice Bulletin, 1973)

Country	Area (ha x 10^3)	Yield (t ha^{-1})
Australia	40	6.8
Spain	61	6.1
Japan	2,845	5.6
Egypt	477	5.5
U.S.A.	769	5.1
Italy	175	5.0
Uruguay	32	4.1
Indonesia	8,108	2.5
Thailand	7,439	1.8
India	37,568	1.7
Philippines	3,121	1.7
Burma	5,022	1.6

RICE GROWING AREAS IN THE MURRUMBIDGEE VALLEY

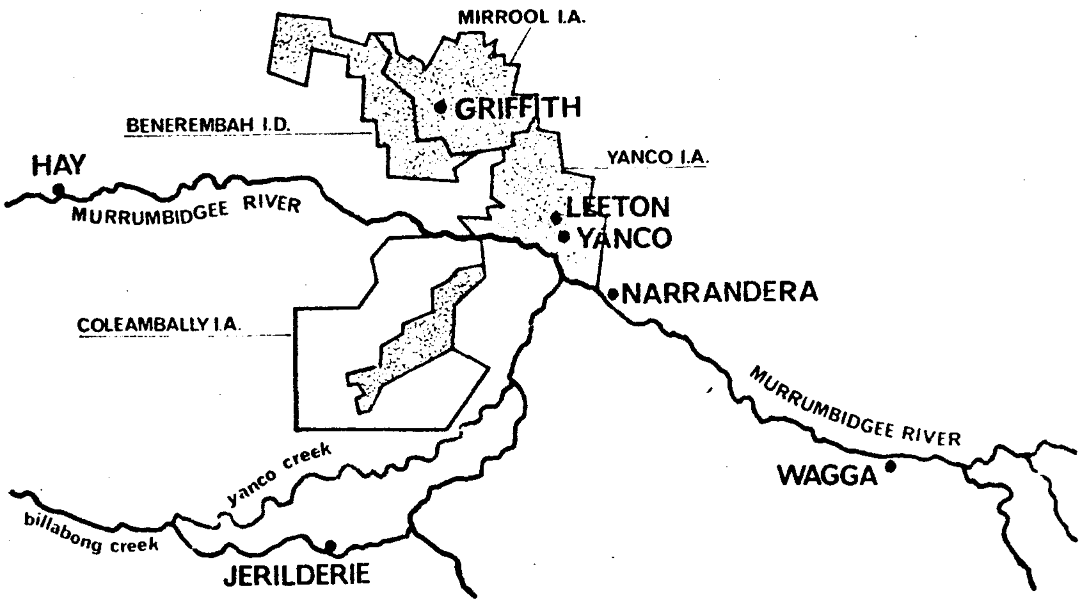


Fig. 1

Yanco, Mirrool and Coleambally Irrigation Area. Farm size ranges from 200-300 ha and rice is allowed to be grown, on annually renewed permits, on areas varying in size from 10-52 ha, depending on previous water usage, water availability, soil type etc. Rice is usually grown in rotation with winter cereals and winter pastures. Although the crop occupies only 10-15% of the total farm area, it provided approximately half of the gross farm income in the years 1963-66 (Ryan, 1968). The crop is grown during the relatively dry summer season under continuous irrigation.

Since introduced, rice yields have steadily increased although they fluctuate from season to season. The gradual long-term increase in yield (Fig. 2) may be attributed to improved crop husbandry, higher-yielding varieties and a more rational use of fertiliser nitrogen. (There are surprisingly high annual fluctuations in yield of this irrigated crop; these are discussed later).

Soil preparation and crop husbandry have improved with the availability of modern machinery. In particular, land levelling and check-bank construction are carried out with more attention to detail. Soil fertility has generally improved by including legume pastures in the rotation.

Nitrogen is the only nutrient limiting yields on most of the soils used for rice growing. Phosphate is rarely deficient in virgin rice soils, but is generally supplied to preceding crops in the rotation. Application of correct doses of nitrogen fertiliser are necessary to obtain the highest yields. Excessive nitrogen may lead to lodging, a high rate of floret sterility and the occurrence of inperfectly ripened

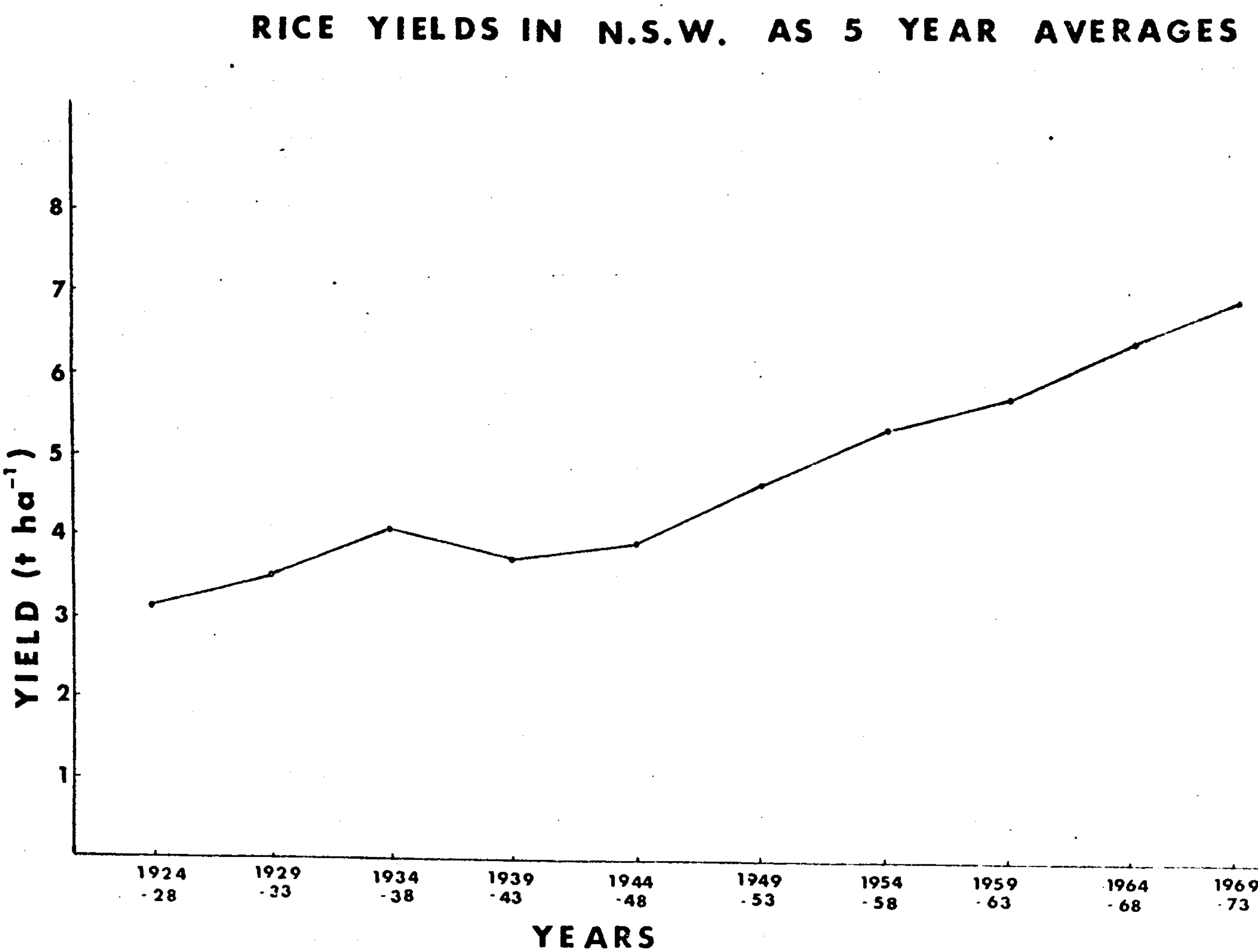

RICE YIELDS IN N.S.W. AS 5 YEAR AVERAGES
YIELD (t ha^{-1})
1
2
3
4
5
6
7
8
1924 -28
1929 -33
1934 -38
1939 -43
1944 -48
1949 -53
1954 -58
1959 -63
1964 -68
1969 -73
YEARS

Fig.2

grain (Matsushima and Wade, 1958; Togari and Kashiwakura, 1958; Boerema, 1963). It is difficult to determine the amount of nitrogen required for a certain soil to obtain the highest yield with the lowest cost of production. The strongly adsorbed NH_4^+ ion is changed to the mobile ion NO_3^- in aerated soil. Following flooding denitrification to free nitrogen occurs; this is unavailable to rice plants. For each situation it is necessary to find the best source, the best method and the best time of application of fertiliser nitrogen to obtain maximum benefits. This can only be predicted adequately when more detailed and expansive measurements of rates of nitrification and denitrification are available. Losses of both soil and applied nitrogen can be high and depend on factors such as length of cultivated period, previous history, soil type, soil temperature, pH, method of establishment and length of flushing period.

Improved varieties have possibly contributed least to the long-term upward trend in yield, especially during the past decade. Traditionally, short- and medium-grain varieties have yielded better than long-grain varieties, but during the last decade there has been a considerable change towards the long-grain types which are in greater demand on the export market on which 85% of the crop is sold. Long-grain varieties now occupy approximately 50% of the total acreage. However, there is no doubt that continuous selection within individual varieties has improved their yielding ability.

Year-to-year fluctuations of yield in the Murrumbidgee Valley usually reflect changes in seasonal conditions. Possibly most significant of the factors contributing to low yields are high levels of floret

THE GROWTH OF RICE IN RELATION TO MINIMUM
TEMPERATURE AND SOLAR RADIATION IN THE M.I.A.

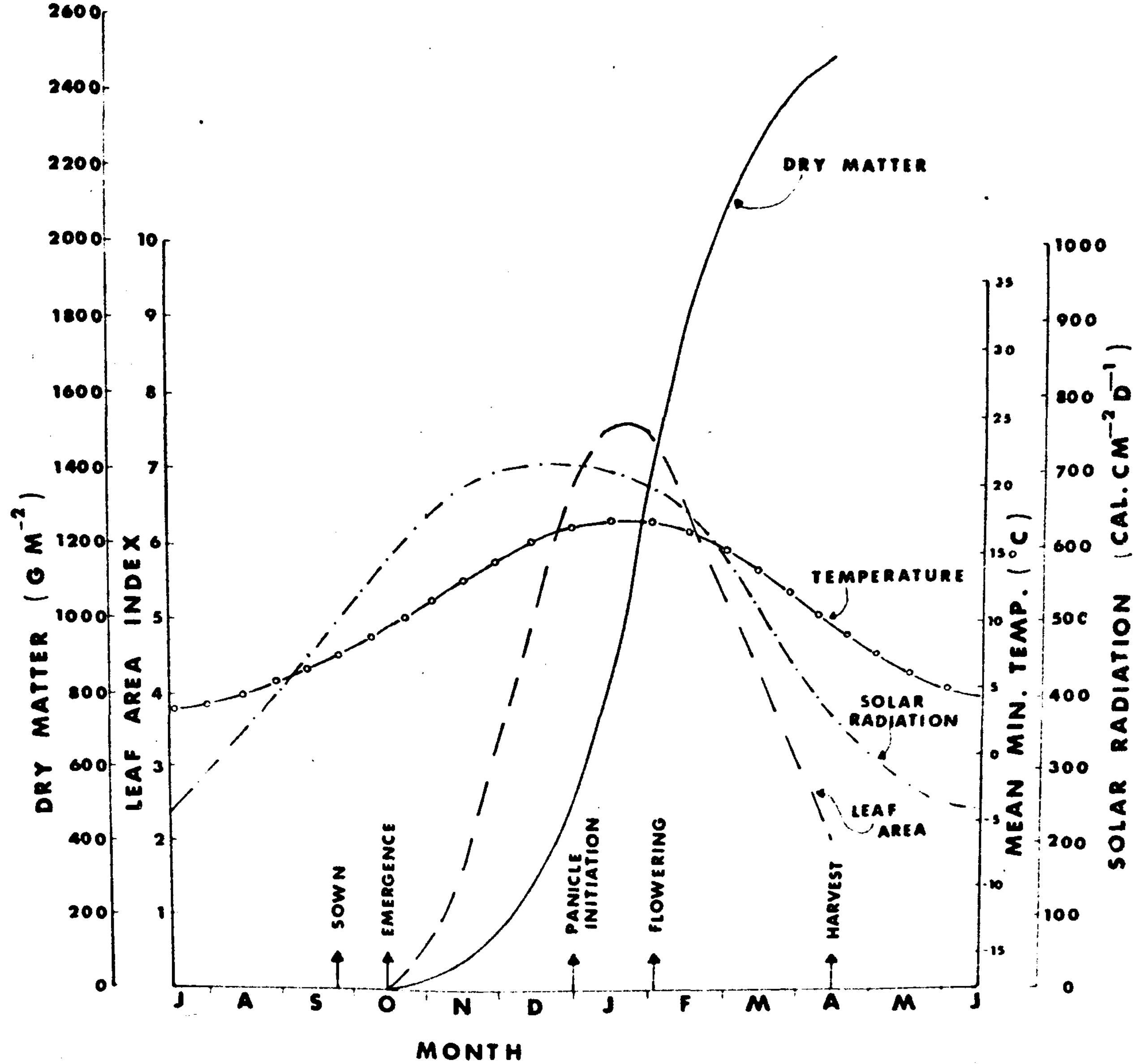


Fig. 3

sterility, which are attributed to low temperatures at or around flowering (Owen, 1971). Exceptionally low rice yields following low minimum temperatures are said to have caused the three great famines in Japan (Arakawa, 1957). Low yields in the Murrumbidgee Valley also have generally occurred when low minimum temperatures have been recorded around flowering.

The main features of growth in relation to some climatic factors are illustrated by reference to Fig. 3. Temperatures at sowing are low, resulting in a slow emergence and early growth. Vegetative development takes place during a period of increasing temperatures and radiation, and panicle growth occurs during a period of high seasonal temperatures and radiation. Grain-set and ripening occupy a period of falling temperatures.

The climate in the Murrumbidgee Valley can be described as temperate with high temperatures, high total radiation and long periods of daylight during summer and a cool winter with short days (Table 2). Rainfall is distributed fairly evenly throughout the year, but evaporation is high during summer. The growing season for crops sensitive to low temperatures is restricted to the period of about 200 frost-free days in the M.I.A.

Times at which the crop reaches critical stages in its development can vary greatly within the area due to variations in time of sowing, method of establishment and level of soil fertility. Consequently, a period of low minimum temperatures may affect crops differently, depending on their stage of development. The normal sowing period is

Table 2

Summary of climatic data for Yanco Agricultural College and Research Centre, N.S.W.

(1941-1971)

Month	Temperature (°C)		Mean Daily Rainfall (mm)	Mean Daily Evaporation (mm)	Hours of Sunshine* (daily average)	Total Global Solar Radiation* (cal $cm^{-2}d^{-1}$)	Mean Wind Ru (km d^{-1}
	Max.	Min.					
Jan.	30.9	16.5	0.9	7.6	10.6	700	251
Feb.	30.3	17.5	1.1	7.4	9.9	670	262
Mar.	27.6	14.2	1.2	5.3	9.3	520	209
Apr.	22.7	10.0	1.1	3.6	7.9	380	164
May	16.7	6.7	1.4	2.0	6.6	260	153
June	13.8	3.1	1.1	0.5	5.3	250	137
July	12.8	0.4	1.2	1.3	5.4	240	119
Aug.	14.8	3.1	1.1	1.8	6.6	340	174
Sept.	17.7	5.6	1.2	2.8	8.1	460	193
Oct.	21.9	8.9	1.4	4.3	8.6	560	212
Nov.	26.7	11.3	1.2	6.4	9.7	720	236
Dec.	28.9	14.2	1.1	7.4	9.7	710	243

* Data from Griffith (1932-1971)

from the last week of September to the first two weeks in October, although some crops are sown as late as mid-November. Under favourable weather conditions, permanent flood is applied within the first half of November. Panicle initiation occurs in late December or early January and flowering follows in the first half of February.

Average rainfall for the growing season is 205 mm or 48% of the annual precipitation. Long periods of hot dry weather can be experienced with most of the precipitation coming from a few storms. Water requirements for rice in the tropics are generally reported to be between 6 and 16 mm d^{-1}, averaging 8.8 mm d^{-1} (Anon. 1963). I am advised by Mr. A. van der Lely that the average water use on rice crops by 263 farmers in the southern part of the Valley during the 1968-69 season was 18400 m^3ha^{-1} with a standard deviation of 5800 m^3ha^{-1}. Over the total growing season this represents approximately 10 mm d^{-1}. The rate of pan evaporation is also high, averaging 6.5 mm d^{-1} over the rice season. Water balance studies of four rice crops by van der Lely (1972) showed that the average evapotranspiration ranged from 9.9 to 11.0 mm d^{-1} whilst drainage losses averaged 1.7 mm d^{-1}. Percolation losses in the heavy clays are very low, averaging about 1 mm d^{-1}.

Rice yields in the tropics are greater during the dry season than in the wet season, possibly due to longer periods of sunshine, higher levels of radiation and, in many areas, lower temperatures during ripening. Chandler (1963) has shown that high grain yields depend on long periods of high radiation during the last 60 days of crop growth. Monteith (1965) pointed out that with the same daily amounts of solar radiation gross photosynthesis should be greater in temperate regions than in the tropics, due to the longer day.

Differences in minimum temperature, day length, hours of sunshine and levels of solar radiation for the 5-month wet season growing period near Darwin (N.T.) are compared with similar data for the 6-month growing season in the Murrumbidgee Valley (Fig. 4). Minimum temperatures are much higher near Darwin, but days are shorter and less radiation is received from fewer hours of sunshine than in the Murrumbidgee Valley.

Stewart (1970) found that although crop yields were much higher in southern than in tropical Australia, yields per day of crop duration were higher from dry season crops in the tropics. Efficiencies of grain yield per unit of radiation were of the same order in both dry and wet seasons in the tropics and averaged 50 percent higher than those in southern Australia. He attributed the low efficiency in southern areas to the very high levels of radiation which were probably far above that needed for light saturation of the photosynthetic process. Slow emergence and early growth of the crop in the Murrumbidgee Valley and the long ripening phase due to low temperatures are largely responsible for the lower calculated efficiency of the solar energy conversion to grain yield.

Work described in this thesis is primarily concerned with agronomic aspects, including methods of establishment, nitrogen nutrition and plant density, on the growth and yield of rice. The experiments were all carried out in the field and were conducted at the Yanco Agricultural College and Research Centre in the 1970-71, and 1971-72 rice-growing seasons. The methods which were common to all experiments are first described but the

Differences in some important climatic factors between rice growing areas in tropical and temperate Au

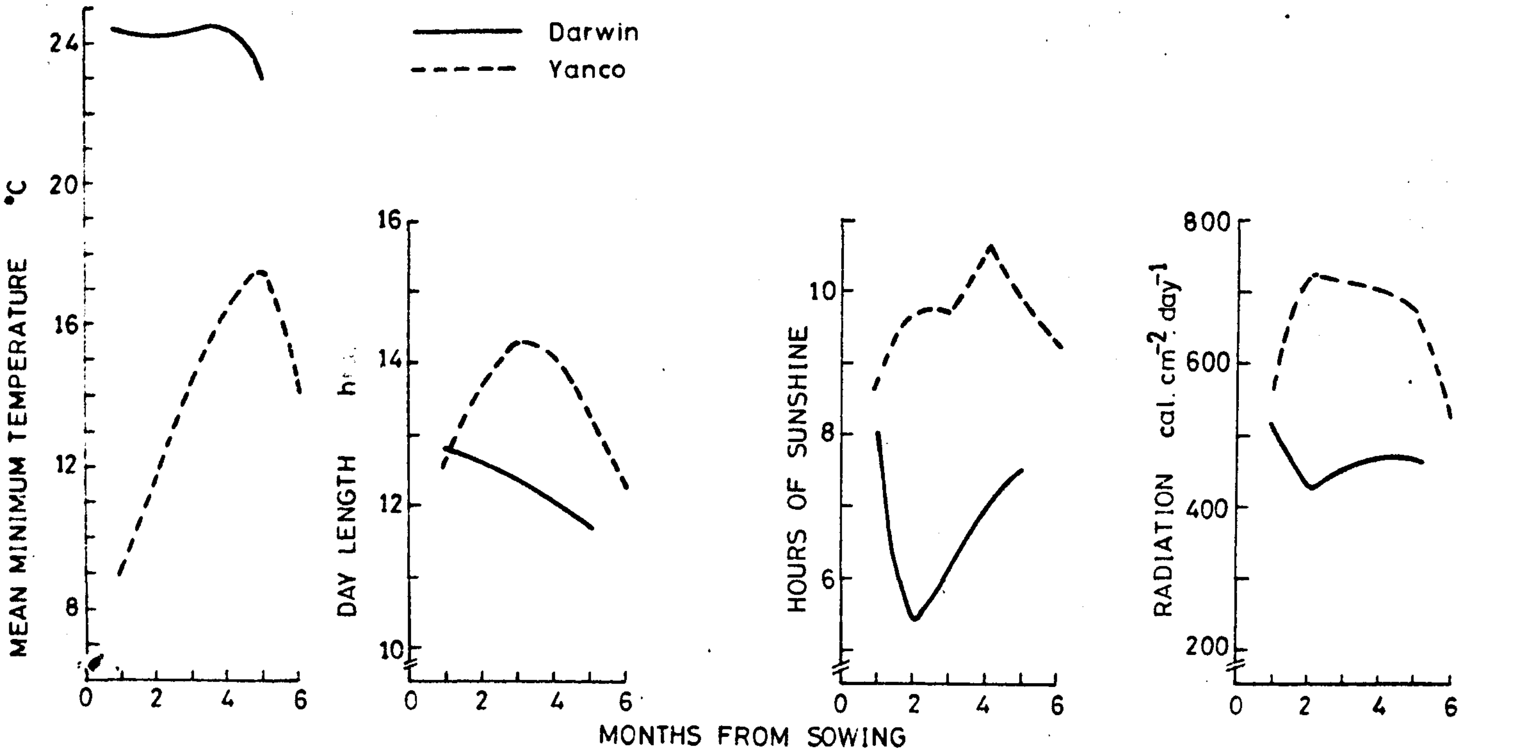


Fig.4

II. MATERIALS AND METHODS

All experiments were carried out on the same site and used a range of standard techniques. These and the components measured are briefly described.

Soil and rotation

A red-brown earth of the Merungle series, as classified by Mr. M. Stannard, containing 49% sand, 14% silt and 37% clay was used. Experimental areas in the two seasons were adjacent and were irrigated and drained through the same channel systems. Water was available at all times.

Rice was grown following a widely used rotation, i.e. for one year following four years of a legume pasture. The pasture received an annual application of 110 kg superphosphate ha^{-1}. Prior to sowing the soil was fallowed throughout the winter. Final seedbed preparation consisted of scarifying twice and two or three operations with a land plane.

Methods of establishment

Combine sowing. The seed was sown by combine at a rate of 110 kg ha^{-1}, together with the required experimental levels of ammonium sulphate, into a dry seedbed at a depth of 1-2 cm. Following sowing the fields were flooded and then drained after about 12 hours. This process is known as "flushing" and is carried out to promote germination and to provide moisture for emerging seedlings. When soils form a hard surface crust, flushing may be necessary to allow seedlings to emerge. Depending on weather conditions and soil type, up to five flushings were required before permanent flood was applied (when rice plants were from 10-15 cm high). Flood water was not removed until the lower grains on the later-maturing panicles were in the "hard dough" stage. The grain was harvested at moisture contents ranging from 20-23%.

A complete control of *Echinochloa* spp. was achieved by applying molinate (s-ethyl hexahydro-1H-azepine-1-carbothioate) at the rate of 3 kg ha^{-1} when the grasses were in the 3-4 leaf stage.

Aerial sowing was simulated by broadcasting seed into water. Ammonium sulphate was applied at the required rates by combine to a depth of 7-8 cm. The soil surface was left ridged to prevent excessive wave action which could dislodge seedlings. Permanent flood was applied to a depth of approximately 8 cm as soon as practical after applying fertiliser. Seed was pre-germinated by soaking for 24 hours and then draining for 48 hours under cover. Sprouted seed was broadcast into permanent flood water, which was not removed until grains were in the hard dough stage. Bloodworms (*Chironomus tepperi* Skuse) were controlled by using 0.5 l 25% emulsifiable DDT ha^{-1} (Jones, 1968). Aerial-sown stands were free of weeds.

Varieties

The varieties used were:

(a) *Calrose*, a medium-grain variety, originating in California and well adapted to the whole of the New South Wales rice-growing area. It is now grown on approximately 50% of the area.

(b) *Kulu*, a fine, long-grain variety, selected at Yanco from a cross between Calrose and Bluebonnet 50. Kulu was released in 1967 and, due to its export demand, it was grown on approximately 45% of the area and attracted a premium of $10 per tonne in the 1971-72 season. It is not well adapted to the harsher climate of the Murray Valley.

(c) Baru. A newly released (1972) long-grain variety with a high yield potential, but not as widely adapted as Calrose. It was selected at Yanco from a cross between Caloro II and Century Patna.

Measurement of Crop Development

At fortnightly intervals from emergence 0.5 m^2 randomly selected sub-samples were uprooted and transported to the laboratory for measurement of plant density, tiller or panicle number, plant height, leaf area, dry weight and nitrogen content. Outside rows were not used. All plants and tillers or panicles were counted. Plant height was measured from the soil surface to the highest leaf before panicle initiation or the tip of the extended panicle of 20 randomly selected plants. Leaf Area Index (L) was determined from all leaves of 20 plants at seedling stage, from 10 plants during tillering and from 10 tillers after completion of tillering. The plants or tillers were randomly selected from the sub-sample and the leaf area was measured with an airflow planimeter (Jenkins, 1959). Dry Matter (W) was determined after drying the whole sample in an airflow dehydrator at a temperature of 70°C. Nitrogen content was determined by multiplying total dry weight by its N concentration, which was determined in a small sub-sample by the macro Kjeldahl method using a selenium copper catalyst (Anon., 1970).

Crop Growth Rate (C) is taken as the mean rate of increase of dry weight per unit area of land per unit time over the interval t_2-t_1 (14 days) and is expressed as:

$$C = (w_2-w_1)/(t_2-t_1) \text{ g m}^{-2} \text{ land d}^{-1} \text{ or as } C = dw/dt)$$

Net Assimilation Rate (E) is a measure of the excess of gain in dry matter by photosynthesis over the loss through respiration and was calculated as:

$$E = (w_2-w_1)\ (\ln L_2-\ln L_1)/\ [(t_2-t_1)\ (L_2-L_1)] \text{ g m}^{-2} \text{ leaf d}^{-1}$$

or as $E = (L/w)\ dw/dt$ where w_1 and w_2 are the dry weights and L_1 and L_2 are the leaf area indices at the times t_1 and t_2 respectively.

This relationship assumes that (1) the leaf area measured is the photosynthetic surface, which is sometimes difficult to determine especially in older leaves, and (2) that the relationship between L and W is linear over the time period involved. For field crops this condition appears to be reasonably well satisfied for periods no longer than 14 days (Watson, 1952). Here, measurements were made of area of green leaves only and the dry weight of roots was not considered; hence the net assimilation rate may well be underestimated.

Relative Growth Rate (R) represents the efficiency of existing material in adding new material or the rate of increase of dry weight per unit weight present. It is given by:

$$R = (1/\bar{w})\ [(w_2-w_1)/\ (t_2-t_1)] d^{-1} \text{ or as } R = (1/w)\ dw/dt$$

Light profiles at flowering were established with a Swissstico linear net radiometer, covered with a plastic sleeve to give a sensitivity range between 0.4 and 0.7 nm. The radiometer was 53.3 cm long and had a short-wave sensitivity of 1.3 mV (mW $cm^{-2})^{-1}$ at 20^{o}C. Measurements were made within 1 hour of noon on clear days only. The average of 5 spot readings above and within the crop canopy at 20-cm intervals from soil level was taken. Light transmission ratios (LTR) at 20 cm intervals from ground level were calculated as a percentage of the radiation measured above the crop canopy.

Light attenuation within the crop canopy was related to the distribution of plant parts by the "stratified clip" method. Successive 20-cm horizontal layers of 1 m^2 of the uniform plant community were harvested and the leaf area and dry matter determined. In one experiment the stem area was calculated by measuring the diameter of the 20-cm stem section, including leaf sheath, with a pair of callipers.

Leaf characteristics: Leaf length, width, specific leaf weight (g dm^{-2}), leaf angle (with the vertical), height of leaf attachment and panicle length were determined on 50 randomly selected main tillers at flowering, after complete extrusion of the panicle.

Yield components: Before harvest small bundles of plants were randomly selected from each plot. Twenty panicles, randomly gathered, were threshed by hand. Empty florets were separated from filled grain by a carefully adjusted aspirator. Empty florets were counted by hand and filled grains by an electronic grain counter. Percentage floret sterility was then calculated.

Grain yield was determined as the mean of two randomly selected 2-m^2 sub-plots, avoiding edge rows. The plants were cut by sickle at soil level, then threshed, and the grain dried and cleaned. Yields were expressed at 14% moisture.

Sub-samples of 0.5 m^2 were threshed separately to determine grain/straw ratio and total dry weight at harvest. The samples were dried at 70°C. Sub-samples of both grain and straw were ground for the determination of N-concentration of grain and straw. Protein content was calculated by multiplying the N-concentration by 5.95 (Juliano, 1972).

Climatic data: Air temperatures in the rice field were obtained from a thermohygrograph with a weekly chart, placed within a standard Stevenson Screen at a height of 1 m. Soil and water temperatures were recorded on weekly charts of frequently calibrated Negretti and Zambra thermographs with 2-m leads. Other climatic data were obtained from standard meteorological lawns at the Yanco Agricultural College and Research Station and at the C.S.I.R.O. Division of Irrigation Research.

Soil data: "Available" nitrogen was determined by incubating 5 g of a representative soil sample (sampled to a depth of 15 cm) in 12.5 ml distilled water at a temperature of 30°C for two weeks. After incubation 12.5 ml saturated KCl in a N/5 H_2SO_4 solution was added. For the exchange of the ammonium ion the tube was agitated for one hour. Then 15 ml of the solution was decanted and cleared by centrifuging. The total ammonium nitrogen was then determined with an Auto Analyser, using the alkaline phenate-sodium hypochloride colorimetric method (Russell, 1944). Results are reported on an oven-dry soil basis in ppm.

III. SOME INFLUENCES OF CLIMATE ON GROWTH AND YIELD OF RICE IN THE MURRUMBIDGEE VALLEY

A. Introduction

During the last decade commercial yields in the M.I.A. have varied between 5930 and 7630 kg ha^{-1} per annum. The variation in yield has occurred despite the fact that little changes in potential yield of the varieties has occurred and that farming techniques have also changed little. The effect of climate on growth and yield has been examined from long-term data and from measurements made in two successive seasons, 1970-71 and 1971-72, in which high and low commercial yields of 7480 and 6450 kg ha^{-1} were harvested. Only simple regression analysis techniques have been used, it being recognised that these can provide little more than crude indications of possible responses.

B. Climatic differences within the Valley

Observations from recording stations in Griffith and Yanco were compared with those from an experimental rice field, some 2 km from the meteorological lawn at Yanco during the 1971-72 rice season to examine temperature differences within the Murrumbidgee Valley (Tables 3 and 4).

Maximum and minimum temperatures at Griffith did not differ significantly from those at Yanco. Maximum temperatures in the rice field were about 2°C lower than the standard data. This is attributed mainly to a higher evaporation rate from the flooded field than from a well-watered lawn. Differences in albedo between rice and turf

Table 3

Mean maximum and minimum temperatures during the 1971-72 rice season in the M.I.A.

Location	October		November		December	
	Max.	Min.	Max.	Min.	Max.	Min.
Griffith	22.9 ± 3.7	7.8 ± 3.9	24.1 ± 4.7	11.6 ± 3.5	28.5 ± 4.4	14.1 ± 4[illegible]
Yanco	22.2 ± 3.9	8.0 ± 4.1	23.5 ± 4.8	11.9 ± 3.4	28.3 ± 4.0	14.7 ± 3[illegible]
Rice Field Yanco	20.5 ± 3.63	7.5 ± 4.4	22.2 ± 4.8	12.0 ± 3.30	26.3 ± 4.6	14.4 ± 3[illegible]

Location	January		February		March	
	Max.	Min.	Max.	Min.	Max.	Min.
Griffith	29.3 ± 4.1	16.2 ± 3.3	28.8 ± 3.7	15.8 ± 3.3	27.4 ± 3.5	10.9 ± 3[illegible]
Yanco	29.1 ± 3.3	17.3 ± 3.6	29.1 ± 3.8	16.3 ± 3.3	27.2 ± 3.5	11.5 ± 3[illegible]
Rice Field Yanco	27.4 ± 3.8	16.9 ± 3.1	26.6 ± 3.7	15.6 ± 3.3	25.6 ± 3.5	10.4 ± 3[illegible]

Location	Rice season 6 months	
	Max.	Min.
Griffith	26.8 ± 4.7	12.7 ± 4.6
Yanco	26.5 ± 4.7	13.3 ± 4.8
Rice Field Yanco	24.8 ± 4.7	12.8 ± 4.8

Table 4

Comparison between the sites

Comparison		Difference (y-x, °C)		Correlation Coefficient	
Y	X	Max.	Min.	Max.	Min.
Yanco	Griffith	+0.34 N.S.	0.58 N.S.	0.891**	0.963**
Rice Field	Griffith	-2.07**	0.07 N.S.	0.970**	0.971**
Rice Field	Yanco	-1.73**	0.52 N.S.	0.873**	0.979**

are not known, but are expected not to differ greatly. Minimum temperatures in the rice field did not differ significantly from standard data.

Hours of sunshine and wind run were also compared for Yanco and Griffith. Differences between the two stations were not significant. As may be expected the variations in total radiation, evaporation and hours of daylight within the region are too small to be likely to cause any differences in the performance of rice crops at the same stage of development.

C. Some influences of temperature during ontogony

i. On long-term yield. The yields from the area over a 38-year period were correlated with monthly maximum and minimum temperatures and with hours of sunshine. The only significant positive correlation was between yields and mean minimum temperature during February ($r = 0.36*$). The relationship was $Y = 0.06\ T - 1.68$ where Y = yield in kg ha^{-1} and T = mean minimum temperature in ^{o}C. In the majority of rice crops meiosis, heading and anthesis take place at this time. Low temperatures during these stages are widely reported to be critical for determining yields (Owen, 1971).

Some low yields during the 38-year period are attributable to floods, ducks and mice and, in the early years of rice growing, parts of the crops had to be abandoned due to bogging of unsuitable harvesting machinery. Due to the above factors and the very crude techniques of analysis that have so far been attempted, only very poor relationships between yield and climatic conditions have so far been obtained - or indeed expected. It is, however, of some importance that low minimum temperatures during critical stages of panicle development in February have reduced yield.

ii. <u>On overall development</u>. One procedure which has been widely used to assess the influence of temperature on crop performance is the calculation of the number of degree-days required for growth. Although a convenient measure for climatic comparisons between regions and assessing the development of different phases during ontogeny, it is recognised that this procedure has many elements of crudity including the difficulty of determining the base temperature below which there is no growth and the assumptions that the base temperature remains constant throughout ontogeny and that growth is linearly related to temperature above the base. Much evidence (e.g. Milthorpe, 1965) shows both assumptions to be the crudest of approximations. Nevertheless, in the absence of a detailed simulation model, there is little else which offers the same degree of convenience and it is used with these reservations.

Nuttonson (1965) tried day-degree summations above 4.4, 7.2 and 10.0°C to determine the temperature base that would yield the least variable summations for different phenological events in rice. The smaller coefficients of variation for mean day-degree requirements of heading and ripening were obtained using a base temperature of 10°C. No upper temperature limits were used.

Computed on a 10°C base, the day-degree requirement for the growing period of rice varieties grown in non-tropical areas of the world range from 700 at Santakheza, U.S.S.R. (lat. 43° 40' N) to over 2780 at Beaumont, Texas (lat. 30° 04' N). In tropical areas requirements range from 1780 at Camp Cotaxtla, Mexico (lat. 18° 50' N), to 3330 at Kununurra, Northern Australia (lat. 15° 7' S, Nuttonson, 1965).

Van Royen (1954) stated that most rice varieties need an accumulated temperature regime of 3000 to 3600 degree-days (based on sum of daily mean temperatures during the growing period, i.e. base temperature of 0°C) whereas Grist (1965) using the same criteria, claimed that the minimum requirement is between 1670 and 2220°C.

The variety Calrose is almost exclusively grown in the U.S.A. and southern Australia. A total of 1840 degree-days (base 10°C) are claimed to be needed for crop growth in California and 2170 in Louisiana (Nuttonson, 1965). The average requirement at Yanco over three years was 1894 varying from 1637 to 2151. In 1971-72 the total at the Meteorological Station was 1797, but this was reduced to 1607 if temperature observations above the rice crop - where maximum temperatures were approximately 2°C lower - were used.

Low and McMahon (1970) calculated the day degrees (base (10°C) from 45 localities throughout South East Australia. Their data were used to construct a degree-day contour map, covering the whole of the N.S.W. rice growing area (Fig. 5). The period October to February was selected to include all developmental stages of rice, except ripening. Values ranged from approx. 1600 - 1800 for the whole rice area of which

GROWING DEGREE DAYS (x 100) (38 year average)

from October 1 to February 28

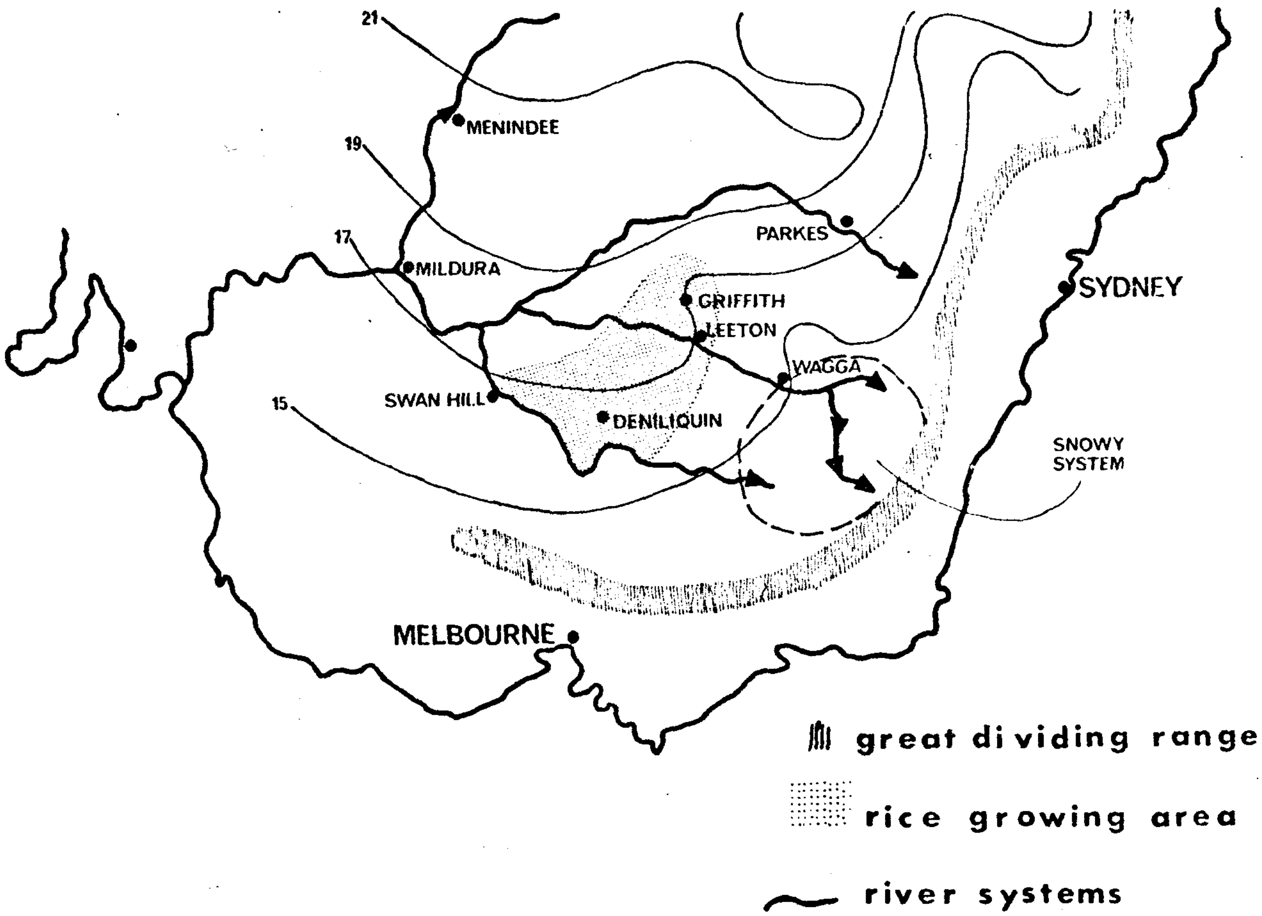


Fig. 5

the Murrumbidgee Valley only represents the northern part. Differences in degree-days between locations in the Murrumbidgee Valley were very small and assumed to be unimportant.

It is obvious from these data that the supposed accumulated temperature required for growth varies considerably and it appears that it has a large "regional" component, i.e. one divorced from the physiology of the crop.

Fiducial limits are useful to show differences in temperatures between seasons. Eighty percent confidence limits for maximum and minimum temperature in Griffith were calculated by McMahon and Low (1972). These are compared in Fig. 6 with data from the two contrasting rice seasons at Yanco (1970-71 and 1971-72). These show that maximum temperatures in 1971-72 were generally lower than in the previous year and were below average. Maximum temperatures in either season are not considered to have adversely affected growth or yield of rice.

Minimum temperatures in late October and November 1970 were below those in the following year. This resulted in a slow, but still satisfactory, establishment. In November and December 1971 minimum temperatures were lower than those experienced in the previous year, but these were not below average and are not considered to have had an adverse effect on vegetative development. Low minimum temperatures during February 1972 were in distinct contrast to the high minimum temperatures in 1971. Most rice crops flower during February and it is suggested that low minimum temperatures occurring during this critical

Minimum temperature (10 days running average)
at Yanco for the seasons 1970-71 and 1971-72
(confidence limits for Griffith)

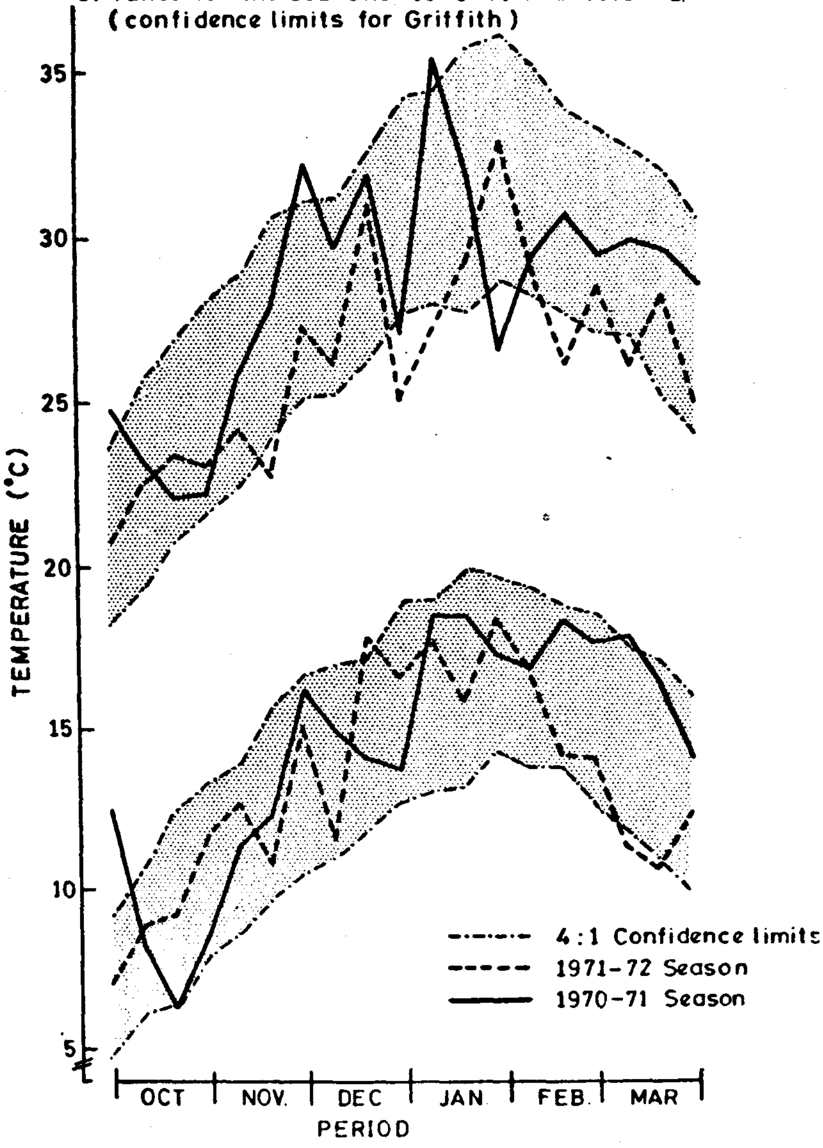


Fig. 6

stage of development may greatly influence the yield of normally grown crops.

iii. On the length of separate stages of development. Minimum rather than maximum or mean temperatures are used since growth and yield of rice is usually restricted by low minimum temperatures at some stage during ontogeny in a temperate environment. It is recognised that a mean temperature weighted for diurnal variations and taking into account the response curves for the particular physiological parameters would be more appropriate, but data on the latter are lacking. High maximum temperatures rarely cause damage, unless they are accompanied by dust storms, which may induce much floret sterility (Owen, 1971).

The effect of minimum temperatures on the length of growth stages at Yanco in 1970-71 and 1971-72 is shown in Table 5. High minimum temperatures after sowing promoted quick emergence. The vegetative stage of development took 65 days at an average minimum temperature of 12.9°C but only 48 days at 15.8°C. In 1971-72 the lower temperature encountered by late sown rice lengthened the period from panicle initiation to heading from 34 to 41 days, whilst in the previous season the lower temperature shortened this period from 32 to 26 days. The much longer time in 1971-72 is attributed to a period of very low temperatures (12°C from 10-15 days prior to heading, see also Table 6).

In 1970-71 the October-sown crop matured 51 days after heading, which is earlier than normal and which is considered due to the relatively high minimum temperatures after flowering. Much cooler

Table 5

The effect of mean minimum temperature on the length of developmental stages of rice grown in the 1970-71 and 1971-72 season.

Stages of Development	Early October Sowing				Late November Sowing		
	8-10-70		1-10-71		21-11-70		26-
	Duration (days)	Mean Min. Temp. °C	Duration (days)	Mean Min. Temp. °C	Duration (days)	Mean Min. Temp. °C	Duration (days)
Sowing to emergence	21	5.1	25	7.6	9	12.9	10
Emergence to panicle initiation.	65	12.8	65	13.0	56	14.4	48
Panicle initiation to heading.	32	18.5	34	17.2	26	17.3	41
Heading to maturity (20% moisture)	51	17.1	70	13.4	59	16.8	61
Duration of growing season.	169		194		150		160

conditions in the following year caused an extremely slow ripening with the crop considered ripe 70 days after heading. In both seasons the time from emergence to panicle initiation and from panicle initiation to heading were similar and minimum temperatures during these periods did not vary greatly.

Both November-sown crops initiated panicles at almost the same time, early in the fourth week of January. Flowering is generally recorded some 30-35 days after panicle initiation (Owen, 1969), but the 1970 crop headed only 26 days from panicle initiation, whilst it took 41 days under only slightly lower minimum temperature conditions in the second year. It is not clear why this considerable difference in time to heading has occurred, since the same varieties were used and day lengths were similar. Crop maturity was recorded 59 and 61 days after heading notwithstanding the very low temperatures in the second year. For mid-November sown crops ripening takes usually some 60 days after heading and minimum temperatures are generally lower than those recorded during the ripening period of the first year.

iv. On germination and emergence. Germination will occur at temperatures in the range 10-40°C with an optimum between 25-30°C (Sazaki and Yamazaki, 1970; Herath and Ormrod, 1965; Chaudhary and Ghildyal, 1970; Chapman and Petersen, 1962). At 10°C germination is initiated but normal seedlings do not develop, but there are large varietal differences in the effect of low temperatures on germination percentage (Ormrod and Bunter, 1960; Herath and Ormrod, 1965).

The optimum temperature for emergence through soil was found to be 30°C by Inoue and Katayama (1966).

The number of days to emergence of combine-sown rice from 17 sowing dates over a period of 10 years were related to screen minimum temperatures (Fig. 7). Screen temperatures were readily available and it had been established that the soil minimum temperature (at a depth of 2 cm)in October was closer related to screen minimum temperatures (minimum seedbed temperature averaged 0.6°C higher than screen minimum temperature) than to mean temperatures (mean seedbed temperature averaged 2.3°C higher than mean screen temperature).

A linear regression was fitted to these data although they appear to conform also to the inverse hyperbolic relationship which may be expected between rate of growth and temperature.

When minimum temperatures were below 10°C, 12 or more days were necessary for emergence of seedlings, while generally less were required at minimum temperatures between 10 and 15°C.

Soil types within the area vary from sandy loam to heavy clay with colours from light red to almost black. The lighter red loams are locally considered "early soils", from which emergence occurs more quickly than from the heavy black clays when sown at the same time.

Rice is established by combine-sowing dry seed at a depth of approximately 2 cm, or by aerial sowing pre-germinated seed into 7-10 cm water. Normally pre-germinated aerial sown seed has a distinct advantage over drill-sown dry seed since germination and "emergence" are complete and growth can continue if temperature conditions are favourable. The germination process of seed sown in dry soil commences

Relation of number of days to seedling emergence with mean minimum temperature for 1961–71 at Yanco.

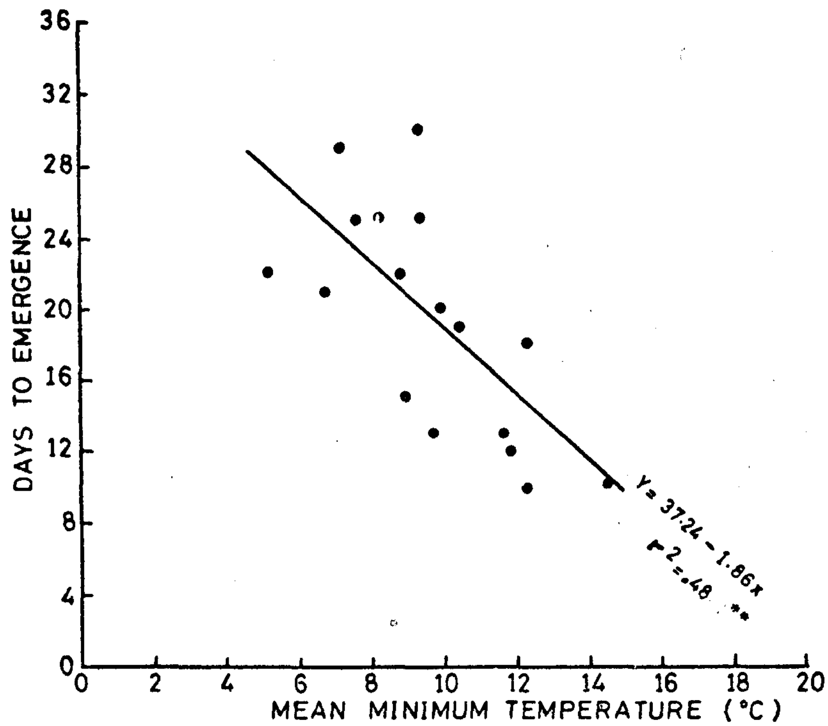


Fig.7

only when water and temperature requirements are met, and emergence may take up to 30 days in unfavourable conditions. Under very windy conditions this advantage in establishment of aerially sown pre-germinated seed may, however, be entirely off-set. This occurred in 1971 when in October the daily soil temperature at a depth of 2 cm averaged 16.7°C and exceeded 20°C on only 4 days. During the same period the temperature at the soil-water interface averaged only 13.8°C but exceeded 20°C on 8 days. Water temperature was often depressed due to very strong winds, but soil temperature was affected less. During warm sunny weather the temperature of dry soil at 2 cm depth rose much higher than the water temperature at the soil-water interface. Consequently aerial sown rice emerged slowly from the water and high plant losses occurred due to uprooting of plants by wave action.

In the previous year the mean temperature during establishment was 13.9°C in the unflooded soil and 15.0°C at the soil-water interface, whilst the mean screen temperature was only 11.8°C. This resulted in much quicker establishment and more vigorous early growth of aerial-sown rice.

v. <u>On panicle initiation</u>. Panicle initiation generally occurs between the last week in December and the third week in January. Heading follows some 30 to 35 days later. Low temperatures following panicle initiation delay heading. Bhattacharyya and De Datta (1972) reported that in the dwarf variety IR 22 the time from initiation to heading was 33 days at temperatures between 25 and 35°C. Lowering the temperature to 15°C for 24 days after initiation extended the time required by eight days. The optimum range of temperatures for floret initiation is reported by Inoue (1964) as 25-30°C by day and 20-25°C by night for japonica varieties. No initiation occurred with a day/night regime of 15°/10°C or at a constant temperature of 15°C. High floret sterility results when low temperatures occur during the meiotic stage of the pollen mother cells, approximately 11 days before heading (Satake, 1969). However, Sataka and Hayase (1970) have shown that the most sensitive stage for low temperature damage is the young microspore stage from tetrad to first contraction. The critical temperature for inducing sterility differs with varieties, the diurnal temperature range and growth conditions. It ranged from 15 to 17°C in the variety Hayayuki and from 17 to 19°C in Norin 20 when young panicles were exposed during the meiotic stage (Nishiyama, 1969). Sterility was less severe when low night temperatures were followed by high day temperatures, then when both day and night temperatures were low (Satake, 1969). An abundant supply of nitrogen made the plant more susceptible to low-temperature-induced sterility. This was confirmed by Kleinig and Noble (1967) in experiments near Deniliquin in the Murray River Valley.

Development of female organs is unaffected by temperatures low enough to prevent anther development. Nishiyama (1970) reported that pistils subjected to low temperatures could be successfully pollinated with normal pollen from untreated plants.

vi. On anthesis. Optimum temperatures for anthesis are stated to lie between 27.5 and 32.5°C, with a minimum of 22.2°C (Anon, 1969). It is not known what happens when the minimum temperature required for anthesis is only exceeded for a short period during the day. Preliminary experiments at the International Rice Research Institute (I.R.R.I.) in the Philippines suggest that 40 minutes at 32°C or 1 hour at 27°C is required for 50 percent anthesis of the variety IR 8 (Anon., 1969).

The maximum temperature for pollen germination is 40-50°C and the minimum 7-14°C (Enomoto et al., 1956 and Kiyosawa, 1962). Pollen grains deposited on a stigma germinate in 3 minutes at 27°C and fertilisation is affected in about 3 hours after pollination (Chandraratna, 1964).

Minimum temperatures at Yanco, averaged over 5-day periods from early January (panicle initiation) to late February (late flowering), were compared for the years 1971 and 1972 (Table 6). In 1971 record yields were obtained, whilst they were low in 1972. It is considered that the very low average yields recorded in 1972 can be attributed to the low temperatures recorded during the periods 21-30 January (meiosis in most crops) and 15-24 February (flowering). Floret sterility was the main yield reducing factor.

The effect of minimum temperature during critical reproductive stages of plots heading on 3 and 21 February, 1971 and 2 February and 5 March, 1972 were examined (Table 7). Low minimum temperatures during meiosis (10-15 days before heading) and flowering caused high floret sterility and low yields. High levels of nitrogen, combined with low minimum temperatures increased floret sterility and reduced yields.

vii. <u>On ripening</u>. It is generally acknowledged that ripening during cool conditions is advantageous to yield, possibly due to reduced

Table 6

Mean Minimum and Maximum Temperatures in °C at 5-day intervals in January and February

Period	Mean Min. Temp.		Mean Max. Temp.	
	1971	1972	1971	1972
6 - 10 Jan.	19.0	20.7	36.5	30.7
11 - 15 Jan.	18.9	17.9	35.4	30.6
16 - 20 Jan.	16.3	15.9	31.7	29.1
21 - 25 Jan.	19.3	15.7	29.3	29.8
26 - 30 Jan.	17.0	17.6	29.6	30.7
31 Jan. - 4 Feb.	17.6	17.6	26.4	33.2
5 - 9 Feb.	19.3	17.9	30.0	32.4
10 - 14 Feb.	14.4	16.7	27.6	29.9
15 - 19 Feb.	18.0	15.8	29.9	25.9
20 - 24 Feb.	18.0	11.3	30.0	24.1
25 - 29 Feb.	16.9	17.4	29.0	30.0
Overall mean	17.7	16.8	30.5	29.7
Mean 1st 25 days in Feb.	17.5	15.9	28.8	29.1
Yield in N.S.W. (Kg ha^{-1})	7480	6450		

Table 7

Mean Minimum Temperature (^{o}C) around heading, floret sterility and yield in the 1970

and 1971-72 rice seasons

Period	Mean Min. Temperature as from date of hea			
	3.2.71	2.2.72	21.1.71	5.3
10-15 days before heading	17.2	15.0	19.3	12
5 days before heading	15.9	18.2	18.0	16
5 days after heading	18.7	18.3	18.0	11
10 days after heading	18.1	18.3	17.4	11
15 days before to 10 days after heading	17.8	17.4	17.3	13
% floret sterility 0 N	12	18	8	3
155 N	15	29	12	5
Yield (kg ha^{-1}) 0 N	9200	8820	9660	54
155 N	11290	9450	11330	56

respiration rates and longer retention of photosynthetic leaf area. In the Murrumbidgee Valley ripening is slow and always under relatively cool conditions compared to tropical areas. However, good grain set is far more important than slow ripening in temperate regions. Very low temperatures before heading of the 1971-72 November sown crop resulted in a very irregular ripening and extremely high floret sterility on later emerging panicles and on lower parts of early panicles. Under these very unfavourable conditions ripening did not take longer than in the previous year, but the yield was much lower (see Table 7).

D. Conclusions

Climatic conditions within the rice growing area of the Murrumbidgee Valley varied little during the two seasons studied. It appears that observations from one recording station can be used to represent the entire Valley.

The duration on rice growth was determined by the occurrence of low minimum temperatures. When these occurred after sowing it caused slow emergence and early growth. Their occurrence during and following panicle initiation could delay heading. Ripening was generally slow, some 60-70 days, but with high minimum temperatures it was shorter.

Low minimum temperatures during meiosis and flowering resulted in a high percentage floret sterility and low yields. High levels of nitrogen accentuated the effects of low temperatures during the reproductive stage.

IV. GROWTH AND YIELD OF COMBINE- AND AERIAL-SOWN RICE

A. Introduction

Until the early 1960's all rice in New South Wales was sown by combine into a well-prepared seed bed. The required fertiliser was drilled with the seed. Only a few progressive farmers tried in-water seeding - with mixed results. However, in 1964, due to adverse seasonal conditions many farmers were unable to prepare a seed bed in time for combine sowing and were forced to sow by air into water. Most crops lodged seriously and the technique was discarded by all but a few growers in the Murrumbidgee Valley.

In the Murray Valley approx. 80% of crops were aerial sown by 1969. In that area the growing season is shorter and soils are less fertile. Many soils also crust badly with intermittent watering. Under these circumstances establishment with a combine is more difficult. Boerema and McDonald (1967) found that in-water seeding improved the plant stand, gave more vigorous seedling development and earlier ripening, but not always increased yields.

Aerial seeding into water is popular in all U.S.A. rice growing areas and on a large rice project in Surinam (ten Have, 1967). Faulkner (1960) and McIlrath (1968) reported higher yields from crops sown in water than from drill-sown crops under similar conditions. Improved weed control was usually said to be responsible.

Gerlouw (1964) analysed the costs of producing in-water-sown and drill-sown crops in Louisiana. He demonstrated that sowing in-water required one-third less labour and soil preparation costs, although sowing costs increased slightly. Yields and net returns were increased.

The effect of method of sowing on crop growth, canopy development, yield and yield components is described. Experiments were carried out over two years 1970-71 and 1971-72.

B. Methods and Treatments

The varieties Calrose, Kulu and Baru were established by combine and aerial sowing techniques. N was applied at 0, 78 and 155 kg/ha as ammonium sulphate. A split-split plot design was used with methods of establishment as main plots, nitrogen as sub-plots and varieties as sub-sub plots. There were three replications of treatments in the first year.

Special levee banks were constructed to facilitate a separate water management during the period of establishment of rice sown by the two methods. Seed was sown at 110 kg ha^{-1}. Imbibition of seed was synchronised; aerial-sown rice was soaked at the same time as combine-sown rice was first flushed. Once permanent flood was established on combine-sown rice, water management of all treatments was identical. Aerial-sown rice matured 14 days earlier than combine-sown rice.

In the second year the same treatments were used as in the first, but these were not replicated. Aerial- and combine-sown plots were in separate, adjacent bays which had an identical history.

In the first year a complete growth analysis was made on 0 and 155 N plots with sampling at fortnightly intervals. Because of the large number of samples to be processed the 78 N treatments could not be included. In the second year samples were taken at critical growth stages only.

C. Results

1. 1970-71 Experiment

(a) Yields: The overall responses from the experiment are shown by the final yields of grain (Table 8). Unfortunately these were far from simple as the second-order interaction was significant. Explanation of these effects require a detailed analysis of yield components and growth. However, a brief examination of the results shows that combine-sown rice produced highest yields when 155 N was applied; this in contrast to aerial-sown rice which yielded highest at .78 N, whilst 155 N reduced yields to below those obtained from the unfertilised treatment. When combine sown, yields of Calrose and Baru were similar, but that of Kulu was inferior. Kulu and Baru were both inferior to Calrose when aerial sown.

(b) Yield components: Detailed analysis of the intermediate N-rate was omitted (Table 9).

Aerial-sown rice produced more panicles than that combine-sown and 155 N increased the panicle number for both methods of sowing. With both sowing methods Baru produced fewest panicles. Calrose produced more panicles than Kulu when combine sown, but the difference was not significant when aerial sown.

Panicle size as determined by the number of florets per panicle was greatest for Baru, with little difference between Calrose and Kulu.

TABLE 8. The effect of method of sowing and three N-rates on the yield of three rice varieties in 1970-71.

Sowing Method (S)	N-rates (N) kg/ha	Grain yield in kg ha^{-1} at 14% moisture			
		Varieties (V)			
		Calrose	Kulu	Baru	Mean
Combine	0 78 155	10180 10880 12060	8320 - 9790	9090 10620 11950	9200 10050 11270
Mean Combine Sown		11040	8920	10550	10170
Aerial	0 78 155	8660 11210 9100	9050 10530 7080	7850 10470 6560	8520 10740 7580
Mean Aerial Sown		9660	8890	8290	8950

L.S.D. (P = 0.05)
between V means at same S and same N = 743.
between N means at same S and same or different V = 784.
between S means at same or different N and V = 1574.

Analysis of Variance

Sources of Variation	d.f.	Mean Square
Replications	2	510094
Method of Sowing (S)	1	15083910
ERROR (A)	2	1618957
N-rates (N)	2	7656316**
S x N	2	17537454**
ERROR (B)	8	210199
Varieties (V)	2	6918430**
S x V	2	3997991**
N x V	4	1025318*
S x N x V	3	1033885*
ERROR (C)	21	191492
Total	49	

Standard deviation: (A) 1272 kg/ha or 13.3%
(B) 458 kg/ha or 4.8%
(C) 438 kg/ha or 4.6%

TABLE 9. Yield and Yield Components of three Varieties at 0 and 155 N when Combine and Aerial Sown.

Variety (V)	Sowing Method (S)	Nitrogen (N) (kg ha^{-1})	Yield (kg ha^{-1})	Grain/ Straw Ratio	Panicles m^{2}	Florets Panicle^{-1}	Florets m^{-2} x 10^{3}	Floret Sterility (%)	Panicle Weight (g)
Calrose	Combine	0	10180	1.09	605	72.6	43.9	7.8	1.89
	Combine	150	12060	0.85	661	67.1	44.4	10.2	1.74
	Aerial	0	8660	0.85	704	58.7	41.3	16.3	1.37
	Aerial	150	9100	0.74	745	75.0	55.9	28.2	1.49
Kulu	Combine	0	8320	0.95	473	66.0	31.2	11.9	1.66
	Combine	150	9790	0.77	651	78.6	51.2	14.6	1.86
	Aerial	0	9050	1.10	615	62.4	38.4	16.5	1.47
	Aerial	150	7080	0.57	796	76.3	60.7	33.1	1.15
Baru	Combine	0	9090	1.21	351	109.1	38.3	16.3	2.69
	Combine	150	11950	1.02	432	139.1	60.0	28.2	3.22
	Aerial	0	7850	0.80	427	97.4	41.6	28.4	1.98
	Aerial	150	6560	0.46	593	100.9	59.8	52.4	1.29
LSD P = 0.05	S		1715	0.12	101	NS		6.5	0.42
	N		520	0.11	63	6.8		8.1	NS
	V		406	NS	68	8.6		3.6	.20
	S x N		735	NS	NS	NS		NS	.35
	S x V		574	0.08	NS	12.1		5.1	.29
	N x V		574	0.08	NS	NS		NS	NS
	S x N x V		981	0.11	NS	17.1		NS	0.40

An application of 155 N increased the panicle size under both sowing methods. Only Baru showed significant decrease in floret number when aerial sown as compared with combine sown.

Panicle weight is influenced by panicle size, grain weight and percentage floret sterility. Baru had the heaviest panicles when combine sown, but when aerial sown its panicles were only heavier than those of Calrose. Nitrogen had a slight, but insignificant positive effect on combine sown rice and a negative effect on that aerial sown.

Baru had most sterile florets from both methods of sowing and at 155 N. The three varieties had more empty glumes when aerial sown and at high N. All three varieties had also a very high percentage floret sterility when aerial sown at 155 N; that of Baru exceeded 50%.

Grain weights of all varieties were lowest when aerial sown and nitrogen had for both varieties a detrimental effect but grain of aerial sown rice at 155 N was considerably lighter than that of other treatments. Kulu grains were smaller than those of Calrose and Baru at 155 N.

Although aerial sown rice produced more panicles, at both N-rates this did not result in higher yields. At 0 N, this was because of a higher percentage floret sterility and fewer florets per panicle giving a lower panicle weight. At 155 N, fairly large, but light weight panicles were produced as a result of a very high percentage floret sterility and a very low 1000-grain weight.

Aerial sown rice had a higher grain-straw ratio than combine sown rice. An application of 155 N reduced this ratio considerably, especially when applied to the aerial sown varieties Baru and Kulu.

(c) Crop growth

(i) Seedling development. Aerial-sown rice was established from pre-germinated seed and treatments established by this method grew more vigorously early. The affect of N became apparent very early (Plate 1). During mid-tillering (9 December) the effect of treatments on root- and shoot growth was determined (Table 10, Plate 2). Aerial-sown rice had developed a larger canopy of leaves, giving a shoot-root ratio almost double that of combine-sown rice. Calrose had developed most vigorously and Kulu least. Both roots and shoots almost doubled in weight with 155 N.

The effect of nitrogen and varieties on four major growth parameters is presented separately.

(ii) Nitrogen on the growth of aerial- and combine-sown rice. The early advantage in growth of aerial-sown rice was maintained throughout ontogeny. All significant growth stages were reached from 10-14 days earlier.

Crop growth, as represented by tillering, leaf area index (L), dry matter production (W) and net assimilation rate (E) have been presented for the sowing and nitrogen treatments (averages all varieties) in Fig. 8. Dry matter accumulation during ontogeny is presented as a fitted curve of the natural logarithims, whilst observed values are also plotted. Note that the values given are of the logarithims. A general logistic curve did not fit the data as well. Analyses of variance for ln W and L are presented in appendices 1 and 2 respectively.

Plate 1

General view of method of sowing experiment at first heading. Combine sown plots in the foreground. Aerial sown plots behind meteorological station received 78, 155 and 0N from left to right.

TABLE 10. Shoot and root development at tillering (9.12.70).

Method of Sowing	Dry Matter Shoots (g/m^2)	Dry Matter Roots (g/m^2)	Shoot/root Ratio
Combine	128	90	1.4
Aerial	365	139	2.6
S.E.	± 11.2	± 6.6	
Varieties			
Calrose	280	139	2.0
Kulu	218	99	2.2
Baru	241	106	2.3
S.E.	± 13.8	± 8.1	
N-rates			
0 N	177	81	2.2
155 N	316	148	2.1
S.E.	± 11.2	± 6.6	

Plate 2. The effect of method of sowing and nitrogen on the early growth of the varieties Calrose, Kulu and Baru (then selection YR 6-100-9).

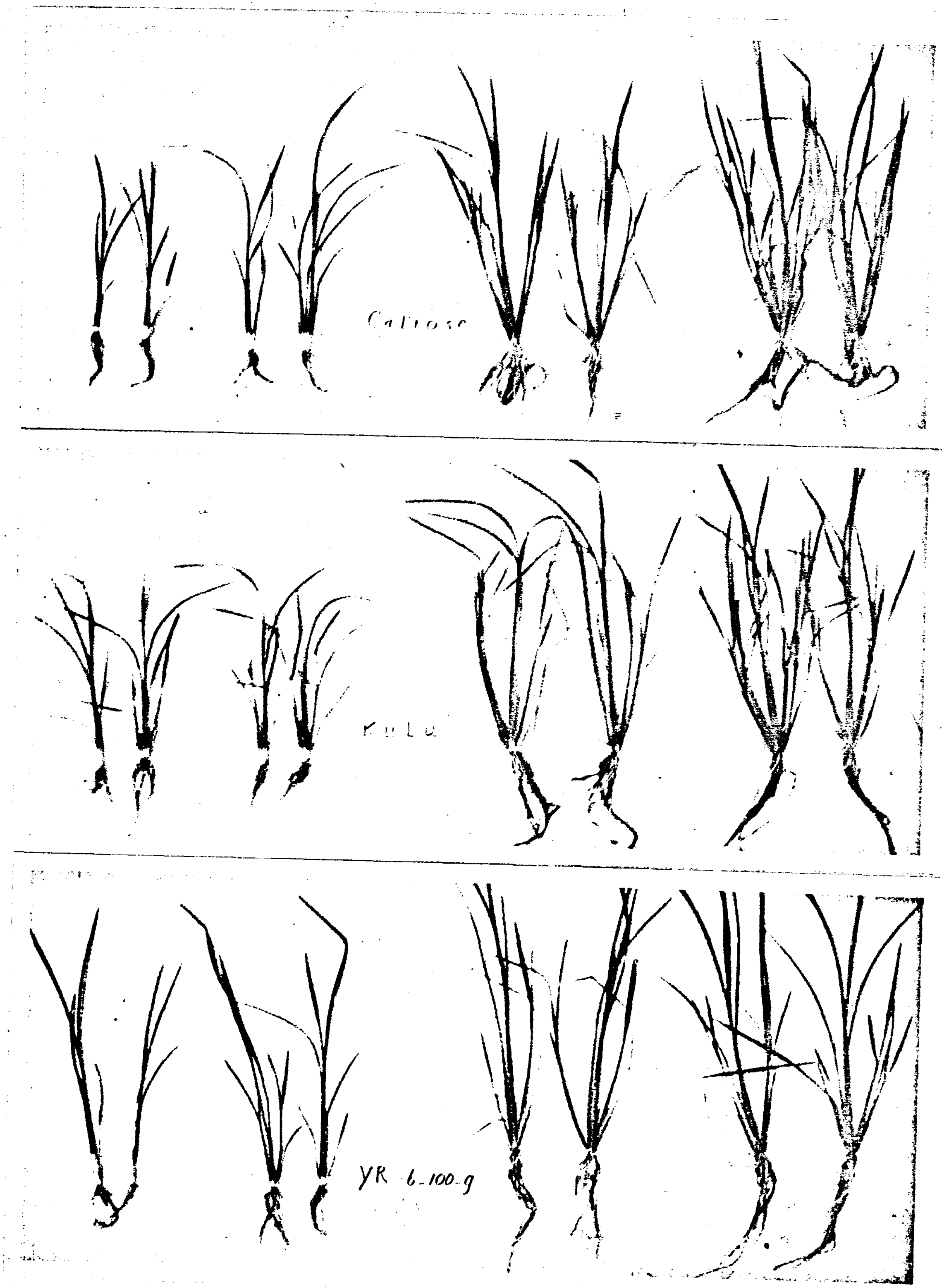


Plate 2

0 N   155 N   0 N   155 N

Combine Sown   Aerial Sown

DRY MATTER PRODUCTION, NET ASSIMILATION RATE, TILLERING AND LEAF AREA INDEX OF COMBINE AND AERIAL SOWN RICE AT TWO NITROGEN RATES.

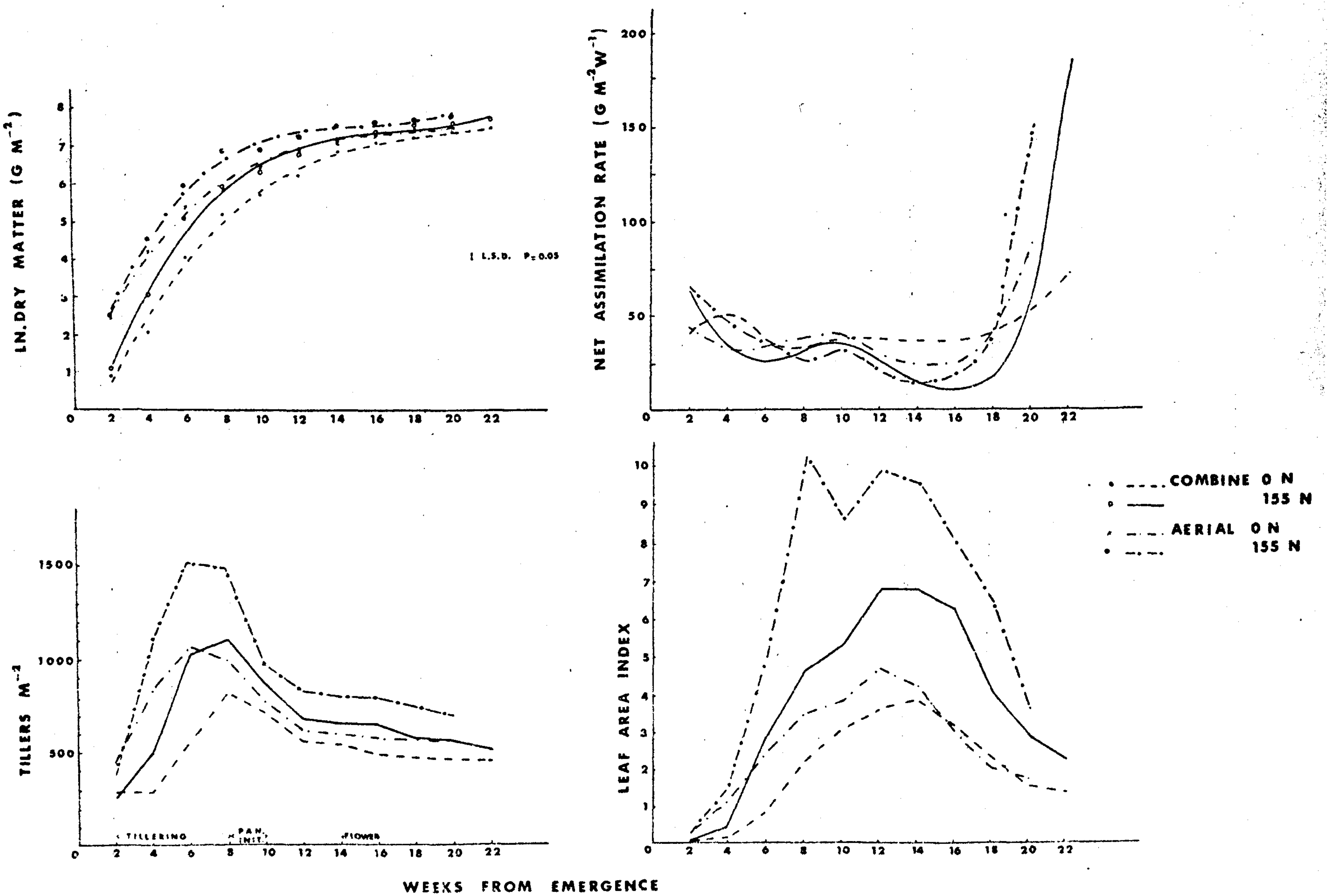


Fig.8

The equations were:-

combine 0 N : $\ln W = -1.383 + 2.347t - .219t^2 + .007t^3$ $r^2 = .994$

combine 155 N : $\ln W = -1.502 + 3.001t - .347t^2 + .014t^3$ $r^2 = .994$

aerial 0 N : $\ln W = .662 + 2.132t - .228t^2 + .009t^3$ $r^2 = .994$

aerial 155 N : $\ln W = .117 + 2.858t - .371t^2 + .016t^3$ $r^2 = .995$

Net assimilation rates ($E = 1/L \times dw/dt$) were obtained from the derived crop growth rate ($C = dw/dt$) and the actual leaf area index (L). Throughout ontogeny, dry matter production of fertilised rice was greater than that unfertilised for the same sowing method. From panicle initiation onwards there was no difference between fertilised combine and unfertilised aerial sown rice. The greatest difference in W between sowing method and nitrogen applications was during maximum tillering.

Lodging after flowering of aerial sown rice with 155 N had no apparent effect on dry matter production, but grain weights were significantly reduced. The fitted cubic curves show a surge in total dry matter production during the last period of ripening. This apparent surge is statistically not significant, i.e. real differences between adjacents points cannot be distinguished; it will be discussed later.

Net assimilation rates of unfertilised combine- and aerial-sown rice were initially low. Towards the end of tillering, net assimilation rates of all treatment combinations decreased and then increased temporarily during panicle initiation. During the final ripening period high rates of nitrogen produced very high E values, but that of combine sown rice being higher than that of lodged aerial sown rice.

An application of 155 N increased tiller numbers at all times for both methods of sowing. Over all treatments, aerial-sown rice produced more tillers and panicles than combine-sown rice. There was a distinct lag-phase in tillering prior to panicle initiation. Tiller mortality was highest at 155 N, i.e. where the greatest numbers were initiated.

During early growth, leaf area index was closely related plant- and tiller number. Aerial sown rice had a higher L than combine sown rice at comparable N-rates. Maximum L was reached 2 weeks earlier in aerial sown rice. At maturity aerial-sown rice had a higher L than combine sown rice, although many leaves were rotting in the dense lodged mat of material in the 155 N treatments.

(iii) Varietal effects on the growth of combine- and aerial-sown rice. Baru tillered less and produced fewer panicles than Kulu and Calrose (Table 11). Kulu commenced tillering somewhat later than Calrose, but they produced similar panicle numbers, although there were significantly more when aerial sown. Maximum tiller number was reached shortly before panicle initiation. There was no distinct lag phase in tillering of any of the varieties. When aerial sown, all varieties had a higher initial L and this was then maintained until harvest.

Differences in leaf area index (L) between varieties were statistically not significant and the V x N interaction was also not significant. (Table 12)

Calrose produced more dry matter than Kulu and Baru during the

TABLE 11. Tillering production of three combine and aerial sown rice varieties (mean 0 and 155 N).

(Tillers m^{-2})

Weeks from emergence	Combine Sown			Aerial Sown		
	Calrose	Kulu	Baru	Calrose	Kulu	Baru
2	375	232	215	396	433	420
4	608	317	271	943	967	1016
6	945	865	592	1267	1512	1112
8	1045	1097	778	1313	1341	1092
10	914	885	620	901	957	791
12	728	665	514	747	779	687
14	697	652	482	820	749	639
16	656	656	434	728	806	569
18	595	592	401	708	746	585
20	590	563	391	725	706	510
22	581	561	394			

first 14 weeks of ontogeny (until heading) (Table 13). Baru had less dry matter production than Kulu during establishment. From tillering onwards there was no difference between Kulu and Baru. When aerial sown, however, Baru produced more dry matter than Kulu during tillering (2-8 weeks from emergence). There was no difference in dry matter production between Baru and Calrose during tillering. From panicle initiation onwards there was no difference in dry matter production between aerial sown varieties.

Regression equations and r^2 values for ln W curves were:

Combine Calrose: $\ln W = -.859 + 2.513t - .265t^2 + .010t^3$ $r^2 = .996$

Combine Kulu: $\ln W = -1.520 + 2.660t - .281t^2 + .010t^3$ $r^2 = .993$

Combine Baru: $\ln W = -1.948 + 2.849t - .302t^2 + .011t^3$ $r^2 = .993$

Aerial Calrose: $\ln W = .312 + 2.494t - .300t^2 + .012t^3$ $r^2 = .996$

Aerial Kulu: $\ln W = .383 + 2.419t - .293t^2 + .012t^3$ $r^2 = .994$

Aerial Baru: $\ln W = .471 + 2.537t - .319t^2 + .014t^3$ $r^2 = .993$

A slight surge in ln W is again apparent in the last 2 weeks before maturity; differences between the last two harvests were statistically not significant.

Kulu had a lower initial net assimilation rate than Calrose and Baru , but in the second fortnightly period E of Kulu was slightly higher. Combine sown varieties showed a very high net assimilation rate during ripening.

TABLE 12. Leaf Area Index of three combine and aerial sown rice varieties (mean 0 and 155 N)

Weeks from emergence	Combine sown			Aerial Sown		
	Calrose	Kulu	Baru	Calrose	Kulu	Baru
2	.07	.06	.04	.23	.23	.26
4	.52	.21	.25	1.32	1.09	1.54
6	2.30	1.86	1.43	3.53	3.40	4.26
8	3.89	2.96	3.38	7.05	6.11	7.40
10	4.69	4.18	3.71	6.07	5.52	7.07
12	5.93	4.47	5.35	6.65	7.20	8.01
14	6.10	5.11	4.78	6.93	6.65	6.86
16	5.02	5.01	4.19	5.24	5.89	5.59
18	3.51	3.32	2.80	3.82	4.09	4.79
20	2.49	2.41	1.83	2.73	2.29	3.07
22	2.11	1.84	1.52			

Analysis of Variance: See Appendix 2

TABLE 13. Dry matter production (ln W) of three combine and aerial sown rice varieties (mean 0 and 155 N) ($g\ m^{-2}$)

Weeks from emergence	Combine Sown			Aerial Sown		
	Calrose	Kulu	Baru	Calrose	Kulu	Baru
2	1.40	.87	.61	2.52	2.52	2.70
4	3.18	2.76	2.63	4.20	4.15	4.38
6	4.55	4.21	4.18	5.43	5.34	5.58
8	5.57	5.29	5.32	6.28	6.17	6.39
10	6.29	6.06	6.12	6.83	6.71	6.89
12	6.78	6.58	6.65	7.16	7.03	7.17
14	7.09	6.90	6.98	7.34	7.21	7.29
16	7.28	7.11	7.17	7.44	7.33	7.36
18	7.40	7.24	7.28	7.54	7.45	7.44
20	7.53	7.38	7.39	7.51	7.66	7.62
22	7.71	7.58	7.56			

LSD $P = 0.05$ Between varieties - at all times = .190

(d) Canopy development

(i) Stem area. At flowering, the area of stem, including leaf sheaths, was about half the leaf area. Nitrogen exerted the greatest effect, 0 N having a Stem Area Index (SAI) of 1.57 and 155 N an SAI of 3.53. Kulu with its many tillers had the highest SAI of 2.70, that of Calrose being 2.58 and Baru 2.38. The difference between sowing method was not significant.

(ii) Leaf size, thickness and angle. Leaf length and width are both important in determining canopy structure and light interception characteristics. Results of measurements carried out at flowering are presented in Table 14. The effect of sowing method varied with the leaf position. Highest leaves tended to be shorter and lower leaves longer with aerial sowing.

Baru had a short broad flag leaf, but lowest leaves tended to be longer than those of other varieties. Kulu had rather long narrow leaves. Calrose and Kulu rarely had more than 4 leaves per tiller, but Baru frequently had 5 or 6.

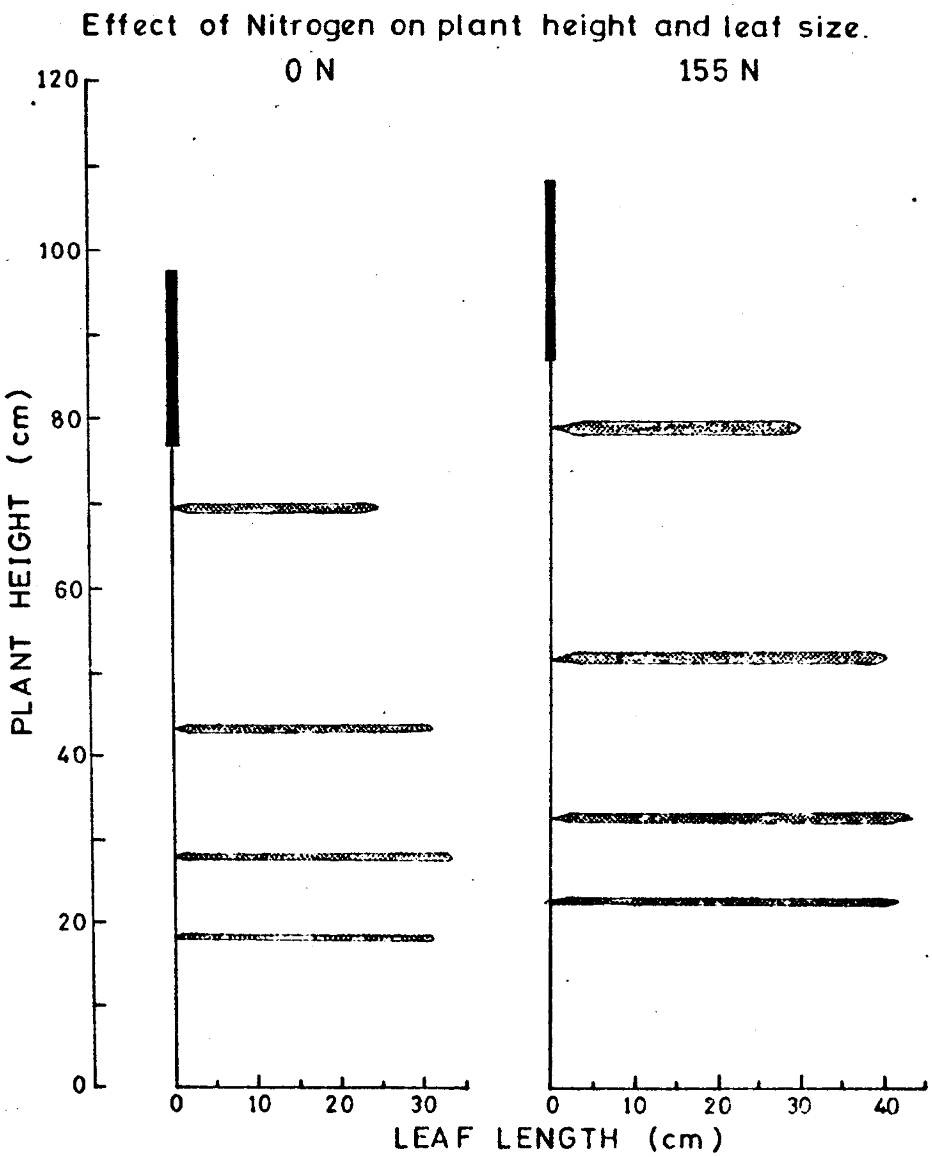
Nitrogen exerted the greatest effect on leaf size (Fig. 9). An application of 155 N increased leaf length by about 100 mm and the width by 20 mm.

Overall Calrose had thinnest leaves (0.52 g/g dm^{-2}) followed by Kulu and Baru with 0.53 and 0.56 g dm^{-2} respectively. Both aerial sowing and 155 N reduced leaf thickness from 0.56 to 0.51 g dm^{-2}.

Leaf angle was measured on all leaves of 50 tillers. Curvature of the leaves was negligible, except for Kulu where they tended to droop.

TABLE 14. The effect of variety, method of sowing and nitrogen on leaf dimensions. (Length and width in mm).

Method of Sowing	Flag Leaf		2nd Leaf		3rd Leaf		4th Leaf	
	L	W	L	W	L	W	L	W
Combine	285	10	357	10	373	9	338	9
Aerial	253	11	354	10	398	9	382	8
S.E.	±14	±.43	±21	±.19	±17	±.26	±20	±.97
Varieties								
Calrose	296	11	344	10	373	9	332	8
Kulu	280	11	376	9	384	9	371	7
Baru	258	12	346	10	398	9	376	9
S.E.	±17	±.53	+26	+.79	+21	+.32	+25	+1.18
N-rates								
0 N	242	10	310	9	331	8	305	7
155 N	296	12	400	11	439	10	414	9
S.E.	±17	±.43	±21	±0.65	±17	±.26	±68	±.97



Effect of Nitrogen on plant height and leaf size.
0 N
155 N
PLANT HEIGHT (cm)
120
100
80
60
40
20
0
0
10
20
30
0
10
20
30
40
LEAF LENGTH (cm)

Fig. 9

The Standard Error varied between $\pm 3.2^{\circ}$ and $\pm 10.9^{\circ}$, with the greatest variation occurring in the angle of flag leaves of Kulu at 0 N. Physical plant characteristics are presented in Fig. 10.

Leaves of Kulu had the greatest spread, whilst those of Baru were more upright. Calrose leaves were attached at an intermediate angle. The peduncle of Kulu was extremely short and many panicles were not completely exserted from the leaf sheath. Florets "caught" in the leaf sheath of the flag did not set grain.

Leaf area per panicle. This is expressed as the leaf area index at each time of observation divided by the final panicle number. It is considered to be the photosynthesising leaf area for the average panicle (Fig. 11). Tiller mortality, especially at high N, was high. Aerial sown rice with 155 N had a tiller mortality of almost 50%. It is assumed that some or most of the assimilation products from dying tillers is translocated to viable tillers.

Kulu had the smallest leaf area per panicle, whilst Baru, the least tillering variety, had the largest photosynthetic system per panicle. The large photosynthetic area of Baru developed early and it was maintained after flowering. Baru had paler leaves than Calrose and Kulu and the leaves tended to become lighter in colour during ripening.

(iii) Straw strength is determined by plant height, stem diameter and breaking strength of the culm. The first two were determined.

Plant height and internode length. Tall plants with thin stems and a high leaf canopy are very susceptible to lodging (Plate 3). The length

Comparative plant profile of three varieties of rice.

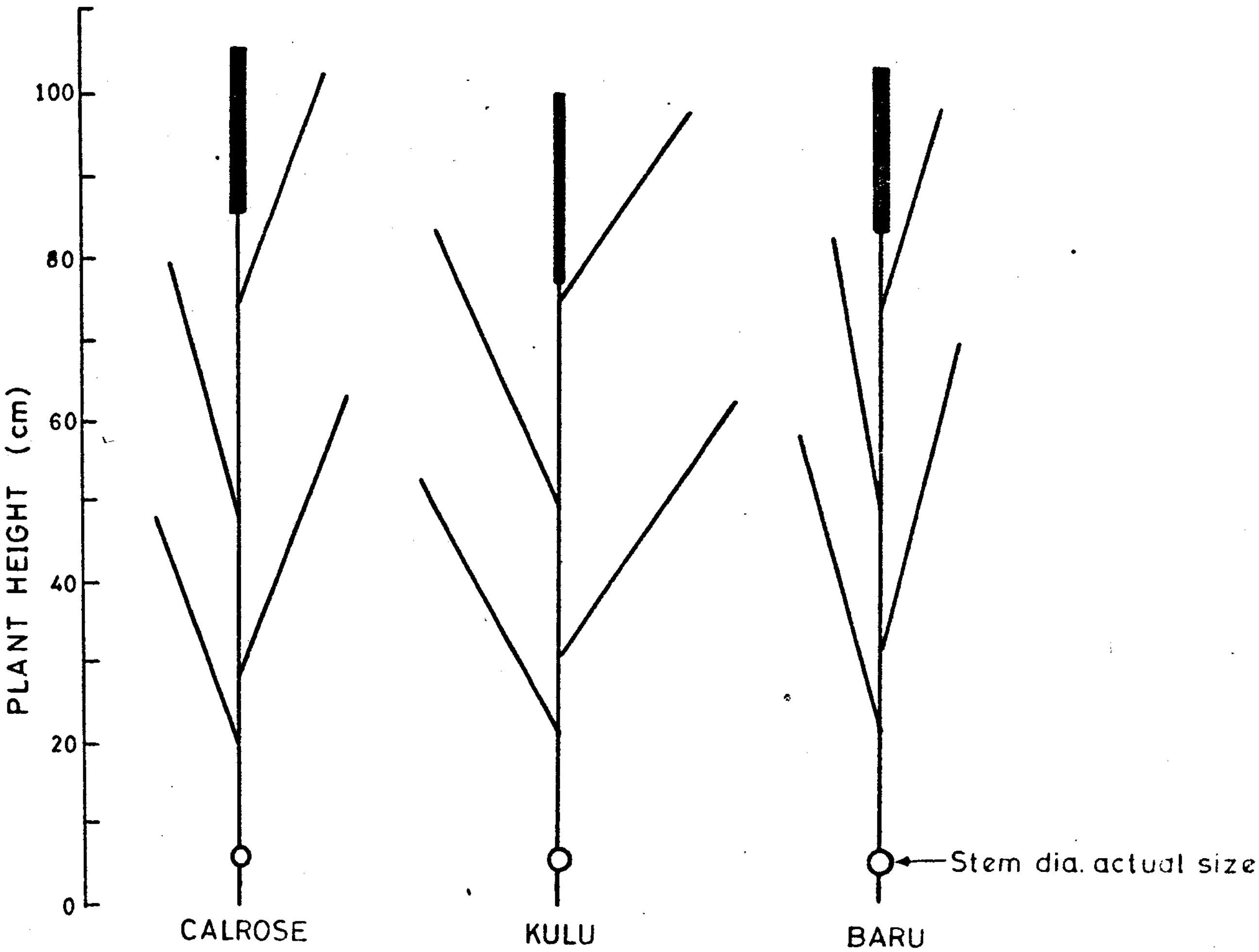


Fig.10

Changes in Leaf Area per panicle during growth.

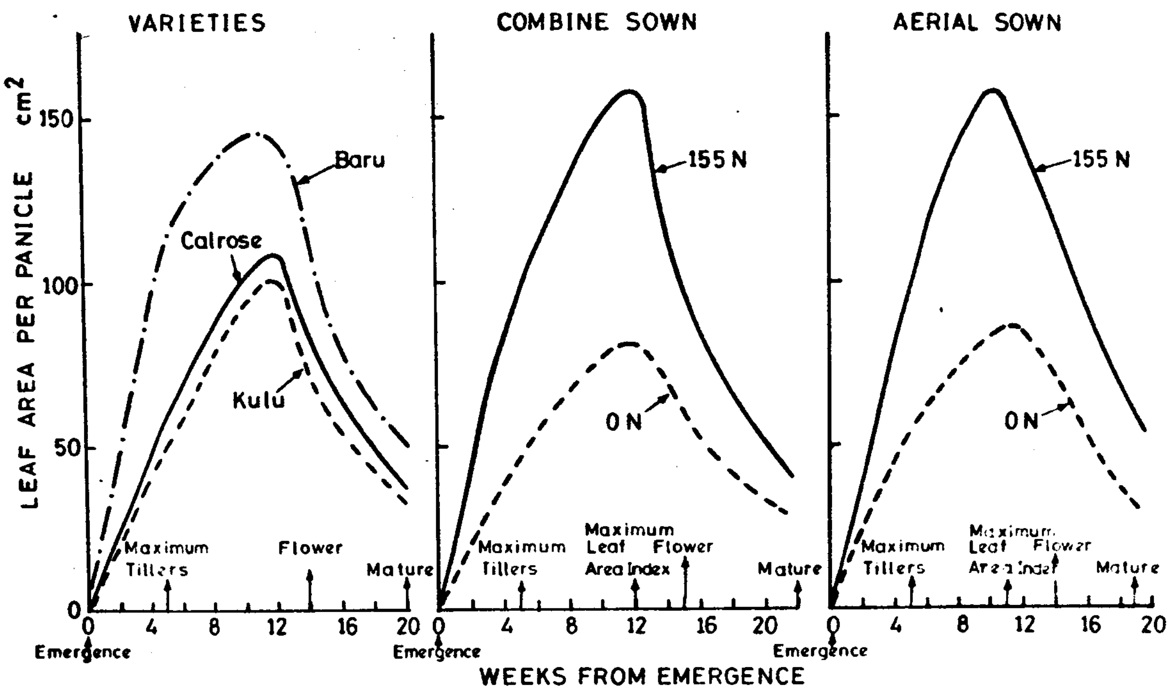


Fig.11

Plate 3

Aerial sown rice at 155N lodged seriously. Almost completely sterile panicles of Baru remained upright.

of the main tillers was determined when maximum height was reached about 7 weeks after the panicle was exserted (Fig. 11 a).

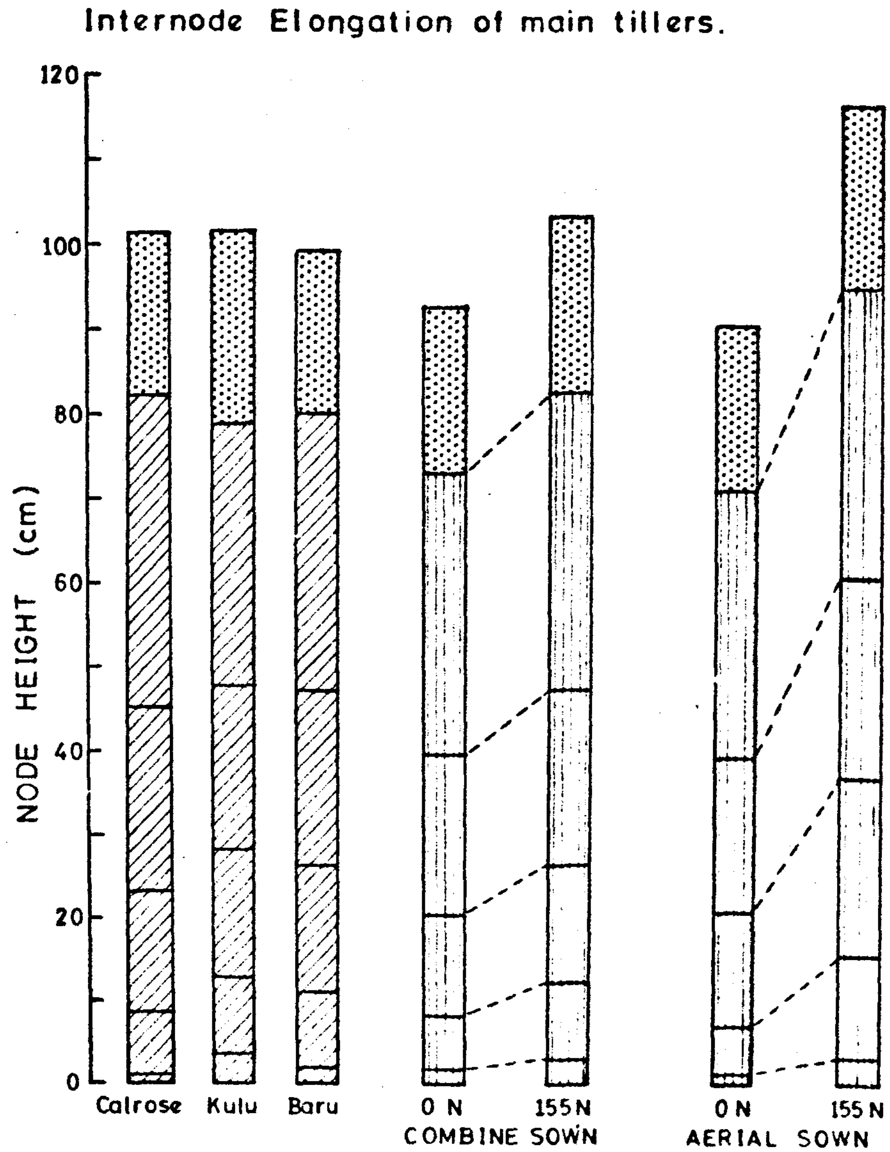
Kulu had the shortest straw and the longest panicle. This variety also had the longest first internode. Nitrogen increased plant height for all varieties under both methods of establishment. Fertilised aerial sown rice was taller than that combine sown. Unfertilised aerial sown rice was, however, slightly shorter.

There was a high positive correlation between tiller number per plant and variation in plant height. Kulu tillered most and tiller height varied also greatly. Baru had fewest tillers per plant and had least variable tiller length.

Stem diameter. The leaf sheath assists in strengthening the straw and preventing lodging. Stem diameters (including leaf sheaths) at heights of 10 and 30 cm from the ground are presented in Table 15.

Aerial-sown rice had thinner stems than combine-sown rice. Stems of Baru had the largest diameter and those of Calrose were thinnest. Nitrogen had a relative small effect on the diameter of lower parts of the tillers. At a height of 30 cm the stem diameter of rice fertilised with 155 N was larger due to a thicker leaf sheath.

(iv) Canopy structure. The distribution of leaf area and dry matter of stems, leaves and panicles (before grainset) within the crop canopy was determined at flowering by stratified clipping. At the same time light transmission ratios (LTR) were measured at 20 cm intervals from ground level. Unfertilised treatments (all varieties both combine



Internode Elongation of main tillers.
120
100
80
60
40
20
0
NODE HEIGHT (cm)
Calrose
Kulu
Baru
0 N
155N
COMBINE SOWN
0 N
155 N
AERIAL SOWN

Fig.11 a

TABLE 15. The effect, method of sowing, variety and nitrogen on the stem diameter (including leaf sheath).

Method of sowing	Stem diameter in mm	
	at 10 cm height	at 30 cm height
Combine	6.00	3.51
Aerial	5.03	3.03
S.E.	.092	.062
Varieties		
Calrose	5.12	2.96
Kulu	5.19	3.25
Baru	6.23	3.61
S.E.	.089	.076
N-rates		
0 N	5.53	2.96
155 N	5.49	3.59
S.E.	.061	.062

and aerial sown) gave a very similar distribution of dry matter and leaf area. Generally, foliage was sparse with a total L between 2 and 3, with most leaves at 20-60 cm. LTR at 20 cm varied between 35 and 40%. Because of the small differences between unfertilised plots, only results from treatments receiving 155 N are presented for the three varieties in Fig. 12. In Fig. 13 data for 0, 78 and 155 N (mean 3 varieties) for both methods of sowing are presented.

At 155 N, aerial sown rice had more leaf at higher levels in the canopy (60-100 cm) than combine sown rice. Combine sown rice carried most of its leaf between 40 and 60 cm. Calrose and Baru had most leaves lower (60-80 cm) than Kulu (80-100 cm).

Combine sown rice had most dry matter at 0-20 cm and this gradually decreased upwards. Aerial sown rice had also most dry matter at 0-20 cm, but it was in all cases much less, whilst the dry matter was more uniformly distributed up to 100 cm.

The greater weight of dry matter and a larger leaf area higher up the stem predisposed aerial sown rice to lodging.

(v) Light interception. Light Transmission Ratios (LTR) were determined before stem elongation (22.12.70) and at flowering (Table 16). Flowering occurred at different times for different treatments and light conditions were not identical. With a slightly overcast sky, LTR appeared to be higher than on clear sunny days.

Before panicle initiation, aerial sown rice had a denser canopy and N reduced LTR significantly for both methods of sowing. The large difference between methods of sowing, which may have been partly due to the row effect

LEAF AND DRY MATTER DISTRIBUTION WITHIN THE CANOPY OF COMBINE AND AERIAL SOWN RICE FERTILIZED WITH 155 N.

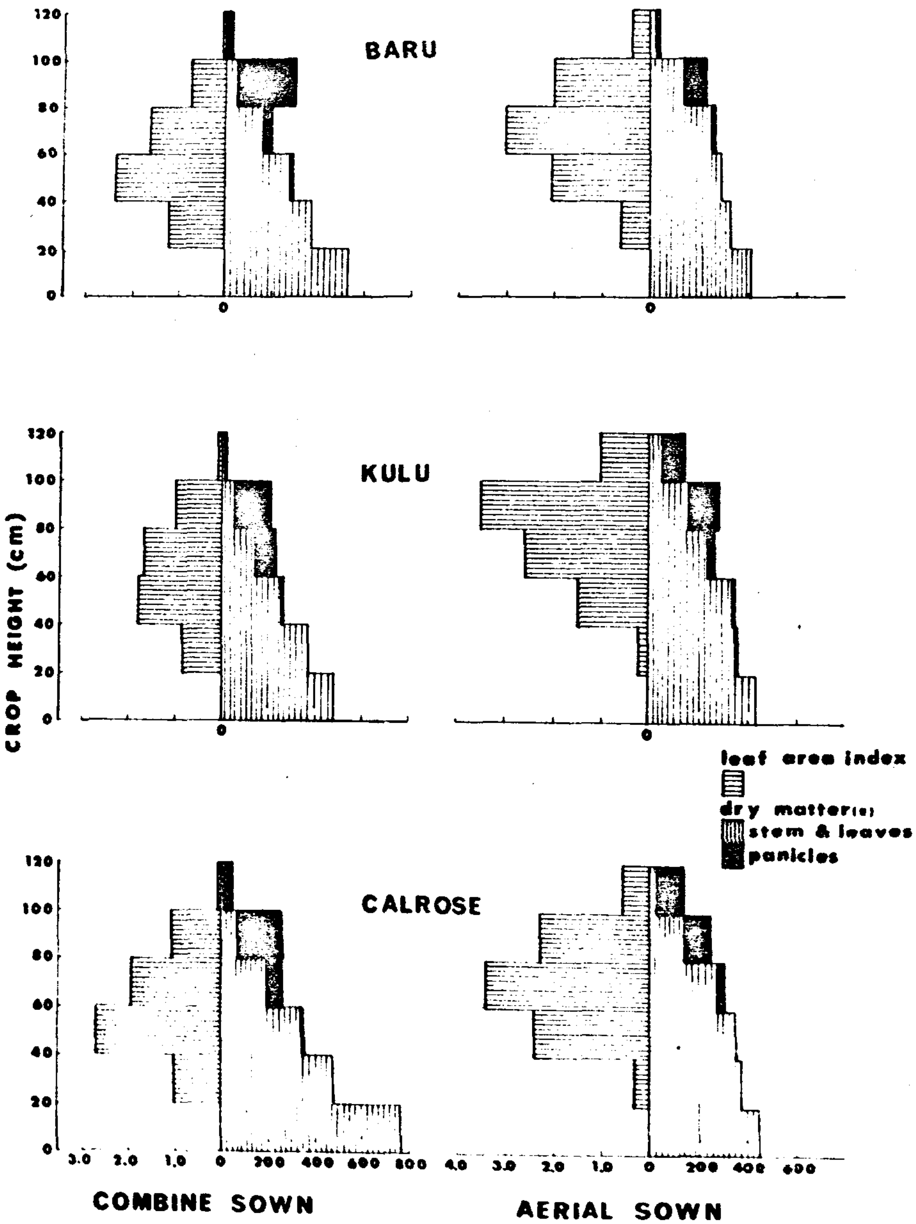


Fig.12

THE EFFECT OF METHOD OF SOWING ON THE VERTICAL DISTRIBUTION OF LEAF AREA AND DRY MATTER AT THREE LEVELS OF NITROGEN (MEAN 3 VARIETIES) 1970-71

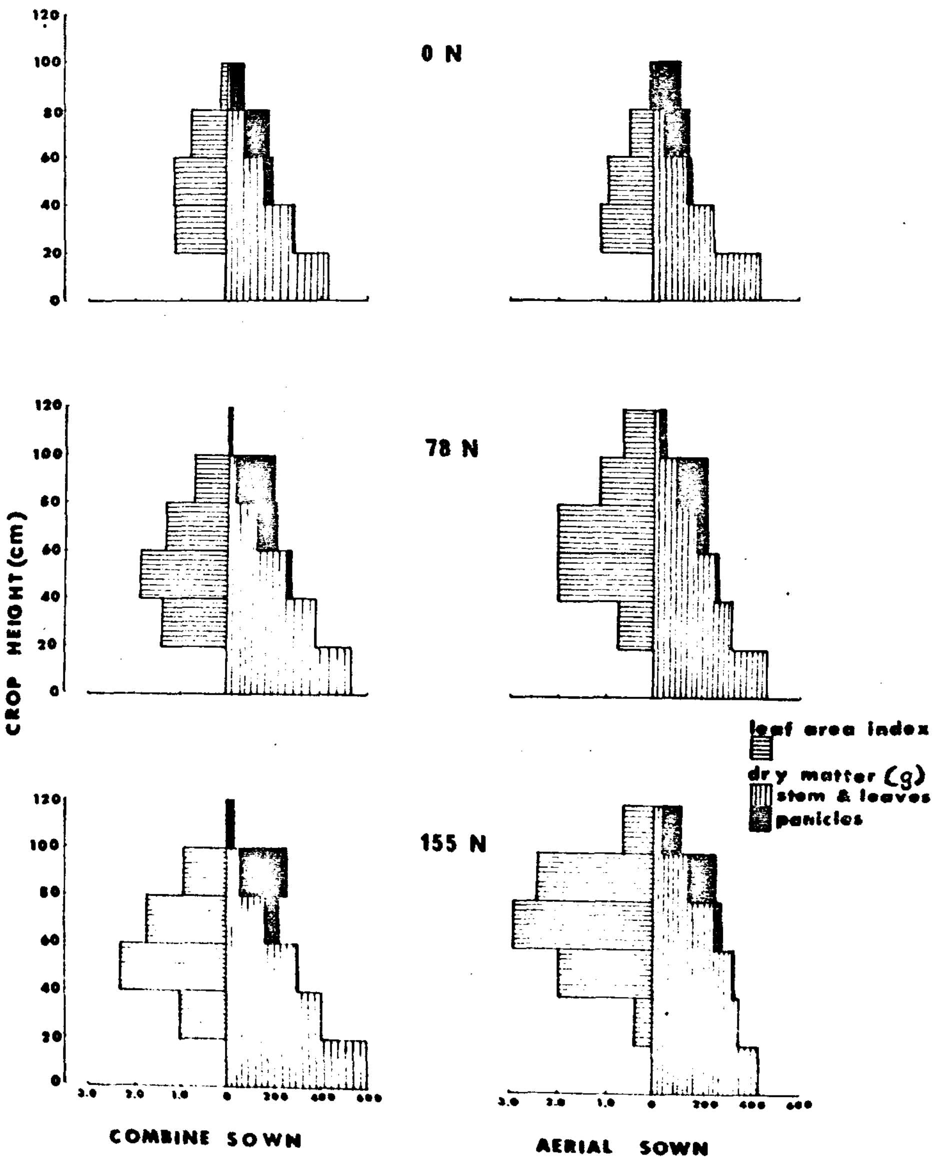


Fig.13

TABLE 16. Light interception within the canopy. (The extinction coefficient, K, is defined by $Q = Q_o \exp(-KL)$ where Q is the flux of visible radiation within the crop below a leaf area index of L and Q_o that above the crop).

Treatment	L.T.R. (%) before panicle initiation on 22.12.70	L.T.R. (%) at flowering	K before panicle initiation on 22.12.70	K at flowering
Combine sown 0 N	93.4	36.7	0.246	.321
Combine sown 155 N	59.6	21.3	0.235	.265
Aerial sown 0 N	75.3	40.3	0.118	.364
Aerial sown 155 N	36.1	19.7	0.068	.200
Calrose	68.3	30.0	0.237	.261
Kulu	61.5	28.0	0.250	.316
Baru	68.6	30.5	0.230	.387
LSD P = 0.05				
Method of sowing	7.6	NS		NS
Varieties	NS	NS		NS
N-rates	7.6	9.8	*	.083

* Analysis of Variance not available.

in combine sown rice, had disappeared at flowering but the N-effect remained. At flowering, canopies of both combine and aerial sown rice were completely closed. Kulu had the most dense canopy, but differences between varieties were statistically not significant.

Differences in K-values for the sowing methods were far greater when measured before panicle initiation than at flowering, whilst varietal differences were smaller before panicle initiation.

(e) Reproductive development

(i) Panicle initiation was recorded as the time the panicle first became visible to the naked eye. Using a microscope, initiation was apparent 4-5 days earlier. Panicle initiation occurred first in primary tillers, followed by secondary and then tertiary tillers.

Aerial sown rice initiated panicles earlier than combine sown rice. Panicle initiation was also advanced by using 155 N. First panicle initiation was recorded for aerial sown Baru on 25.12.70, 77 days after first flooding. Combine sown Kulu initiated last, 87 days after first water.

Internode elongation accompanies panicle initiation and internode length is a guide to time since initiation. Internode length 80 and 87 days after first flooding is recorded in Figure 11.

(ii) Heading was first recorded for unfertilised aerial sown Baru on 20.1.71, 103 days after first flood. Combine sown Kulu with 155 N headed last, 120 days after first water. Overall, aerial sown rice headed 5 days earlier than that combine sown. An application of 155 N delayed heading by 3 days, although panicle initiation was earlier. Baru headed after 108 days, but Calrose and Kulu took 111 and 115 days respectively.

(iii) <u>Maturity</u>. The crop was considered mature when a moisture content of 20-22% was reached. At this moisture level highest whole grain mill returns are obtained and the grain is not very susceptible to "suncracking". Aerial-sown rice was harvested after sampling on 17 March and combine-sown rice on 31 March. The average total period of growth was 159 and 173 days respectively for aerial and combine sown rice. Baru matured on an average 7 days earlier than Calrose and Kulu. The last two varieties matured at the same time, Kulu having a slightly shorter period of ripening. The growing period was shorter than usual due to the very favourable seasonal conditions.

<u>Nitrogen uptake</u>. The uptake of nitrogen by aerial and combine sown rice is presented in Chapter VI. Aerial sown rice took up more N during early growth than combine sown rice and this higher uptake was maintained until maturity. It was concluded that nitrogen losses from both native and applied nitrogen were high during the flushing period of combine sown rice.

Large differences in grain protein content were apparent. Main effects were statistically different (P = 0.01), but none of the interactions were. Aerial sown rice had a protein content of 7.47% compared with combine sown rice of 6.41%. An application of 155 N increased it from 6.21% to 7.67%. Baru had the highest percentage of 7.29%, compared with Calrose 6.50% and Kulu 7.04%.

2. 1971-72 Unreplicated Experiment

(a) Introduction: This experiment was conducted in 1971-72 with identical treatments and on similar soil. Weather conditions were, however, completely different. Record winds after sowing uprooted most of the aerial sown seedlings, which resulted in a sparse plant stand. Combine sown rice emerged very slowly and permanent flood was applied later than normal, thus allowing for a longer period of flushing.

(b) Results: Growth parameters, yield, yield components and N-uptake are presented in Table 17 for the effect of method of sowing on 3 varieties (mean 3 N-rates) and in Table 18 for the effect of three rates of nitrogen (mean 3 varieties). Aerial sown rice tillered extremely well and this, together with a much lower tiller mortality, with increasing N, compensated for lack in plant density. Over all treatments, aerial sown rice yielded 1180 kg ha^{-1} more than that combine sown. There were only small increases in yield of combine sown rice from applied N. A yield increase of only 630 kg ha^{-1} was obtained from 155 N. Unfertilised aerial sown rice yielded 1310 kg ha^{-1} more than that unfertilised combine sown. 78 N increased the yield by 500 kg ha^{-1}, but 155 N reduced the yield substantially.

Tillering, plant height, leaf area, dry matter production, grain-straw ratio and N-uptake show little response of combine sown rice to 78 N, but with 155 N the response is substantial. Aerial sown rice, however, showed an almost linear response to N-additions for all growth parameters. A lower yield from 155 N is also reflected in a lower

TABLE 17. Growth Parameters, Yield and Yield Components of three combine and aerial sown rice varieties (Mean 3 N-rates) (1971-72 Experiment)

Parameter	Combine Sown			Aerial Sown		
	Calrose	Kulu	Baru	Calrose	Kulu	Baru
Plants m^{-2}	387	311	375	66	121	66
Max. Tillers m^{-2}	1200	1279	942	717	931	627
Tiller Mortality (%)	42.1	45.4	44.1	26.1	29.0	23.4
Panicles m^{-2}	695	698	527	530	661	480
Panicles $plant^{-1}$	1.80	2.24	1.41	8.03	5.46	7.27
Plant height (cm)	96.6	97.1	96.1	112.0	105.7	106.3
LAI at flowering	4.74	4.69	3.76	5.31	5.85	3.84
Mean leaf angle (°)	19.6	30.8	11.9	19.4	34.5	15.4
Yield (kg ha^{-1})	9130	8350	10030	10020	8610	11100
Grain-straw ratio	0.84	0.88	1.05	0.90	0.78	1.00
Florets $panicle^{-1}$	68.8	68.0	102.2	129.3	97.1	159.8
Floret sterility (%)	17.0	30.3	23.7	26.7	34.3	24.7
1000 grain weight (g)	28.81	27.95	29.53	25.43	23.88	28.37
Grain protein (%)	5.53	5.95	5.83	7.02	8.03	7.79
N-uptake (kg ha^{-1})	145.2	126.2	96.6	195.6	160.5	193.5
Dry matter (t ha^{-1})	20.26	18.16	19.73	22.86	20.18	24.04

TABLE 18. Growth Parameters, Yield and Yield Components of Combine and Aerial Sown Rice (mean 3 varieties) at three N-rates (1971-72 Experiment).

Parameter	Combine Sown			Aerial Sown		
	0 N	78 N	155 N	0 N	78 N	155 N
Plants m^{-2}	411	334	327	79	98	76
Max. Tillers m^{-2}	1044	1085	1293	853	730	683
Tiller Mortality (%)	42.0	43.7	45.5	42.4	25.3	7.2
Panicles m^{-2}	605	611	705	491	545	634
Panicles $plant^{-1}$	1.47	1.83	2.16	6.22	5.56	8.34
Plant height (cm)	91.3	94.6	103.9	97.0	109.1	117.8
LAI at flowering	3.02	3.99	6.18	3.72	5.19	6.09
Yield (kg ha^{-1})	8820	9230	9450	10130	10630	8980
Grain-straw ratio	0.97	0.94	0.86	0.93	0.88	0.86
Florets $panicle^{-1}$	77.7	78.6	82.7	117.7	140.5	128.0
Floret sterility (%)	17.7	24.3	29.0	21.0	26.0	38.7
1000-Grain weight (g)	29.50	28.22	28.58	27.40	26.08	24.19
Grain protein (%)	5.65	5.65	6.01	6.60	7.50	8.75
N-uptake (kg ha^{-1})	125.4	128.9	142.3	142.0	201.3	206.3
Dry matter (t ha^{-1})	17.58	18.93	21.64	19.95	23.03	24.09

grain-straw ratio.

Aerial sown rice had larger panicles than that combine sown, but at comparable N-rates aerial sown rice had more empty glumes and a lower 1000-grain weight. For both methods of sowing, increasing rates of N produced increased floret sterility and smaller grain.

Unfertilised aerial sown rice utilised as much nitrogen as combine sown rice with 155 N. Combine sown rice utilised little from an application of 78 N, whilst aerial sown rice used a large proportion of the 78 N applied. The efficiency of 155 N was, however, considerably reduced.

Aerial sown rice had a higher grain protein content than that combine sown. Increasing rates of N gave proportional increases in grain protein content in aerial sown rice, whilst only 155 N increased the protein content of combine sown rice.

Kulu established poorest when combine sown and best when aerial sown. Baru tillered least and Kulu most. Baru had also fewest panicles, but these were considerably larger than those of the other varieties. Kulu, the latest flowering variety, had most sterile florets. Baru had also the heaviest grain. When combine sown, Baru yielded 1680 kg ha^{-1} more than Kulu and 900 kg ha^{-1} more than Calrose. Kulu yielded clearly inferior to Calrose and Baru when aerial sown.

Leaf area index and dry matter distribution within the canopy were determined at flowering. Results are presented in Fig. 14.

Combine sown rice was shorter than that aerial sown at all N rates.

LEAF AND DRY MATTER DISTRIBUTION WITHIN THE CANOPY

OF COMBINE AND AERIAL SOWN RICE AT FLOWERING 1971.72

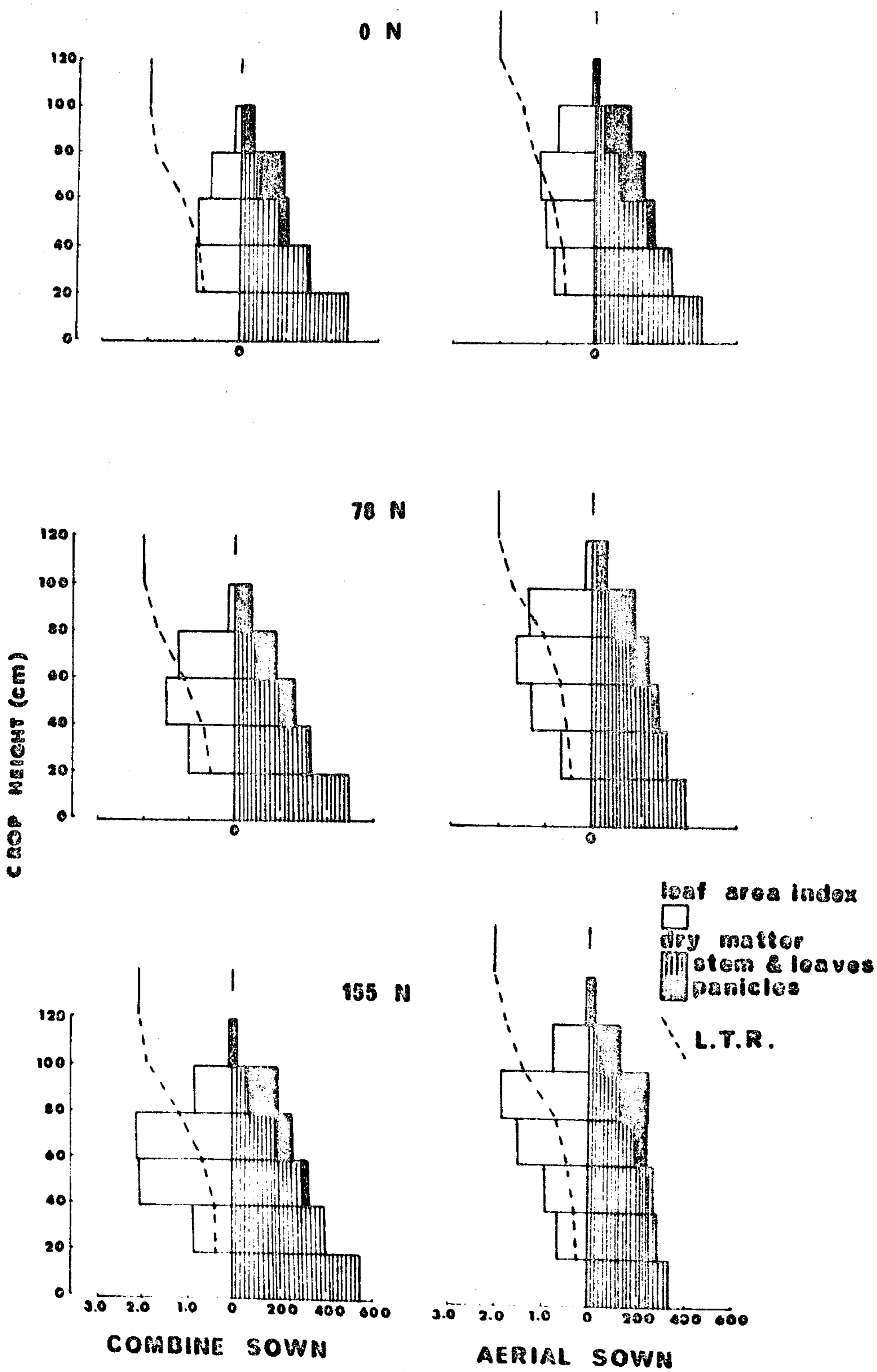


Fig.14

It produced most dry matter (all stems) in or near the flood water and it decreased gradually upwards. The difference in dry matter production between 0 and 78 N was small which may be reflected in the small yield differences (8820 and 8890 kg ha^{-1} respectively). With 155 N the increase in yield was greater (9450 kg ha^{-1}) which may also be reflected in the considerably higher leaf area index and dry matter production.

Aerial sown rice had also most of the dry matter at 0-20 cm. With 78 and 155 N much more leaf was higher in the canopy and this resulted in a very much more even distribution of dry matter within the crop profile. At 155 N this resulted in lodging of the varieties Kulu and Calrose after grain set, simply because the plants became top-heavy

3. Comparative performance over the two seasons

There were considerable climatic differences. In 1970-71 weather conditions were almost ideal for rice growing, but in the following year emergence was slow and low temperatures during meiosis and flowering caused a higher percentage floret sterility. Yield comparisons are presented in Table 19.

In the first year, combine sown rice responded excellently to nitrogen, giving yield increases of 850 and 2070 kg ha^{-1} from 78 and 155 N respectively. In the second year unfertilised rice yielded somewhat less, and it responded little to nitrogen; only 410 and 630 kg ha^{-1} respectively from 78 and 155 N. Kulu yielded less than Calrose and Baru in both years. There was no difference in yield between the latter two varieties in the first year but Baru outyielded Calrose in the second,

TABLE 19. Comparison of yields from Method of Sowing x N-rates x Varieties. Experiments over two seasons.

Method of Sowing	Variety	N(kg ha^{-1})	Yield kg ha^{-1} 1970-71	Yield kg ha^{-1} 1971-72
Combine	Calrose	0	10180	8960
		78	10880	9310
		155	12060	9120
	Kulu	0	8320	8110
		78	-	8750
		155	9790	8180
	Baru	0	9090	9390
		78	10620	9630
		155	11950	11060
Mean combine sown Varieties	Calrose		11040	9130
	Kulu		8920	8350
	Baru		10550	10030
Mean combine sown N-rates	0 N		9200	8820
	78 N		10050	9230
	155 N		11270	9450
Aerial	Calrose	0	8660	10630
		78	11210	11150
		155	9100	8270
	Kulu	0	9050	9650
		78	10530	8740
		155	7080	7440
	Baru	0	7850	10060
		78	10470	12000
		155	6560	11230
Mean aerial sown Varieties	Calrose		9660	10020
	Kulu		8890	8610
	Baru		8290	11100
Mean aerial sown N-rates	0 N		8520	10130
	78 N		10740	10630
	155 N		7580	8980

especially at 155 N. Over all treatments, combine sown rice yielded 1000 kg ha^{-1} less in the second year.

However, aerial sown rice in the second year yielded some 1630 kg ha^{-1} more than that combine sown. The low yield of unfertilised rice in 1970-71 was thought to be due to a very rapid early growth, resulting in many small panicles with a high floret sterility (possibly also partly due to 1 or 2 early cold nights, since these unfertilised treatments flowered earlier than others). In both seasons aerial sown rice responded well to nitrogen up to 78 N. When 155 N was applied, it resulted in drastic yield reductions, mainly due to early lodging. The reduction in yield was most serious in the first year.

Baru yielded poorly at low and high N in the first year. Calrose yielded highest at both 78 and 155 N and proved to be well adapted to all levels of fertility. In the second year the variety Kulu was clearly inferior. Baru, with greater culm strength had a relatively small yield reduction at 155 N. At 78 N Baru produced an exceptionally high yield. Calrose performed better than Baru at low N.

D. Discussion

It was clear that higher temperatures following sowing was advantageous to pre-germinated aerial sown seed, and to a lesser extent also applied nitrogen was beneficial to an early start and this resulted in more rapid growth, earlier development and earlier ripening. However, high supplies of nitrogen, especially with aerial sowing, resulted in very high leaf area and subsequent lodging and poor grain set, small grain and low yields. It is likely that this lodging was directly associated with

N-uptake - this will be explored in a later chapter - and that this in time interfered with the light supplies to the leaves, leading to the small grain. The factors involved in the relation between grain set and nitrogen supply are much more uncertain.

Curvilinear relationships between grain yield and leaf area have often been claimed for many species. Rather poor relationships were found in the present study (Figs. 15 and 16) but there was usually evidence of a decline in yield associated with maximum leaf area of about 8. However, it was clear that there was no relationship between yield and leaf area, mainly because lodged treatments were included in the analysis; many other components must have been involved. Higher order polynomials may have given a improved fit.

Many authors working with tall _indica_ varieties have reported a distinct optimum L, mainly because of mutual shading of leaves in low light intensity situations (Tanaka and Kawano, 1966;

Kanada and Sato, 1963; Murata, 1961). Nevertheless, with the non-lodging variety IR 8, a distinct optimum has been detected, although a plateau was reached (Yoshida, et al., 1972). These workers concluded that the detrimental effects of a large L were due to lodging and increased leaf droopiness which reduced photosynthesis. However, no positive analysis was made by them, nor attempted in this study.

Correlations of grain yield with L measured at intervals throughout the season were also explored (Table 20). This simple analysis provided good correlations until flowering, but it failed with the aerial-sown treatments.

Leaf area is greatly dependent on the number of tillers produced per unit area. There was considerable difference in tillering ability of

Yield as a function of maximum Leaf Area Index.

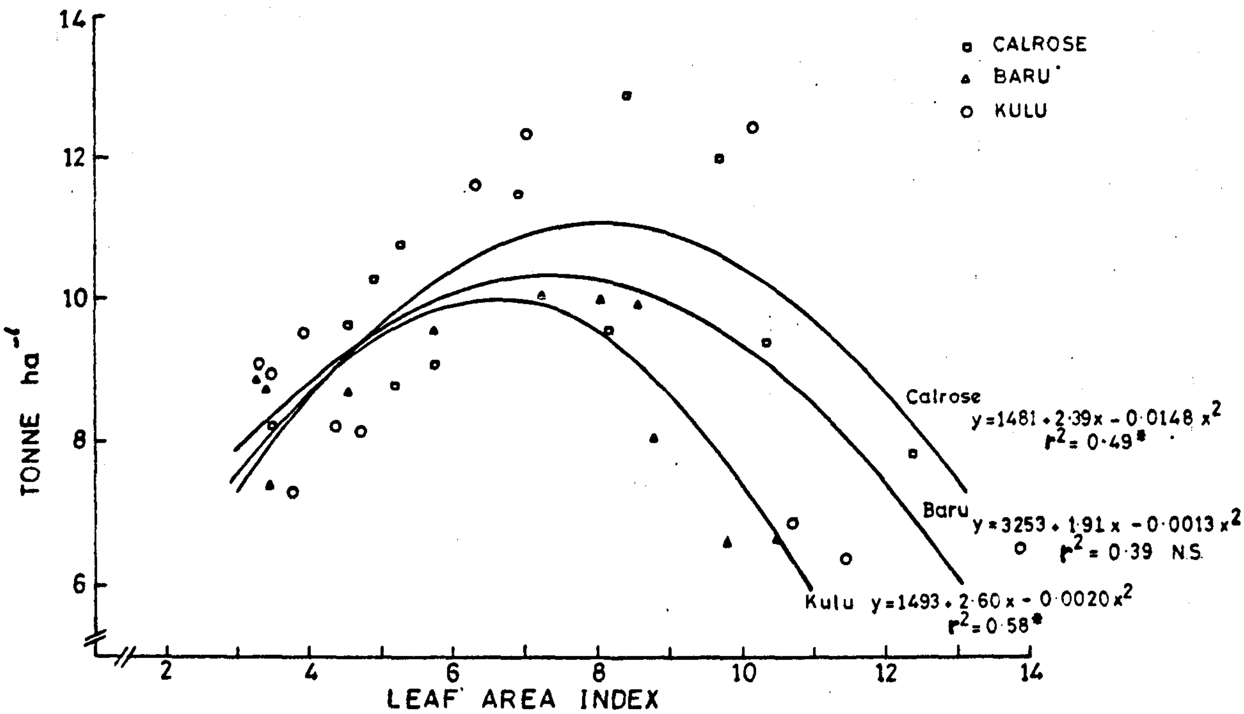


Fig.15

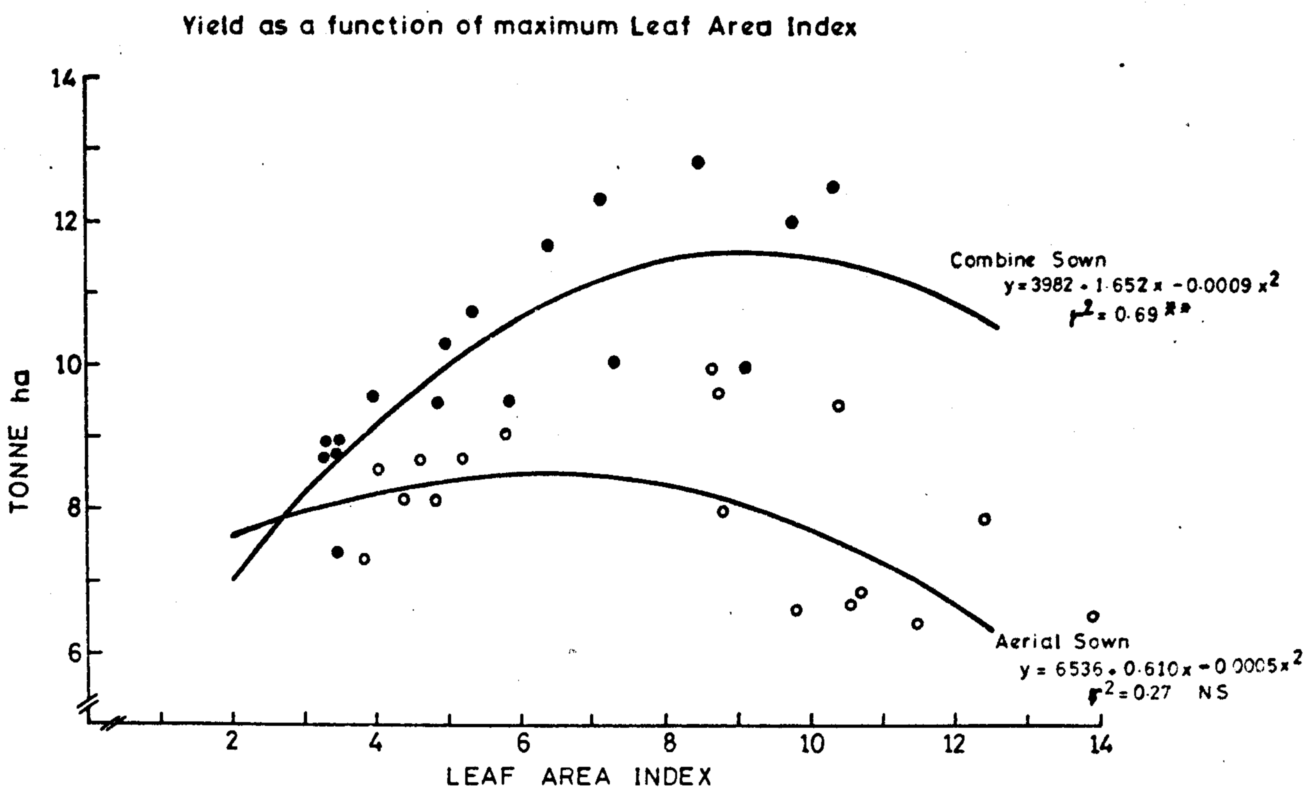

Yield as a function of maximum Leaf Area Index
14
12
10
8
6
TONNE ha
Combine Sown
y=3982 + 1.652x - 0.0009x²
r² = 0.69 **
Aerial Sown
y = 6536 + 0.610x - 0.0005x²
r² = 0.27 NS
2
4
6
8
10
12
14
LEAF AREA INDEX

Fig.16

TABLE 20. Correlation of Grain Yield with Leaf Area Index (mean 0 and 155 N) of combine and aerial sown rice.

Sampling date	Combine Sown	Aerial Sown
11 November	NS	NS
25 November	.78**	NS
9 December	.58**	NS
23 December	.82**	NS
6 January	.65**	NS
20 January	.76**	NS
3 February	.76**	NS
17 February	.54*	-.48*
3 March	.53*	-.56*
17 March	.58*	NS

* significant at P = 0.05

** significant at P = 0.01

the varieties. Baru tillered least, and compensated for a lack of tillers by producing large panicles. To fill these individual sinks this variety produced the largest leaf area per tiller. This leaf area did not appear to be capable of filling each floret, resulting in a high percentage floret sterility. The lower grains on the large panicles were somewhat smaller than the higher ones, indicating either an incomplete filling of the endosperm or smaller florets. Evolution in wheat has involved a parallel increase in leaf and grain size (Evans and Dunstone, 1970). A higher yield due to a larger panicle size may be similarly synchronised with the larger leaf area per panicle for Baru. Few of these possible relationships have yet been documented adequately with any cereal.

The number of tillers equivalent to the final panicle number was obtained 5-6 weeks after emergence of combine-sown rice. This number was reached after only 4 weeks with aerial sowing. Many more tillers were subsequently produced but most died before heading. Similar results were obtained by Mahapatra and Sharma (1970), who found that over 90% of the total grain yield was produced from tillers developed within 4 weeks of transplanting. The first-formed tillers contributed most to yield. It is expected that tiller development of direct-sown rice under the cooler conditions in New South Wales is slower than that of transplanted rice in India. The excellent vigour of aerial-sown rice, however, compares favourably with that of transplanted rice in the tropics.

Tiller mortality was high, reaching with aerial sowing and high nitrogen almost 50%. Sterile and dying tillers are, however, not to be considered as a complete loss. They may act as a temporary reservoir for fertile plant parts, as Rawson and Donald (1969) found that most of the N from dying wheat tillers was remobilised and apparently directed to other parts of the plant. (The proportions involved depend, however, on supplies still available in the soil, balances with other nutrients and on the potential rate of growth).

Greater seedling vigour due to aerial sowing and high N was reflected in a high initial crop growth rate. Peak growth rates were observed at stem elongation, just prior to flowering. Combine sown Calrose with 155 N had maximum C of 43 g m^{-2} d^{-1} during a 14-day period. This is higher than reported for rice elsewhere. Over a comparable period C was 28 g m^{-2} d^{-1} in the Philippines (Anon. 1968) and 33 g m^{-2} d^{-1} in Japan (Murata, 1961). This is possibly due to higher levels of solar radiation, a high plane of nutrition and a suitable plant type. Van Ittersun (1971), using models, considered high growth rates during the generative period necessary for high yields.

In recent years research workers have shown that the photosynthetic rates of rice varieties, although generally low, vary considerably (Osada, 1964; Osada and Murata, 1965; Tanaka et al. 1966; Anon., 1968; McDonald, 1971). High photosynthetic capability is, however, not positively correlated with grain yield.

Rice leaves remain green, or partly green until maturity, whilst the panicle turns yellow relatively early. Reported values of panicle photosynthesis range from 8 to 23 percent of the total amount photosynthesised in rice (Enyi 1962; Takeda and Maruta, 1956). Other authors found, however, very low rates of panicle photosynthesis (Yoshida, 1972). It is suggested from ^{14}C translocation studies that only the top three leaves are important in grain filling (Tanaka, 1958). Since the top leaves remain green and may be photosynthesising actively until a late stage, together with possible photosynthesis in the panicle, a high E may result during ripening. E was not as high with the fertilised aerial-sown treatments as in the other treatments because of lodging, where a large number of florets did not fill, although many leaves remained green.

It has been demonstrated by Kobayashi and Hitaka (1968) that lodging of rice at ripening severely affects the photosynthetic activity and the associated translocation of photosynthates from leaves to grain. Their results were confirmed in this experiment where lodged aerial sown rice had low yields, although their potential was high because of the larger number of florets per unit area. A high percentage floret sterility and a low 1000-grain weight caused the yield reduction and this could be due to a low photosynthetic activity, a reduced translocation after lodging, or both.

Watson (1952) has shown that the time trend of E under field conditions follows the seasonal climatic trend. He considered that short period deviations can be related to fluctuations in climatic factors. Low E values in the first week in January did coincide with a period of very low minimum temperatures. Before and during flowering, temperatures were favourable for crop growth and this may be reflected in a slight peak of the E curve for both combine- and aerial-sown rice. That this occurs one period earlier for aerial sown rice indicates, however, that this peak may be associated with the developmental stage of the crop. There was considerable increase in dry matter during this stage whilst L decreased.

Nitrogen appears to have had little effect on E, although the high L obtained with 155 N may have reduced E somewhat through mutual shading and possibly through reduced CO_2 concentrations lower in the canopy.

Models for photosynthesis in plant communities have established that erect leaves are the most efficient arrangement for maximum photosynthesis when L is large (Yoshida, 1972). Matsushima et al. (1964) concluded, however, that plants with erect upper leaves grading to more horizontal ones lower in the canopy are most desirable. An erect-leaved arrangement can only be beneficial when L is large, or when light intensity is low. There was very little difference in leaf angle between the sowing and nitrogen treatments. However, there was a large varietal difference, with Baru having very erect leaves and Kulu having the most droopy ones. Together with a large leaf area per tiller it makes Baru a very attractive plant type for the interception of radiation.

Combine-sown rice established slowly, but leaves of the young plants could photosynthesise immediately after emergence. Aerial sown rice developed quickly, but the whole plant was under water for the first 15-20 days. Then the leaves floated on the water and only the new leaves became erect, whilst the floating leaves died. Combine-sown rice emerged 20 days after sowing. Active photosynthesis commenced therefore almost at the same time. After permanent flood was applied 21 days after emergence, most of the lower leaves were submerged and this could have reduced the rate of photosynthesis.

Total dry matter production is the integral of C over the entire period of growth. It is related to grain yield by the "harvest index", which Donald (1968) called the coefficient of effectiveness of formation of the economic part of total yield. The harvest index is equivalent to the grain-straw ratio. Grain yield can be increased either by increasing the total dry matter production or by improving the grain-straw ratio. It has been shown by Kiuchi et al. (1966) that in rice an allometric relationship holds between yield of paddy rice, and total dry matter production up to about 10,000 kg ha^{-1}, grain yield increasing more slowly than total dry matter production. Yoshida (1972) quotes Murayama (1967) and Shigemura (1966), who found that the grain-straw ratio tends to be less favourable as the dry matter production increases.

Tall tropical indica varieties which are supposed to show little response to nitrogen, have a very low grain-straw ratio. Varieties highly responsive to N with a semi-dwarf stature are non-lodging and have usually a ratio of one or better. Baru with very large panicles had the most favourable grain-straw ratio, whilst the most leafy variety Kulu produced the least favourable ratio. Aerial sown rice with 155 N grew similarly to the tall indica varieties in the tropics and produced a very low ratio, whilst combine-sown rice with 155 N had a ratio of almost 1.0.

As was to be expected there was a linear increase in panicle weight with increasing numbers of florets per panicle in the combine-sown treatments (Fig. 17). However, aerial-sown rice showed very little variation both in panicle weight and panicle size as determined by number of florets

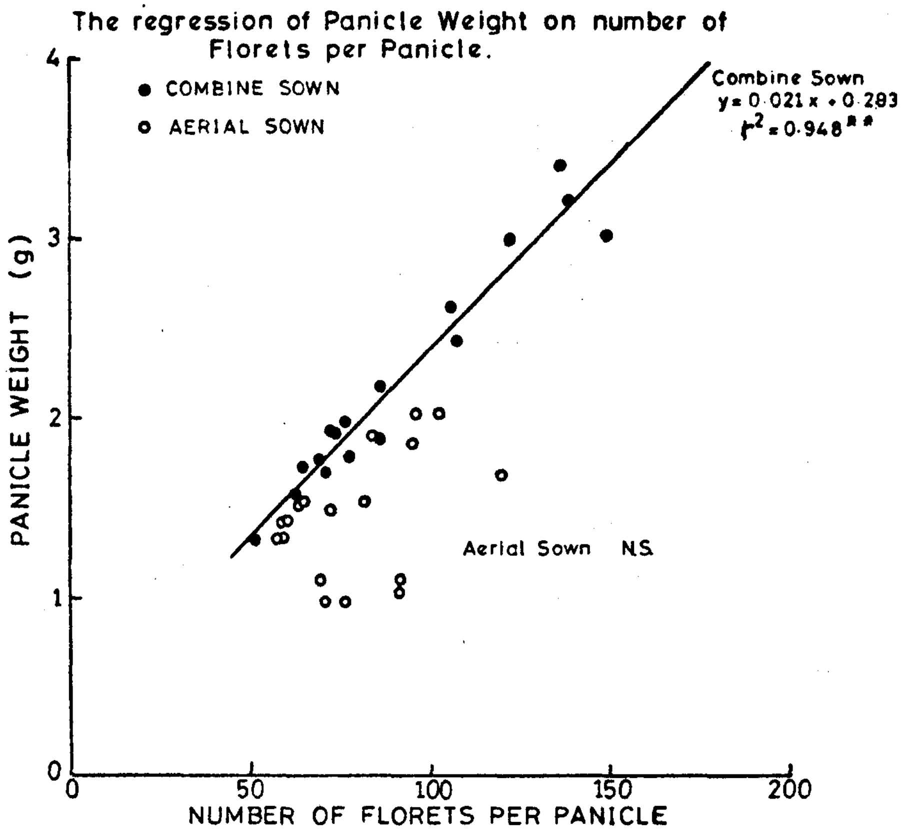

The regression of Panicle Weight on number of Florets per Panicle.
● COMBINE SOWN
o AERIAL SOWN
Combine Sown
y= 0.021x + 0.283
r² = 0.948**
Aerial Sown N.S.
PANICLE WEIGHT (g)
NUMBER OF FLORETS PER PANICLE
0
1
2
3
4
0
50
100
150
200

Fig.17

per panicle. This was due to the many small panicles at 155 N.

Potential grain yield as determined by the number of panicles, number of florets per panicle and a 1000-grain weight of 28.6 gram was calculated and compared with the yield actually obtained from combine and aerial sown rice with 0 and 155 N. The discrepancy was then compared with the floret sterility and the reduction in grain size (Table 21). The calculated difference between potential and actual yield for combine sown rice was about 22 percent, irrespective of N supply. This difference was considerably higher with aerial sowing, 29.8 percent for that unfertilised and 55.6 percent for rice fertilised with 155 N. A high percentage floret sterility and a reduced grain weight accounted for most of this difference. It is estimated that a sampling error of 5-10 percent may have occurred due to the relative small sample of 20 panicles per plot for the estimation of grain number per panicle and the floret sterility.

The lower grain-set for unfertilised aerial-sown rice may have been due to lack of nitrogen which caused a smaller leaf area during grain-set or possibly to slightly lower temperature conditions during or before flowering. The high percentage floret sterility and a low 1000-grain weight of fertilised aerial sown rice was no doubt due to lodging, which may have reduced the flow of assimilates to the panicle or reduced the photosynthetic capacity of the plant.

Calculations were made on a 1000-grain weight of 28.6 gram. With added nitrogen a significant lower grain weight was obtained. For aerial sown rice this was due to lodging. Grain weight is a quite stable

TABLE 21. The effect of floret sterility and grain weight on yield of combine and aerial sown rice at 0 and 155 N.

Treatment	Potential Yield t ha-1	Actual Yield kg/ha x 10^3	Percent deficit between actual and potential yield	Percent Floret Sterility	Percent Decrease in 1000-grain weight
Combine sown ON	11.7	9.2	22.4	11.8	-
Combine sown 155N	14.4	11.3	21.5	15.0	- 1.9
Aerial sown ON	12.1	8.5	29.8	20.4	-
Aerial sown 155N	17.1	7.6	55.6	37.9	-13.1

varietal character with a variation coefficient of usually less than 5 percent over different years (Matsushima, 1970). A reduced grain weight is likely to arise from incomplete filling of the endosperm.

The increase in crop growth rate and net assimilation rate during the last 2-3 harvests has been noted earlier and is worth comment. The major issue concerns the reality of this response; is it simply an artifact of fitting a cubic curve (when slight trends could well be exaggerated) or is it a real response? The final harvests were made at the time when the grain moisture content was 20-23% which is required to obtain the highest economic yield and highest return of whole grains following milling (McDonald, 1967). There were then an appreciable number of immature grains and 2-3 green leaves. Rates of senescence as well as rate of grain growth could contribute to the overall effect but evidence is not available on these aspects. Differences between adjacent harvests in any one treatment or overall means were not significant but this is a crude test. This apparent surge was found in treatments at both times of sowing in both years, which at least suggests that it may be real. It is worth exploring much more fully with harvests of greater frequency and separating grain and panicle weights from the remainder of the plants.

V. PLANT DENSITY AND NITROGEN ON GROWTH, YIELD AND YIELD COMPONENTS OF THREE RICE VARIETIES

A. INTRODUCTION

Farmers in the Murrumbidgee Valley use from 110 to 160 kg seed ha^{-1} for combine sown crops of Calrose and Kulu. From previous experiments it had been found that a seedrate of 120 kg ha^{-1} was adequate for most seedbed and soil temperature conditions when the crops were adequately irrigated.

The newly developed variety Baru (Boerema, McDonald and Lewin, 1974) has a high yield potential but it tillers very poorly. It was therefore necessary to investigate if a denser plantstand than normal was required at different levels of nitrogen nutrition.

The literature on interactions between plant characters, spacing and nitrogen has been reviewed in general by Donald (1963) and in respect of rice by Yamada (1961) and Matsuo (1964) and more recently by Yoshida (1972). Higher plant densities and increased nitrogen supply generally produced a higher LAI and more total dry matter. Yamada (1961) concluded that rice is generally very tolerant to high plant densities. Grain yield did not increase above a certain panicle density due to a reduction in number of grains per panicle. Strong tillering is important under conditions of poor establishment; this can only be offset by a high seedrate if the occurrence of such conditions can be predicted.

Varieties have been divided into "panicle-number" types which tiller strongly and "panicle-weight" types which produce large panicles on fewer tillers. There are strong indications that direct-seeded crops in the tropics produce higher yields from panicle-weight type than from panicle-number type varieties (De Datta, 1969; Langfield, private communication).

B. METHODS

Identical experiments were carried out in 1970-71 and 1971-72, using all combinations of the varieties Calrose, Kulu and Baru at a low plant density (34 kg seed ha^{-1} sown at a row spacing of 36 cm) and a high density (135 kg seed ha^{-1} at an 18 cm row spacing) and with 0 and 155 kg nitrogen ha^{-1}. Both trials were drill sown and fertiliser was applied as ammonium sulphate with the seed at a depth of approximately 2 cm. Fertiliser was always applied in 18-cm rows irrespective of the space between seed rows. Seed was treated with a fungicide (Captan) and insecticide (DDT) mixture.

Experiments were carried out in adjacent bays. Levels of soil fertility in each year were similar; each experiment followed 4 years of legume pasture, and nitrogen levels were fairly high.

In the first year, only data on plant number, yield and yield components were obtained, whilst in the second year a complete growth analysis was carried out with sampling at fortnightly intervals.

C. RESULTS

I. Experiment I, 1970-71

Plant density at time of permanent flood was significantly affected by the seedrate used and by the variety (Table 22). Calrose establishment was superior at both seedrates. Nitrogen did not affect the plant stand.

Calrose and Kulu produced almost identical yields with very little difference between yield components of the two varieties (Table 23). Baru yielded significantly less and had fewer panicles per unit area. These panicles had almost double the number of florets, but many did not set grain.

There was no difference in yield due to seeding rate. Low plant densities were largely compensated for by more tillers, larger panicles and less floret sterility. The 1000-grain weight was higher at high seedrate because of the low grain weight obtained from the very large panicles of Baru at high N and low density.

Nitrogen increased yield by increasing the number and size of panicles, although floret sterility increased and 1000-grain weight decreased.

II. Experiment II, 1971-72

Length of growing season from the first irrigation on 1.10.71 to harvest on 12.4.72 was 195 days. Panicle initiation was recorded on 24.12.71 for Baru with Calrose 6 days and Kulu 13 days later. All varieties took 35 days from initiation to heading. Date of first heading coincided with first flowering which continued for approximately 14 days in the same treatments. The experiment was drained when Calrose reached the late dough stage on 23.3.72, and was harvested on 12.4.72. Although there was considerable difference in time of first heading, the

TABLE 22. Plant density as affected by seedrate and variety at time of permanent flood (Exp. I). The figures in brackets indicate the estimated numbers of seed sown using Calrose, Kulu and Baru with a 1000 grain weight of 28.5, 27.0 and 28.0 respectively.

Variety	Number of plants m^{-2}		Variety Means
	34 kg seed ha^{-1}	135 kg seed ha^{-1}	
Calrose	86 (97)	353 (385)	220
Kulu	33 (92)	161 (365)	97
Baru	44 (95)	198 (378)	121
Seedrate means	54	238	

L.S.D. P = 0.05

Variety means (V) = 33

Density means (D) = 27

V x D = 46

TABLE 23. The effect of plant density and nitrogen on yield and yield components of Calrose, Kulu and Baru in Experiment I.

Variety	Yield kg ha^{-1}	Panicles $-m^2$	Florets $Panicle^{-1}$	Empty Glumes (%)	1000-grain weight (g)
Calrose	9230	538	87.5	14.8	28.51
Kulu	9150	525	90.9	13.3	27.09
Baru	8340	335	156.0	23.4	27.78
Density					
Low	8710	400	132.0	15.0	27.19
High	9100	532	91.0	19.3	28.40
N-rate					
0 N	8060	434	102.9	15.7	28.01
155 N	9750	498	120.0	18.7	27.58
L.S.D. P = 0.05					
Variety (V)	472	52	10.1	1.92	.47
Density (D)	NS	42	8.3	1.56	.38
N-rate (N)	385	42	8.3	1.56	.38
V x D	NS	73	14.3	2.71	NS
V x N	NS	73	14.3	NS	.66
D x N	NS	NS	11.7	NS	NS
V x D x N	NS	NS	NS	NS	NS

three varieties matured together. The average harvest moisture content was 21.2% which is close to the optimum for high milling quality. The growing season was longer than normal due to low temperatures during establishment and around heading.

1. Yield and Yield Components

Baru outyielded Calrose and Kulu at both N-rates (Table 24). An application of 155 N increased yields significantly in both Calrose and Baru but not in Kulu, which gave rise to the significant V x N interaction.

Baru produced least panicles, had characteristically a large panicle and had a relatively high percentage floret sterility. Its grain was larger than that of Kulu and Calrose. Kulu yielded less than Calrose, mainly due to a higher percentage floret sterility and smaller grains.

Yield differences due to plant density were not significant. Fewer panicles were compensated for by a greater panicle size (number florets $panicle^{-1}$). Nitrogen increased yields greatly by producing more and larger panicles. At high N floret sterility was higher and the 1000-grain weight was reduced, which prevented a realisation of even higher possible yields.

2. Tillering

Plant density was only affected by seed density. At high density the average plant density was 298 plants m^{-2} and at low density this was 73 plants m^{-2}. There was no difference due to variety or N-rate.

Tillering commenced after first sampling on 10.11.71 and continued

TABLE 24. The effect of Variety, Plant Density and N-rate on Yield and Yield Components in Experiment II.

Variety	Yield kg ha^{-1}	Panicles m^{-2}	Florets $Panicle^{-1}$	Empty Glumes (%)	1000-grain weight (g)
Calrose	9280	591	83.4	19.4	28.51
Kulu	8480	601	81.1	30.5	27.85
Baru	10700	445	123.6	25.2	29.32
Density					
Low	9370	427	109.8	24.9	28.82
High	9600	664	82.3	25.2	28.30
N-rate					
0 N	8900	501	93.5	23.1	28.84
155 N	10070	590	98.6	27.0	28.29
L.S.D. P = 0.05					
Varieties	550	37	10.4	2.9	.65
N-rates	449	30	NS	2.4	.53
Density	NS	30	8.5	NS	NS
V x N	778	NS	NS	NS	NS
V x D	NS	NS	14.7	4.1	NS
N x D	NS	NS	NS	NS	NS
V x N x D	NS	NS	NS	NS	NS

until 8.12.71. The greatest increase in tillers occurred between 24.11.71 and 8.12.71. Thereafter tiller number gradually decreased until a constant level was reached at flowering in mid February 1972 (Fig. 18).

Both maximum number of tillers and final panicle numbers were largest at 155 N at both plant densities. Most tillers and panicles were produced at high plant density. Baru tillered significantly less than Calrose and Kulu and produced therefore significantly fewer panicles (Table 25).

Baru produced fewest panicles but these were extremely large. All varieties produced more and larger panicles at low density. Nitrogen had a much greater effect on panicle number than on panicle size.

3. Leaf Area

The leaf area index (L) was small during early growth and increased rapidly during tillering. Maximum L was reached at, or slightly after flowering. It was reached earlier at high N and at high density, where it also produced the highest maximum L (Table 26).

Calrose had the greatest L, but there was little difference between Kulu and Baru. Maximum L increased by a value of 2.75 when 155 N was applied, however values were appreciably lower than in the experiments described in the last chapter where aerial seeding was used and more nitrogen was available. At harvest, L varied between 1.0 and 2.5, which indicates that photosynthesis could still have been substantial. A quadratic equation fitted all data well (Fig. 19), although observed

TABLE 25. The effect of plant density and nitrogen on panicle development of the varieties Calrose, Kulu and Baru in Experiment II.

Varieties (V)	Panicles m^{-2}	Panicles Plant $^{-1}$	Panicle Size (Florets panicle^{-1})
Calrose	591	4.27	83.4
Kulu	601	4.98	81.1
Baru	445	3.36	123.6
Density (D)			
Low	427	6.06	109.8
High	664	2.35	82.3
Nitrogen (N)			
0 N	501	3.80	93.5
155 N	590	4.62	98.6
L.S.D. P = 0.05			
V	37	.87	10.4
D	30	.71	8.5
N	30	.71	NS
V x N	NS	NS	NS
V x D	NS	NS	14.7
N x D	NS	NS	NS
V x N x D	NS	NS	NS

TABLE 26. The maximum leaf area index of three varieties, low and high plant densities and 0 and 155 N in Experiment II.

Varieties	Max. L	Density	Max. L	Nitrogen	Max. L
Calrose	6.30	Low	5.22	0 N	4.22
Kulu	5.28	High	5.97	155 N	6.97
Baru	5.18				
L.S.D. P = 0.05	.74		.60		.60

Interactions were statistically not significant.

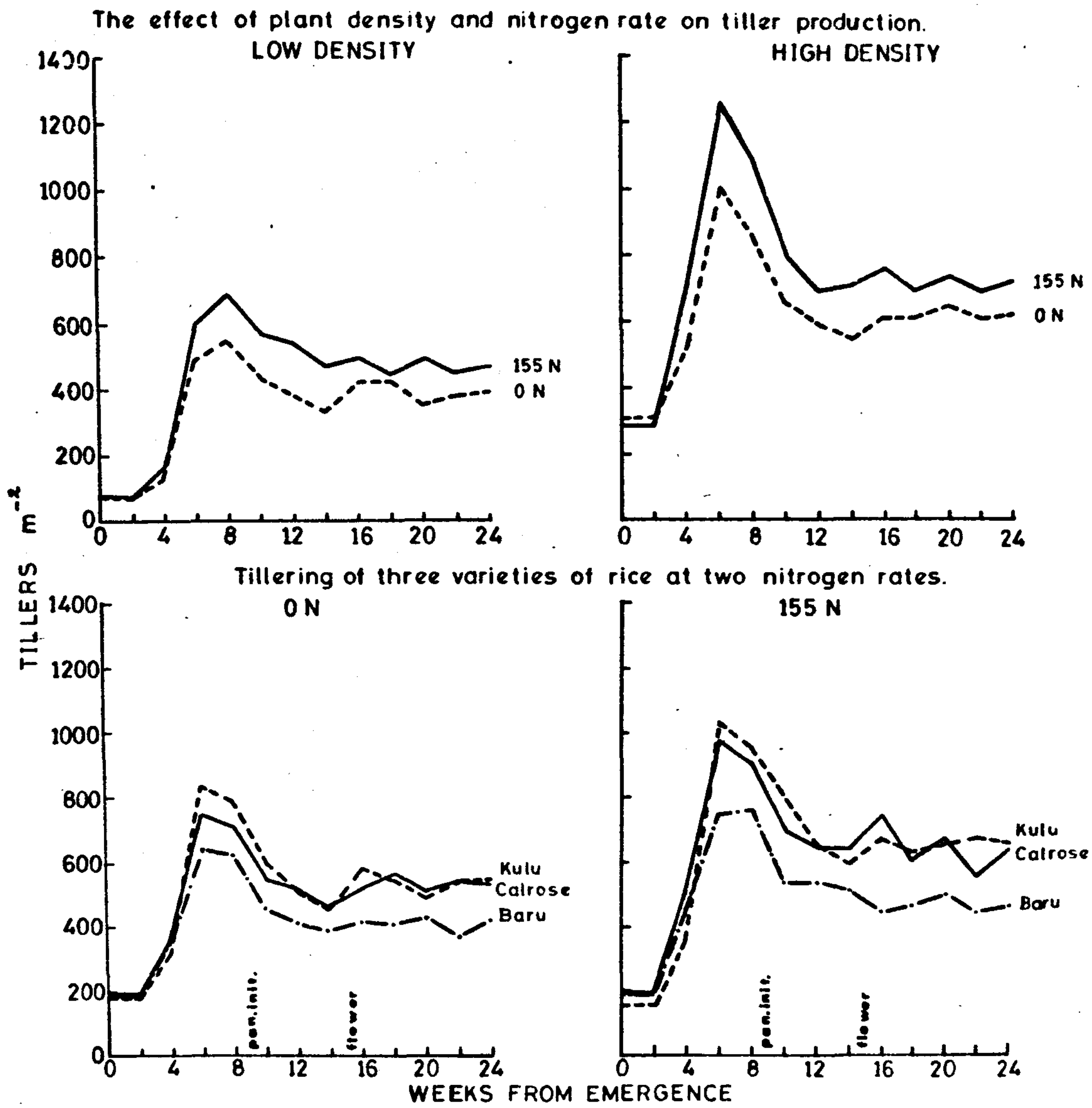

The effect of plant density and nitrogen rate on tiller production.
LOW DENSITY
HIGH DENSITY
155 N
0 N
Tillering of three varieties of rice at two nitrogen rates.
0 N
155 N
Kulu
Calrose
Baru
pan. init.
flower
TILLERS m⁻²
WEEKS FROM EMERGENCE

Fig.18

The effect of plant density and nitrogen on the Leaf Area Index.

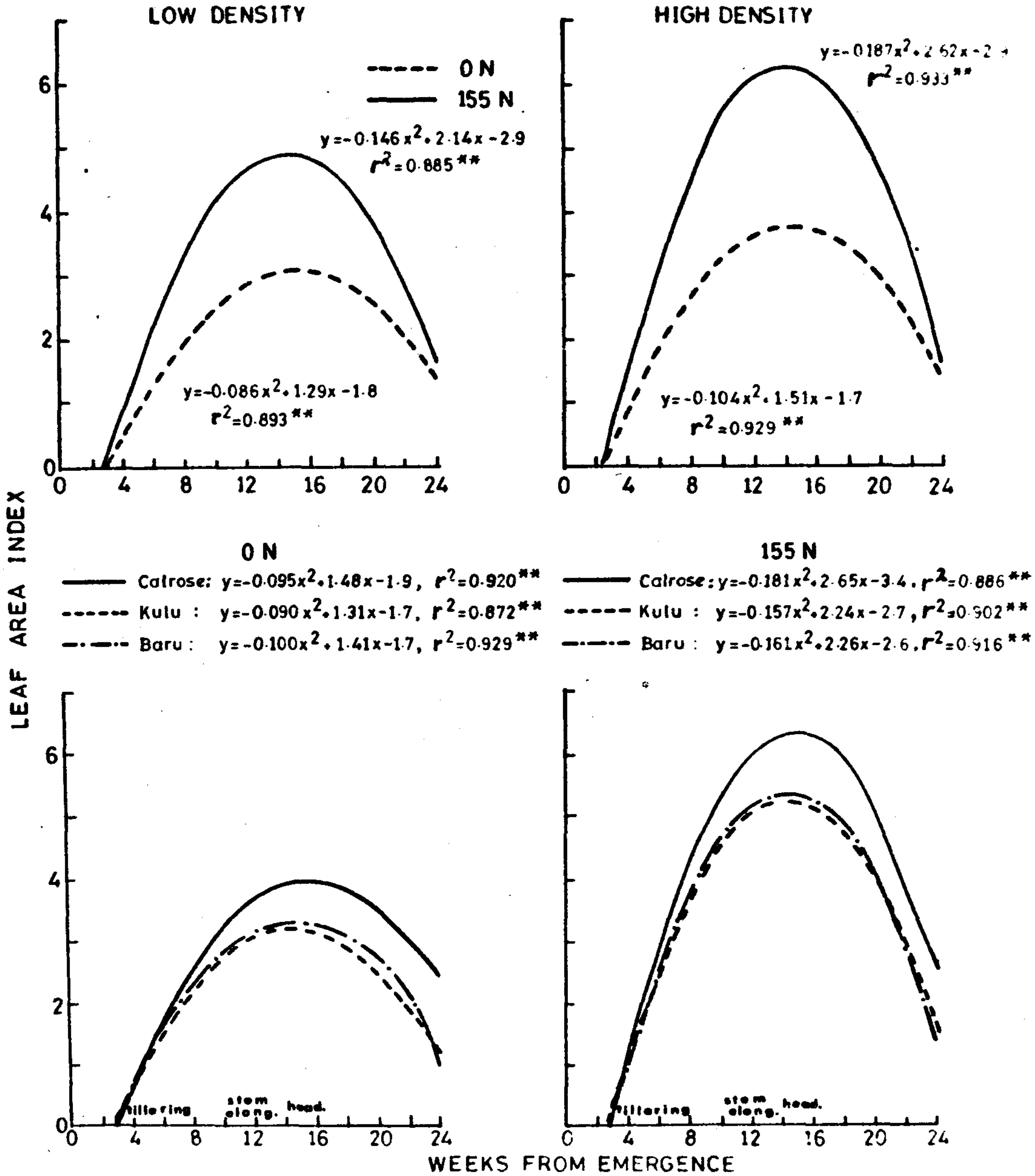


Fig. 19

values around the time of stem elongation were consistently greater than those predicted.

An application of 155 N produced more leaf per panicle at both low and high densities (Fig. 20). Leaf area per panicle was always greater at low density. Baru reached its maximum leaf area per panicle 3-4 weeks earlier than Calrose and Kulu. During grain set and filling Calrose had most photosynthetic leaf area per panicle and Kulu had least.

Plant height was measured every two weeks until 1.3.72 when grain had set. The increase in height was essentially linear with time (Fig. 21). Low minimum temperatures caused a lag in growth between 10 and 24.11.71 (5 weeks from emergence). Stem elongation ceased during the last period of measurement and little increase in height occurred. Baru was the tallest variety and Kulu the shortest but differences in height between varieties at flowering were statistically not significant. An application of 155 N increased height at flowering by 8.6 cm. Low density plots were also 6.3 cm taller at flowering than high density ones.

4. Dry Matter

Dry matter accumulation with time is presented both as cubic polynomials of ln W and general logistic curves of W. Both relationships fitted the data well, r^2 values being greater than .99 for all treatments or treatment combinations. Differentiating ln W data gave the relative growth rate (R) and these values were used to calculate net assimilation rates (E) (Fig. 22).

The appropriate regressions and r^2 values for the ln W curves were:

The effect of plant density and nitrogen rate on Leaf Area per panicle for 3 varieties.

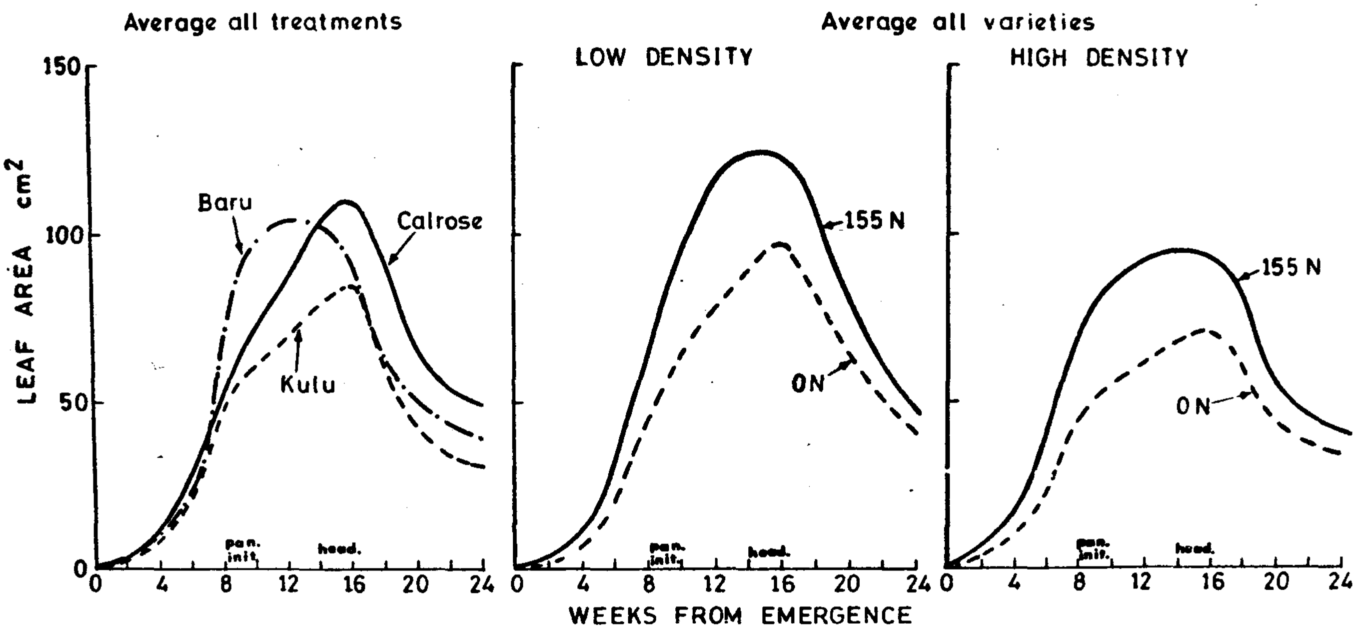


Fig. 20

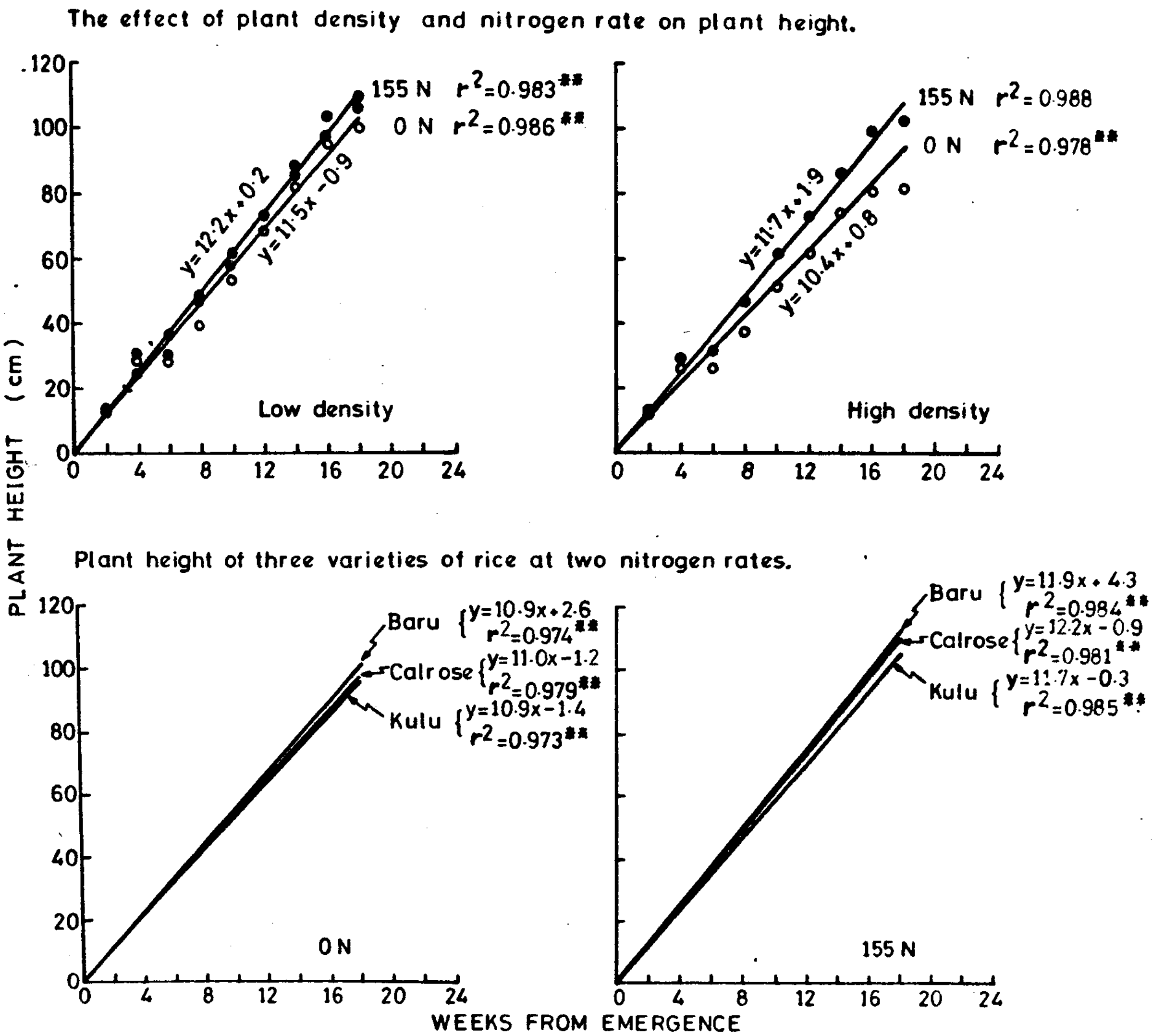

The effect of plant density and nitrogen rate on plant height.
155 N r2=0.983**
0 N r2=0.986**
y=12.2x+0.2
y=11.5x-0.9
Low density
155 N r2=0.988
0 N r2=0.978**
y=11.7x+1.9
y=10.4x+0.8
High density
PLANT HEIGHT (cm)
Plant height of three varieties of rice at two nitrogen rates.
Baru {y=10.9x+2.6 r2=0.974**
Calrose {y=11.0x-1.2 r2=0.979**
Kulu {y=10.9x-1.4 r2=0.973**
0 N
Baru {y=11.9x+4.3 r2=0.984**
Calrose {y=12.2x-0.9 r2=0.981**
Kulu {y=11.7x-0.3 r2=0.985**
155 N
WEEKS FROM EMERGENCE

Fig. 21

DRY MATTER PRODUCTION AND NET ASSIMILATION RATE OF 3 VARIETIES SOWN AT 2 N-RATES AND 2 DENSITIES.

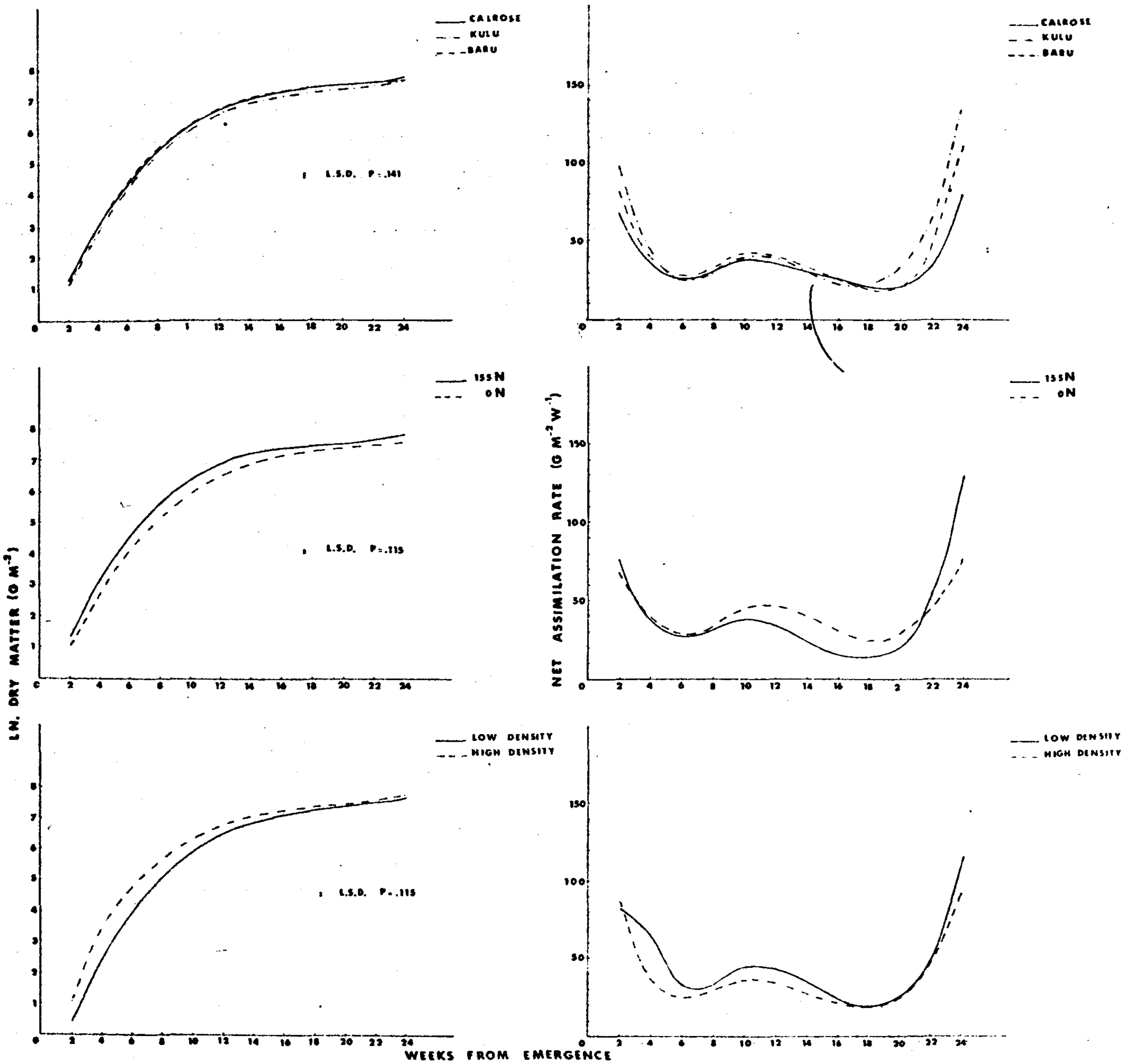


Fig. 22

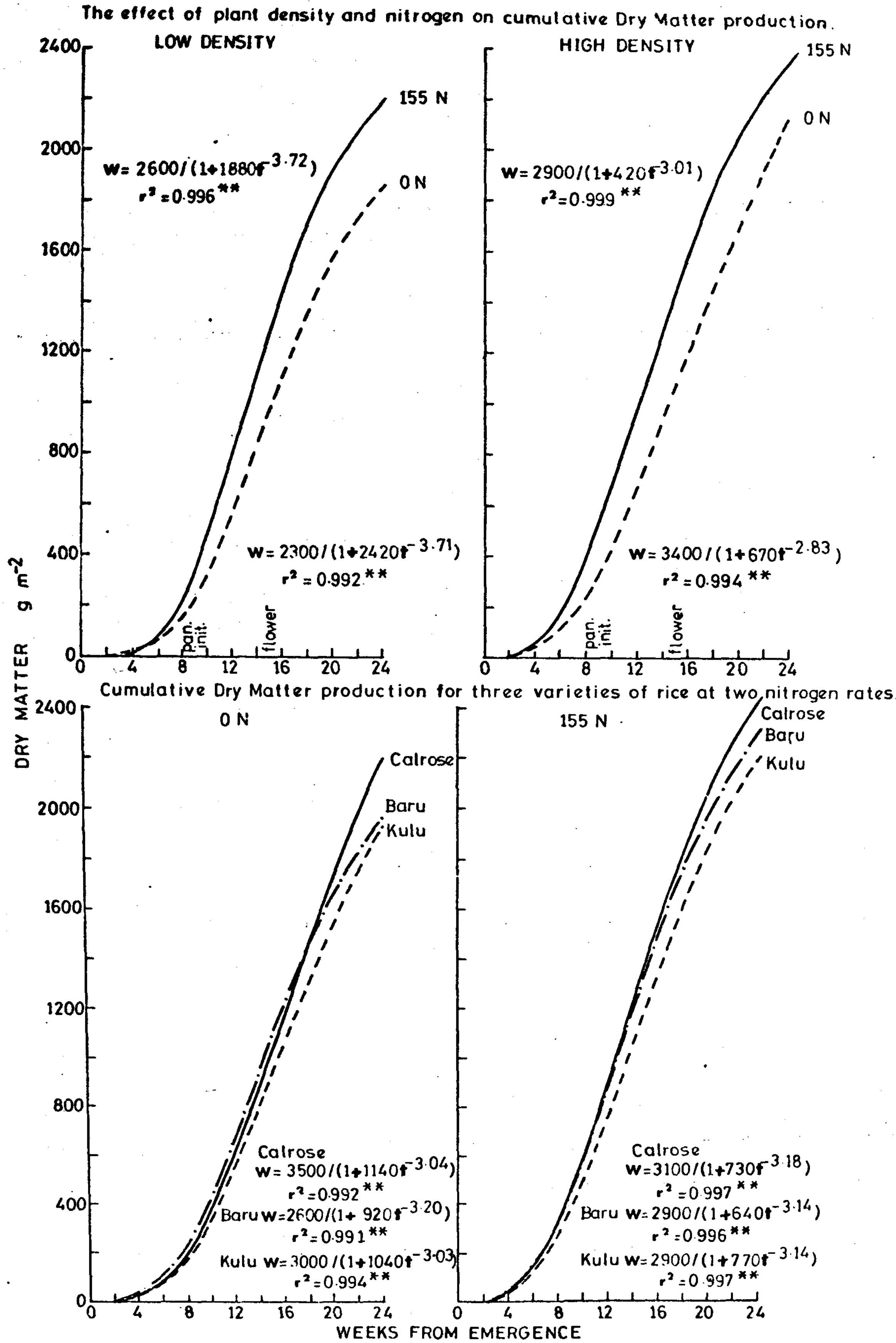
Calrose	$\ln W = -.8104 + 2.3114t - .2215t^2 + .0074t^3$	$r^2 = .998$
Kulu	$\ln W = -1.0623 + 2.4003t - .2367t^2 + .0081t^3$	$r^2 = .997$
Baru	$\ln W = -.9895 + 2.4251t - .2376t^2 + .0080t^3$	$r^2 = .999$
low density	$\ln W = -2.0224 + 2.6930t - .2642t^2 + .0089t^3$	$r^2 = .997$
high density	$\ln W = .1136 + 2.0650t - .1998t^2 + .0067t^3$	$r^2 = .998$
0 N	$\ln W = -.9493 + 2.2301t - .2048t^2 + .0065t^3$	$r^2 = .998$
155 N	$\ln W = -.9594 + 2.528t - .2591t^2 + .0091t^3$	$r^2 = .999$

Analyses of variance for both ln W and E indicated that none of the treatment interactions were significant (Appendix 3 and 4 respectively).

The data were also represented excellently by a logistic equation in the form $W = A/(1 + e^{c}t^{-B})$ (Fig. 23), in which $0 \leq W \leq A$ as $0 \leq t \leq \infty$. (This is easier to fit, but is more cubmersome, less exact and more difficult to attach biological meaning to the parameters than to the more usual form $W = A/(1 + be^{-kt})$ in which $A/(1 + b) \leq W \leq A$ with $0 \leq t \leq \infty$).

Throughout ontogeny Kulu produced less dry matter than Calrose and Baru. Calrose produced slightly more dry matter than Baru from heading to maturity. Rice grown at high density and at 155 N produced at all times more dry matter than that grown unfertilised and at low plant density.

There was little tapering off at harvest. The ln W curves showed a slight surge, but the logistic curves, of course, flattened out as they are constrained to do by this relationship. Actual data suggest a continuing slight increase in dry matter production.



The effect of plant density and nitrogen on cumulative Dry Matter production.
LOW DENSITY
HIGH DENSITY
155 N
0 N
W= 2600/(1+1880t^-3.72)
r² = 0.996**
W= 2300/(1+2420t^-3.71)
r² = 0.992**
W= 2900/(1+420t^-3.01)
r² = 0.999**
W= 3400/(1+670t^-2.83)
r² = 0.994**
pan. init.
flower
Cumulative Dry Matter production for three varieties of rice at two nitrogen rates.
0 N
155 N
Calrose
Baru
Kulu
Calrose W= 3500/(1+1140t^-3.04)
r² = 0.992**
Baru W=2600/(1+ 920t^-3.20)
r² = 0.991**
Kulu W= 3000/(1+1040t^-3.03)
r² = 0.994**
Calrose W=3100/(1+730t^-3.18)
r² = 0.997**
Baru W= 2900/(1+640t^-3.14)
r² = 0.996**
Kulu W= 2900/(1+770t^-3.14)
r² = 0.997**
DRY MATTER g m⁻²
WEEKS FROM EMERGENCE

Fig. 23

Relative growth rates (R) curves also suggest a surge in growth during ripening. Differentiation of ln W data during ripening has accentuated the surge. Hyperbolas were also fitted to the relative growth rates calculated from consecutive harvests. Curves fitted the data well when the first 2 weeks of slow growth after emergence were omitted. These curves, derived from actual data did not show a surge in R during ripening and it is concluded that differentiation of ln W data has overemphasised the slight surge found in ln W data.

Low plant densities produced very high R values during tillering because fewer plants tillered vigorously and they accumulated much dry matter during this period. Baru showed a lower R than Calrose after flowering. Regression equations and r^2 values of relative growth rates as calculated from actual data are presented in Table 27.

Crop growth rates (C) increased until heading. They decreased then until grain set, but during ripening there was a distinct increase.

Net assimilation rates (E) followed the normal broad U-shape, with a distinct surge for all treatments during panicle initiation. Throughout most of ontogeny low plant densities had a higher E than high densities. Only during establishment and ripening had treatments receiving 155 N a higher E. Especially during stem elongation and heading, unfertilised rice had a higher E. The varieties had a similar E during mid-season but during early tillering and ripening Kulu had the highest and Calrose the lowest E.

TABLE 27. Regression equations and r^2 values of the Relative Growth Rates of the varieties Calrose, Kulu and Baru at 0 and 155 N (average low and high plant densities).

Variety	0 N		155 N	
	regression equation	r^2	regression equation	r^2
Calrose	R = -.0198 + .2754/t	.960**	R = -.0209 + .2663/t	.978**
Kulu	R = -.0212 + .2802/t	.927**	R = -.0229 + .2770/t	.967**
Baru	R = -.0203 + .2709/t	.962**	R = -.0255 + .2856/t	.984**

5. Canopy structure

The distribution of leaf area and dry matter within the crop canopy at flowering was determined by stratified clipping at 20-cm intervals and it was averaged over the three varieties for the main components low and high density and 0 and 155 N (Fig. 24).

When unfertilised, L at all heights above 20 cm (water level) was greater at the higher density and also total dry matter was greater at all levels for this treatment. When 155 N was used, high density rice had a greater leaf area between 40 and 100 cm, but less between 20-40 cm. In the 155 N, low density combination, the panicles were all above 60 cm, whilst at high density there were a number of panicles below this level.

There were important differences between varieties in canopy structure (Fig. 25). At high-density with 155 N, both Calrose and Kulu had much leaf in the 60-80 and 80-100 cm layers which may have caused some mutual shading. The distribution of leaf area of Baru allowed a greater light penetration below 60 cm, making it possibly more efficient. At low density both Calrose and Kulu produced more leaf at the 40-60 cm level, but Kulu, with its more horizontal flag leaf, had a large L between 80 and 100 cm, and this may have reduced the light penetration to lower levels to some extent. Although Baru had a considerably lower total L than the other varieties, the leaves were distributed within the profile to allow maximum light penetration.

6. Grain-Straw Ratio

At time of harvest lodging did not occur. Shortly after harvest the

THE EFFECT OF PLANT DENSITY AND NITROGEN ON THE LEAF AREA INDEX AND DRY MATTER DISTRIBUTION WITHIN THE CANOPY AT FLOWERING (mean 3 varieties)

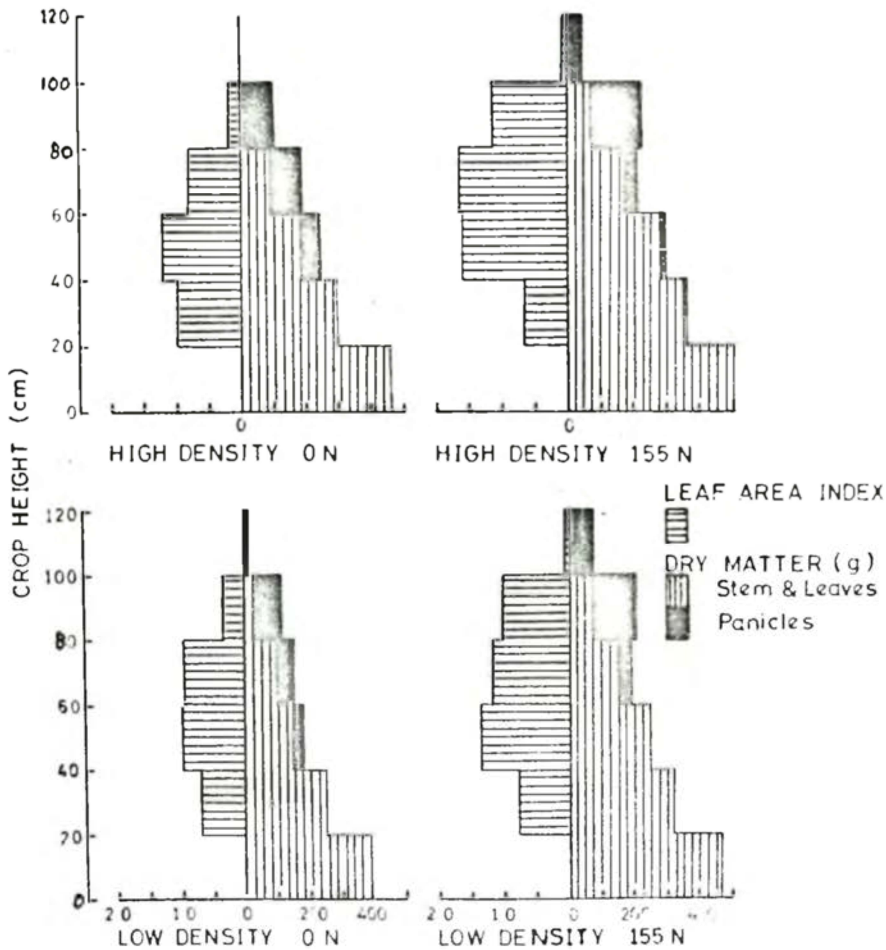


Fig.24

LEAF AND DRY MATTER DISTRIBUTION WITHIN THE CANOPY OF THE VARIETIES CALROSE, KULU AND BARU AT 155 N AT FLOWERING

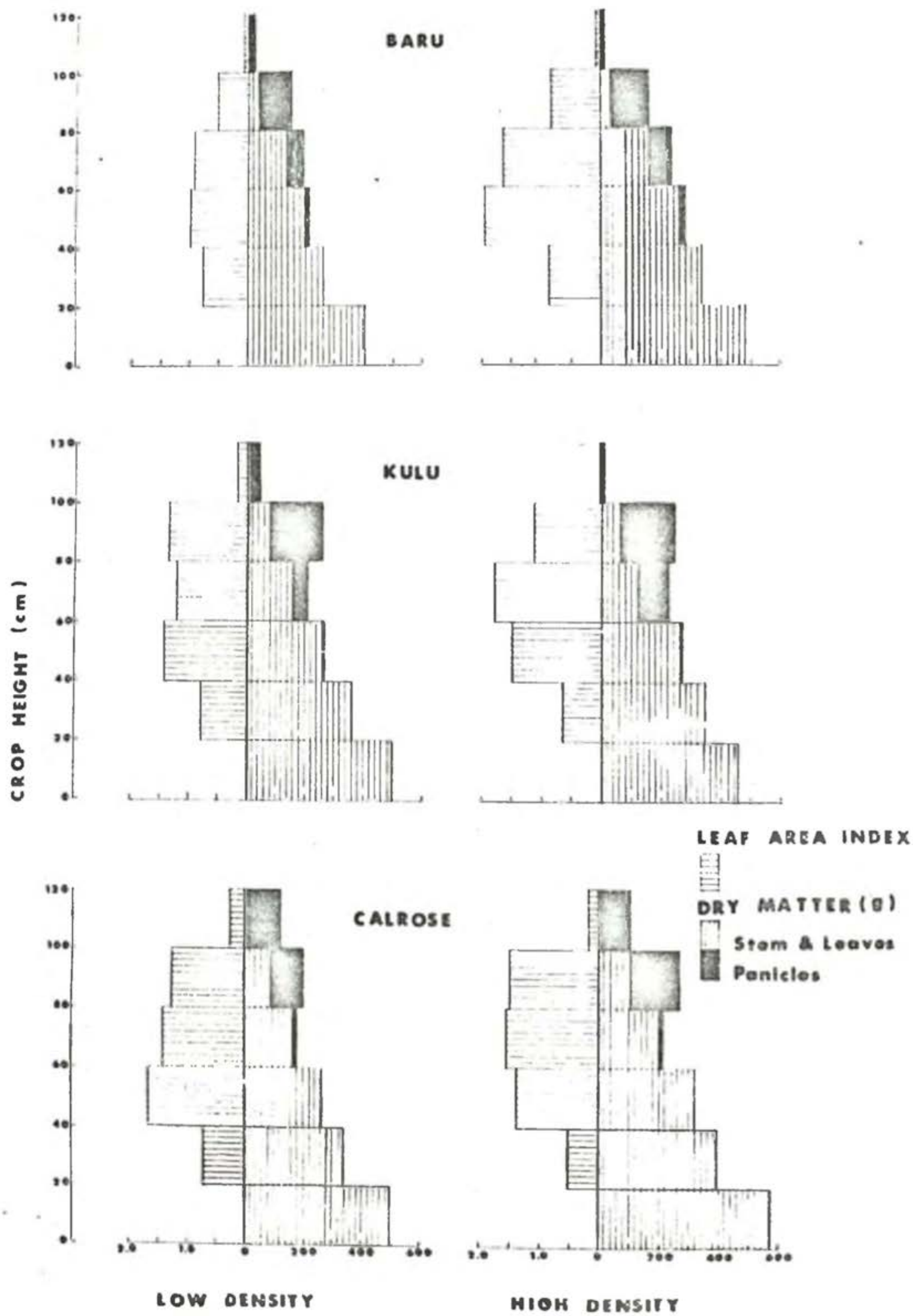


Fig. 25

remainder of Kulu plots lodged where high N was applied at both low and high densities. Also Calrose at high N tended to lodge, but this was not serious. Baru had very strong culms and even very late in the season there were no signs of lodging (Plate 4).

Kulu and Calrose had lower grain-straw ratios than Baru, despite the heavy stems of the latter variety (Table 28). The average stem diameter 2 cm above soil level of Baru was 4.7 mm, whilst that of Calrose and Kulu was 3.2 and 3.4 mm respectively. All varieties had larger stem diameters at low density (average 4.05 mm) than at high density (average 3.43 mm).

7. Nitrogen Utilisation

Samples for estimation of N-uptake were taken at four weekly intervals from emergence. Uptake was linear with time for all treatments (Fig. 26).

Without added N there was no significant difference in slope or intercept of the regressions for low and high density. The pooled equation was $N = 4.16 + 34.05\ t$. At 155 N the regressions had the same slope, but the high density intercept was greater. This is most likely because more plants were in close contact with the fertiliser at the narrow spacing and took up N sooner.

Total N contents of grain and straw and the grain protein contents are presented in Table 29. Only small differences in total uptake between varieties occurred but Calrose took up significantly more N in the straw than Kulu and Baru, and Baru had a very much greater uptake by the grain.

Plate 4

Calrose sown at 135 kg ha^{-1} at a row spacing of 18 cm and at 34 kg ha^{-1} at a spacing of 36 cm.

TABLE 28. Grain-Straw Ratios for Varieties and N-rates

Varieties	N-rate		Mean Varieties
	0 N	155 N	
Calrose	0.736	0.629	0.683
Kulu	0.891	0.653	0.772
Baru	1.140	0.917	1.029
Mean N-rates	0.922	0.733	

L.S.D. P = 0.05 Varieties 0.084

N-rates 0.069

V x N NS

Nitrogen uptake of combine sown rice at two plant densities and two nitrogen rates.

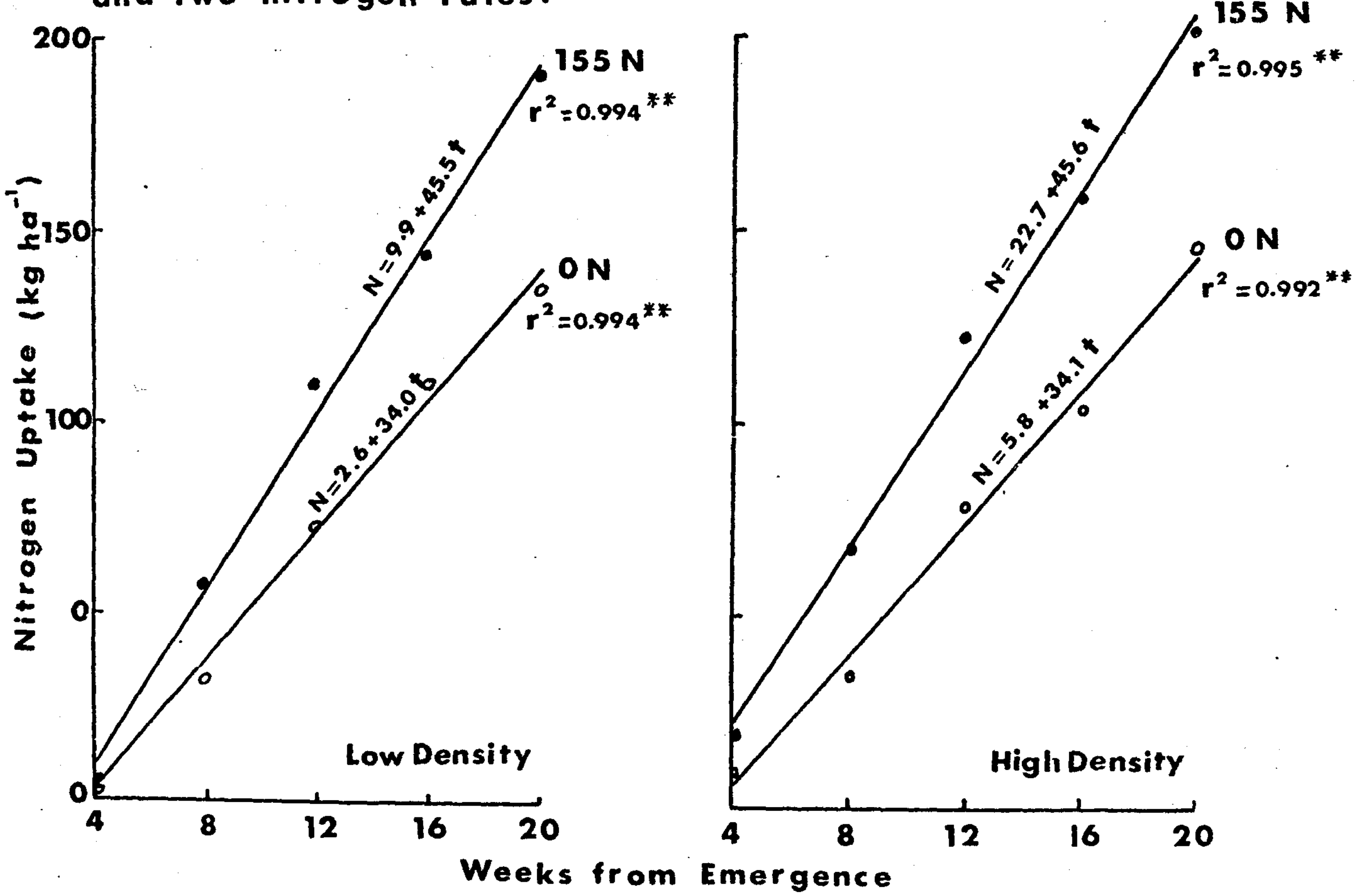


Fig. 26

TABLE 29. Nitrogen uptake and grain protein content of three varieties of rice grown at low and high plant densities and at 0 and 155 N in Experiment II.

Varieties	N-uptake in kg ha^{-1}			Grain Protein %
	Straw	Grain	Total	
Calrose	75.7	98.1	173.7	6.25
Kulu	61.2	99.0	160.3	6.96
Baru	51.5	117.1	168.6	6.37
<u>N-rate</u>				
0 N	47.3	92.3	139.6	6.07
155 N	78.3	117.2	195.4	6.96
<u>Density</u>				
Low	57.0	104.8	161.8	6.66
High	68.6	104.6	173.2	6.43

L.S.D. P = 0.05				
Varieties	10.9	6.8	NS	.232
N-rates	8.9	5.5	11.9	.190
Density	8.9	NS	NS	.190
V x N	NS	NS	NS	.327

Varieties were not significantly different in total N-uptake. Kulu yielded least grain with the highest grain protein content.

An application of 155 N caused significantly greater uptake of nitrogen by grain and straw and raised the grain protein content.

Plant density had less effect on N content at harvest, but significantly more was located in the straw of high density treatments. Grain protein content was higher at low than at high density.

III. Combined data over two seasons

Seedling emergence was affected by weather conditions after sowing. Rice in experiment II emerged 10 days earlier (25 days from first irrigation) and plant densities were 35 and 25% higher at low and high seed rates respectively than in experiment II. Cold, rainy weather was the major cause of low plant densities and a slow emergence. Averaged over two seasons only 50% of all seeds sown produced viable seedlings, despite seed treatment.

Calrose established better than Kulu and Baru in experiment I, but there was almost no difference in plant density between varieties in the second season. High density sowings gave best plant stands in all cases. A high rate of 155 N as ammonium sulphate had no adverse effect on emergence, but it did improve seedling vigour after emergence.

Combined data for yield and yield components were analysed. Treatment differences were tested against the year x treatment interaction. Where differences are significant it indicates that these are real differences in response to treatment and these are consistent from season to season, but are not necessarily of the same size.

Mean squares of the combined analyses are presented in Table 30, whilst yield and yield components are graphically presented in Fig. 27.

Year x treatment interactions were significant at the 1% level for all varieties. None of the other interactions reached significant levels.

The 1000-grain weight was the least variable yield component whilst floret sterility was most variable.

Yields were only significantly affected by applying 155 N. However, varieties obtained their yields differently. Both Calrose and Kulu produced more panicles per unit area than Baru, but Baru compensated for this by producing larger panicles (more florets per panicle). Kulu produced most panicles per plant and the low plant density situation encouraged tiller production.

In experiment I there was a positive linear relationship between plant density and panicle number for the varieties Calrose and Baru (for Calrose, $r^2 = .783^{**}$ and for Baru $r^2 = .509^{*}$). This relationship did not exist for Kulu because it tillered more in low density high N situations. Combined over both seasons panicle numbers averaged over all treatments were linearly related with yield. In experiment II there was no linear relationship between panicle density and yield. Calrose yield improved with up to 700 panicles m^{-2} but no further yield improvement was obtained at higher densities. Kulu reached its maximum yield at around 600 panicles m^{-2} and Baru produced highest yields with slightly in excess

TABLE 30. Mean squares of the combined data for yield and yield components of Experiments I and II.

Source of Variation	d.f.	Mean Squares				
		Yield	Panicle number	Florets/ Panicle	Floret sterility (%)	1000-grain weight (g)
Years	1	6008900	113764	4280	1118	10.58
Varieties (V)	2	3047867	240897**	23396**	323	8.92
Density (D)	1	1715567	612724**	21084**	94	2.16
Nitrogen Rates (N)	1	36693900**	105340**	2219	216	4.33
V x D	2	9533	6663	1644	231	1.36
V x N	2	1283767	14163	392	3	1.40
D x N	1	692667	145	330	.01	.42
V x D x N	2	266933	3065	84	11.0	.36
Years x Treatment	11	3117633**	9541**	560**	86**	2.43**
Pooled Error	43	366828	2798	146	10	.45
Standard Deviation (%)		19.2	19.3	22.8	43.9	5.5

* L.S.D. P = 0.05
** L.S.D. P = 0.01

THE EFFECT OF PLANT DENSITY AND NITROGEN ON PANICLE NUMBER

PANICLE SIZE AND YIELD OF 3 VARIETIES

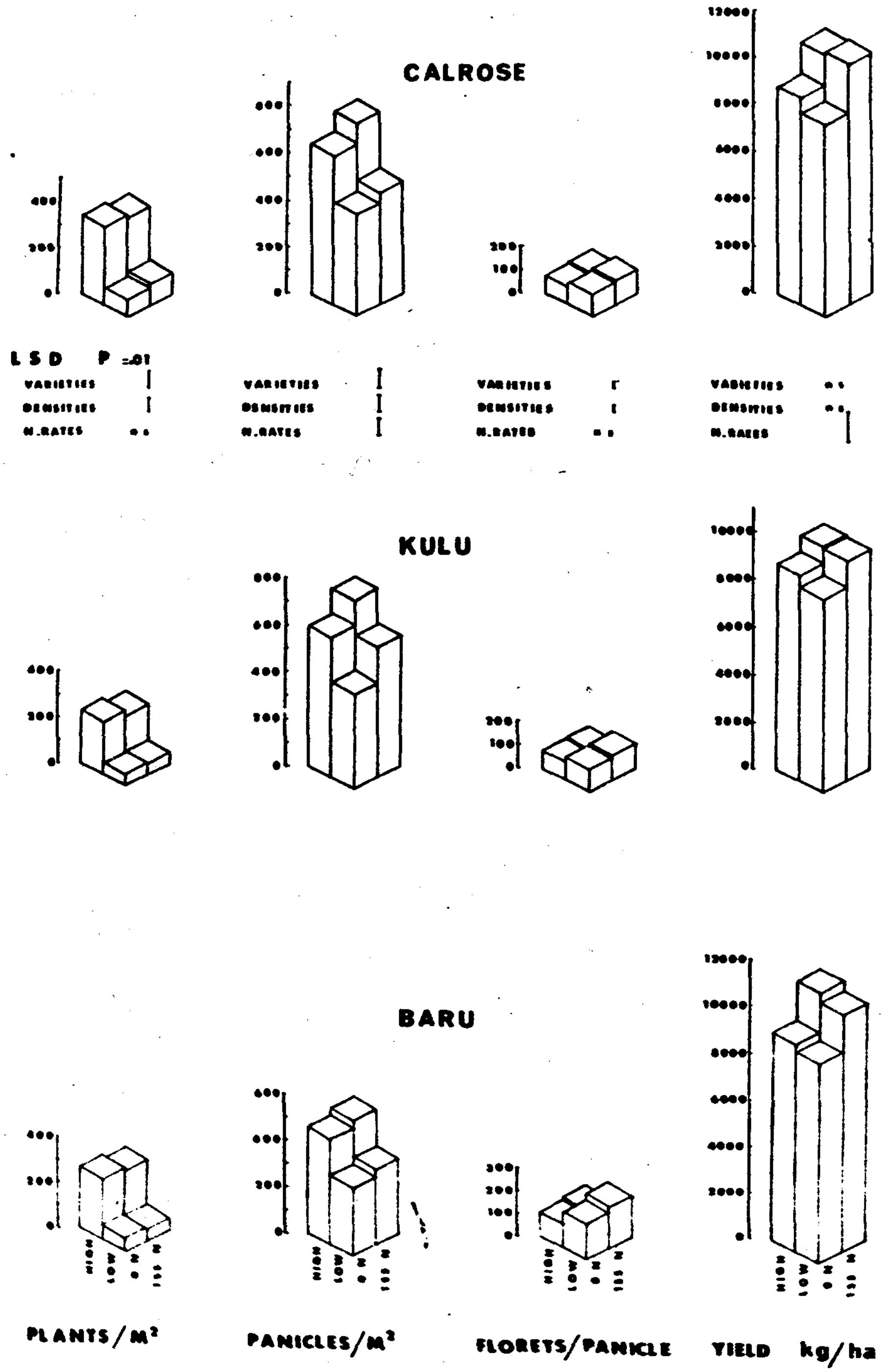


Fig. 27

of 400 panicles m^{-2}.

D. DISCUSSION

Seedling vigour is a very important factor in the establishment of rice in cooler areas where direct seeding is practiced. Under more favourable temperature conditions, emergence and seedling vigour of all three varieties was satisfactory. When low soil temperatures occurred Calrose established best.

Grain yield is a function of the number of panicles per unit area, the number of filled florets per panicle and the grain weight. To fill a large sink it is necessary to have an adequate leaf area arranged for efficient use of solar energy and a high rate of CO_2 uptake, whilst the translocation system must be capable to transport the carbohydrates to the florets.

Hayashi (1972) and Tanaka (1972) agree that the greatest yield gains are to be obtained by breeding varieties with a larger sink or by using cultivation practices whereby a larger sink is obtained.

The sink may consist of a large number of small panicles, "panicle number" varieties, or of fewer large panicles, "panicle weight" type varieties. Tillering ability is largely genetically controlled, but there is a big environmental interaction. In very sparse plant stands panicle number varieties are able to fill the space with a large number of tillers in response to high levels of nitrogen. Panicle weight type varieties may not fill the space completely and the very large panicles produced at high N are often not able to compensate fully for the lower panicle number. The very large panicles, produced at high levels of N, have frequently an incomplete grain set, they have either a high percentage floret sterility or a lower 1000-grain weight, especially on the lower part of the panicle. The latter situation existed for the panicle weight variety Baru in experiment I, where it established poorly and yielded inferior to Calrose and Kulu. The latter varieties tillered freely and produced a good size panicle. Baru, however, produced 36% fewer panicles and almost double the number florets per panicle. Floret sterility was high and the 1000-grain weight was lower than normal for this variety. It indicated that either insufficient photosynthates were produced or these did not reach the florets.

In experiment II, where Baru established well, it produced more and somewhat smaller panicles. Floret sterility was relatively high but the 1000-grain weight was normal for Baru. In this situation Baru produced higher yields than the panicle number varieties Calrose and Kulu. De Datta *et al.* (1969) found that panicle weight type varieties, when directly seeded, produced higher yields than free tillering panicle number varieties. Also Langfield (private communication) found that panicle weight varieties in both dry and wet seasons in northern Australia produced highest yields when drill sown. However, Yammamoto and Toriyama (1972) found that yield was positively related to panicle number per unit area under direct seeded conditions in the temperate climate of Japan. Panicle size and 1000-grain weight were negatively correlated with yield in that situation. Results from described experiments indicate that in a temperate environment, "panicle weight" varieties may be advantageous at an adequate plant density.

It is generally acknowledged that each variety has a certain minimum plant density requirement at a certain level of nutrition. Beyond this minimum plant density, variations can be quite large without change of yield (Takeda and Hirota, 1972; Anon. 1968; Yamada, 1961). Baru required a relative higher plant density than Calrose and Kulu. Given optimum plant densities for each of the varieties, the panicle weight variety Baru outyielded Calrose and Kulu.

Both experiments were conducted under high levels of solar radiation. Leaf area index did not exceed 7.5. There was no close relationship between L and yield or total dry matter production, and L was not large enough to be yield reducing.

Highest yields were obtained when 155 N was applied and all three varieties responded to N. Baru and Calrose required at least 155 N for maximum yield. Kulu produced lower yields than Baru and Calrose in experiment II which can be ascribed to a very high percentage floret sterility and smaller grains (a varietal characteristic). Stratified clipping revealed that Baru had a more advantageous leaf distribution within the canopy and may therefore be a more efficient variety.

Baru had the most favourable grain-straw ratio. This is considered by Yoshida (1972) to be closely related to high nitrogen responsiveness. Sturdy stems combined with the favourable grain/straw ratio make Baru a highly lodging resistant variety and it is therefore possibly more responsive to N than Calrose and Kulu.

Excess nitrogen may easily lead to high floret sterility when lodging is not a problem (Kleinig and Nobel, 1967; Boerema, 1963). There appears to exist a rather narrow optimum N-rate for each of the varieties. This optimum N-rate is lowest for Kulu, which lodges easily and produces a high percentage sterile florets and it is possibly highest for Calrose which is less susceptible to floret sterility than Baru, although it lodges easier.

Floret sterility may, however, also be due to low temperatures during meiosis and flowering (Owen, 1971; Petersen et al., 1972). In the first season temperatures were favourable and both Calrose and Kulu had reasonably low levels of floret sterility. In the second season, however, average percentage floret sterility was 7.8% higher, mainly due to low temperatures (see Chapter 2). Kulu flowered later than Calrose and it is therefore possible that it was more severely affected by low minimum temperatures. Because of longer vegetative phase of Kulu, this variety will generally be more susceptible to floret sterility due to low temperatures than the earlier flowering Baru.

Grain size is a rather stable varietal characteristic. The size of the hull, which is determined about one week before flowering (Yoshida, 1972) restricts the size of the grain. Results from these experiments confirm that grain size varied little over the two seasons. In experiment I the standard deviation from the mean was 2.0% whilst it was 2.1% in experiment II.

High rates of nitrogen decreased 1000-grain weight. There was a tendency for all varieties to have smaller grains on larger panicles. Baru produced a very low 1000-grain weight at low plant density and high N and it was noticed that lower grains on the panicle filled incompletely. Incomplete filling of grains could be due to insufficient leaf area, low levels of solar radiation or a reduced or lacking translocation. At harvest, Baru culms had always at least 2 green leaves and radiation levels remained above 500 cal cm^{-2} d^{-1}. It is, however, not known if the leaves were actively photosynthesising during grain filling. Translocation was not restricted because of lodging. Nakayama (1969) has suggested that an early senescence of the conductive system in the rachilla may occur. It may also be, that because of ageing, it loses efficiency of photosynthesis or translocation or the sink strength of grains on the lower rachillas becomes inadequate.

E. CONCLUSIONS

Low plant densities had most serious effect on the yielding ability of Baru of its limited ability to tiller. Calrose and Kulu were able to compensate for low plant densities because of their profuse tillering habit when sufficient nitrogen was available.

Within the range of densities tested, adequate nitrogen was more important for all three varieties than high plant densities, which confirms the finding of Ten Have (1971). Optimum levels of N depend on the variety and the soil fertility; some varieties respond to high levels of soil nitrogen by producing a very large leaf canopy and lodging may result, whilst other varieties with semi-dwarf characteristics produce highest yields at very high levels of nitrogen.

Dry matter production of all varieties increased greatly with added N. Excessive vegetative development and high sterility reduced grain yield of Kulu at the highest N-rate. Calrose was the most widely adapted variety, yielding well under all conditions of experimentation. Baru had the highest yield potential but yielded less than Calrose and Kulu at low plant density.

In field situations, where establishment problems occur due to adverse soil conditions or soil temperatures, high seedrates may be necessary to achieve minimum plant densities for high yields.

VI. THE NITROGEN ECONOMY OF RICE CROPS

A. INTRODUCTION

Nitrogen is the most important and usually the only nutrient needed to be supplemented to obtain high yields of rice in this region. The inclusion of a legume pasture in the rotation reduces the need for fertiliser nitrogen (Boerema and McDonald, 1965). Usually the pasture consists of subterranean clover (Trifolium subterraneum and rye grass (Lolium rigidum) and is maintained for 4-5 years. Very little or no nitrogen is then required for the rice crop which occupies only one year of the rotation.

Virgin soils in the Murrumbidgee Valley are generally low in phosphorus and most other crops require phosphate fertiliser for high yields. However, rice rarely responds to phosphate additions (Boerema, 1963; Boerema and McDonald, 1965) and decreases in yield sometimes result. Where pasture is included in the rotation, superphosphate is applied annually to encourage clover growth. Much of this added phosphate is fixed in the soil and a proportion no doubt becomes available to the subsequent rice crop. According to Shapiro (1958), rice grown under flooded conditions can extract phosphate which is normally not available under dry land conditions. He states that this may be due to hydrolysis of phosphate in the highly reductive conditions that prevail.

There is no record of beneficial responses to potash additions in the Murrumbidgee Valley and also minor elements have not given any yield increases.

Nitrogen requirements of rice are modified by the method of sowing used. The most widely adopted practice is to prepare a fine seedbed and sow by combine, applying nitrogen fertiliser in the same operation. Alternatively, aerial sowing or sod-seeding techniques may be used. For combine and aerial seeding a seedbed must be prepared. During soil cultivations the profile is aerated which leads to the breakdown of organic matter and accelerates nitrification. Subsequent wetting and drying, associated with flushings of the soil, accelerates these processes in combine-sown rice.

During aerial sowing, pre-germinated seed is distributed into permanent flood water. When flood water is applied the process of oxidative breakdown is halted; hence, this may occur from 3-6 weeks earlier with aerial-than combine-sown rice.

Sod-seeded crops are planted directly into the pasture sod and there is little disturbance and aeration of the profile. Therefore, despite repeated flushing during establishment, the rate of nitrification of organic matter is relatively slow.

Nitrogen requirements during different growth stages of rice have been reviewed by Matsushima (1965). He identified four stages as being particularly important:

(a) at active tillering, to increase the number of tillers and panicles;

(b) at panicle initiation, to increase the number of spikelets;

(c) at meiosis, to prevent degeneration of differentiated spikelets and increase the size of the hull;

(d) at full heading, to increase the percentage of grain which ripen.

The need for topdressing at these times depends on the capacity of the soil to supply nitrogen, seasonal conditions, cultural practices, varietal characteristics, etc.

Before the experiments described in the past two chapters (III and IV) were completed, M.I.A. rice growers applied ammonium sulphate together with the seed when sowing by combine.

The requirements for aerial-sown rice were drilled into the soil prior to flooding. Topdressing with nitrogen fertilisers at different growth stages was rarely considered and only very underdeveloped crops received a nitrogen supplementation just prior to flowering.

Detailed aspects of these experiments in respect of nitrogen are considered here; before doing so, some basic issues of nitrogen transformations, as presented in the literature, are considered.

B. LITERATURE REVIEW

1. Nitrogen transformations in rice soils

Where pasture is included in the rotation, considerable quantities of organic matter are accumulated in the soil. When this pasture is ploughed and the profile aerated, the organic matter is quickly decomposed and organic nitrogen compounds are mineralised, leading to an increase in NO_3^- ions. Following flooding, diffusion of oxygen into the soil is retarded and that present consumed, so only the few surface millimetres of the profile remain aerobic. Under flooded conditions the transformations of organic nitrogen beyond the formation of NH_4^+ ions and free ammonia are mostly suppressed. In the reduced soil, conditions favouring the activity of denitrifying microorganisms are established and the process of denitrification commences. Facultative anaerobic and then obligate anaerobic bacteria take over the decomposition of soil organic matter.

(i) Ammonification: The rate and magnitude of ammonium becoming available from a soil is a good index of the capacity of the soil to meet the nitrogen demands of a flooded rice crop. The most important factors controlling this rate are temperature and the nature and content of organic matter. The ammonification rate increased dramatically with increasing temperatures according to Mitsui (1956); for example, the rate of ammonia production from anaerobic incubation was approximately doubled by raising the temperature from 26 to 40^{o}C.

The type and amount of organic matter is perhaps the most important factor influencing the release of ammonia in flooded fields. Generally, soils rich in organic matter release ammonia rapidly. Workers at the International Rice Research Institute in the Philippines (Anon. 1963) studied the rate and magnitude of ammonia release of 31 soils over a period of submergence of 200 days. In soils rich in organic matter (8 percent) a peak concentration of over 300 ppm NH_3-N was reached within 30 days of submergence. The maximum concentrations reached in soils low in organic matter (%) were less than 30 ppm.

Ponnamperuma (1965) found that ammonia production follows an asymptotic course described by the function

$$y = A(1-e^{-ct})$$

where A is mean maximum NH_3-N in ppm of the dry soil, y is the actual concentration after t days of submergence and c is a constant relating to the particular soil and temperature. The value of A was found to be closely related to the organic matter content of the 31 soils studied at I.R.R.I., being given by 14.4 + 38.44 M where M is the percentage organic matter. Strickland (1969) obtained values in agreement with the above equation from field experiments in northern Australia. Other investigators have observed different courses of ammonium production with time. This is most likely due to differences in the nature and content of the organic matter or to different methods of incubation.

(ii) Nitrification: Both groups of nitrifying bacteria, *Nitrosomonas* and *Nitrobacter*, are usually found together in soil. The activity of the latter is inhibited by strongly alkaline conditions. However, the process is most rapid in neutral or slightly alkaline conditions. A high C:N ratio reduces the output of nitrate since much of it is used by the organisms affecting breakdown.

In old pasture soils, where much organic nitrogen is present, the rate of nitrification can be very high if temperatures are favourable and there is adequate aeration. Generally, the mineral N content (i.e. N as NO_3^-) of grassland is much lower than that of comparable arable land. In uncropped land the NO_3^- content fluctuates but NH_4^+ levels are always low. In grasslands the NO_3^- content never attains a significant level, while NH_4^+, although always low, never falls to unmeasurable quantities and generally is in the range of 3-9 ppm (Harmsen and Schreven, 1955). Nitrate ions are very mobile and are easily lost by leaching on sandy soils. In periods of heavy rainfall nitrate losses due to leaching can be very high and this is one of the causes of nitrate fluctuations in arable land.

Increase of temperature increases the rate of nitrification, but the process can proceed at even low temperatures. Gerretsen (1942) reported that, at a temperature of 5°C, only 14 days were required for the complete nitrification of amounts of ammonium sulphate equivalent to a high rate of fertiliser supplementation. Optimum temperature for the process is reported to be 24°C (Broadbent, 1966).

Not all the ammonium ions are nitrified under aerobic conditions, some being firmly held within the clay mineral lattice. Takahashi (1965) referred to work by Harada in Japan, which demonstrated that soils containing montmorillonite clay held ammonium strongly and those containing mainly kaolin or allophane could not hold it well.

Considerable nitrification can occur in the oxidised few surface millimetres of flooded soils. Nitrates are easily leached from this layer into reduced zones beneath where denitrification occurs.

(iii) Denitrification: This is the reduction of nitrate to lower oxides of nitrogen or nitrogen gas. Nitrite is not a common end-product and there are no reports of concentrations greater than 3 ppm in submerged soils (Ponnamperuma, 1965). It occurs only in the presence of some organic compound to support the growth of the organisms and to act as a hydrogen donor. The rate of denitrification depends on temperature, pH, degree of water saturation and type and amount of organic matter.

The rate of denitrification increases rapidly with rising temperatures from 2 to 25°C, but is not significantly affected by increases beyond this point (Bremner and Shaw, 1958). The same authors found that the rate of denitrification was slow below pH 4.8, increases gradually with a rise in pH and it was rapid between pH 8.0 and 8.6.

Readily decomposable organic compounds induce rapid denitrification. Bremner and Shaw (1958) found that, within 20 days of submergence, 20 to 80 percent of added nitrate was lost from water-logged soils containing 1.13 percent carbon or less. With the addition of glucose as an energy source for denitrifying bacteria 67 to 90 percent of added nitrate was lost from soils having native carbon contents ranging from 0.80 to 5.71 percent. Macrae et al. (1968) using 6 soils from the Philippines, found that tagged nitrate disappeared most rapidly (within 2 weeks of flooding) from the two soils having the highest organic matter content (8.0 percent).

2. Preventing nitrogen losses

When rice is sown by combine, oxidising conditions persist at seed depth during flushing. Where ammonium fertiliser is applied with the seed it can be readily nitrified during this period. Losses from the profile may then result because of denitrification after permanent flooding.

Methods of preventing or minimising losses from applied ammonium fertilisers may be enumerated as follows:

(i) Aerial sowing: This technique was developed for use with heavy-textured soils with poor drainage and subject to weed infection (Hall, 1960). On such soils it was difficult to obtain an adequate plant stand when seed was sown by combine into a prepared seed bed. Faulkner (1960) and McIlrath (1968) reported better yields from aerial-sown crops than from combine-sown crops under similar conditions. They attributed this mainly to better establishment and weed control.

Previous workers do not seem to have recognised that improved utilisation of ammonium fertiliser could be an important advantage of aerial sowing, although it has been acknowledged that the ammonium fertiliser should be placed, prior to flooding into the soil rather than on the surface (Mikkelsen and Finfrock, 1957). Improved N-utilisation from continuous flooding compared to alternate flooding and drying has been reported by Patrick et al (1967) and Oelke and Mueller (1969).

(ii) Deep placement of ammonium fertilisers: After permanent flood water is applied, a very shallow layer of oxidised soil remains on the surface. Below this, reduced conditions develop quickly. When ammonium fertilisers are placed in the reduced zone and no further aeration occurs, ammonium cannot be nitrified and losses should be slight.

Workers in tropical areas have found that deep placement of urea or ammonium sulphate of both transplanted and drill-sown rice, usually gives improved fertiliser efficiency and high yields. Abichandani (1959) found that placement of ammonium fertiliser at a depth of 5-10 cm between rows of transplanted rice was about 2.5 times more effective than surface applications. Similar results were obtained in India by Wahhab and Azim

(1958) and Abichandani and Patnaik (1958). In Japan, Mitsui (1956) reported that losses from surface-applied ammonium were 30-50 percent higher than from deep-placed fertiliser. Picciurro and Piacco (1969) obtained similar results in Italy.

Recently, the F.A.O. Division of Atomic Energy in Food and Agriculture (Anon. 1970) carried out 16 field experiments in 12 countries with 15 N-labelled ammonium sulphate. The fertiliser was placed 5 cm deep or on the surface at the time of transplanting. On acid soils of intermediate pH, deep placement resulted in 30-40 percent greater uptake. In soils containing $CaCO_3$ with pH higher than 7.0, surface application was as effective as deep placement.

Combine sowing is not widely practised in tropical areas. Langfield (1959, 1962), working in Northern Australia, found ammonium sulphate at the rate of 28 kg N ha^{-1} drilled to a depth of 7½ cm as effective as double this quantity (56 kg N ha^{-1}) drilled 2½ cm deep. Deep placement delayed maturity and caused lodging in the variety Meli No. 2. Plant establishment was quick and permanent flood was applied within 15 days.

In temperate areas where temperatures are low during the period of establishment it may take 30-50 days before permanent flood can be applied. During this long period of flushing permanent reducing conditions are not established in the zone where deep-placed fertiliser is situated and nitrification of applied ammonium fertiliser could occur. Boerema (1967) advanced this as the reason for poor results achieved with deep-placed ammonium sulphate in New South Wales. He obtained greater tillering and an increased panicle number but not increased yields when the fertiliser was placed at a depth of $7\frac{1}{2}$ cm. Plant densities were lower because of the sinking in the deep cultivated soil. Deeply placed rice seed gives always a poor plant stand, especially in cold soils.

Deep placement of nitrogen fertiliser is also reported to improve its effectiveness when the seed is aerially sown. In California, Mikkelsen and Finfrock (1957) found that incorporating fertiliser in the dry soil to a depth of 5-10 cm prior to flooding increased N-uptake by 20 percent and yield by 25-30 percent compared to surface broadcasting. Amer (1960) obtained almost identical results in Egypt. In Louisiana, best results from ammonium sulphate have been obtained from preplant applications $7\frac{1}{2}$ - 10 cm deep (Patrick and Peterson, 1967).

New South Wales farmers usually apply fertiliser 5-7 cm deep with the last cultivation when aerial sowing is used.

(iii) Chemical control of nitrification: Nitrification inhibitors are highly toxic to nitrifying bacteria but have little effect on other soil organisms or rice seedlings. Under laboratory and glasshouse conditions it has been shown that the following chemicals are very effective in preventing the conversion of ammonium to nitrate:

- 2-chloro-6(trichloromethyl) pyridine (N-serve$^{(R)}$) (Goring 1962, a and b, Patrick et al. 1967, Prasad and Lakhdive, 1968).
- 2-amino-4 chloro-6 methyl pyrimidine (A.M.$^{(R)}$) (Prasad and Lakhdive, 1968). A.M.$^{(R)}$ is slightly soluble in water as compared with N-serve$^{(R)}$, which is insoluble in water, and was considered slightly inferior to N-serve$^{(R)}$ by Patrick et al (1967) and Anon. (1970).

- Dicyandiamid (Reddy, 1964).
- Thiourea (Weir, 1965).

Results from field trials are far less conclusive. Patrick et al (1967) found N-serve$^{(R)}$ of limited effectiveness in increasing nitrogen utilisation in rice yields under field conditions in Louisiana. Extensive work by the International Atomic Energy Agency in Vienna (Anon. 1970) in several countries has shown that 10 or 20 kg N-serve$^{(R)}$ ha^{-1}, mixed with labelled ammonium sulphate, affected the uptake of N from fertiliser applied on the soil surface. However, placement of the same fertiliser without the inhibitor at a depth of 5 cm was more effective than any N-serve$^{(R)}$ treatment. A.M.$^{(R)}$ had similar effects to N-serve$^{(R)}$ in the field.

Experiments with both N-serve$^{(R)}$ and Dicyandiamid have been carried out in New South Wales by Boerema (1970) since 1966 with varying results. On some soils both chemicals applied at a rate of 5 kg ha^{-1}, mixed with ammonium sulphate, have significantly increased yields. On other soils, yields from treated plots have been identical to those from plots fertilised with ammonium sulphate alone. The latter soils have been found to nitrify added ammonium slowly in the laboratory.

(iv) Delayed nitrogen applications: Fertiliser efficiency will be maximised when supply of nitrogen is matched to the requirements of the plant for growth and development. Application of large amounts of fertiliser at one time increases losses and often results in luxury consumption and lodging.

Ten Have (1967) working with rice sown on-mud or in-water in Surinam found that a basic application of 25 kg N ha^{-1} at planting increased yields by 136 kg ha^{-1}. If more than 25 kg N ha^{-1} was required to obtain the highest yield, a split application some 48 and 68 days from sowing produced best results. Patrick and Peterson (1967) in Louisiana obtained more grain from fertiliser applied at or before seeding than from later topdressed applications. When a pre-plant application was not made, best results were obtained from applications within the first three weeks following emergence, before flooding. If rice growth was unsatisfactory they found that a corrective application could be given at panicle initiation.

Extensive research carried out in Arkansas by Hall et al (1968), Sims et al (1967) and Wells and Johnston (1970) has led to the general practice of topdressing at or near the onset of internode elongation. It was found that maximum yields were obtained with topdressing at an average stem elongation of 21.0, 28.5 and 5.0 mm for the varieties Bluebelle, Nova 66 and Starbonnet respectively. Delaying N applications until these stages, simultaneously maximised yields and minimised vegetative growth and lodging. They found that internode elongation was very rapid, about 6 mm per day, which necessitated a very close inspection of crops for optimum timing of topdressings.

Mikkelsen (1965) in California has shown that no yield advantage is obtained by splitting nitrogen applications for aerial-sown rice. Applying all the fertiliser into the soil prior to flooding gave best results. If crop development indicated that supplementary N was necessary then it was most efficiently utilised when applied at a rate of 20-40 kg ha^{-1} between 50 and 60 days after sowing.

Using ^{15}N, the Atomic Energy Agency (Anon. 1970) concluded from a large number of experiments with transplanted rice in many countries that the most efficient use of fertiliser was achieved when ammonium sulphate was applied as a single dose two weeks before panicle initiation. Splitting N-applications in two or three doses was of no advantage. The magnitude of the response to time of application depended on the type of soil. The greatest response was obtained on soils of a low pH (4.8 - 5.2) and moderate organic matter content. On sites of medium to high pH and organic matter there was little difference between the N-utilisation from fertilisers placed at 5 cm depth before transplanting and that from fertiliser applied on the surface three weeks before panicle initiation.

The diversity of establishment methods used precluded generalised rules for timing N-applications. However, there is a general tendency to apply all the nitrogen as a basal application for early maturing varieties. When additional nitrogen is required the optimum time of application is around panicle initiation (or stem elongation).

The need for additions of nitrogen fertiliser to combine-sown rice depends on three factors:-

(a) the length of flushing period and rate of nitrification during this period,

(b) the ability of the soil to supply ammonium to the crop during its ontogeny,

(c) the nitrogen response of the variety.

When a long period of flushing is required, losses from applied ammonium fertiliser can be large, depending on the rate of nitrification in the soil. Thus there may be some saving of nitrogen by applying most of the fertiliser just before permanent flood, even though it cannot be incorporated in the soil. There is evidence that efficiency of broadcast fertiliser is greatest when applied to dry soil and quickly flooded (Ten Have, 1967; Kapp, 1948). In the later stages of crop growth, fertiliser can be applied just as effectively into flood water (Wells, 1972).

From this background, the nitrogen transformations in a red-brown earth at Yanco will be examined, and the nitrogen economy under two methods of sowing and with several methods of applying ammonium fertiliser to combine-sown rice will be discussed.

C. NITROGEN TRANSFORMATIONS AND METHOD OF SOWING ON A RED-BROWN EARTH

Introduction

From the earliest years of rice growing in New South Wales, crops have been sown by combine. Seed was placed to a depth of 2-3 cm together with the required sulphate of ammonia into a well prepared seed bed. Seed bed preparation often commenced in Autumn, especially when re-contouring was necessary. During this very long period of fallow the soil was usually kept free of weeds. At times a crop of fodder oats was established; it was grazed and ploughed in before the final preparation for rice. Aerial sowing was only used as an emergency measure when farmers were late with their soil preparation. On fertile soils which had previously been under pasture this led almost invariably to serious lodging of the crop and for this reason the technique never became popular. However, on the poorer soils in the Murray Valley, aerial-sown crops have given better plantstands and higher yields. This led to an almost universal acceptance of the technique in this area with its poorer soils and a harsher climate. Early problems with seed distribution, floating of seedlings, etc. were quickly solved.

From crop observations it appeared that aerial-sown rice could utilise more nitrogen from the same soil than that sown by combine. Nitrogen transformations in the soil during a period of fallow and the period of flushing were studied and the uptake of nitrogen by rice under both combine- and aerial-sown methods of sowing was explored. These investigations, which include observations from the experiment previously described, are presented here.

(a) Method: The experimental area was situated on a red-brown earth of the Merungle series. The soil contained 49% sand, 14% silt and 37% clay. The organic carbon content was 4.0%, total nitrogen 0.16% and pH 5.0. Rice was previously grown on this site in 1964-65, followed by pasture established in the autumn of 1966. The pasture was utilised for grazing sheep and hay making. The area was first cultivated on 23 April, 1970, fallowed until October when rice was again planted.

Soil samples were taken to a depth of 15 cm at irregular intervals during fallowing and, following the first watering, at 9-day intervals from both fertilised and unfertilised plots. Each sample consisted of

30 cores collected from a zig-zag path. A systematic pattern was used to ensure equal sampling of fertilised and unfertilised bands in the plots to which fertiliser had been added. After drying, grinding and sub-sampling, ammonium nitrogen produced after 14 days incubation under water at 30°C, was determined (Polhill, 1967). This gave an estimate of the potential ammonium production of the soil.

After applying 0, 78 and 155 kg N ha^{-1} as ammonium sulphate, combine-sown rice was flushed for a period of 36 days whilst aerial-sown rice was kept continuously flooded. After permanent flood was applied no further soil samples were taken since "in-water" soil sampling technqiues are not satisfactory. Crop establishment, management and plant analysis were as described in Chapter II. From the 1971-72 unreplicated experiment only harvest samples for N-uptake were obtained.

(b) <u>Results</u>: The rate of decline in the NH_4^+ generating power of the soil during the fallow and the rate of loss of applied ammonium sulphate (155 kg N ha^{-1}) after sowing is illustrated in Fig. 28. Where N is available NH_4^+ ions and t is time from first cultivation or sowing as appropriate rate.

The incubated NH_4^+ concentration fell from 87 ppm to 28 ppm in 129 days of fallow during autumn and winter. During the 36-day period of flushing it continued to fall to 5 ppm. In the soil to which the ammonium sulphate was added the incubated NH_4^+ concentration fell from 168 to 88 ppm during flushing, representing a loss of almost half the nitrogen applied.

During the period of fallow the rate of nitrification averaged 0.46 ppm d^{-1}

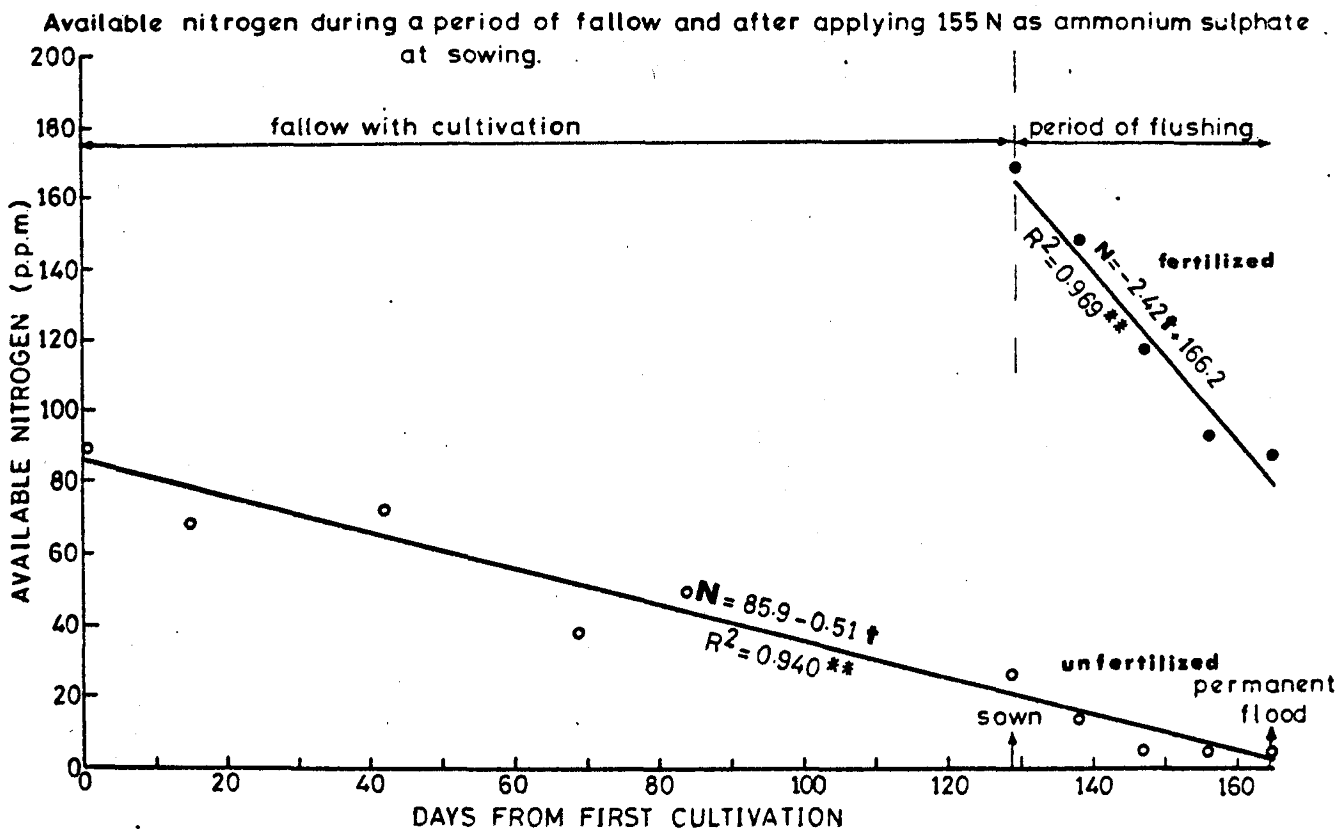

Available nitrogen during a period of fallow and after applying 155 N as ammonium sulphate at sowing.
fallow with cultivation
period of flushing
N = -2.42t + 166.2
R2 = 0.969**
fertilized
N = 85.9 - 0.51 t
R2 = 0.940**
unfertilized
sown
permanent flood
AVAILABLE NITROGEN (p.p.m.)
DAYS FROM FIRST CULTIVATION

Fig.28

Following the application of 155 N as ammonium sulphate the nitrification rate rose to 2.2 ppm d^{-1} over the 36-day period of flushing.

Nitrogen uptake by combine-sown rice was taken as linear with time throughout the growing season, although there was some evidence of curvilinearity, especially with the aerial sown 155-N treatment. (Fig. 29). Significantly more was taken up from 155 N than from 0 N treatments, but there were no differences between the methods of sowing in uptake towards the end of the season. Large differences were found during establishment and tillering; aerial-sown rice with 155 N showed luxurious nitrogen consumption during tillering, resulting in a very large number of leafy tillers of which approximately 50 percent died. From tillering to grain set the uptake was negligible. It is assumed that developing panicles utilised nitrogen from dying tillers. A further small amount of nitrogen was taken up during ripening.

Serious lodging occurred shortly after flowering on aerial-sown treatments receiving 155 N. This resulted in a high percentage floret sterility, a low 1000-grain weight and low yields (Table 31).

It is expected that the major part of fertiliser nitrogen was taken up during early stages of growth and that the later uptake was mainly from nitrogen becoming available from the soil. As the early rate of uptake was much greater for aerial-sown than for combine-sown rice, it is most likely that this extra nitrogen became available due to reduced losses of nitrogen from both soil and fertiliser nitrogen under aerial-sown conditions.

Total N-uptake and the calculated efficiency of applied nitrogen is

TABLE 31. Yields (kg ha^{-1}) from two methods of sowing at three nitrogen rates (mean 3 varieties).

N-rate (N)	Method of Sowing (S)		Mean (N)
	Combine Sown	Aerial Sown	
0 N	9200	8520	8860
78 N	10050	10740	10400
155 N	11270	7580	9430
Mean (S)	10170	8950	

L.S.D. $P = 0.05$

Between N means:	352
Between N means at same level of S:	498
Between S means at same or different levels of N:	1512

presented in Table 32. In 1971-72, fertilised combine-sown rice absorbed considerably less nitrogen than in the previous year, whilst aerial-sown rice took up almost the same amount in both years. The lower uptake of fertilised combine-sown rice was reflected in yields.

In the first year combine-sown rice utilised slightly more N for grain production than in 1972, whilst the reverse was true for aerial-sown rice. The low N-uptake by grain of aerial-sown rice fertilised with 155 N in the first year reflects the very unfavourable grain/straw ratio resulting from early lodging. In the second year aerial-sown rice utilised much more of the applied N than combine-sown rice. This was particularly so at 78 N, where lodging and excessive floret sterility were not problems. The efficiency of applied nitrogen fertiliser to combine-sown rice was particularly poor in the second year. This could be due to a longer period of flushing to establish the crop, with consequently higher nitrogen losses and to a higher percentage floret sterility due to low temperatures around flowering. The lower efficiency of 155 N on aerial-sown rice was due to lodging and a high percentage floret sterility.

(c) Discussion: Nitrogen losses both from native sources and applied nitrogen fertiliser were high before permanent flood was applied. The losses occurred during a long fallow and during "flushing" of combine sown rice and may be attributed to nitrification of ammonium ions with a subsequent denitrification of the nitrate after flooding.

The rate of nitrification usually corresponds closely with the rate of decrease of incubated NH_4^+. Horth (private communication) studied six Murrumbidgee Valley rice soils for their ability to nitrify ammonium

TABLE 32. The nitrogen uptake and the efficiency of applied nitrogen of combine and aerial sown rice.

Parameter	1970-71				1971-72					
	Combine		Aerial		Combine			Aerial		
	0 N	155 N	0 N	155 N	0 N	78 N	155 N	0 N	78 N	155 N
Total N uptake (kg ha^{-1})	127	183	135	196	125	139	142	142	201	206
Percentage N in the grain	73	70	68	56	69	67	68	70	69	68
Percentage utilization of applied N.		35		39		14	7		57	31

Nitrogen uptake of combine and aerial sown rice at two nitrogen levels.

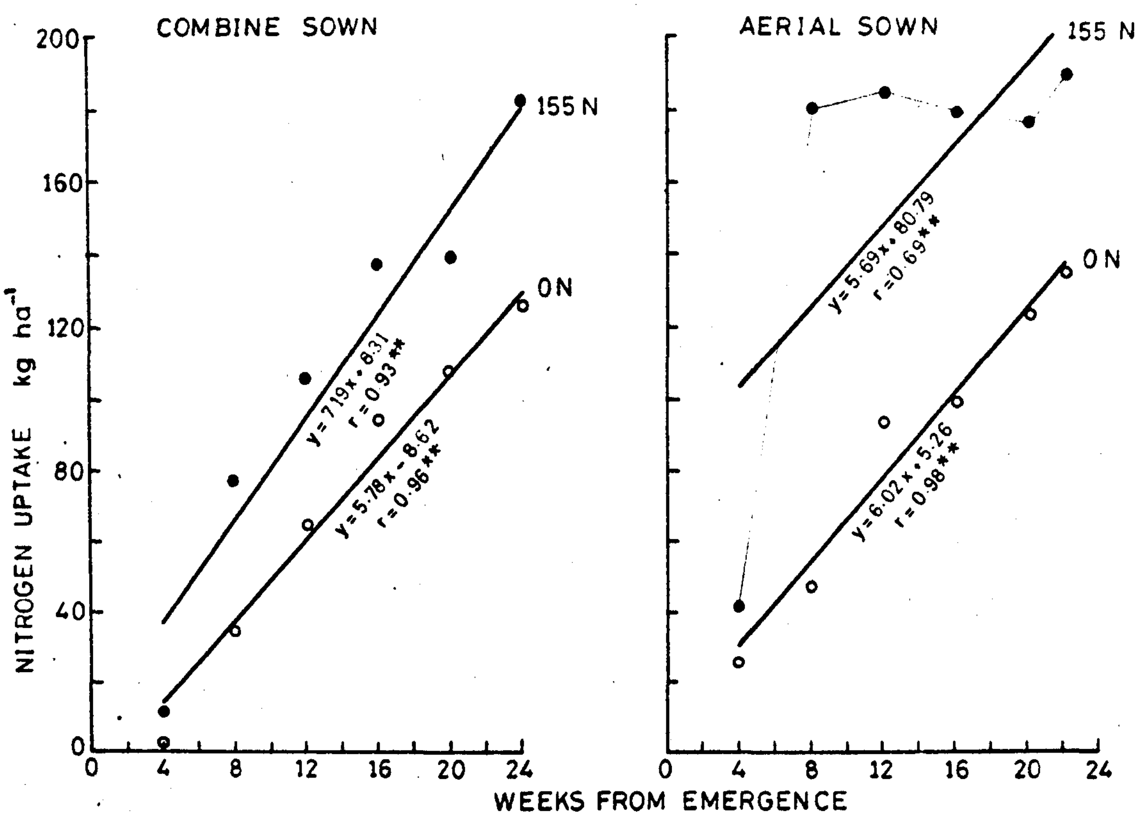


Fig.29

sulphate under laboratory conditions. Soils with low pH were found to be slow nitrifiers. The regression equation expressing the linear relationship between rate of nitrification, R (ppm d^{-1}), and pH (P), was found to be

$$R = 3.7P - 16.3 \quad r^2 = .65^*$$

At a pH of 4.4 the "theoretical" rate of nitrification was zero, a large increase being obtained by an increase of one unit of pH. On soils with a pH of 7 to 7.5 "theoretical" rates of nitrification of around 10 ppm d^{-1} were obtained.

Widely varying nitrifying capacities of arable soils, supplied with 400 ppm of Urea-N, were also noted by Clark et al. (1960), and grassland soils are known to have slower rates of nitrification than arable soils (Harmsen and Van Schreven, 1955). Horth (private communication) has found a large variation between the rates of nitrification of Riverina soils, the described red-brown earth having one of the highest rates.

It is therefore not surprising to find that aerially sown rice which received permanent flood immediately after applying the fertiliser could utilise more nitrogen during early growth stages than combine-sown rice. This led to a far more vigorous growth and late lodging with reduction of yields. Because of the very good nitrogen supply from the soil even unfertilised rice produced reasonable yields.

The frequently observed lodging of aerial sown rice on old legume pasture can be attributed to a greater availability of nitrogen, combined with a less firm seedling anchorage.

D. PREVENTING NITROGEN LOSSES OF COMBINE-SOWN RICE

Introduction

It was established above that losses from ammonium fertiliser applied at sowing are high on a red-brown earth when combine-sowing is practiced.

An experiment was conducted at the Yanco Agricultural College and Research Centre in 1971-72 to determine the effect of (1) deep placed fertiliser, (2) the addition of a nitrification inhibitor, (3) delayed application until permanent flood, and (4) delayed application until panicle initiation.

(a) Method: Soil samples taken 27 days before sowing indicated that 68 ppm N (incubated NH_4^+) was available in the soil. This represents a fairly high level of fertility and not more than 40-60 kg N ha^{-1} would be required for maximum yield.

Sulphate of ammonia was used at rates equivalent to 0, 52, 104, 155 and 270 kg N ha^{-1}. There were five methods of application:

(a) all N with the seed at sowing.

(b) mixed with 8 kg DDA (Dicyanidiamide)ha^{-1} with the seed.

(c) 26 kg N ha^{-1} with the seed and the rest at a depth of 7-8 cm before sowing.

(d) 13 kg N ha^{-1} with the seed and the rest on the dry surface immediately before permanent flooding.

(e) half with the seed and half at panicle initiation.

The effectiveness of DDA in preventing N-losses from the soil was also tested by spraying the chemical at 8 and 16 kg ha^{-1} onto the soil before sowing. Normal cultural practices were followed and yields were determined by harvesting complete plots, including edge rows. Boerema (1972) found that inclusion of edge rows, although giving higher plot yields, did not affect the relative experimental results on a similar soil.

(b) Results and discussion: Prior to permanent flooding, unfertilised plots could always be distinguished by their pale colour. Only 13 kg ha^{-1} was required to improve early growth and colour of rice seedlings. After permanent flooding rice grew vigorously, but there was with all methods of fertiliser application an apparent response to N. The heaviest plots lodged during ripening.

Deep-placed fertiliser reduced plant density (Table 33); this was due to sinkage of seed into the loose soil following watering. High rates of ammonium sulphate in contact with rice seed had no significant effect on seedling emergence.

All yields (Table 34) were high due to the high soil fertility of the experimental site. There was no significant difference in yield between 52, 104 and 155 N, but all produced significantly higher yields than the unfertilised control. The highest N-rate (207 N) depressed yields significantly due to excessive vegetative growth and lodging (except for the treatments with deep placed fertiliser and topdressing at panicle initiation, where lodging did not occur).

The significant differences between "method" means was mainly due to the relatively low yields obtained when the two highest N-rates were applied at permanent flooding, which resulted in serious early lodging (especially at 207 N) and the consistently good performance of the panicle initiation treatment. The high yields obtained with topdressing

TABLE 33. The effect of methods of applying nitrogen on the plant density (plants m^{-2}) of combine sown rice.

Inhibitor (I)		Method (M)	N-rate(N) (kg ha^{-1})				Mean (M)
Rate	Plants m^{-2}		52	104	155	207	
Nil	346	Seed depth	282	270	335	297	296
8 DDA	331	Inhibitor	322	304	317	317	315
16 DDA	311	Permanent flood	346	322	315	321	326
		Deep placed	210	248	268	236	241
		Panicle initiation	351	336	306	305	325
		Mean (N)	302	296	308	295	

L.S.D. P = 0.05 Between M means = 26

TABLE 34. The effect of methods of applying nitrogen on yield ($kg\ ha^{-1}$) of combine sown rice.

Inhibitor (I)		Method (M)	N-rate (N) ($kg\ ha^{-1}$)				Mean (M)
Rate	$kg\ ha^{-1}$		52	104	155	207	
Nil	10030	Seed depth	10670	10760	11430	10550	10850
8 DDA	10770	Inhibitor	10940	11020	10740	10290	10750
16 DDA	10140	Permanent flood	11290	11390	10500	8540	10430
		Deep placed	10580	10900	11080	10790	10840
		Panicle initiation	11020	10990	11250	11320	11140
		Mean (N)	10900	11010	11000	10300	

L.S.D. P = 0.05 Between N means = 425

Between I and N means = 735

Between M means = 358

Between M means at same level of N = 717

Between N means at same or different level of M = 769 at the highest N-rates indicates that the fertiliser applied at sowing was not too much to produce excessive vegetative growth and that topdressing at panicle initiation did not weaken the straw. Inclusion of the nitrification inhibitor led also to lodging at 155 and 207 N. At 207 N this occurred earlier than at 155 N.

Highest yields were obtained when the major part of 52 and 104 N was applied at permanent flooding. Split applications of 155 and 104 N at sowing and panicle initiation also yielded well, but this was achieved at much higher N-rates.

Inhibitor applied to the soil did produce neither improved crop growth nor improved yields. This indicates that the chemical was apparently not effective in reducing N-losses by arresting nitrification of soil N during flushing. However, the inhibitor prevented some losses from the applied ammonium sulphate.

The greater vegetative development of rice on treatments utilising the applied fertiliser most efficiently was reflected in the grain-straw ratio (Table 35). When most of the fertiliser was applied at permanent flooding, the highest yielding plots had a more favourable ratio than the leafy plots which received high rates of fertiliser. Applying half the fertiliser at sowing and the rest at panicle initiation was effective in reducing the amount of straw.

Panicle number (Table 36) increased with the amount of N applied. Permanent flood treatments had more panicles than plots receiving all nitrogen at sowing, indicating that more N was available to support the tillers through to the reproductive stage. The low plant density on

TABLE 35. The effect of methods of applying nitrogen on the grain/straw ratio of combine sown rice.

Inhibitor (I)		Method (M)	N-rate (N) ($kg\ ha^{-1}$)				Mean (M)
Rate			52	104	155	207	
Nil	.832	Seed depth	.889	.846	.786	.683	.801
8 DDA	.892	Inhibitor	.898	.835	.781	.689	.801
16 DDA	.835	Permanent flood	.907	.836	.752	.581	.769
		Deep placed	.854	.861	.819	.765	.825
		Panicle initiation	.915	.894	.815	.831	.864
		Mean (N)	.893	.854	.791	.710	

L.S.D. P = 0.05 Between N means = .054

Between I and N means = .132

Between M means = .029

Between M means at same level of N = .059

Between N means at same or different levels of M = .075

TABLE 36. The effect of methods of applying nitrogen on the panicle density (panicles m^{-2}) of combine sown rice.

Inhibitor (I)		Method (M)	N-rate (N) ($kg\ ha^{-1}$)				Mean (M)
Rate	Panicles m^{-2}		52	104	155	207	
Nil	660	Seed depth	636	670	703	799	702
8 DDA	612	Inhibitor	623	718	780	770	723
16 DDA	582	Permanent flood	673	715	817	807	753
		Deep placed	571	574	667	739	638
		Panicle initiation	632	639	683	727	670
		Mean (N)	627	663	730	768	

L.S.D. $P = 0.05$ Between N means = 55

Between I and N means = 95

Between M means = 42

deeply placed fertiliser plots was not compensated for by tillering and it is suspected that considerable losses of nitrogen must have occurred.

Floret sterility (Table 38) increased with N-rates. Differences between methods of applying N were statistically not significant. Both highest N-rates reduced grain size. Rice topdressed at panicle initiation had also a smaller 1000-grain weight (Table 39). It is difficult to advance a plausible explanation for this, since a greater N-supply during flowering and ripening usually results in an improved grain filling. It may, however, be that improved N availability at panicle initiation led to a slightly larger panicle (Table 37) (statistically non significant) and that inadequate residual N from this topdressing was available for complete grain filling.

Results indicate that losses of applied N occurred and that the extent of losses depended on method of application. Losses were reduced by (1) delaying the application until permanent flood, (2) by applying half at panicle initiation and, (3) by using a nitrification inhibitor mixed with the fertiliser.

The efficiency of applied nitrogen fertiliser was measured as changes in grain yield per kg applied N and changes in N-recovery by the whole crop. Although individual treatment yields were higher at higher N-rates, the yields did not increase significantly when more than 52 N was applied. Efficiency calculations were therefore confined to this rate of application (Table 40).

TABLE 37. The effect of methods of applying nitrogen on the number of florets per panicle of combine sown rice.

Inhibitor (I)		Method (M)	N-rate (N) ($kg\ ha^{-1}$)				Mean (M)
Rate	Florets $panicle^{-1}$		52	104	155	207	
Nil	68.2	Seed depth	82.9	68.8	68.4	62.0	73.0
8 DDA	70.0	Inhibitor	79.0	69.7	76.0	71.0	73.9
16 DDA	69.9	Permanent flood	72.1	75.5	69.0	69.7	71.6
		Deep placed	80.7	72.8	83.1	80.5	79.3
		Panicle initiation	73.7	80.8	76.5	77.6	77.2
		Mean (N)	77.7	75.5	74.6	72.2	

L.S.D. $P = 0.05$ No differences significant.

TABLE 38. The effect of method of applying nitrogen on the floret sterility (%) in combine sown rice.

Inhibitor (I)		Method (M)	N-rate (N) ($kg\ ha^{-1}$)				Mean (M)
Rate	% Floret Sterility		52	104	155	207	
Nil	16.2	Seed depth	16.5	15.7	21.0	28.0	20.3
8 DDA	14.5	Inhibitor	15.7	19.5	21.0	21.7	19.5
16 DDA	15.0	Permanent flood	13.5	19.7	22.2	27.0	20.6
		Deep placed	15.7	16.7	21.2	23.7	19.3
		Panicle initiation	14.2	17.7	22.5	22.0	19.1
		Mean (N)	15.1	17.9	21.6	24.5	

L.S.D. P = 0.05 Between N means = 1.2

Between I and N means = 2.0

TABLE 39. The effect of methods of applying nitrogen on the 1000-grain weight (g) in combine sown rice.

Inhibitor (I)		Method (M)	N-rate (N) (kg ha^{-1})				Mean (M)
Rate	g		52	104	155	207	
Nil	27.76	Seed depth	27.70	27.56	27.67	27.18	27.53
8 DDA	28.04	Inhibitor	27.39	27.70	27.21	26.77	27.27
16 DDA	27.41	Permanent flood	28.40	28.02	27.24	26.72	27.60
		Deep placed	28.05	28.26	27.53	27.27	27.78
		Panicle initiation	27.56	27.30	27.27	26.17	27.08
		Mean (N)	27.82	27.77	27.38	26.82	

L.S.D. P = 0.05 Between N means = .32

Between I and N means = .56

Between M means = .42

TABLE 40. Efficiency of applied N in producing grain by applying 52 N.

Method of Application	Yield Increase from 52 N (kg ha^{-1})	kg grain per kg applied N
Permanent flood	1267*	24.4
Panicle Initiation	992*	19.1
With nitrification inhibitor	912*	17.6
At seed depth	647	12.4
Deep placed	550	10.6
* significant yield increase		

To recover cost of fertiliser (1973 prices) approximately 6 kg ha^{-1} grain is required per kg applied N. All methods of applying 52 N were sound economically. However, highest returns were obtained when the fertiliser was applied at permanent flood. This was followed by a split application, half at sowing and half at panicle initiation and by using the nitrification inhibitor DDA.

Applying 104 N at permanent flood with a return of 13.1 kg grain per kg N was also financially rewarding, but applications of 155 N at panicle initiation and at seed depth with returns of 8.0 and 9.0 kg grain per kg N respectively were marginal.

The recovery of nitrogen from 52 N applied was also determined at this rate only, since main effects were statistically significant at this rate. Results are presented in Table 41.

Recovery rates were very low. Highest utilisation was obtained when most of the fertiliser was applied at permanent flood. When compared with the normal seed depth application, the use of the nitrification inhibitor improved the recovery rate somewhat (2.4%). Deep placement of the fertiliser and topdressing at panicle initiation were ineffective in improving the utilisation of fertiliser nitrogen. The low N-recovery at panicle initiation reflects the lower straw yield and a lower N content in the straw.

(c) Conclusion: Losses from applied fertiliser can be most effectively reduced by applying the bulk of the fertiliser at permanent flood. Deep placement of ammonium sulphate was ineffective in saving N, but the use of a nitrification inhibitor saved some N. Topdressing at panicle initiation did not maximise yields at low N, but at high rates it did not lead to lodging with reduced yields.

TABLE 41. The utilisation of nitrogen applied at 52 N

Method of Application	Total Recovery of N (kg ha^{-1})	% in whole plant	% in grain
Permanent flood	15.9	30.6	19.3
With nitrification inhibitor	9.7	18.7	11.7
At seed depth	8.5	16.3	10.3
Deep placed	3.4	6.6	4.1
Panicle initiation	2.5	4.8	3.2

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METHOD OF SOWING X VARIETY X NITROGEN TRIAL Y.
MR E.B.BOEREMA S REPORT.

Appendix 1

ANALYSIS OF VARIANCE FOR LOG

SOURCE OF VARIATION	D.F.
REPLICATIONS	2
METHOD OF SOWING S	1
ERROR (A)	2
VARIETIES (V)	2
S X V	2
ERROR (B)	8
N-RATES (N)	1
S X N	1
V X N	2
S X V X N	2
ERROR (C)	12
T LINEAR	1
T QUADRATIC	1
T CUBIC	1
T QUARTIC	1
T REMAINDER	5
S X T LIN.	1
S X T QUAD.	1
T X S REMAINDER	7
V X T LIN.	2
V X T QUAD.	2
T. X V REMAINDER	14
N X T LIN.	1
N X T QUAD.	1
T X N REMAINDER	7
T X S X V	18
T X S X N	9
T X V X N	18
T X S X V X N	18
REPS X T	18
ERROR (D)	198
TOTAL	359

ANCO 70/71

(DRY MATTER)

MEAN SQUARE		% PROBABILITY
.11833		81.647
43.73417	*	1.182
.52644		
.99571	**	.001
.74954	**	.004
.01645		
18.59316	**	.000
.65571	**	.358
.06479		31.153
.00445		91.591
.05033		
993.88018		.000
192.50256		.000
16.62778		.000
1.55446		.000
.48984		.000
21.65591		.000
1.37906		.000
.39674		.000
.06848		9.212
.14044		.799
.01495		91.551
.75205		.000
1.14895		.000
.30397		.000
.11194		.000
.11808		.006
.01786		87.389
.01222		97.994
.07516		.051
.02837		

METHOD OF SOWING X VARIETY X NITROGEN TRIAL   YANCO 70/71
MR E.B.BOEREMA S REPORT.

Appendix 2

ANALYSIS OF VARIANCE FOR L.A.I.

SOURCE OF VARIATION	D.F.	MEAN SQUARE		% PROBABILI
REPLICATIONS	2	4.0523		61.775
METHOD OF SOWING S	1	184.9271	*	3.364
ERROR (A)	2	6.5488		
VARIETIES (V)	2	2.9475		21.877
S X V	2	11.3324	*	1.682
ERROR (B)	8	1.5943		
N-RATES (N)	1	689.5775	**	.000
S X N	1	62.3962	**	.003
V X N	2	1.6631		36.802
S X V X N	2	3.0266		18.074
ERROR (C)	12	1.5290		
T LINEAR	1	352.4620		.000
T QUADRATIC	1	1071.9722		.000
T CUBIC	1	19.1329		.004
T QUARTIC	1	34.0179		.000
T REMAINDER	5	5.7181		.013
S X T LIN.	1	1.9125		18.292
S X T QUAD.	1	45.5551		.000
T X S REMAINDER	7	3.7462		.146
V X T LIN.	2	.3963		69.113
V X T QUAD.	2	1.2648		30.903
T X V REMAINDER	14	.7707		75.304
N X T LIN.	1	45.4840		.000
N X T QUAD.	1	150.4570		.000
T X N REMAINDER	7	3.6176		.198
T X S X V	18	.6265		90.775
T X S X N	9	4.2863		.010
T X V X N	18	1.3116		24.389
T X S X V X N	18	.2547		99.953
REPS X T	18	1.0316		50.343
ERROR (D)	198	1.0707		

TOTAL 359

ANALYSIS OF VARIANCE FOR LOG(DRY MATTER)

Appendix 3

SOURCE OF VARIATION	D.F.	MEAN SQUARE		% PROBABILI
REPLICATIONS	2	.420593		2.448
VARIETIES (V)	2	.655334	**	.479
DENSITY (D)	1	19.647262	**	.000
N-RATES (N)	1	9.492600	**	.000
V X D	2	.076524		46.080
V X N	2	.019765		81.431
D X N	1	.015442		69.122
V X D X N	2	.123603		29.355
ERROR (A)	22	.095329		
T LINEAR	1	1388.668000		.000
T QUADRATIC	1	304.838200		.000
T CUBIC	1	25.453282		.000
T QUARTIC	1	1.177646		.000
T REMAINDER	7	.247606		.000
V X T LIN.	2	.032640		25.969
V X T QUAD.	2	.089886		2.529
V X T REMAINDER	18	.016196		83.660
D X T LIN.	1	17.527185		.000
D X T QUAD.	1	5.513098		.000
D X T REMAINDER	9	.186554		.000
N X T LIN.	1	.800335		.000
N X T QUAD.	1	.174503		.759
N X T REMAINDER	9	.105883		.003
T X V X D	22	.015462		89.078
T X V X N	22	.021485		60.517
T X D X N	11	.016144		76.580
T X V X D X N	22	.031394		16.875
REPS X T	22	.053222		.192
ERROR (B)	242	.024075		

TOTAL 431

STANDARD DEVIATION = .309 OR 5.2 PERCENT

STANDARD DEVIATION = .155 OR 2.6 PERCENT

ANALYSIS OF VARIANCE FOR L.A.I.

Appendix 4

SOURCE OF VARIATION	D.F.	MEAN SQUARE	% PROBABILI
REPLICATIONS	2	6.7676	3.258
VARIETIES (V)	2	19.7579**	.034
DENSITY (D)	1	54.4655**	.001
N-RATES (N)	1	188.5171**	.000
V X D	2	.7366	65.133
V X N	2	.1542	91.288
D X N	1	5.6012	8.187
V X D X N	2	.8894	59.713
ERROR (A)	22	1.6848	
T LINEAR	1	189.5559	.000
T QUADRATIC	1	819.7557	.000
T CUBIC	1	3.4165	.682
T QUARTIC	1	62.8716	.000
T REMAINDER	7	2.7887	.000
V X T LIN.	2	9.0387	-.000
V X T QUAD.	2	.8205	16.935
V X T REMAINDER	18	.7475	5.367
D X T LIN.	1	1.3470	8.787
D X T QUAD.	1	10.1554	.000
D X T REMAINDER	9	.6698	16.346
N X T LIN.	1	2.8235	1.378
N X T QUAD.	1	61.8991	.000
N X T REMAINDER	9	1.2066	.640
T X V X D	22	.1617	99.730
T X V X N	22	.4891	38.492
T X D X N	11	.3435	69.071
T X V X D X N	22	.2894	89.976
REPS X T	22	.5464	25.621
ERROR (B)	242	.4587	
TOTAL	431		

STANDARD DEVIATION = 1.30 OR 45.3 PERCENT

STANDARD DEVIATION =Y .68 OR 23.6 PERCENT

NEW SOUTH WALES DEPARTMENT OF AGRICULTURE
YANCO AGRICULTURAL COLLEGE AND RESEARCH STATION

E.B. BOEREMA

Rice cultivation in Australia

Estratto da

Rivista **IL RISO** - Anno XXII

Giugno 1973 - N. 2

Rice cultivation in Australia

by E.B. Boerema

Introduction

Rice has been cultivated for thousands of years in widely differing agroclimatic regions in the tropics and sub-tropics. Due to improved varieties and better cultural techniques, rice growing has gradually expanted to cooler areas and now extends to latitudes of 49° N and 35° S, in regions with a plentiful supply of water as rain or irrigation, and with minimum temperatures wich do not restrict emergence (10 °C) and grain set (15 °C).
Cultivated rice varieties, with exception of some cultivars of *Oyza glaberrima* Steudel grown in Africa, belong to the species *Oryza sativa L.* In the course of many centuries, thousands of local varieties have been selected. These now produce more than 300 million metric tons of grain per annum providing approximately 27 % of the world's carbohydrate. In south-east Asia rice provides abount 50 % of the energy intake of the population.
The classification and nomenclature of species in the genus *Oryza* remains controversial (Chang, 1964). Two main sub-species, *japonica* and *indica,* are usually distinguished. They differ in geographic adaption, morphological characters, serological reactions and sexual affinity. Japonicas are generally adapted to a temperate climate, whilst indicas are mostly grown in tropical areas. There are some temperate indica varieties, but these are morphologically distinct from tropical indicas. Hybrid sterility in crosses between the two sub-species ranges from 66 to 100 % (Chandraratna, 1964). To produce hybridis of higher fertility Jennings (1966) suggested: (i) substitution of Taiwanese japonicas for Japanese japonicas as one of the parents, since the latter are highly temperature sensitive and many are photoperiodic; (ii) crossing each potential indica parent with one or two japonica test lines and selecting those giving the most fertile hybridis; (iii) using U.S.A. lines derived from indica x Taiwanese japonicas as substitutes for japonica parents; (iv) using the single backcross of the F_1 to the indica parent, followed by F_2 selection.
Typicaly, indicas are tall, tiller profusely, have broad light green leaves and long slender grains. Japonicas are shorter, tiller less profusely, have narrow dark green leaves and short round grain. Generally, japonicas have a higher yield potential than indicas. Lodging of the tall weak-strawed indica varieties is one of the main causes of low rice yields in tropical areas. A higher protosynthetic capacity during ripening, prima-

The medium grain rice variety Calrose yielded 13,500 kg/ha when sown with 56 kg/ha N following four years legume pasture (left plot). The unfertilised plot at the right yielded 12,300 kg/ha.

rily due to slower leaf senescence, is advanced by Samarrai (1969) as the major factor allowing japonicas to be more efficient in grain production.

The discovery of a single dwarfing gene in some widely adapted, photoperiod-insensitive japonica varieties from Taiwan (« ponlais ») has resulted in a major breakthrough in tropical rice yields. This gene has been used by the International Rice Research Institute (I.R.R.I.) in the Philippines in developing new varieties like IR 8 and further IR selections which are short-statured with erect leaves and are highly responsive to nitrogen fertilisation.

In New South Wales, where rice is grown at a latitude of 34-35° S, the very high yelding Californian *japonica* varieties Caloro and Calrose have been grown since 1924. To meet the demand for an export quality long-grain product, the variety Kulu was selected from a cross between the *japonica* variety Calrose and the Texan *sub-indica* variety Bluebonnet 50 (McDonald and Boerema, 1969). Kulu combines some of the useful indica and japonica traits. It is high yielding, has a short stature, tillers rather profusely, has narrow medium green leaves, is N-responsive and has long slender grains. It is somewhat softer cooking than traditional *indica* and *sub-indica* varieties grown in areas where ripening occurs during a period of higher temperatures.

Growth stages and parameters influencing yield

Four stages in growth can be recognised; germination and emergence, vegetative development, reproductive development and ripening. Yield capacity or potential yield may be expressed as a function of the number of panicles per unit area of crop, the number of filled florets per panicle and the grain weight. The number of panicles per unit of crop area is determined during the first two stages. Maximum panicle number is reached about ten days after the number of tillers reaches a maximum. Grain number and size are fixed during the reproductive and ripening stages with the total number of florets per panicle being determined approximately ten days before anthesis (Murata, 1969). The main features of rice growth in New South Wales are illustrated in Fig. 1. Temperatures at both ends of the season are low. Emergence is slow but further vegetative development takes place during a period of increasing temperatures and radiation. Panicle differentiation and growth occurs during the period of highest temperature and radiation. Grain set and ripening occupy

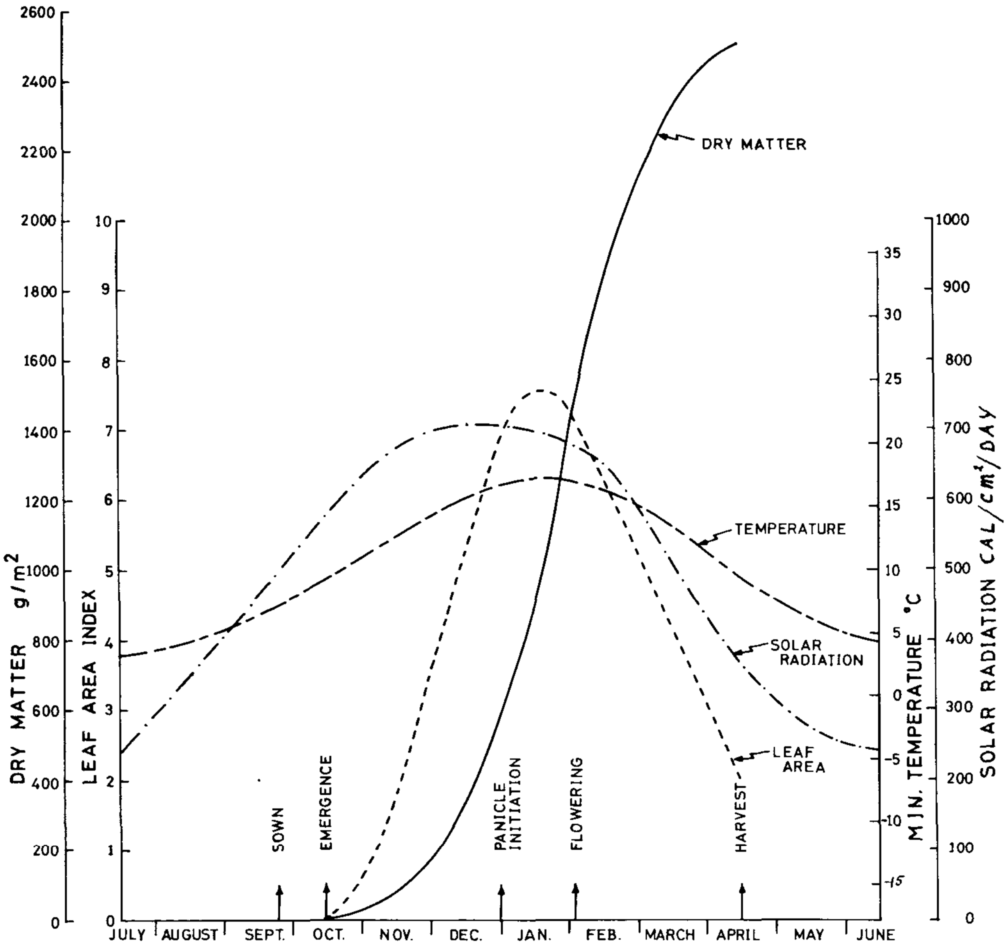


Fig. 1 - The growth of rice in relation to minimum temperature and global solar radiation in the Murrumbidgee Irrigation Area.

a period of falling temperature. The significance of these stages and the effects of environmental variation will be explored in some detail in this paper.

Germination and emergence

Seed quality is affected by the moisture content at harvest, duration and quality of storage and the existence of seed dormancy. Rice for use as seed is generally harvested at a lower moisture content than rice for milling from which maximum returns of whole grain are required.

Dormancy is common in indica varieties but not in japonicas (Matsuo, 1957). It is closely associated with sensitivity to photoperiod. Insensitive varieties usually have no period of dormancy (Chandraratna et al., 1952). Seed dormancy is considered a valuable trait in tropical area, where frequent rainfall occurs during the harvest, because it prevents sprouting of seed in the panicle. Some varieties have a dormancy period of 8-9 weeks after harvest at full ripeness (Anon., 1963). Dormancy can be broken by a number of chemical treatments and by heat. Heat treatment at a temperature of 50 °C over a period of 4 days is generally most convenient. Dormancy is of no importance in temperate areas where severe lodging is rare and where the seed is not immediately required for sowing.

Germination will occur at temperatures within the range 10-40 °C with an optimum between 25-30 °C (Sazaki and Yamazaki, 1970; Herath and Ormrod, 1965; Chaudhary and Ghildyal, 1970; Chapman and Peterson, 1962; Phillis, 1962). At 10 °C seeds germinate but abnormal seedlings develop. There are large varietal differences in the effect of low temperatures on germination percentage (Ormrod and Bunter, 1960; Herath and Ormrod, 1965).

Seedling vigour, expressed in rapid emergence from the soil, is a necessary characteristic of drill-sown or broadcast rice. Time from sowing to emergence decreases with increased depth of sowing. The optimum temperature for emergence through soil was found to be 30 °C by Inouye and Katayama (1966). When sown under the same temperature and moisture regimes, japonicas take longer than most indicas, because of a generally shorter mesocotyl (Anon., 1965). Severe surface crusting of a soil can prevent the emergence of drill-sown rice and rewetting of the crust is then required in low rainfall areas.

Direct-sown rice is seeded at rates varying from 60-150 kg/ha (200-700 grain/m^2) depending on variety, soil fertility, and expected seedling emergence. The lower seedrates are used in tropical areas where emergence is quick and seedling losses generally are low. In cool temperate regions germination and emergence are slow. Seed protection with fungicides is often beneficial in preventing excessive seedling losses during the long period of emergence.

Rapid root development is necessary for successful establishment of rice sown into water. Seedlings remain at the soil surface with roots entering the soil freely when water temperatures are below 30 °C (Phyllis, 1962). Flotation of seedlings occurs at temperatures above 30 °C due to poor root anchorage. This is attributed to low concentrations of dissolved oxygen in the irrigation water. Irrigation water should contain at least 5-6 ppm dissolved oxygen for quick anchorage and penetration of seedling roots (Chapman and Peterson, 1962). Increasing water depths result in decreased dry matter production during early growth. Varga (1967) found that the rate of formation of photosynthetic leaf pigments, chlorophyll a and b, decreased with increasing water depths and decreasing rate of aeration. Turbid irrigation water reduces light penetration to the submerged seedlings and results in a marked temperature gradient from top to bottom during the day. Clear water is of uniform temperature at all times and at all depths (Rose and Chapman, 1968).

Vegetative development

Roots: The radicle or primary seminal root breaks through the coleorhiza and is followed by two or more secondary seminal roots, all of which develop lateral roots. Seminal roots are sparsely branched and persist only for a short time after germination. They are replaced by adventitious roots which develop from the nodes of the stem below ground level (Chang and Bardenas, 1965). Tillers are produced at the nodes and further adventitious roots are formed from the lower nodes of these new culms. Katayama (1951) first proposed a theory of synchronous leafing. This was expanded by Fujii (1961), who found that the roots of a certain node and the third leaf above the node emerged and elongated simultaneously. This synchronous growth between roots and leaves in successive nodes was then maintained. The number of roots increases gradually until a maximum is reached at heading.

Rice generally develops a shallow root system (Fig. 2). Roots emerge horizontally from the nodes and spread through the relatively oxidised upper 0.5 cm layer of the soil developing profuse lateral roots and root hairs. The crown roots which penetrate deeper in the soil produce fewer lateral roots and root hairs.

Rice roots require oxygen for respiration and other metabolic activities. However, after submergence of the soil the normal process of gaseous exchange between soil and air is restricted because the diffusion coefficient of oxygen

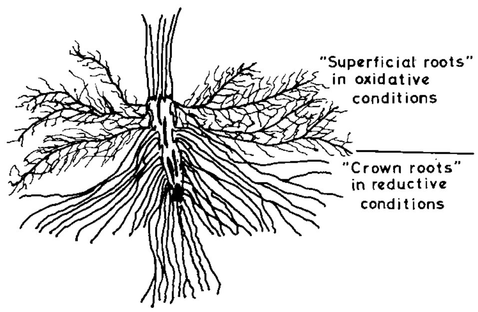


Fig. 2 - Root system in rice plant. (Fujii, 1960).

through water is only about 10^{-4} times that in air.

Naphade (1971), in reviewing the literature concluded that the rice plant possesses three adaptive mechanisms which enable it to grow in a submerged soil:

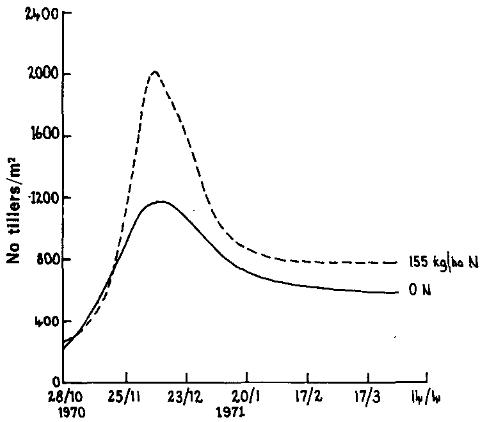
i) a highly developed system of anaerobic respiration, especially during early growth;

ii) transport of oxygen from leaves to roots through aerenchymatous tissues;

iii) development of very fine, abundantly branched negatively geotropic roots on the soil surface at the time of panicle initiation. This special system supplies roots with oxygen when stem elongation temporaly obstructs the internal downward movement of this gas.

Van Raalte (1943) first demonstrated that oxygen also diffuses from the roots into a flooded soil. This activity by roots leads to the oxidation of ferrous iron to ferric iron around the peripheries of active roots. Young roots have a high oxydising ability and remain white. As they age they lose their oxidative powers gradually and deposits of red-brown ferrous iron appear on their surfaces. Under highly reduced conditions ferrous iron may penetrate into tissues, changing the root colour to black or grey by the formation of ferrous sulphate (Ota, 1970). Physiological functions such as the rate of uptake of nutrients and the rate of root respiration are correlated with

Fig. 3 - Tillers/m² during 1970/71 for Kulu sown into water.



root size, elongation of the root tip and root colour. The rate of absorption of nitrogen, potash and phosphorous is proportional to the number of new white roots with long root apices (Inada, 1967).

Leaves: There are from three to five active leaves on each culm prior to flowering. Leaf size, thickness and angle of inclination differ greatly between varieties. Early maturing varieties bear their longest leaf on the node second from the top, whilst late maturing varieties have the longest leaf on the third or fourth node (Matsushima *et al.* 1968). Varieties with the highest yield potential usually have erect, rather small and thick leaves which intercept the light, whilst low-yelding varieties and those unresponsive to nitrogen have thin, long lax leaves which cause much mutual shading within the foliage canopy. The maximum leaf area is reached between panicle initiation and anthesis.

Tillers: Tiller buds form in the axil of each leaf on the main stem but only the lowest buds from the crowded nodes at ground level normally develop into tillers. Adventitious roots are formed concurrently with the development of tillers around each node within the tillering locus. Primary tillers are formed alternately in a vertical plane on both sides of the main shoot. Secondary and tertiary tillers are produced in a similar way. Many of the late-formed secondary and tertiary tillers, and sometimes whole plants, fail to develop. Tiller mortality in New South Wales is usually 20 to 30 % and can be in excess of 50 % (Boerema, unpublished data) (Fig. 3).

The size of the main tillers determine the initiation of tillering (Anon., 1968). Tillering is closely related to the nitrogen content of the plant. Tanaka et al. (1964) reports the critical N-content of the straw to be about 1.7 %, below which tillering does not occur. There are wide differences in tillering ability between varieties which are independent of nitrogen content. Other factors such as hormones may also control the tillering habit of different varieties (Anon., 1968). In areas where transplanting of seedlings is customary, Mahapatra and Sharma (1970) found that most varieties, irrespective of their growth duration, produced 90 % of their total grain yield from tillers developed within four weeks after transplanting. The rate of tiller formation is positively and linearly related to the rate of nitrogen applied; for this reason relatively lower plant densities can be tolerated without loss of yield on soils of high fertility (Lei and Xi, 1962).

Both the rate of tiller production and the length of the tillering period are affected by temperature. Owen (1969 a), studying the effects of night temperatures of 15° and 23 °C on final tiller numbers, found that a tall *indica* variety from Ceylon produced more at 23 °C, a U.S.A. variety more at 15 °C, and a dwarf *indica variety* from Taiwan showed little difference. There is some evidence of differences in temperature response betwen photoperiod-sensitive and-insensitive *japonica* varieties. Water temperature is more important than air temperature during active tillering. Matsushima et al (1964) ascribe this to the fact that the growing points of the plants are submerged during this period. Deep water on rice fields decreases tillering (Oelke and Mueller, 1969).

The value of high tillering capacity for maximising yield depends on the variety and the cultural practices employed. In tropical Asia, rice is grown with minimum care, transplanting is irregular and generally sparse whilst weeding is not thorough. To obtain some degree of weed control, early and rapid tillering is important so that early ground cover is obtained. In countries where great care is taken in trasplanting, spacing is adjusted according to known soil fertility and to the tillering capacity of the variety. However, when 100-150 kg/ha seed is sown in rows 18-20 cm apart into clean seedbeds and weed competition is prevented with chemicals, as is done in New South Wales, tillering is less important and the grain produced per unit crop area depends more on plant population and panicle size than on number of tillers per plant (Owen, 1968 & 1969a; Boerema, unpublished data).

Interception of light

Leaf Area Index: The foliage canopy may be characterised collectively by the leaf area index L, the area of leaves per area of ground (Watson, 1952). $L > 3$ is generally required for 95 per cent light interception with the sun above 60° elevation because of gaps in the leaf distribution (Monteith, 1969).

L is a function of the number of leaves per unit field area and the average leaf size. At an early growth stage L increases are parallel to increases in leaf tiller number. Average leaf size assumes more importance in determining L at later growth stages. Leaf area in 18 varieties of rice was dominantly controlled by leaf length and to only a limited extent by leaf width in trials. (Tanaka and Kawano, 1965).

Interception of light is dependent upon the patterns of chlorophyll display within the crop profile.

In dense stands a wide range of light environments exist. Upper leaves receive intense radiation while lower leaves are generally shaded, but may occasionally receive rays of direct sunlight. The rate of dark respiration of heavily shaded leaves is much less than in sunlit leaves (Ludwig et al 1965; McCree and Throughton, 1966).

If this was not so, net photosynthesis of the community would increase to a maximum (optimum L) and then decline as leaf area increased.

The existence of an optimum leaf area for maximum dry matter production was shown theoretically by Monsi and Saeki (1953) and experimentally by Takeda (1961), Murata (1961) and Tanaka et al. (1966). They observed that this optimum L varied with light intensity and plant type. Researchers at I.R.R.I. (Anon., 1969) found that the improved dwarf indica variety IR 8 had no such distinct optimum. Rather there was a critical L beyond which dry matter production remained constant with increasing L. Basinski and Airey (1970) calculated on theoretical grounds that the optimum L should have been in the order of 6.5 for the improved variety IR 8 in northern Australia, but the highest yields of grain and total dry matter were actually obtained with $L = 12.3 \pm 1.05$ (Fig. 4).

L reaches its maximum just before heading. Fagade and DeDatta (1971) reported that the leafy tropical variety Peta at a dense spacing and high nitrogen levels gave a maximum L of 14.6,

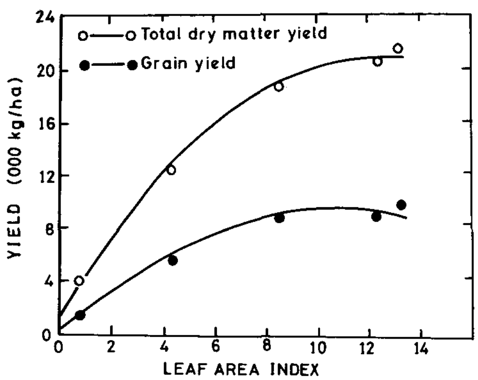


Fig. 4 - Relationship between leaf area index at flowering and grain and total dry matter yields with IR8 in Northern Australia. (Basinski and Airey, 1970).

which is one of the highest recorded for rice. In New South Wales highest yields are obtained when the maximum LAI does not exceed a value of 9. When a higher LAI develops lodging usually occurs.

The extinction coefficient (K) varies strongly with solar angle and to a lesser extent with cloudiness (Loomis and Williams, 1969 and Anderson, 1966). It is correlated with leaf angle and leaf spread. Erect leaves have a small K, regardless of their size (Hayashi and Itoh, 1962), and long lax leaves give the highest K values, up to 0.73 for an indica variety (Tanaka et al., 1966). Values varying from 0.38 to 0.48 were reported by Hayashi (1969) for eleven japonica varieties with a similar maturity range but with a widely differing growth habit.

Leaf activity: A high photosynthetic rate is associated with high leaf nitrogen content, high chlorophyll content, and thick leaves (Anon., 1968). Loomis and Williams (1969) found that the photosynthetic ability of leaves increases with chlorophyll content up to 3 mg/dm^2.

Chlorophyll concentrations in rice leaves vary from 0.42 to 1.53 % (Yamaguchi, 1942). Indica varieties are often paler green than japonicas. Within varieties the amount of nitrogen applied to the plant affects leaf colour. Darker leaves from heavily fertilised plants contain more chlorophyll (Anon., 1968). Tanaka and Navasero (1964) found that shaded leaves had a reduced capacity to retain nutrients. Phosphorous and nitrogen moved out of these leaves while sugar and starch content decreased until available energy was critically low and protein degradation took place. Soluble nitrogen in the form of amino acids, amides and ammonium ions accumulated in shaded leaves. They claimed that this accumulation, particularly that of ammonium ions, caused the leaves to die. However, leaf senescence is not well understood and other factors are certainly involved.

Highest yields in tropical areas have been recorded from semidwarf varieties with relatively short dark leaves. Chang and Tagumpy, (1970) found that erect flag leaves had the largest direct effect on yields of semi-dwarf varieties. Plants with erect upper leaves which became gradually more lax at lower canopy levels would be most desiderable for high yields according to Isobe (1969).

Reproductive Development

Generally, rice can be considered as a short-day plant (Best, 1959). Varieties vary from almost completely insensitive to highly sensitive to photoperiod. Temperature effects complicate the photoperiodic response. Varieties from Japan and southern Australia, for example, grow very rapidly, flower extremely early and produce weak stunted plants, when exposed to short days with high temperatures in the tropics. For this reason short grain varieties from Taiwan, which are more suited to high temperatures, are used for breeding work in the tropics instead of Japanese varieties which are highly temperature sensitive (Jennings, 1966). Most indica varieties from tropical countries do not mature during the normal growing season in temperate areas (approximately 180 days).

The number of photoinductive cycles required to initiate panicle development varies from 5 to 24, depending on variety and photoperiod (Vergara et al., 1969). The photoperiodic stimulus is probably received by the younger leaves of the rice plant, although the leaf sheath is also able to receive it (Best, 1961). The stimulus is not translocated from one tiller to another in the same plant (Anon., 1969).

Photo — and temperature — sensitive varieties complete the vegetative phase when threshold values for photo — and thermo — induction have been exceeded. Heading is usually reported to occur 30-35 days after initiation of the inflorescence becomes apparent. Phillis (Private communication) has elaborated on work by Ormrod et al (1960) and found that the variety Caloro was sensitive to photoperiod in the 13-15 hrs range and rather unresponsive to photoperiods between 11 and 13 hrs.

At controlled temperatures of 30 °C day and 25 °C night the time to first flowering increased from 61 to 110 days with change in day length from 13 to 14 ½ hours. Reproductive development of Caloro was also dependent on temperature. With photoperiods below 13 hrs and at temperatures of 35-30 °C, it flowered in 50 days. Reducing the temperature by 5 °C prolonged the developmental period to about 120 days whilst a 10 °C reduction prolonged it to 240 days. The delay in flowering was due to both a longer vegetative stage and a prolonged period of panicle development. Flowering can be delayed by long periods of light after panicle initiation. Exposure to long photoperiods increased the number of spikelets per panicle (Owen, 1969 b). Vergara et al. (1969) showed that inflorescence development was accelerated by short days.

Internode elongation: The number and length of internodes determine plant height. Elongation commences before panicle initiation in varieties with a long growth duration (Vergara et al., 1964) and a vegetative lag phase occurs between maximum tillering and panicle initiation (Tanaka, 1964). In varieties in which the total growth duration is very short the reproductive phase and the active vegetative phase may overlap. This occurs in photosensitive varieties exposed to short days. Elongation proceeds from the lower to the upper internodes. Four internodes below the panicle elongate rapidly after panicle initiation in japonica varieties. Shading accentuates culm elongation (Seko et al., 1957 and Oshima and Murayama, 1960).

Temperature sensitivity: An optimum temperature range for floret initiation in japonica varieties of 25-30° by day and 20-25 °C by night was reported by Inoye, (1964). No initiation occured with a day/night regime of 33 °C/15 °C in four varieties tested but both initiation and flowering was satisfactory at 33 °C/23 °C. Development of ther flower organs, other than the stamens, is unaffected by low temperatures. Low temperatures prevented anther bevelopment, but pistils from plants subjected to low temperatures coud be successfully pollinated with normal pollen from untreated plants (Nishiyama, 1970).

Satake (1969) in reviewing the effects of low temperatures on rice yields in Japan, concluded that the critical period in which floret sterility is induced is around the meiotic stage of the pollen mother cells, approximately 11 days before heading (Fig. 5). However, a recent study by Satake and Hayase (1970) has

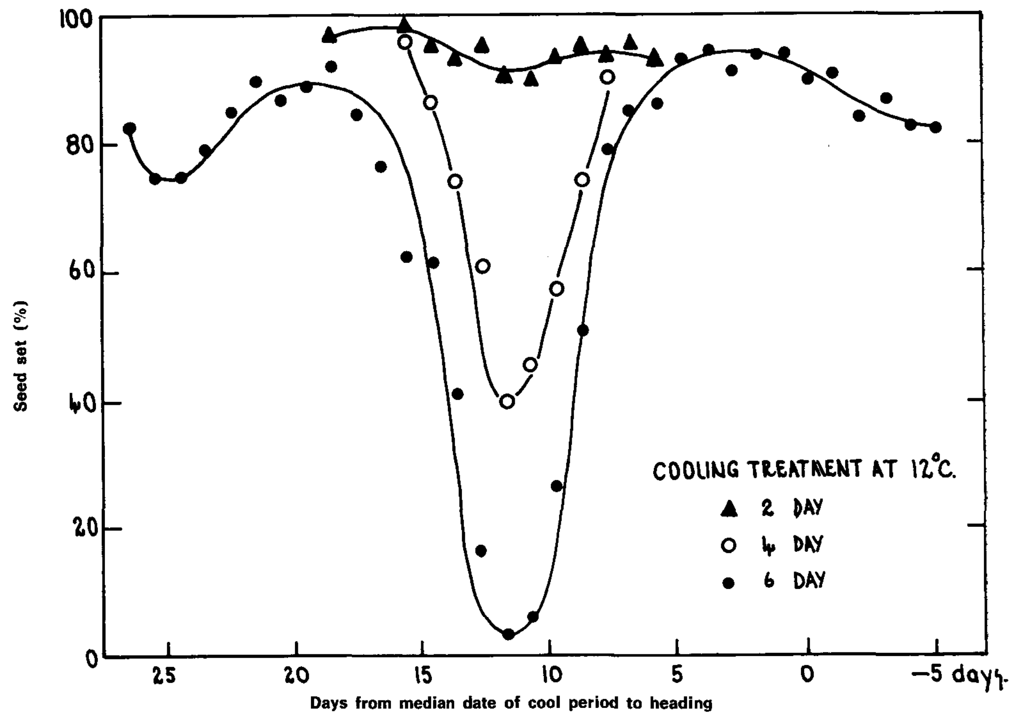


Fig. 5 - Relation between growth stage and sterility outbreak. (Satake, 1969).

shown that the most sensitive stage for low temperature damage was not the meiotic stage of the pollen mother cells, but the young microspore stage from tetrad to the first contraction phase. The critical temperature differed with varieties, the diurnal temperature range and growth conditions. Sterility was induced by temperatures ranging from 15-17 °C in the variety Hayayuki and 17-19 °C in Norin 20 when exposed to these temperatures during the meiotic stage by Nishiyama (1969). Sterlity was less severe when low night temperatures followed high day temperatures and when both day and night temperatures were low (Satake, 1969). An abundant supply of nitrogen made the plant more susceptible to sterlity induced by low temperature.

Anthesis depends on the prevailing atmospheric temperature, the light intensity and other climatic conditions. Optimum temperatures under field conditions are generally stated as between 27.5 and 32.5 °C, with a reported minimum of 22.2 °C (Anon., 1969). It is not known with certainty what happens when the temperature required for anthesis falls below the minimum for a short period only. Preliminary experiments at the International Rice Research Institute in the Philippines suggest that an exposure of 40 minutes is required at 32° C and 1 hr at 27 °C for 50 percent anthesis of the variety IR 8.

The maximum temperature for pollen germination is 40-50 °C and the minimum 7-14 °C. (Enomoto et al., 1956 and Kiyosawa, 1962). Pollen grains deposited on a stigma germinate in 3 minutes at 27 °C and fertilisation is completed in about 3 hours after pollination (Chandraratna, 1964).

Floret sterility due to failure of fertilisation processes can be induced under conditions of heavy nitrogen applications in combination with low light intensities. Togari and Kashiwakura (1958) found this to be due to a reduction in number of pollen grains which germinated on the stigma and this in turn was attributed to incomplete dehiscence of anthers and abnormal behaviour of filaments at time of flowering. After fertilisation, susceptibility to low temperature damage in reduced.

It has been shown by Best (1959) and Phillis (1963, private communication) that panicle development, especially in its later stages, is accelerated at high temperature (33-37 °C).

Ripening:

The effect of the environment during ripening has received relatively little detailed attention. Most conclusions are drawn from yield correlations with temperature and radiation regimes occurring from heading to harvest. High levels of solar radiation with relatively low temperatures during ripening usually induce high rice yields. (Chandler, 1967; Murata, 1966; Tanaka and Vergara, 1967). Yields have been found to be positively related with the amount of radiation from 10-15 days before flowering until harvest (Murata, 1965 and De Datta and Zarate, 1970) and also with that during the ripening period alone (Moomaw et al., 1967). This suggests that rate of photosynthesis is a major determinant of yield during these periods. Shading experiments by Stansel et al. (1965) and Munakata et al. (1968) confirm that grain yield is positively related to the amount of photosynthesis during the flowering and ripening periods. Temperature effects are difficult to separate from those of solar radiation.

Highest rice yields are obtained in temperate areas where ripening occurs under conditions of relatively high solar radiation and lower minimum temperatures. Ripening is slower than in the tropics whilst the photosynthetic leaf area is maintained over a longer period due to slower leaf senescence. Aimi et al. 1959 and Nagato et al., 1966 found that retarded translocation of carbohydrates to the developing grain was due to lower temperatures, but with an extended ripening period this resulted in greater total accumulation of dry matter.

High temperatures during ripening result in a premature reduction of the capacity of the grain to act as a sink for assimilates. This causes chalky centred kernels and an increased thickness of the bran and aleurone layers (Ebata, 1961; Nagata et al., 1966).

Grain Yield

Yield is determined by the capacity of the crop to photosynthesise, its capacity for translocation of assimilates and the size of the « sink » or « yield » container. It can be separated into these components.

Yield = number of panicles x number of filled florets x grain size.

Panicle number: The number of panicles per unit crop area is determined shortly after the maximum tillering stage and is greatly dependent on light intensity and nutrient supply. Yamada (1961) found that on low fertility soils, higher plant densities achieved by transplanting produced the highest yield and total dry matter. On fertile soils plant growth was faster, leaf area larger and the total dry matter production per unit area at harvest became constant, regardless of plant density. The author, working with three varieties under drill sown conditions in southern Australia, has also found that the level of nutrition is more important than plant density in determining yield, provided a regular plantstand is obtained. All varieties compensated for low plant density by increased tillering or by producing larger panicles.

Heavy tillering varieties with short, erect leaves can be transplanted at distances ranging from 10×10 to 30×30 cm without any significant change in yield, provided other cultural practices are ideal (Chandler, 1969). Highest yields from tall tropical varieties with applied nitrogen fertiliser have occured at spacings as great as 50×50 cm, provided solar radiation intensity and soil fertility levels were high (Tanaka et al., 1964).

Panicle weight: The weight of a panicle is determined by the number of filled florets and the size of the grain. An increase in nitrogen supply at about the time of panicle initiation resulted in a significant increase in number of florets (Matsushima, 1966; Hall and Railey, 1964; Evatt, 1965; Togari, 1968). Later nitrogen fertiliser applications did not change the floret number, but increased the percentage of fertile florets. Many authors report a beneficial effect on yields from topdressings with nitrogenous fertiliser at panicle initiation. Their primary effect is to increase the number of spikelets differentiated.

Low light intensity at anthesis tends to reduce grain set. Togari and Kashiwakura (1958) found this effect most pronounced at high nitrogen levels and ascribed it to failure of anthers to dehisce.

Grain Size: The size of the grain is restricted by the size of the hull. Hulls reach their maximum dimensions about one week before flowering (Matsushima, 1957). The average grain size has a higher heritability than other components (Anon., 1964) and can be increased only slightly (up to 10 percent) by a topdressing of nitrogen 3-4 weeks prior to 50 percent flowering (Murata, 1969).

Factors affecting photosynthesis

Rice is a temperate grass and has the C_3 or Calvin photosynthetic pathway (Stewart, 1970). Such species exhibit a wide range of photosynthetic abilities but their rates are usually lower than those of species which have the C_4-dicarboxylic acid pathway (Loomis, Williams and Hall, 1971). Photosynthetic ability per unit area of leaf, however, plays only a minor role in determining grain yield.

Varietal difference: High photosynthetic ability is not positively correlated with grain yield, although varietal differences have been reported. (Osada, 1964; Osada and Murata, 1965; Tanaka et al., 1966; Anon., 1968 and McDonald, 1971). Rates of photosynthesis are generally low in rice crops. Workers at the International Rice Research Institute in the Philippines (Anon., 1968) found net photosynthesis rates ranging from 34 to 62 $mg/dm^2/hr$ at 60 Klux (ca 600 W/m^2) at 30 days after transplanting.

The average rate was 46 $mg/dm^2/hr$. They found that low photosynthetic rates were associated with low nitrogen content, low chlorophyll content and thin leaves. McDonald, (1971) found that Bluebelle gave the highest and IR 8 the lowest minimum rate of net photosynthesis of 20 varieties with values of 62 and 40 $mg/dm^2/hr$ respectively. He found that most F_1 hybrids exhibited high parent heterosis (44 and 41 % for the best two hybrids) for rate of photosynthesis. Varieties which respond to high nitrogen have a faster rate of carbon assimilation and growth than low response varieties (Murata, 1969).

CO_2 Concentration: Concentrations of CO_2 greater than the ambient 300 ppm generally increase photosynthesis. Both Murata (1961) and Yamada (1963), experimenting with detached leaves, found up to four times the normal rate of pho-

tosynthesis when they increased CO_2 concentrations under natural light on clear days. However, this is only possible if the plants are enclosed.

The downward flux of CO_2 is at a maximum at maximum tillering, decreases gradually after ear initiation and declines rapidly during ripening. These changes in flux are due to changes in demand for photosynthesis and are closely related to leaf area. (Yabuki and Ishibashi, 1968).

Organic matter in the soil may contribute a small amount of CO_2. Tanaka et al. (1969) noted that incorporation of 12 tonnes straw/ha released 2.74 mg CO_2 dm^2/hr after ten days submergence. After removal of the straw no CO_2 release was detected.

Light: Murata (1961) and Yamada (1963) state that the rate of photosynthesis increased with increasing ligth intensity up to 500-600 W/m^2 above which no further increase could be obtained. They suggest that light saturation occurs at about 50-60 percent of full sunlight levels (1000 W/m^2 or more) at noon on clear summer days. The saturation light intensity is less for lower than for upper leaves and photosynthetic activity is highest in younger leaves (Tanaka et al., 1966).

Temperature: The rate of photosynthesis (P) of rice plants is little affected by temperature within the range 25-53 °C when adequate light is provided. Murata (1961) detected a rapid decrease in P at temperatures below 20 °C and above 35 °C, whilst Yamada (1963) found a stable range of 18-35 °C. Osaka (1967) found the optimum temperature range for indicas to be 25-35 °C whilst Yamada et al. (1955) found the optimum temperature range for japonicas to be 18.5 to 33.5 °C.

Condition of the plants: Regardless of variety, the rate of photosynthesis in rice leaves is high during early growth, reaches a peak during tillering and declines toward maturity (Murata, 1961; Tanaka et al., 1966). The maximum rate of photosynthesis and the saturation light intensity increase with age until panicle initiation, at which stage there is no saturation point, and then decrease (Tanaka et al., 1966). Murata (1961) commented that this decline appeared to be associated with the age of the plant rather than with the particular stage of development.

The photosynthetic rate per unit area at high light intensities is positively related to nitrogen content per unit leaf area (Murata, 1961; Osada, 1966; Takano and Tsunoda, 1971). This relationship held whether differences in nitrogen content per unit leaf area were due to environment or genotype (Tsunoda, private communication).

Even at the highest nitrogen content observed (approximately 20 mg/dm^2) the photosynthetic rate per unit leaf area had not reached its ceiling rate at a light intensity of 85 Klux.

Respiration: Respiration is an indispensable part of growth and is not to be considered merely as a wastefull process. Tanaka (private communication) recently studied the efficiency of respiration by partitioning the essential maintenance respiration and the wasteful respiration. Maintenance respiration takes places at all stages of plant development. At later growth stages elongated internodes and shaded lower leaves form a large proportion of the total plant weight and the respiration of these organs comprises a considerable part of the total respiration. Growth efficiency (E) remains at about 60 % when plants are young and grow rapidly but declines after stem elongation to about 5 % when high N rates are used (Tanaka and Yamaguchi, 1968). Growth efficiency is defined as $E = W/_{(W+R)}$ where W is the net dry matter production

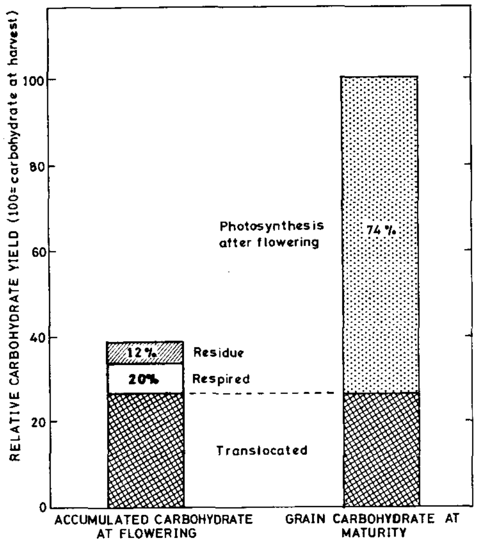


Fig. 6 - Accumulated carbohydrate in vegetative parts at flowering and its contribution to grain yield. (IRRI Ann. Rep. 1970).

and R the respiration. Tanaka (private communication) has suggested that a population with dark erect leaves needs a smaller proportion of maintenance respiration.

The basic cause of low growth efficiency during ripening of tall, leafy indica varieties, leading to low grain yield, is the respiration of non-photosynthesising organs (Tanaka et al., 1966).

The rate of respiration of a rice plant increases up to heading when it is at its maximum and decreases from then on (Yamada, 1963). It varies with temperature and is greatest at about 32 °C above which it declines (Tanaka et al., 1966).

The respiratory rate of a rice population is almost linearly related to its dry weight (Tanaka and Kawano, 1966). Rice plants supplied with abundant nitrogen and kept under low light intensities (400 lux) for 13 days lose their photosynthetic activity completely, but retain respirately activity. This causes the death of lower leaves (Navasero and Tanaka, 1966). Sato (1949) claimed that indica varieties have a higher rate of respiration than japonicas, but this was not fully substantiated by Osada (1964) from experiments in Ceylon.

The respiratory rate of different organs of the rice plant changes in relation to growth stage (Yamada, 1963). I.R.R.I., workers (Anon., 1970) found that the respiratory rate of individual leaves of the variety IR 8 was quite variable and tended to decrease at all leaf positions as L increased. The mean rate was greatest for the third highest leaf and least for leaves directly below and above that. Respiration increased at a decreasing rate as L increased in improved varieties such as IR 8 and a hyperbolic function fitted the relationship well (Anon. 1970). During the dry season in the Philippines 35-60 percent of the total assimilated carbon was released from the plants by respiration. The amount respired from roots was up to 10-15 percent of the total. The major of the remaining carbon was translocated and incorporated into organs which were growing at the time of assimilation (Lian and Tanaka, 1967).

Distribution of photosynthates

Carbon assimilated during tillering is mainly directed to the leaves which are actively increasing in size at that stage. During the senescence of these leaves part of the carbon may be retranslocated to new organs located higher on the plant. Only about 25 percent of carbon assimilated during vegetative growth finds its way to the grain. Starch and sugar accumulate in the leaf sheaths and culm at the time of panicle initiation. The highest levels of these substances are at flowering, after which translocation of temporarily stored carbohydrates to the panicles commences. Grain development is rapid using both the stored and the newly synthesised carbohydrates. Workers at the International Rice Research Institute calculated that 74 percent of the carbohydrate in mature grain was photosynthesised after flowering (Fig. 6).

Nitrogen fertilization promotes protein synthesis. It has a complex effect on carbohydrate metabolism, sometimes promoting its production, whilst on other occasions greatly reducing it, e.g. when severe lodging is induced. A small nitrogen application at heading often increases yields and carbohydrate accumulation. Application of nitrogen fertiliser after floret differentiation also increases the carbohydrate accumulation at heading and maturity if nitrogen is deficient in the soil prior to the application. Later applications have little effect.

Nitrogen responsiveness

Nitrogen exerts a direct and positive effect on several yield components. It has been shown by Murata (1969), in his review on physiological responses to nitrogen, that there was a linear relationship between nitrogen content or supply and leaf area expansion rate, total leaf area development, tiller number, number of florets per unit area and photosynthetic activity. However, excessive nitrogen fertilization results in reduced pollen viability and floret sterility. The promotion of excessive vegetative growth by nitrogen applications, causes a competitive shading which reduces the yield of many varieties in the tropics. Ammonium ions are the principal form of nitrogen available in flooded fields. Since ammonium ions are toxic in many metabolic pathways, rice plants must maintain an adequate supply of carbohydrates to ensure a quick conversion to amino acids (Hageman, 1969).

Rice varieties have been classified as nitrogen responsive and nitrogen unresponsive. The latter usually produce an excessive leaf canopy and lodge easily as a result of high nitrogen fertilizer applications. Tanaka et al. (1966) and Chandler (1969) have shown that shortness and thickness of culm are important factors in avoiding lodging when high levels of nitrogen are used (Fig. 7). Great varietal differences in susceptibility to lodging exist. Some tall varieties lodge at very low nitrogen levels whilst others practically never lodge, even when 150 kg/ha nitrogen is applied. Risk of lodging is minimal when the plant is short, has thick cylindrical culms, a low bending moment, short internodes at the base of the culm, tightly wrapped leaf sheaths, erect narrow leaves and a high degree of lignification in sclerenchymatous tissues in the culm (Hille Ris Lameris, 1970).

High grain/straw ratio under heavy nitrogen fertilization is characteristic of nitrogen responsive varieties. Chandler (1969) claimed that the grain/straw ra-

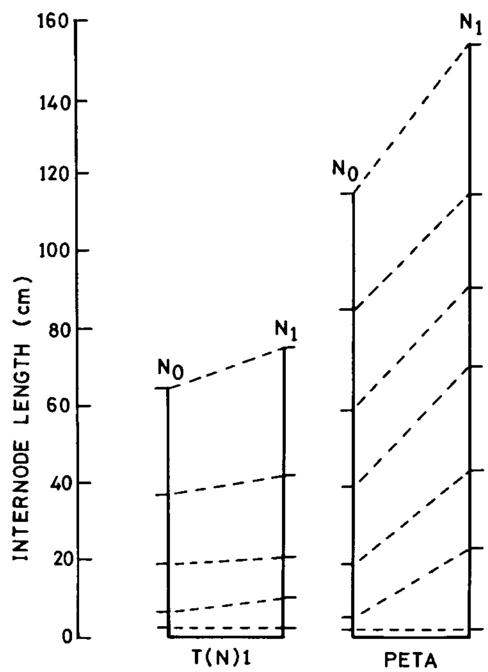


Fig. 7 - Schematic drawing to show the difference in internode elongation when nitrogen is added to a nitrogen-responsive variety (Taichung Native-1) as compared with a low-responder (Peta). (Chandler, 1969).

tio must exceed 1.0 highest grain yields. He concluded that the nitrogen responsive varieties put twice as much into grain production as low nitrogen responders. This appeared to be due to two factors: (1) the tall tropical low nitrogen responsive varieties produced many tillers at high nitrogen levels but many of these produced no panicle; and (2) the nitrogen responsive plant types continued to produce dry matter after flowering, while the leafy non-responsive types showed little increase in dry matter.

Sink-source strength

Translocation of photosynthates within the plant follows a definite distribution pattern which changes during the growth of the plant. Photosynthates for roots are obtained from the lower leaves, while apical points and growing leaves receive them from the upper leaves (Tanaka, 1958). Centres of growth exert some attractive force on the flow of assimilates from source to sink (Stoy, 1969). The mecanism that initiates, directs and regulates this basic translocation process is poorly understood. To accommodate the carbohydrate produced by efficient photosynthesising leaves the crop must have a large sink and an adequate translocation mechanism. It is difficult to determine whether supply or sink capacity or translocation system restricts yield in any particular situation. Evans (1971, private communication) modelled crop growth by statistical procedures and arrived at crop growth rates which compared favourably to the highest rate measured by Tanaka (1966) (55.4 $g/m^{-2}/day$ at a light intensity of 564 $cal/cm^2/day$). Whilst crop growth rates under favourable conditions come close to a computed potential maximum for a short time, grain yields are considerably lower, suggesting that either translocation or storage capacity is limiting. Murata (1965) presented data showing a good correlation between the photosynthetic rate of flag leaves of six varieties and their crop growth rate. Grain yield was poorly correlated with photosynthetic rate, which again suggests that the supply of assimilates did not limit yield.

The author found recently that the new high yielding variety, Baru, produced grain of significantly lower kernel weight when grown at a low plant density with high nitrogen fertilization. Under these conditions floret sterility was high and 1000-grain weight low and variable.

Many of the lower grains of the panicles were incompletely filled. This rice variety possesses large, very erect leaves with a high specific leaf weight and its leaf area per panicle is large.

Stems are thick, it tillers moderately and the panicles are very large. It is probable that insufficient photosynthates reached the panicle because the transport system was either inadequate or failing. At maturity at least two leaves were green which may indicate that photosynthesis occurred during the whole ripening period. Nakayama (1969) has demonstrated that the senescence of the grain commences with failure of conductive tissue of the rachilla. Perhaps neither the photosynthetic capacity or the sink size, but the translocation, may limit grain filling.

Growth Efficiency

Calculated efficiencies of dry matter production, on the basis of incident radiation, for a single rice variety over its full growing period ranged from 0.8-3.7 % with an average of 2.2 % when a caloric value of 4000 cal/g was assumed (Murata et al., 1968). Hayashi (1969) working with eight varieties in Japan found efficiency values of dry matter production of 2.81-3.53 percent on an absorbed energy basis and 1.42-1.71 percent on an incident energy basis when the absorption rate was 37-50 percent. (Reflection 17.3-18.3 percent and transmission 38.4-47.4 percent as measured by linear radiometers with a sensitivity range between 0.3 and 4.0).

High growth efficiency of the panicle during ripening is thought to be due to a change from the formation of conductive structural tissues and protein to the production of starch which requires less energy (Lian and Tanaka, 1967). Stewart (1970) has shown that although yields are much higher in southern Australia than in northern Australia or at I.R.R.I. in the Philippines, the grain yield per day of crop growth was highest during the dry season in the tropics. Efficiency of production in terms of grain yield per unit of radiation was of the same order in both wet and dry season crops in the tropics, and averages 50 percent higher than that in southern Australia. He thought that this difference was probably due to the very high levels of radiation in southern Australia, which probably were far above those needed for light saturation of the leaf canopy. He concluded that contrary to the commonly held opinion that plants in the tropics would have high respiration rates and low net growth rates, rice exhibited a higher efficiency in utilisation of radiation in the tropics than in the temperate climate. It should be stressed, however, that the first 20-30 days of the 175-190 day growing season in southern Australia is required for emergence. The comparable period in the tropics is 3-10 days. During the period of emergence photosynthesis is negligible and growth not measurable. The grain yield per unit radiation improves considerably if this period is neglected in calculating growth efficiency.

The future in Southern Australia

Varieties of improved plant type, together with higher levels of crop management and plant nutrition have contributed greatly to higher yields of rice in tropical areas. Although yields in southern Australia are the highest in the world, averaging 7480 kg/ha (14 percent moisture) from a total area of 37560 ha in the 1970/71 season, there in still room for improvement since yields in experimental plots have already exceeded 13000 kg/ha under favourable conditions.

Further improvements in yield can be achieved with the development of new varieties. With the very high radiation levels and a rather high light transmission in non-lodging high yielding crops, it appears unnecessary to switch to dwarf or semi-dwarf varieties. All currently available dwarf and semi-dwarf varieties are unadapted in southern Australia and perform poorly. Resistance to lodging under high fertility conditions, erect dark green leaves, a moderate ability to tiller and large panicles should be the main features of improved varieties for this region. Varieties are required to perform well over a wide range of leaf area indices and should have a poorly defined optimum leaf area in response to high levels of applied nitrogen.

A variety with a growth duration of 130-140 days, allowing sowing in early November and flowering in mid January, would overcome problems associated with a slow emergence in spring and high floret sterility due to low minimum temperatures. The favourable slow ripening period of 50 to 60 days and as long a period as possible for panicle differentiation must, however, be maintained. Hence there are some conflicts to be resolved to attain the desirable combination of suitable growth duration and high yield.

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Summary

This review describes the development and growth of rice from germination to ripening, with special reference to the temperate region of southern Australia where low minimum temperatures determine the length of the growing season.

Factors affecting germination, leaf development, tillering, panicle initiation, flowering and grain set are considered in individual plants and in the crop community in relation to the efficiency of growth and yield.

The highest yielding varieties in southern Australia, when grown at high fertility, produce a large number of florets per unit area, maintain a large photosynthetic area per panicle, resist lodging and ripen slowly.

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RIASSUNTO

La coltivazione del riso in Australia

L'Autore descrive le condizioni in cui si svolge la risicoltura nelle zone temperate dell'Australia meridionale, dove le basse temperature minime determinano la durata del ciclo vegetativo.

I fattori determinanti la germinazione, lo sviluppo delle foglie, l'accestimento, la formazione embrionale della pannocchia, la fioritura e la formazione della granella sono stati esaminati per singola pianta e per l'intera coltura, in relazione alle attitudini di accrescimento e di produttività.

Le varietà più produttive dell'Australia meridionale, se coltivate su un terreno molto fertile, danno un elevato numero di fiori per unità di superficie, dispongono di una notevole area fotosintetica per pannocchia, resistono all'allettamento, maturano lentamente.