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ENVIRONMENTAL CHARACTERISTICS OF FLOOD WATER IN EASTERN INDIA : RELEVANCE TO FLOODING TOLERANCE OF RICE

T.L. SETTER[1], G. RAMA KRISHNAYYA,[2] P.C. RAM MAURYA[3] AND B.B. SINGH[3]

[1]IRRI, P.O. Box 933, Manila, Philippines

[2]Plant Physiology, CRRI, Cuttack, India

[3]Department of Crop Physiology, NDUAT, Faizabad, U.P., India

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SUMMARY

Data are presented on floodwater O_2, CO_2, HCO_3- and light in rice fields of flood-prone areas in Eastern India. Floodwater $[O_2]$ of submerged or non submerged plants was low in the morning and increased to about 0.12 mol m^{-3} during the day (air saturated water contains 0.24 mol m^{-3} O_2); opposite trends occurred for CO_2. Low $[O_2]$ in floodwater in fields contrasted with measurements at an experiment station where floodwater was supersaturated with O_2 at 0.59 mol m^{-3} (equivalent to >50% v/v O_2). Results demonstrate the need for monitoring plots for relevance to field environments. Results from experimental plots demonstrated the possibility of manipulating floodwater $[O_2]$ to increase submergence tolerance of rice during flooding in the field.

INTRODUCTION

In the rainfed low land environment of Eastern India (Eastern Uttar Pradesh inlcuding locations measured here, Bihar, West Bengal and Orissa, Fig. 1) submergence is the third most important limitation to rice production and is surpassed only by anthesis, drought and weeds (Widasky and O'Toole, 1990). About 10 million ha of rice lands in Eastern India are adversely affected by waterlogging and flash floods each year (Reddy and Sharma, 1992). Some information is available on the timing, duration and intensity of flooding in some of these areas. During 1984 to 1992 in Faizabad (U.P.) over the months of July to October there were 2 to 5 incidents of flooding ranging from 3 to 21 days. Flooding was not always related to the local rainfall in these areas, but may have resulted from heavy rains in neighbouring areas and flooding from rivers (V.P. Singh, IRRI, 1994, person. commun).

The adverse effects of flooding on plant growth and survival are diverse and complex and include effects during submergence such as mechanical damage, low light, soil leaching, increased susceptibility to pests and diseases and limited gas diffusion (Greenway and Setter, 1994). Additional adverse effects may be associated with desubmergence and post-hypoxic injury (see Crawford, 1992, for review). The most important environmental factor during flooding which results in complete submergence of rice is almost certainly limited gas diffusion, since this is a universal consequence of submergence due to the 10,000 fold slower diffusion of gases in water than in air (Armstrong, 1979).

The objective of this research is to obtain detailed environmental measurements of floodwater in flood-prone areas of Eastern India to (i) obtain clues about which gases or other environmental factors may limit rice growth during partial or complete submergence, and (ii) compare floodwater environmental conditions during artificial submergence imposed at research stations with those which occur naturally in farmer's fields.

MATERIALS AND METHODS

Site locations: The following sites were measured for environmental characteristics of floodwater during months of September to October.

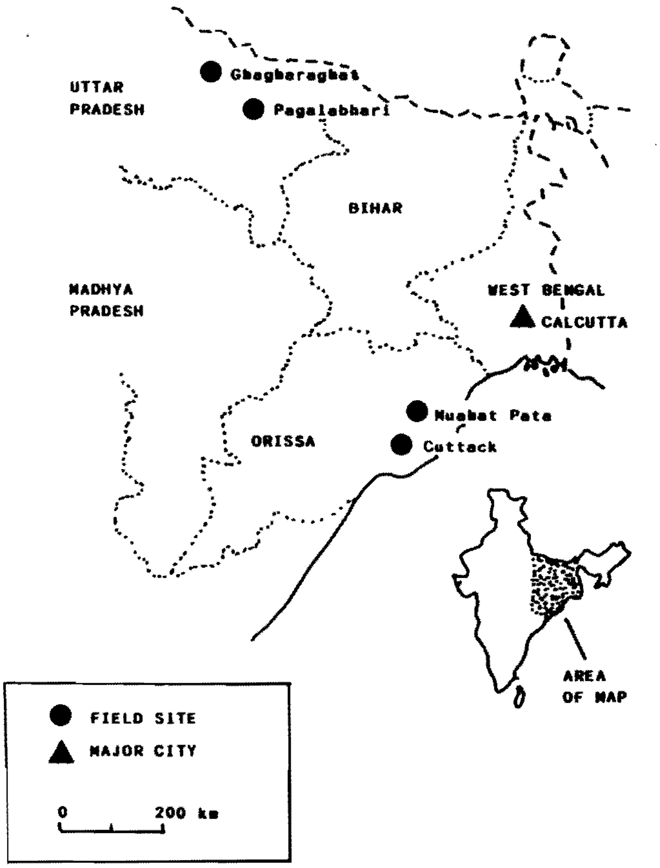

Fig. 1 : Map of Eastern India showing the locations where field surveys were made.

(i) Crop Research Station—Pagalabhari: 15 km S of Faizabad; 5 locations in one field.

(ii) Crop Research Station—Ghagharaghat: 140 km NW of Faizabad adjacent to the Ghaghara River; 3 locations in the chaur each at 140 and >250cm water depths.

(iii) Central Rice Research Institute (CRRI), Cuttack; 340 km SW of Calcutta; several sites varying in water depth.

(iv) Nuahat Pata: farmers fields 60 km NE of CRRI off the Daitari to Paradeep Highway; 60 cm water depth.

Environmental measurements: Collection and analysis of samples for dissolved gas concentrations were as described by Setter *et al.*, (1987, 1988a,b) and a brief summary is provided here. Dissolved oxygen concentrations in floodwater were measured using a submersible polarographic O_2 electrode (Syland Model 610, Heppenheim, West Germany) attached to a measuring rod and either suspended over the side of a boat or held at the stated depths in floodwater. The electrode was moved gently at the required depth until stable readings were obtained for O_2 and temperature. The electrode was calibrated in the field using aerated water prepared by vigorously shaking distilled water in air for 1-2 min.

Samples for dissolved carbon dioxide measurements were assayed in the field within 4 min of collection due to the large changes in CO_2/HCO_3^- which occurred upon storage of samples. Dissolved CO_2 in water was assayed by measuring total inorganic carbon (CO_2, HCO_3^- and CO_3^{-2}) and pH in 5 to 10 ml of floodwater. For total inorganic carbon analysis the floodwater samples or HCO_3^- standards were adjusted with a buffer solution to pH 4.5, and the total CO_2 evolved was measured using a polarographic CO_2 electrode (HNU Systems Inc., Newton Highlands, MASS) with a portable pH/millivolt meter (Orion, Model 250A). The dissolved CO_2 was then calculated from the total inorganic carbon and the initial pH measured using the Henderson-Hasselbach equation with appropriate temperature coefficients (see Umbreit 1964 and HNU instruction manual for further details).

Light was measured using a quantum underwater light sensor (Licor, Model 185B) and turbidity was evaluated using a Secchi disc (Definitions of Terms; Wetzel, 1983).

RESULTS

Pagalabhari (U.P.) Measurements of dissolved gases were inappropriate in most areas around Faizabad since water levels had receded the week before the survey. Diurnal changes in dissolved O_2 and CO_2 concentrations at the Crop Research Station—Pagalabhari were measured for partially submerged plants in 60 cm water. O_2 concentrations $[O_2]$ were always lower than for air saturated water and they changed over diurnal cycles with concentrations of about 0.02 mol m^{-3} at 0600h increasing to about 0.12 mol m^{-3} at 1200h (Fig. 2A). Floodwater $[O_2]$ was also lower at depth than at the surface (cf. 1 and 40 cm, Fig. 2A). CO_2 concentrations $[CO_2]$ showed opposite trends over diurnal cycles; concentrations were high in the morning at about 0.8 mol m^{-3} and decreased to about 0.5 mol m^{-3} during the day (Fig. 2B). The HCO_3^- concentrations in this floodwater were 5.5 ± 0.2 mol m^{-3}; while pH ranged from 6.9 to 7.5 (n=20).

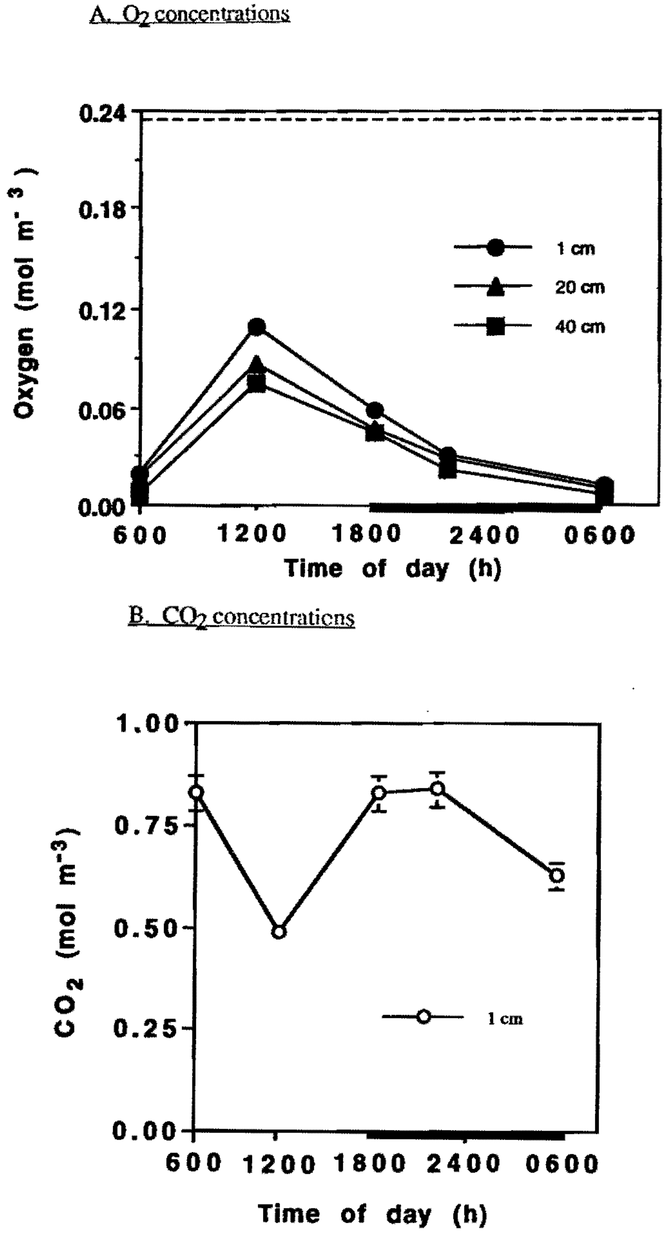

Fig. 2 : Concentrations of O_2 (A) and CO_2 (B) in floodwater of non submerged rice in experimental plots at Pagalabhari Research Station, U.P., India. Floodwater was 40 cm deep. Black bar on x-axis indicates dark period. For O_2, dashed line indicates [O_2] in air saturated water at 30°C and SEms were less than 15% of individual values; for [CO_2], vertical bars indicate twice SEm.

Ghagharaghat (U.P.) A trip northward across the Ghaghara River brought us into areas at the foot of the Himalayas where severe flooding had occured several weeks earlier. Though the crop loss and destruction was devastating around districts of Basti, Gonda and Gorakhpur, we were too late to make extensive measurements-in many locations the floodwater had completely receded. Some data were collected from the rice-fish areas of the large chaur at Ghagharaghat where deepwater rice was growing at 140 to >250 cm water depths. The [O_2] in floodwater was below air saturation at mid morning and the lowest concentrations occurred at greater depths (Table I). Floodwater [CO_2] and pH at Ghagaharaghat were similar to previous measurement of flood water at Pagalabhari (cf. Table 1 with Fig. 2 and above).

Nuahat Pata (Orissa) Only one location in farmer fields was located where floodwater gas concentration could be measured during natural flooding that resulted in partial or complete submergence of rice. This was at Nuahat Pata (approx. 60 km NE of Cuttack, Fig. 1) where in one area approximately 2000 ha of rice crops were lost. Farmers from this location informed us that submergence has occurred for 20 to 30 d at water depths up to 2 m, water was always clear and not turbulent, and drainage was apparently via percolation. The rice fields of Nuahat Pata are in a low lying area beside a long road embankment, and according to the farmers such flooding had become common since these roads were constructed in 1976.

Table I : Concentrations of O_2, CO_2 and HCO_3^- (mol m-3) and pH (± SEm) in floodwater of non submerged rice in the chaur at Ghagharaghat Crop Research Station, Ghagharaghat. U.P., India. Floodwater was 140 cm deep; data were collected at 1000h. CO_2 and HCO_3^- were only measured at 30 cm water depth.

Water depth (cm)	O_2	CO_2	HCO_3^-	pH
1	0.11 ± 0.03	-	-	-
30	0.09 ± 0.03	0.74 ± 0.21	2.47 ± 0.21	6.89 ± 0.16
70	0.08 ± 0.02	-	-	-
140	0.07 ± 0.02	-	-	-

The [O_2] in floodwater at Nuahat Pata was below air saturation (0.24 mol m^{-3}) even though [O_2] tended to increase during the day. In the morning the [O_2] was similar at all depths, while in the afternoon there were singificant increases in [O_2] in the upper water layers (1 and 30 cm, Table II). There were no significant differences in [O_2] or [CO_2] between areas of floodwater with and without rice plants so the mean data are presented in Table 2. The [CO_2] at Nuahat Pata decreased from 0930h to 1230h and was approximately 0.4 mol m^{-3} at midday, while floodwater pH was 6.4 (Table II).

Table II : Concentrations of O_2, and CO_2 (mol m^{-3}) and pH (± SEm) in floodwater of partly and completely submerged rice in farmers' fields at Nuahat Pata, Orissa, India. Floodwater was 60 cm deep and assayed at two times of the day; data for pH are the means of both times. Air saturated water at 30°C contains 0.24 and 0.009 mol m^{-3} O_2 and CO_2 respectively.

	O_2		CO_2		
Water depth (cm)	0930 h	1230 h	0930 h	1230 h	pH
1	0.13 ± 0.02	0.21 ± 0.01	-	-	-
30	0.12 ± 0.01	0.20 ± 0.04	0.47 ± 0.03	0.37 ± 0.06	6.4 ± 0.1
60	0.11 ± 0.02	0.14 ± 0.01	-	-	-

Cuttack (Orissa) In one experiment in large concrete tanks (approx. 20 x 50m) at CRRI, 25 d old rice plants were completely submerged in water up to 80 cm deep. At 7 d after submergence the floodwater $[O_2]$ was measured over a diurnal cycle. Floodwater was supersaturated with O_2: between 0600h and 1200h the floodwater $[O_2]$ increased from 0.23 to 0.33 mol m^{-3} at the surface, while concentrations at 80 cm deep were surprisingly even greater, increasing from 0.26 to 0.59 mol m^{-3} respectively (Fig. 3).

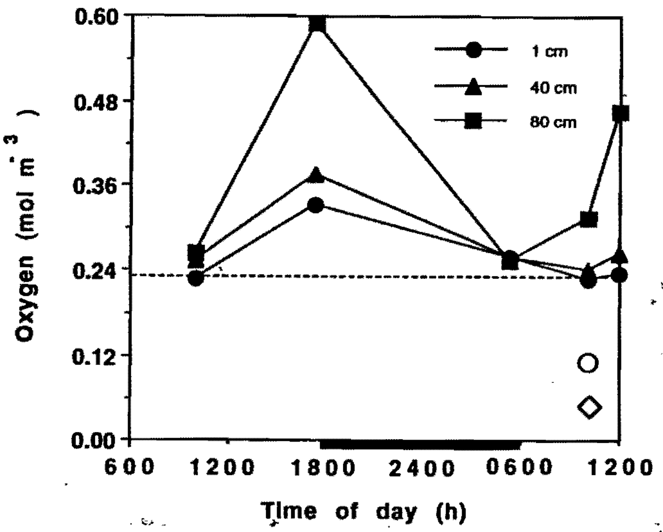

Fig. 3 : Concentrations of O_2 in floodwater of completely submerged and non submerged rice in experimental tanks at CRRI, Orissa, India. Floodwater of completely submerged plants was 80 cm deep. Black bar on x-axis indicates dark period; closed symbols, submerged plants; open symbols, non submerged plants at 1 (circle) and 40 cm (diamond). The dashed line indicates O_2 concentration in air saturated water at 30°C. SEms were less than 15% of individual values.

These increases in $[O_2]$ with depth occurred even though the floodwater was turbid and Secchi disc visibility was only about 30 cm. Irradiance measured at different depths in the floodwater demonstrated that even at 40 cm depth, where the Secchi disc was not visible, irradiance was about 50% of the incident level (Fig. 4), demonstrating that a considerable amount of diffuse light may reach plants submerged in turbid water. In contrast, the large drop in irradiance for non submerged plants from 0 to 1 cm water depth shown in Fig. 4 was due to light interception by the rice canopy.

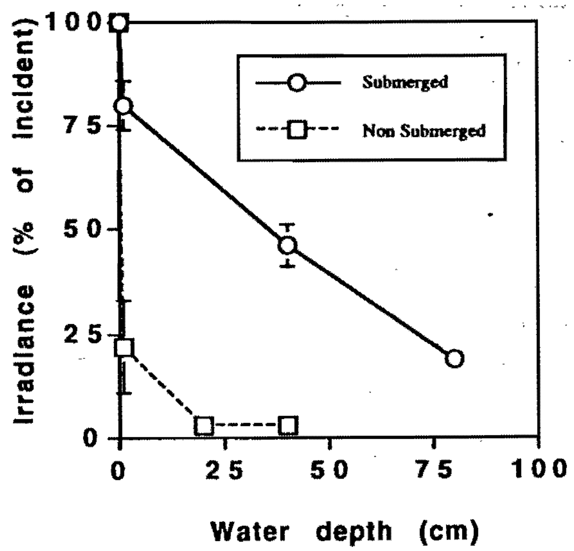

Fig. 4 : Irradiance (± SEm) above and below floodwater of completely submerged or non submerged rice in experimental tanks at CRRI, Orissa, India. Experiment is the same and measured on the same day (at 1015h) as Fig. 2. Irradiance (PAR) above both the water surface and the rice canopy is shown at 0 cm water depth; vertical bars indicate twice SEm.

The results for complete submergence constrasted with measurements of floodwater with non submerged plants from an adjacent plot. The floodwater of non submerged plants had much lower $[O_2]$ concentrations (open symbols in Fig. 3) than submerged plants with 80 cm depth for submerged plants, Fig. 4). In Fig. 4, the incident radiation was 1800 ± 151 and 2047 ± 101 mmol m^{-2} S^{-2} (PAR) for completely submerged and non submerged plants respectively.

Supersaturated $[O_2]$ in the submergence tank occurred even though floodwater contained extremely low $[CO_2]$ The $[CO_2]$ was only 0.004 ± 0.001 mol m^{-3}, i.e. les than half of that in air saturated water (0.009 mol m^{-3} CO_2), while the dissolved HCO_3- in floodwater was 1.09 ± 0.00

mol m^{-3} and pH was 8.8 ± 0.01. It is relevant that approximately 5 days before submergence these plants had received a fertilizer application of 20 kg P_2O_5 and 30 kg N/ha.

Supersaturation of floodwater was also observed in floodwater of a rice-fish culture experiment. A trench bordering the rice field where water was about 150 cm deep for fish culture had supersaturated [O_2] at up to 75 cm water depth, while just above the soil surface the water was below air saturation (Table 3). Where this floodwater extended into an adjacent rice field with water depths about 40cm, the floodwater was supersaturated over the entire water profile (Table III). This occurred even though this water in the rice field was about 100 m from the trench. Several days before measurements in Table 3, this entire plot had received a phosphorous fertilizer application of 20 kg P_2O_5/ha to promote fish growth (Sinhababu, CRRI, 1993, person, commun.).

Table III : Concentrations of O_2 (mol m^{-3}) in floodwater of non submerged rice (A) and an adjacent trench which was used for fish culture (B) in experimental plots at CRRI, Orissa, India. Floodwater was 40 and 150 cm deep in the rice field and the connecting trench bordering the rice field, respectively. Measurements made on the same date as Fig. 2 at 1730h; figures in parentheses are O_2 as % of air saturated water at 30°C.

A. Ricefield Water depth (cm)	O_2	B. Connected trench for fish culture Water depth (cm)	O_2
1	0.35 ± 0.01 (148)	1	0.37 ± 0.02 (157)
30	0.34 ± 0.01 (144)	75	0.33 ± 0.02 (140)
40	0.35 ± 0.01 (148)	150	0.09 ± 0.05 (38)

DISCUSSION

The results are discussed below in terms of comparison of floodwater environmental conditions in India with locations in Thailand and Bangaladesh, the need for close monitoring of experimental plots for relevance to field environments, and an explanation of supersaturated [O_2] in floodwater. The latter is relevant to future reasearch on the potential for alleviation of possible adverse effects of limited O_2 supply on growth or survival of rice during submergence via manipulation of floodwater [O_2] in the field.

Relevance of data to other ecosystems

The general trend of sub saturated concentrations of O_2 and supersaturated concentrations of CO_2 in floodwater of rice fields at Pagalabhari (Fig. 2), Gagharaghat (Table I) and Nuahat Pata (Table II) was similar to floodwater in farmers' fields at several locations in Thailand (Heckman 1979, Setter *et al.*, 1987) and Bangladesh (for O_2 only, Whitton *et al.*, 1988). The diurnal changes of low O_2 in the morning and high O_2 at the end of the day, with the opposite trends for CO_2 (Fig. 2A and B respectively), were also similar to these locations and a rice-fish pond in Cuttack, India (O_2 data only, Sinhababu *et al.*, 1991).

Changes in floodwater [O_2] over a diurnal cycle are likely the result of several factors including the net O_2 increase in day light as a result of photosynthesis of algae and submerged rice plant tissues; and the O_2 decrease during the night due to the metabolism of biomass in the water profile including rice, algae and other organisms. The quantitative contribution of these processes has been analysed in rice fields of Thailand with about 60% of the O_2 uptake during the night being attributed to submerged rice tissues (Setter *et al.*, 1988c).

The data presented here are only from one wet season, hence confirmation of these results at other times and locations is important if this work is to accurately help direct research strategies for alleviating the adverse effects of submergence on rice.

Explanation and possible importance of supersaturated O_2 in floodwater

The O_2 concentrations in floodwater were exceptionally high and supersaturated in one experimental tank where plants were submerged in turbid water (Fig. 3A). This contrasted with field conditions (above), demonstrating the importance of monitoring environmental characteristics at research stations for their relevance to field conditions. The explanation for O_2 supersaturated floodwater and the impact that this might have on survival of rice in flood-prone environments in future deserves further consideration.

The supersaturated O_2 concentrations in floodwater deep below the water surface occurred even though irradiance was reduced to only 50% or less of incident radiation. The O_2 was even greater at water depths with lower light relative to the water surface (Fig. 3). It was unlikely that the submerged rice was responsible for this high [O_2] since (i) the CO_2 concentration in floodwater was less than 0.009 mol m^{-3} (Results) and (ii) terrestrial and semi-aquatic plants like rice are not known to utilise HCO_3^-. Support for the latter is obtained since submerged detached leaves of rice have at least 10 times greater rates of O_2 evolution at pH 6.5 than at pH 7.9 when total inorganic carbon was 6 mol m^{-3} in both cases (Setter *et al.*, 1989a). At these pH values, dissolved CO_2 concentrations would be 2.6 and 0.18 mol m^{-3} respectively (calculated from Umbreit, 1964).

Even if rice would utilize HCO_3- this ion could not cross the gas envelope surrounding leaves during submergence (see Setter *et al.*, 1989a, for further discussion). Hence the likely explanation for high $[O_2]$ in floodwater observed here was associated with photosynthesis from HCO_3- utilizing algae. This is supported by observations that supersaturated O_2 concentrations in floodwater also occurred in deep water used for fish culture where there were no rice plants.

The generation of supersaturated O_2 profiles by algae in water of lakes is well known (Wetzel, 1983). The maximum concentrations of O_2 in water of several lakes often occurred in the metalimnion layer, i.e. where as steep thermal gradient occurs usually several metres beneath the water surface. The algae which commonly grow at these levels are well adapted to low light and low temperatures but have access to nutrient concentrations which are usually higher than for the epilimnion, i.e. the surface water layers (Wetzel, 1983). The access to nutrients is a key factor in sites measured here where floodwater was supersaturated with O_2. In the submergence tank, plants received both P and N prior to submergence, while in the rice-fish plot only P was supplied. It is, therefore, likely that algal growth and floodwater O_2 supersaturation were due to increased P supply.

Such pronounced effects of algal growth on floodwater oxygenation raise the possibility that controlled algal growth by P addition may be used to improve the O_2 supply to rice plants during submergence as long as fields are stagnant and water level decreases occur via percolation rather than run-off. Indeed, this may be an important factor why plants fertilized with P tolerated stagnant submergence better and produced significantly higher grain yields than when no P was applied (experiments repeated 3 years, Reddy *et al.*, 1991). It remains possible that adverse effects of high O_2 concentrations may also occur during submergence due to photorespiration and irreversible damage of the photosynthetic capacity of leaves. Other adverse effects of increasing algal growth in the field would need to be evaluated carefully, e.g. to avoid anaerobic conditions during the night. While the latter did not occur in the present experiments (Fig. 3) this may occur under conditions of excessive P concentrations.

Future reasearch must focus on means of manipulating floodwater $[O_2]$ during submergence as well as a quantitative determination of the importance of different O_2 concentrations of growth and survival of rice during submergence. At present there is no published information on the latter even though it is well known that O_2 is one of the major factors limiting growth during waterlogging of plants (Jackson and Drew, 1984) and submergence of rice (Setter *et al.*, 1989b).

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