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ENVIRONMENTAL CHARACTERIZATION OF FLOODWATER IN EASTERN INDIA: RELEVANCE TO SUBMERGENCE TOLERANCE OF LOWLAND RICE

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SUMMARY

Floodwater was characterized through field surveys over three years in rainfed lowland and deepwater rice areas of Eastern India. Measurements focused on dissolved O_2 and CO_2, pH and irradiance during flash floods in rice fields. Over locations and time, dissolved O_2 concentrations ranged from zero to 0.28 mol m^{-3} (0–1.1 times air-saturated water at 30 °C) while dissolved CO_2 ranged from 0.28 to 1.96 mol m^{-3} (31–217 times air-saturated water). Floodwater pH varied from 6.6 to 9.7. Irradiance decreased with depth in the water profile to an extent depending on turbidity. Turbidity varied greatly over locations and time. The significance of these measurements in assessing rice submergence tolerance is discussed.

INTRODUCTION

About 10 million hectares of rice lands in Eastern India are adversely affected by waterlogging and flash floods each year (Reddy and Sharma, 1992). The timing, duration and intensity of flooding vary greatly and flooding may be due both to local rainfall and to rain in neighbouring areas brought in by flooding rivers. In spite of the importance of the problem, there are no standard methods for describing the floodwater properties relevant to rice growth and survival and for characterizing flood-prone environments.

The adverse effects of flooding are multiple and complex. The effects of submergence include mechanical damage, low light, limited gas diffusion, leaching of soil nutrients and increased susceptibility to pests and diseases (Greenway and Setter, 1996; Setter *et al.*, 1995). Additional adverse effects may occur after the floodwater subsides (Crawford, 1992). The most important environmental factor is likely to be limited gas diffusion in the floodwater. Gases diffuse 10 000-fold more slowly in water than in air (Armstrong, 1979). Hence any of the gases

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involved in plant metabolism, for example, O_2, CO_2 and the plant hormone ethylene, may restrict growth during flooding.

Floodwater properties are not static. Oxygen concentrations show a pronounced diurnal cycle, peaking during the daytime, particularly in rice fields where more than 40% of the plant shoots may be submerged (Setter *et al.*, 1987). Carbon dioxide concentrations also show a diurnal cycle with opposite trends to O_2. Such diurnal cycles are more pronounced in stagnant and shallow water (Heckman, 1979; Setter *et al.*, 1995). In turbulent water, distinct diurnal cycles are seldom observed, probably because the floodwater is continuously mixed with air and reequilibrated (Setter *et al.*, 1987, Fig. 5). Supersaturated O_2 concentrations may arise in the floodwater of some submerged rice fields (Setter *et al.*, 1995) and in lake water (Wetzel, 1983).

Complete information on floodwater characteristics are seldom collected in conjunction with plant measurements in the field. This makes the interpretation of data difficult and incorrect conclusions may be drawn. In particular, conclusions about germplasm flooding tolerance cannot be extrapolated to other sites without information on floodwater characteristics. This paper presents data on floodwater characteristics relevant to submergence tolerance in rice from various sites in Eastern India. We focus on four of the major ways in which flooding may affect plant survival, namely, altered regimes of light, O_2, CO_2 and pH. It is too soon to attempt to rank these factors, but we illustrate how variable they may be, and suggest that such variability may lie behind the different tolerances to submergence shown by plants grown at different sites in India.

MATERIALS AND METHODS

Sites

Measurements were made in rice fields at the following sites during the wet season between August and September in 1993–95. These sites were all exposed to natural flash flooding.

i) Pagalabhari, Uttar Pradesh, 15 km south of Faizabad, where the floodwater depth was 0.4–0.6 m and the plants were partially submerged;
ii) Kalyan Bhadarsa, Uttar Pradesh, 20 km south of Faizabad, where the water depth was 0.8 m and the plants partially submerged;
iii) Matarepur, Uttar Pradesh, 160 km north-west of Faizabad, where the water depth was 1.0 m and plants were completely submerged;
iv) Khamharia Buzurg, Uttar Pradesh, 95 km north-east of Faizabad, where the water depth was 0.6–1.0 m and plants were completely submerged;
v) Ghagharaghat, Uttar Pradesh, 140 km north-west of Faizabad adjacent to the Ghaghra River, where the water depth was up to 0.6–1.0 m in lowland rice fields.
vi) Biraul, Bihar, 120 km north-east of Pusa where the water depth was 0.6–2.0 m.

Environmental measurements

Dissolved O_2, total inorganic carbon (TIC), pH, turbidity and turbulence were measured in the floodwater together with siltation on leaves after the flood receded. The diurnal and depth changes in dissolved O_2, TIC, pH, temperature and irradiance were also measured. Dissolved O_2 and temperature were measured using a Syland O_2 electrode (Setter *et al.*, 1987) fixed to a pole lowered to various depths in the water and gently moved until a stable reading was obtained. Quantum flux densities were measured using an air or underwater quantum sensor (Model LI-185 B, Licor Inc., Lincoln, Nebraska). Values were sometimes supplemented with measurements using a Secchi disk (Wood, 1975). Measurements of pH and TIC were made within 4 minutes of collection. TIC values were obtained from the CO_2 evolved when samples were buffered to pH 4.2 using a polarographic CO_2 electrode (HNU System Inc., Newton Highlands, Massachusetts) with standards containing 0.009–1.000 mol m^{-3} TIC. Dissolved CO_2 was calculated from the pH and TIC measurements assuming the equilibrium:

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \quad (1)$$

for which $$K_a = [H^+][HCO_3^-]/[CO_2] \quad (2)$$

that is $$\log\{[HCO_3^-]/[CO_2]\} = pH - pK_a \quad (3)$$

and $$[TIC] = [CO_2] + [HCO_3^-] \quad (4)$$

Therefore $$[TIC]/[CO_2] = 1 + [HCO_3^-]/[CO_2] \quad (5)$$

and $$[CO_2] = [TIC]/(1 + [HCO_3^-]/[CO_2]) = [TIC]/(1 + 10^{(pH - pK_a)}) \quad (6)$$

where pK_a = 6.36 at 30 °C, and increases by approximately 0.0005 per 1 °C decrease in temperature (Umbreit *et al.*, 1964). Water flow was measured by the time taken for a semi-submerged plastic bottle to move 5–10 m.

All measurements were made at 3–5 locations within each site at each time of day and water depth.

RESULTS

Light

Light profiles in the water are shown in Fig. 1 for four locations during the 1994 wet season and for three locations during the 1995 wet season. The flux densities generally showed an exponential decline with depth and therefore lent themselves to analysis in terms of the Beer–Lambert law for absorption:

$$I/I_0 = \exp(-\lambda z)$$

where I is intensity, I_0 incident radiation, z depth and λ an extinction coefficient. The appropriate half depths $z_{1/2}$, over which irradiance fell by a factor of two, are given in Fig. 1. These data show that the turbidity of the water was similar in both seasons at Pagalabhari and Matarepur, seasonal differences in the actual

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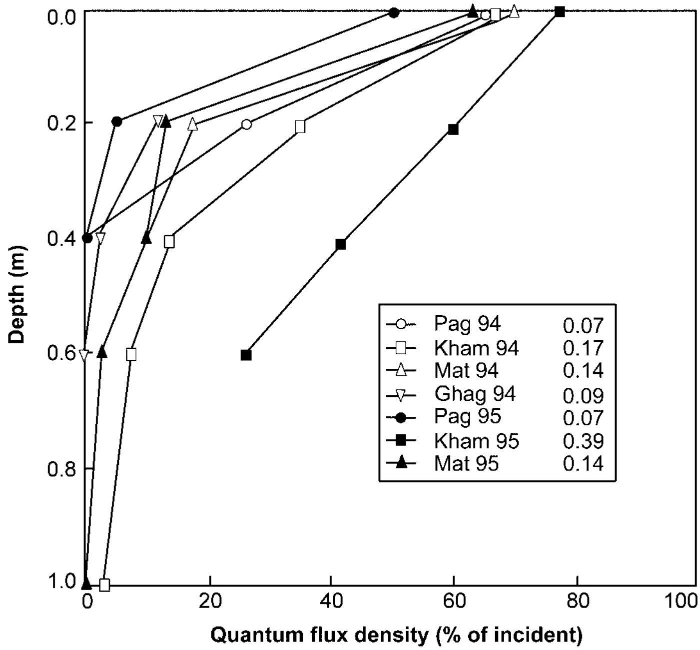

Fig. 1. Radiant flux density profiles in floodwater at Pagalabhari (Pag, —○—), Khamharia Buzurg (Kham, —□—), Matarepur (Mat, —△—) and Ghagharaghat (Ghag, —▽—) in 1994 (open symbols) and 1995 (closed symbols). The water depths (m) at which irradiance is reduced by a factor of 2 ($z_{1/2}$) are given in the legend.

profiles presumably being due to canopy structure and cloudiness; the water itself was more variable and generally clearer at Khamharia Buzurg.

Floodwater was invariably turbid at the onset of floods due to the suspension of particles. Subsequently it became clear at Khamharia Buzurg and Pagalabhari, but at Matarepur and Ghagharaghat it remained turbid over the entire flooding period of one to two weeks. Heavy siltation at Matarepur and Ghagharaghat was also noted, which may have adversely affected plant survival and regeneration. Floodwater temperature also varied with location and with the depth of the water. Surface temperatures increased during the day and decreased during the night, but the reverse was true at the lower depths. These variations were less distinct in turbulent water. The rate of water flow through the fields at the different locations varied between 0.07 and 0.3 m s^{-1}.

Dissolved O_2

The changes in O_2 concentration with depth and over the day were similar for all the locations (Table 1 and Fig. 2). At Pagalabhari and Kalyan Bhadarsa, the plants were partially submerged (0.4 and 0.8 m water), whereas at Matarepur and Khamharia Buzurg, they were completely submerged (> 1.0 m water). At Pagalabhari and Kalyan Bhadarsa, dissolved O_2 concentrations were always

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Table 1. Floodwater O_2 concentrations (mol m^{-3}) at various locations in Eastern India in the 1995–96 wet season.

Location and maximum water depth	0600 hours		1800 hours	
	Water surface	Soil surface	Water surface	Soil surface
Pagalabhari	0.10	0.05	0.22	0.12
(0.40 m)	(0.005)†	(0.003)	(0.004)	(0.008)
Kalyan Bhadarsa	0.02	0.00	0.09	0.00
(0.80 m)	(0.003)	(0.00)	(0.005)	(0.00)
Matarepur	0.12	0.12	0.18	0.11
(1.0 m)	(0.003)	(0.003)	(0.009)	(0.005)
Khamharia Buzurg	0.22	0.21	0.28	0.21
(1.0 m)	(0.003)	(0.006)	(0.01)	(0.003)
Ghagharaghat	0.21	0.20	0.25	0.19
(1.0 m)	(0.006)	(0.001)	(0.01)	(0.01)
Biraul	0.02	0.015	0.039	0.024
(0.60 m)	(0.001)	(0.001)	(0.013)	(0.003)

†Standard errors in parentheses.

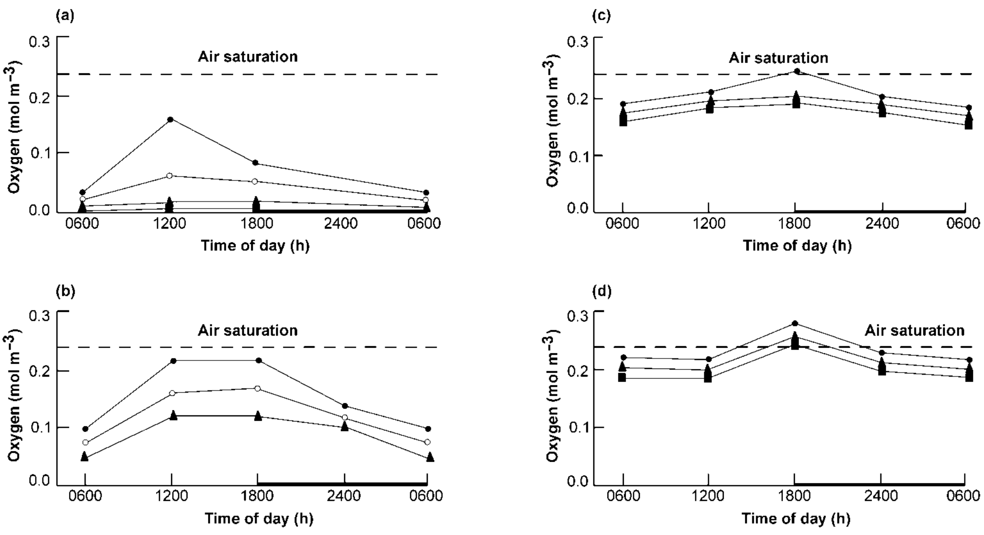

Fig. 2. Diurnal changes in floodwater O_2 concentrations at depths of 0.02 (—●—), 0.2 (—○—), 0.4 (—▲—) and 0.8 m (—■—) at (a) Kalyan Bhadarsa and (b) Pagalabhari (stagnant water) and at (c) Matarepur and (d) Khamharia Buzurg (turbulent water). Standard errors of the means are less than the symbol size. Dark period between 1800 and 0600 hours.

lower than that for water in equilibrium with atmospheric O_2 (0.24 mol m^{-3} at 30 °C), and changed diurnally with the lowest values at 0600 hours and highest at 1200 or 1800 hours. Values were always lower at depth than at the surface. However, at Matarepur and especially at Khamharia Buzurg, peak values at the water surface sometimes exceeded that for equilibrium with atmospheric O_2.

Dissolved CO_2 and pH

Dissolved CO_2 concentrations near the water surface were generally high in the morning and low at midday (Table 2 and Fig. 3). The magnitude of the diurnal changes decreased with depth. At all the locations and times, dissolved CO_2 concentrations were far greater than that for water in equilibrium with atmospheric CO_2 (0.009 mol m^{-3} at 30 °C); the range was 31 to 217 times atmospheric saturation. Higher concentrations at Pagalabhari and Matarepur were probably due to higher plant densities and algal growth (data not shown). Bicarbonate concentrations also varied with location and ranged from 1.8 to 10.4 mol m^{-3} at Kumarganj (data not shown). The floodwater pH at different locations ranged from 6.6 to 9.7 (Table 3). The pH at the water surface was low in the morning, increased during the day and decreased during the night (data not shown).

Plant survival

The importance of floodwater characterization is evident from the observed variability in survival of the same set of genotypes at two different locations in Eastern India (Table 4 and 5). Even the most submergence-tolerant genotype FR13 A showed survival ranging from 59 to 100% at Masodha, Faizabad while at Cuttack, Orissa, the survival was between 53 and 74%. The control, Mahsuri, which was intolerant of submergence, also had 38–75% survival at Masodha compared with 0–63% at Cuttack. The correlation for submergence tolerance of cultivars or lines at Masodha compared with Cuttack was $r^2 = 0.01–0.10$ (calculated from Table 4 and 5).

Table 2. Floodwater CO_2 concentrations (mol m^{-3}) at various locations in Eastern India in the 1995–96 wet season.

Locations and maximum water depth	0600 hours		1800 hours	
	Water surface	Soil surface	Water surface	Soil surface
Pagalabhari	1.96	1.56	0.76	1.22
(0.40 m)	(0.06)†	(0.04)	(0.14)	(0.04)
Kalyan Bhadarsa	1.76	1.43	0.75	1.00
(0.80 m)	(0.26)	(0.17)	(0.01)	(0.28)
Matarepur	1.32	0.48	0.34	1.72
(0.60 m)	(0.12)	(0.18)	(0.06)	(0.08)
Khamharia Buzurg	0.76	1.42	0.54	0.40
(0.60 m)	(0.08)	(0.10)	(0.08)	(0.06)
Ghagharaghat	0.74	0.65	0.50	1.20
(1.0 m)	(0.18)	(0.20)	(0.07)	(0.10)
Biraul	0.76	0.80	0.28	0.28
(0.60 m)	(0.02)	(0.08)	(0.02)	(0.02)

†Standard errors in parentheses.

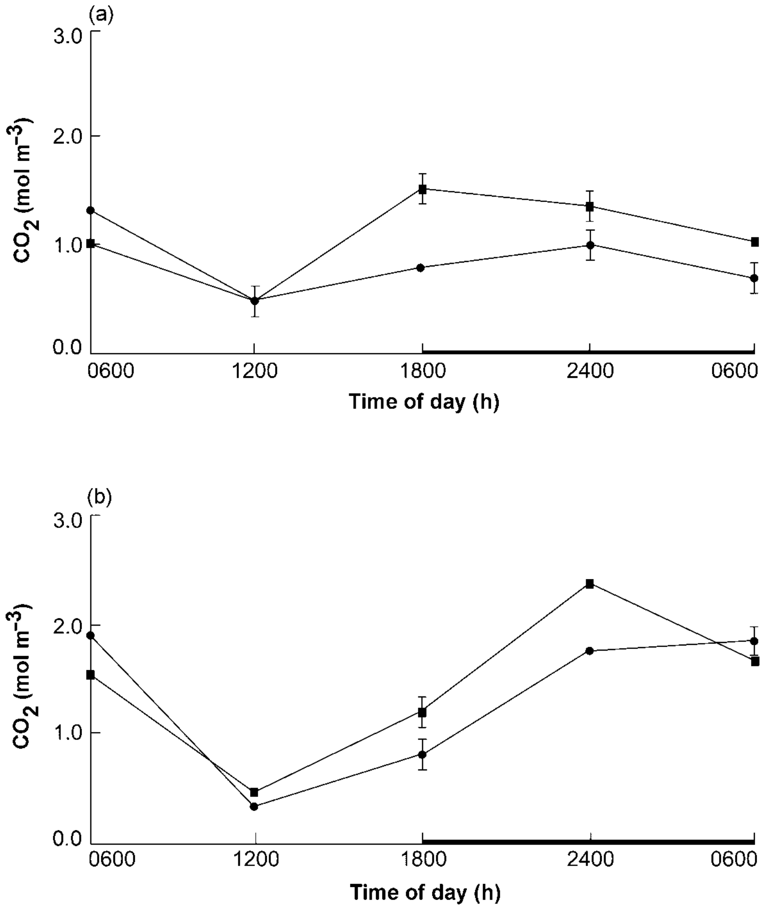

Fig. 3. Diurnal changes in floodwater CO_2 concentrations at depths of 0.02 (—●—) and 0.6 m (—■—) at (a) Matarepur and (b) Pagalabhari. Vertical bars are standard errors of the means. Dark period between 1800 and 0600 hours.

Table 3. Flood water pH at various locations in Eastern India.

	pH range	
Location	1995–96	1994–95
Pagalabhari	6.9–7.5	7.4–7.8
Kalyan Bhadarasa	—	6.9–7.2
Matarepur	6.6–7.5	7.5–8.1
Khamharia Buzurg	6.8–7.6	7.3–8.0
Ghagharaghat	6.9–7.2	7.4–7.8
Pusa	9.5–9.7	—
Biraul	7.3–7.8	—

Table 4. Survival (%) of rice genotypes at two locations in Eastern India in the 1993 and 1994 wet seasons.

	Survival	
Genotype	Masodha (NDUAT)	Cuttack (CRRI)
	1993 Wet season†	
BKP-232	52.9	0.0
BKP-241	65.9	0.0
BKP-242	61.8	0.0
TCA-88-69	66.5	0.0
TCA-88-10-1	60.5	2.8
TCA-48	76.5	13.8
IR-42342-40-3-3-2-3	61.2	0.0
NDE-30013	53.6	0.0
NDR-40013	51.0	3.7
NC-487-77	65.8	22.5
CR-410-6018	80.7	0.0
CR-626-26-26-14-1	90.3	8.0
FR-13A	59.3	74.8
Sabita	64.4	12.6
Mahsuri	49.4	1.1
	1994 Wet season‡	
CR-770-4-6	48.5	0.0
CR-767-1	62.6	0.0
CR-771-3-2	66.5	0.0
CR-728-464-54	88.4	0.0
CR-728-2-2	83.0	0.0
CR-726-239	81.3	7.0
CR-728-187-46	51.1	0.0
CR-665-787-178	94.0	0.0
CR-728-57-4-7	90.7	4.7
CR-740-1-9-1	79.3	12.0
CR-662-1133	91.3	0.0
CR-672-5	98.0	5.8
Sabita	90.9	30.2
FR-13A	99.9	53.2
Mahsuri	74.5	0.0

†30-day-old and ‡21-day-old rice seedlings submerged completely for 14 days in artificial tanks at the Central Rice Research Institute (CRRI) or grown in field plots at the Narendra Deva University of Agriculture and Technology (NDUAT) with a water depth of 80 cm. Survival was recorded 14 days after desubmergence.

DISCUSSION

Floodwater O_2 concentrations were generally less, and the CO_2 concentrations were greater than those in equilibrium with atmospheric O_2 and CO_2. They changed diurnally in consort with presumed changes in plant and algal photosynthetic activity. Similar patterns have been found in rice fields in Thailand (Heckman, 1979; Setter *et al.*, 1987) and Bangladesh (Whitton *et al.*, 1988), and in

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Table 5. Survival (%) of double haploid lines of rice measured at two different locations in Eastern India in the 1995 wet season.

	Survival†	
Genotype	Masodha (NDUAT)	Cuttack (CRRI)
IR-67709-AC6-3	60	20
IR-67709-AC11-2	61	40
IR-67709-AC15-1	58	23
IR-67709-AC15-2	67	20
IR-67709-AC15-4	62	20
IR-67709-AC19-1	69	20
IR-67709-AC26-5	80	30
IR-67709-AC26-6	56	35
IR-67709-AC32-1	16	43
IR-67709-AC32-2	27	60
IR-67709-AC32-3	21	53
IR-67709-AC35-3	60	48
IR-67709-AC35-5	53	25
IR-67709-AC35-6	59	20
IR67709-AC37-1	72	40
FR-13A	73	66
Sabita	61	83
Mahsuri	38	63
IR-42	40	28

†21-day-old rice seedlings were submerged completely for 14 days in field plots at NDUAT or in artificial tanks at CRRI. Survival was recorded 14 days after desubmergence.

rice–fish ponds in Eastern India (Sinhababu *et al*., 1991). The diurnal changes in O_2 and CO_2 arise because transport between sites of consumption or production and the atmosphere is restricted by low diffusion rates in water. Gas transport can also occur in envelopes surrounding rice leaves (Raskin and Kende, 1983) and through lacunae in those leaves. However, a significant barrier to gas exchange remains. Thus O_2 increases and CO_2 decreases during the daytime as these gases are generated and consumed in plant and algal photosynthesis, and then they change in the opposite directions at night. Differences in diurnal patterns between stagnant and turbulent water arises at least partly because of differences in the extent of the gas movement in floodwater.

Oxygen concentrations in floodwater occasionally exceeded that for water in equilibrium with air ($0.24\ mol\ m^{-3}$). These supersaturated O_2 concentrations were presumably due to surface algal photosynthesis rather than plant photosynthesis, the former being favoured by turbulence for a number of reasons. First, since the turbulent water was also turbid, light penetration to depth was reduced. Second, algae can utilize HCO_3^- ions for their photosynthesis as well as CO_2 and they therefore have an advantage over submerged plants; this advantage will be amplified in turbulent water since rates of transport of HCO_3^- through the water are high. Third, once an algal bloom is established, it will shade submerged plants further. High phosphorus in the floodwater also induces algal growth (Rama Krishnayya *et al.*, 1999; Roger, 1996; Wetzel, 1983).

Concentration of CO_2 in the floodwater ranged between 0.28 and 1.96 mol m^{-3}, 31–217 times higher than in equilibrium with the atmosphere. Carbon dioxide concentrations in the soil solutions of flooded rice soils are typically in the range 6–12 mol m^{-3} but values up to 27 mol m^{-3} have been reported (Ponnamperuma, 1984). Setter *et al.* (1988) observed extremely variable CO_2 concentrations in floodwater from deepwater rice areas, ranging from 0.003 to 1.9 mol m^{-3}. Floodwater CO_2 concentrations will depend on plant population, the extent of submergence, and soil and floodwater microbial and algal activity, as influenced by floodwater organic matter and nutrient contents. Therefore, CO_2 concentrations are expected to be highly dynamic.

Transport of CO_2 through the water may limit photosynthesis by submerged or partly submerged leaves, especially in stagnant floodwater. Assuming that irradiance is not limiting, predicted rates of photosynthesis by submerged rice leaves at the maximum CO_2 concentration measured in the present experiments (2 mol m^{-3}) are 2–60% of the rates for plants in air (Setter *et al.*, 1988). However, optimum light and turbulence are seldom observed in floodwater, especially under stagnant conditions (Setter *et al.*, 1987). In some fields, irradiance was reduced to 15–20% at a depth of 0.2 m (Fig. 2). Thus, even in the presence of supersaturated CO_2 concentrations, leaf photosynthesis by submerged rice plants would have been low. High CO_2 can also be advantageous for retention of chlorophyll because it is known to antagonize the adverse effects of ethylene on chlorosis during submergence (Abeles, 1971). However, the effects of high floodwater CO_2 concentrations on submergence tolerance in the field are poorly understood.

Differences in water turbulence may also result in differences in mechanical damage due to forces acting on plant stems and abrasion by particles in the water. Floodwater temperature also varies between locations and with water depth, and may influence plant survival through its effects on gas solubility and rates of metabolic processes.

Environmental conditions prior to submergence, such as those governing irradiance and mineral nutrient supply, may also have a major effect on survival and submergence tolerance at different locations. For example, a high shoot carbohydrate content prior to submergence is found to be important for survival (Setter *et al.*, 1996), and this will be influenced markedly both by irradiance and plant mineral nutrition.

Clearly the interpretation of experiments on submergence tolerance of lines in Table 4 and 5 may be misleading without data on floodwater characteristics which were not measured in either experiment. Such experiments often reveal inconsistent differences between locations. For example, sometimes a given line performs better at one location, but sometimes it performs better at another location. Similarly, the performances of lines in a population at one location may not correlate with their performances at another. Such apparent anomalies may be resolved by considering the differences in floodwater characteristics, shown by the data presented here. The necessary characteristics include O_2 and CO_2 concentrations, pH, turbidity, light and temperature and their changes following submergence. The need to quantify these characteristics correctly when characterizing flooding environments is important since without it screening trials will remain pragmatic and of mainly local importance. Prioritization of these measurements remains an important aspect of future research on submergence tolerance of rice.

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