

## Searching for New Plants for Climate Change

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### Abstract

Trends in night temperatures, ozone concentrations and acid rain are presented. We tested the hypothesis that flowering in the cooler part of day or night could make plants much less vulnerable to high temperature induced sterility. We screened 96 cultivars originating from a range of latitudes and altitudes for the time-of-day when flowering commenced (TDF); no systematic relationship was observed. There was a 3 hour difference in TDF between the cultivars, the earliest being 0800 h. We also screened 87 wild rice accessions for TDF. The earliest was 0500 h and the latest was 2230 h. For the worst climate change scenario (6°C increase in average temperature), the predicted changes in crop duration, respiration and sterility, would reduce the yield of existing cultivars by 89%; yields for accessions with the earliest TDF would decline by 47%. For a temperature increase of 2°C, the predicted yield of existing cultivars would fall by 25%; those with the earliest TDF would fall by only 11%. The model predicted in the absence of climate change, differences in weather between El Niño and La Niña years would decrease yields by 22%; the greatest improvements in germplasm and management would increase farmers yield by 18%.

**Key words:** Climate change, El Niño and La Niña, Flowering time, Temperature, Yield

### 1. Introduction

Changes in air quality and composition, acid rain and climate are in combination producing a new bioclimate for food production systems. Models predict an increase in rice yield with increased atmospheric levels of carbon dioxide (Horie *et al.*, 1995a). However, the potentially beneficial effects of increases in carbon dioxide may be offset by the increases in O<sub>3</sub> at ground level (Maggs and Ashmore, 1998). Despite average atmospheric partial pressure of carbon dioxide increasing by approximately 4.6 Pa between 1968 and 1998, yields for the same cultivar (IR8) grown on the IRRI farm in 1998 were about 2.6 t ha<sup>-1</sup> lower than in 1968 at nitrogen inputs of approximately 150 kg N ha<sup>-1</sup> (Peng *et al.*, 1999).

The highest air temperatures recorded are 49°C, 53°C, 54°C, 57°C and 58°C for the land masses of South America, Australia, Eurasia, North America and Africa respectively (Trewartha and Horn, 1980; Ahrens, 1991). The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001) forecasts that by 2100 mean planet-wide surface temperatures will rise by 1.4°C to 5.8°C. At high temperature, the denaturation of proteins, melting points of lipids, damage to thylakoid membranes or other processes such as pollination disrupt normal plant function. Damage becomes permanent when it is not reversible (physiologically or developmentally) thus eliminating the chance for processes to occur correctly. Reproductive events in once-flowering plants (esp. annual crops) are the conspicuous example. There is only one chance in a year for pollen tubes to grow fast enough in lime trees (*Tilia*) to set seed

(Piggot and Huntley, 1981) or once in the crop growth cycle for anthesis to occur in rice. Short of the critical temperature for catastrophic damage, losses of yield can occur because the daily net acquisition of carbohydrate can be reduced owing to reduced photosynthesis, increased maintenance respiration or both. Increased temperatures can also lead to increases in the rate of crop growth and shortened growing seasons which causes reduced interception of solar radiation and yield (Horie *et al.*, 1995a). Ziska and Manalo (1996) suggested that increasing night temperature can reduce seed set and potential yield of tropical rice, although the mechanism was unclear and night temperatures as low as 29°C could result in reduced grain yield. Peng *et al.* (2004) suggested that increased night temperatures were reducing yields in the field. Recent evidence suggests that night temperature is the cause of increases in global mean temperatures since the middle of the 20<sup>th</sup> century (Kukla and Karl, 1993).

For crop plants, temperatures in the range 45°C to 65°C can cause severe damage and death (Levitt, 1972). Fruit-set was reduced by 6% °C<sup>-1</sup> at temperatures above 33°C in peanut (Vara Prasad *et al.*, 2001). In rice, anthesis is the most temperature sensitive stage for temperature damage. Exposure for a matter of a few hours during flowering can reduce floral reproduction (Satake and Yoshida, 1978; Nishiyama and Satake, 1981; Baker *et al.*, 1992). Osada *et al.* (1973) observed sterility at temperatures exceeding 35°C in the field; rice becomes completely infertile at temperatures above 40°C average daily maximum temperature during the flowering period (Horie *et al.*, 1995a). At those temperatures, female

sterility can occur (Satake and Yoshida, 1978). Mackill *et al.* (1982) suggested that high temperature tolerance at the grain filling stage should be investigated in order to discover high heat tolerance genotypic difference in pollen shedding, pollen germination and pollen tube extension under high temperature. It is interesting to note that despite the fact that only one pollen grain successfully introduces sperm cells into the embryo sac and micropyle, a minimum number (~20) have to be deposited on the stigma before pollen tubes elongate (Satake and Yoshida, 1978). Matsui *et al.* (2001) suggested that rather than low numbers, poor germination was the cause of sterility at high temperature. Once a pollen tube has entered the micropyle, all other pollen tubes cease elongating and eventually degenerate. A complex signaling process must take place in both cases. What those signaling mechanisms are and whether they are disrupted by high temperature is unknown.

In this paper, some aspects of the climate and how it is changing are described. We calculated the effects of year-to-year weather variation on yield using data obtained at our location in the Philippines. The main objective was to quantify the deleterious effects on rice of the higher temperatures that may be caused by climate change. We focused on identifying plants that might avoid damage to the reproductive processes that lead to sterility and subsequent loss of yield. One way of avoiding thermally induced sterility would be to complete the reproductive processes in the cooler parts of the day. Identifying genes that control the time-of-day when flowering commences (TDF) would be crucial for that avoidance mechanism. We tested the hypotheses that cultivars from different thermal origins have different TDF and that wild rice accessions had a greater range than cultivated types in TDF.

## 2. Materials and methods

### 2.1 Weather Data

Weather data were collected from an agrometeorological station situated on the IRRI farm, Los Baños, Philippines, at lat 14°11'N, long 121°15'E and an elevation of 21 m. Data recording began on January 1, 1979. The site measures 10.5 m x 9.5 m and is surrounded by irrigated rice throughout the year. It conforms to the World Meteorological Organization standard specifications. Data for the acidity of rainwater, O<sub>3</sub>, SO<sub>2</sub> and NO<sub>x</sub> were collected from a site adjacent to the IRRI wetland weather station. The gas analyzers and data logger were supplied by EMC Environment Engineering Limited, UK. Data for continuous, diurnal changes in temperature for 2003 were available and those data were used to calculate the effects of TDF on the sterility of spikelets.

### 2.2 Management

Irrigated rice crops were grown at the International Rice Research Institute, Los Baños, Philippines, in the dry season (January-May). Management practices

were employed to achieve minimum possible stress from all biotic and abiotic factors so that yields could approach the maximum achievable yield in the weather conditions experienced (Sheehy *et al.*, 1998).

To test the hypothesis that cultivars from different thermal origins have different TDF, 96 cultivars were selected from the IRRI germplasm collection. They were selected from different latitudes and altitudes (surrogates for temperature at the origin of the germplasm); 91 were *Oryza sativa*s and 5 were *Oryza glaberrima*s. All of the cultivars were grown in the field in 2000 and the cultivars with the earliest TDF and latest TDF were grown again in 2001. The cultivars were sown in plots (1 m x 2 m) and each was replicated twice; they were transplanted at a spacing of 20 cm x 20 cm. A basal application of 60-60-60 kg ha<sup>-1</sup> NPK (N as urea, P as solophos and K as muriate of potash) and 10 kg ha<sup>-1</sup> Zn as zinc sulfate was applied and they were later top-dressed with 60 kg N ha<sup>-1</sup> at 30 and 50 days after transplanting (DAT). The time of day at which the first flower on the main stem opened was recorded during the period of flowering.

To test the hypothesis that wild rice types had a greater range than cultivated types in TDF, 87 accessions were selected from the IRRI germplasm collection. They were selected to represent a wide range of countries with hot climates. The wild types could not be grown in the field so they were grown in 2002 and 2003 in a screen house conforming to the appropriate protocols for such materials. They were germinated in petri dishes for 14 days and then four seedlings were transplanted at a spacing of 20 cm x 20 cm into plastic buckets (45.5 cm diameter and 62.5 cm in height) containing lowland soil. A basal application of 18.2 g per bucket of complete fertilizer (NPK) was applied. Subsequently, 2 g of nitrogen were added monthly and the soil was kept saturated throughout the experiment.

### 2.3 Model

Ultimately, solar radiation is the energy source for growth and it has to be intercepted by the leaves of the canopy. There is a linear relationship between accumulated intercepted photosynthetically active solar radiation and accumulated biomass when the crop is growing in adequate conditions of temperature, water and soil nutrient supply (Monteith, 1977). The slope of that linear relationship is known as the radiation use efficiency (RUE). In this work, the simple model of Sheehy *et al.* (2004) based on RUE was used to predict yield. The value of RUE used was 2.6 g DW MJ<sup>-1</sup> (above-ground dry matter, intercepted photosynthetically active radiation, PAR) and it is the value obtained from very high-yielding rice experiments (Mitchell *et al.*, 1998; Sheehy *et al.*, 2000; Horie, 2001). The effects of increases in temperature caused by climate change were simulated by adding 1°C to 6°C to the daily values of average temperature for the growing season of 1997 when an RUE of 2.6 g DW MJ<sup>-1</sup> was recorded. The model was used to calculate yield and to separately estimate (a) the effect

of temperature on the length of the growing season and (b) the additional effects of changes in maintenance respiration caused by temperature. It was assumed that the coefficient for maintenance respiration was  $0.015 \text{ day}^{-1}$  (Thornley and Johnson, 1990) and the  $Q_{10}$  for temperature effects on the coefficient of respiration was 1.22 with a reference temperature of  $20^\circ\text{C}$  (Sheehy *et al.*, 1980; Frantz *et al.*, 2004). The model was driven by monthly averages of climatic data collected from the IRRI weather station.

### 3. Results and discussion

#### 3.1 Climate and aspects of change

Measurements of the acidity of rainwater at IRRI were taken over 5 years (1995-1999). The annual trend in the mean pH of the rainfall followed a quadratic trend,

$$y = 5.1288 - 0.0088x + 0.0000206x^2 \quad (1)$$

where  $x$  is day number (January 1=1) and  $y$  is pH. The minimum value of 4.2 occurred at the end of July and the maximum value of 5.1 occurred during December. Measurements of gaseous  $\text{SO}_2$  at crop height showed concentrations were less than 5 ppb, except after an application of sulfur-containing fertilizer  $[(\text{NH}_4)_2\text{SO}_4]$  when they rose to 25 ppb for a few days. On a sunny day, the concentration of  $\text{NO}_x$  reaches a maximum at 0730 h and the concentration of  $\text{O}_3$  reaches its maximum at 1500 h. The maximum concentrations of both gases were 55 ppb. The average value of  $\text{O}_3$  for April, the month of flowering, was 18 ppb and the maximum was 55 ppb.

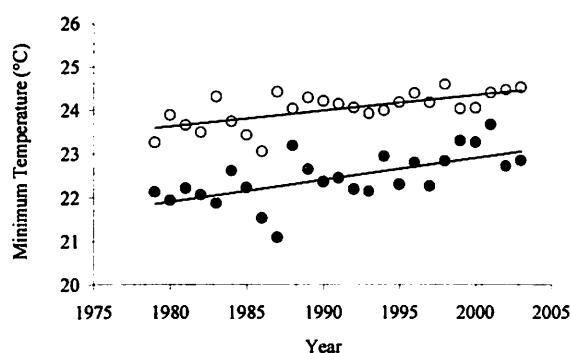


Fig. 1. The increase in the average minimum temperature of the dry season (solid circle) and wet season (open circle), at IRRI Los Baños (1979-2003). The lines through the data represent linear regressions between minimum temperature and year. For the wet season, the function is  $y = 0.0363x - 48.3$  ( $r = 0.66$ ,  $P \leq 0.001$ ) and for the dry season the function is  $y = 0.0502x - 77.6$  ( $r = 0.63$ ,  $P \leq 0.001$ ).

Between 1979 and 2003 minimum temperatures of the wet season have been greater than those of the dry season; both are increasing at approximately  $0.04^\circ\text{C year}^{-1}$  (Fig. 1). Over the same period, there was a

significant increase in the maximum temperature of the wet season ( $0.02^\circ\text{C year}^{-1}$ ,  $P \leq 0.05$ ). However, there was no increase in the maximum temperature in the dry season. The deviation of solar radiation in any year, from the mean value of the 25 years, was calculated. The deviation of temperature from the linear regression, or from the mean value of 25 years (in the absence of a regression), was calculated. There was a significant correlation between the deviations of solar radiation and the deviations of maximum temperature for both the wet and dry seasons ( $y = 0.23x$ ,  $P \leq 0.05$ ) showing that solar radiation caused much of the variation in maximum temperature. During the wet season, a similar relationship existed for minimum temperature ( $y = 0.16x$ ,  $P \leq 0.05$ ). However, there was no significant relationship in the dry season, although the trend appeared to be negative. High solar radiation on clear days may have been associated with increased back-radiation at night, so that sunny days may have been associated with cool nights.

#### 3.2 Weather variability and yield

Climate change implies a gradual change in the weather which is expected to influence yield. Those gradual changes are masked by variations in annual weather patterns e.g. El Niño and La Niña events. In El Niño years, there are more clear days, less rainfall and increased solar radiation whereas the opposite is experienced in La Niña years. To calculate the effects of weather variability on rice, we used the model of Sheehy *et al.* (2004). In particular, yields for irrigated rice in the dry season were predicted for 3 weather data sets: (1) the average weather data at IRRI (1979-2003), (2) the weather data in 1997 (El Niño) and (3) 1989 (La Niña). There are two possible future scenarios with respect to the yield potential of rice. In the first, we assume that new high-yielding cultivars will be available to farmers enabling them to reach maximum attainable yield ( $\text{RUE} = 2.6 \text{ g DW MJ}^{-1}$ ) and in the second, we assume that the existing elite germplasm will be used by farmers adopting the best management ( $\text{RUE} = 2.2 \text{ g DW MJ}^{-1}$ ).

Table 1. Predicted rice yields ( $\text{t ha}^{-1}$ , 14%mc) for different weather conditions at Los Baños, Philippines. The best yield currently achievable by farmers ( $\text{RUE} = 2.2 \text{ g DW MJ}^{-1}$ ) and the maximum attainable yield ( $\text{RUE} = 2.6 \text{ g DW MJ}^{-1}$ ).

Year	Weather conditions	Farmers yield	Maximum attainable yield
1989	La Niña	7.5	8.9
1997	El Niño	9.6	11.4
1979-1999	Average	8.5	10.1

For both scenarios (Table 1), farmers would obtain 13% more yield in an El Niño year and 12% less in a La Niña year relative to the yield in an average year.

The biggest possible improvements in germplasm and management in the coming decades could increase farmer's yields by 18%. Yield improvements made by plant breeders can easily be masked by fluctuations in weather. Going from a La Niña to an El Niño year would increase yield by 28%.

### 3.3 Temperature, crop duration, respiration and yield

Horie *et al.* (1995a) suggested that temperature increases could result in serious decreases in yield across Asia. To examine the effects on yield of up to a 6°C rise in temperature caused by climate change, we used the model of Sheehy *et al.* (2004) and the weather data for 1997 and we assumed that harvest index remained constant. It was assumed that any potential benefits from increasing CO<sub>2</sub> were offset by degradation in air quality such as increased concentration of tropospheric O<sub>3</sub>. For these calculations, we assumed that the greatest improvements in germplasm and management would be made in the coming decades (RUE=2.6 g DW MJ<sup>-1</sup>).

Increasing temperatures can lead to shorter growing seasons. For the 6°C increase, the predicted duration of the crop shortened from 101 days to 95 days and yields declined by 6%. The relationship between crop duration and the temperature increase is linear ( $y = -0.89x + 100.25$ ,  $P \leq 0.001$ ). Changes in crop duration are likely to be unimportant.

It is commonly assumed that maintenance respiration increases with increasing temperature, although the magnitude of this effect is unclear. To gain some insight into its possible impact over the 6°C rise in seasonal average temperature, we calculated its effect on RUE (Mitchell *et al.*, 1998). RUE declined from 2.6 to 2.0 g DW MJ<sup>-1</sup> ( $y = -0.097x + 5.17$ ,  $P \leq 0.001$ ). When this effect was added to the shortening of crop duration, the predicted yield fell from 11.4 to 8.2 t ha<sup>-1</sup>; 28% for a 6°C increase.

### 3.4 Fertility, temperature and TDF

Potentially, the most damaging effects of climate change on rice yields could come through the effects of temperature on fertility. Events surrounding and including pollen tube extension in the hour following anthesis fail completely at temperatures between 35°C and 40°C. Using controlled environments, a decline in the fertility of spikelets with increasing temperature was observed by Satake and Yoshida (1978). A similar relationship between the fertility of spikelets and maximum temperature was observed by Horie *et al.* for plants growing in temperature gradient tunnels (1995b).

Flowering, specifically fertilization, is not an instantaneous process. The elite indica-type rice cultivar IR72 has a large number of tillers and it flowers over approximately 20 days. Breeding lines of the new plant type (Peng *et al.*, 1994) have a low number of tillers and they complete flowering in a week.

The 96 cultivars selected from different latitudes and altitudes flowered over several hours on any day (Fig. 2). There was no relationship between either latitude or altitude and TDF of the cultivated types. The cultivar that flowered the earliest was *Oryza glaberrima-Marori* which commenced flowering at 0830 h and finished at 1330 h. The cultivar with the latest TDF was *Oryza sativa-Ganja Ratria* which commenced flowering at 1000 h and finished at 1400 h.

The wild rice accessions had a greater range of TDF than the cultivated types (Fig 2). Of the 87 wild rice accessions, the one with the earliest TDF was *Oryza eichingeri* which commenced flowering at 0540 h and finished at 0600 h. The accession that flowered the latest was *Oryza alta* which commenced flowering at 2230 h and finished at midnight; similar observations for those accessions were reported by Matsuo and Hoshikawa (1993). Of the 87 wild rice accessions, 21 did not flower. Of the remaining 66, 48 accessions had a similar TDF in each of the two experimental years.

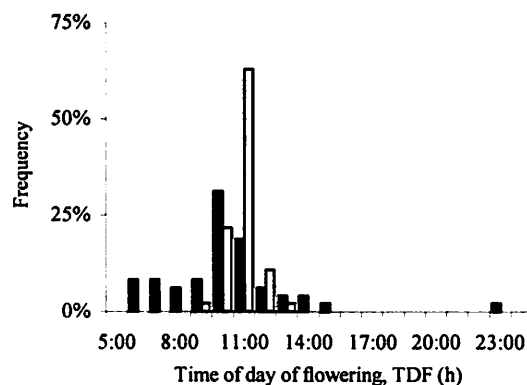


Fig. 2. The frequency distributions of the time-of-day when flowering commences (TDF) in wild rice accessions (filled bars) and rice cultivars (unfilled bars). The materials were obtained from the IRRI Gene Bank.

If we define the sterility of spikelets to be  $\psi$  and the fertility to be  $\phi$ , then  $\psi = 1 - \phi$ . The relationship between fractional sterility and maximum temperature ( $T_m$ ) as observed by Horie *et al.* (1995a) can be written as

$$\psi = 1 - 1/(1 + \exp(0.853(T_m - 36.6))) \quad (2)$$

so that at 36.6°C, the fractional sterility and fertility are both 0.5. Spikelet sterility increased from 20% to 95% as temperature increased from 35°C to 40°C, respectively. For the purposes of this paper, the maximum temperature is assumed to occur 4 hours after the start of flowering.

To test the benefits of changing TDF we used equation (2) to estimate the effects of a 2°C, 4°C and 6°C temperature increase on sterility in a current elite cultivar, *Oryza glaberrima-Marori*, and *Oryza eichingeri* (Table 2). It can be seen that the adverse effects of a 2°C or 4°C increase in temperature could

be largely avoided if the TDF was 0540 h. However, a 6°C increase would still result in a 27% loss in fertility even with the accession with the earliest TDF observed in this work. For a 6°C increase in seasonal average temperature, yields would decline by 28% owing to changes in respiration and crop duration, and then by a further 85% owing to sterility, giving a total yield loss of 89%.

Table 2. The effect of increasing the maximum temperature during flowering on the sterility of rice: (a) current elite cultivar with a TDF of 1000 h, (b) cultivated rice with a TDF of 0830 h and (c) wild rice with a TDF of 0540 h.

Temperature increase	Sterility (%)		
	a	b	c
2°C	16	11	1
4°C	52	39	6
6°C	85	78	27

#### 4. Concluding Discussion

The rates at which plants develop are a function of temperature, but some crucial processes such as reproduction have a critical temperature bandwidth outside of which irreversible damage occurs. Given that the response of fertility to temperature is almost identical in species as different as *Oryza* and *Tilia cordata*, it is likely that the mechanisms that get damaged by high temperature are similar for many plant species. In cultivated rice, at maximum temperatures >33°C, fertility falls at about 14% °C<sup>-1</sup>. We have shown that early TDF could protect fertility from future adverse effects of climate change. Wild rice accessions had a wider range of TDF than of the cultivated rice. No systematic relationship of TDF with the latitude or with the altitude of the origin of a cultivar was observed. The mechanisms controlling TDF are not well understood and Nishiyama and Satake (1981) suggested that one extra hour of darkness could delay the time of day when the treated plants flowered. Nonetheless, discovering the genes that control TDF may be of universal importance.

It has been suggested (Ziska and Manalo, 1996; Peng *et al.*, 2004) that increasing night temperature can reduce seed set. We have shown that seasonal average minimum temperatures are increasing by 0.4 °C every ten years. Increases in seasonal temperature could cause yields to decline by at least 5% for every 1°C increase because of increased maintenance respiration and reduced crop duration. However, there is little or no information concerning the respiratory behavior of the rice crop throughout its growth cycle. Furthermore, the relationship between respiration and temperature for rice remains obscure. The mechanisms through which night temperature could directly affect seed set are also unknown.

Changes in weather can cause large variations in the yield of irrigated rice and they can mask the more gradual, but substantial effects of climate change. We have shown that acid rain, NO<sub>x</sub> and O<sub>3</sub> are at levels that could affect yield (Maggs and Ashmore, 1998; Mansfield, 1999; 2002) and their combined effects on yield warrant further study. Increasing CO<sub>2</sub> concentration adversely affects floral sterility (Ziska *et al.*, 1996; Matsui *et al.*, 1997). In this paper, we have been unable to deal with the combined effects of increasing CO<sub>2</sub> concentrations and gaseous pollutants which have opposite effects on photosynthesis. Furthermore, we recognize that air temperature can be a poor guide to tissue temperature (Nishiyama, 1981; Sheehy *et al.*, 1998).

Finally, it has not escaped our notice that plants are most sensitive to water stress during the reproductive period. A pre-dawn TDF might help plants avoid the damaging effects of both high temperature and water stress on yield.

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