

Effect of Low Water Temperature on Rice Yield in California

A. Roel, R. G. Mutters, J. W. Eckert, and R. E. Plant*

ABSTRACT

Water temperature has increasingly become a matter of concern for California rice (*Oryza sativa* L.) growers due to a need for public water agencies to improve habitat for fish. Prudent management of water resources to balance the needs of environmental and agricultural interests requires the quantification of water temperature effects on rice productivity. Our objective was to evaluate two alternative thermal unit models for the effect of low water temperature on yield. One model was based on the total number of hours below a given threshold water temperature T_b (abbreviated TNHB T_b) and the other was based on the concept of inverse degree days (i.e., degree days below a given threshold water temperature) (abbreviated IDD). We tested these models at a range of values of T_b between 10 and 25°C on data from two commercial fields during 2 yr. Results showed that the effect of low water temperature may be much greater than would be apparent from the visual appearance of the rice plants. Values of IDD and TNHB T_b were very highly correlated for 4 of the 4-yr field combinations. A logistic curve model based on TNHB 20°C provided the best fit to the aggregated data.

WATER TEMPERATURE has increasingly become a matter of concern for California rice growers due to a need for public water agencies to improve habitat for fish. Prudent management of water resources to balance the needs of environmental and agricultural interests requires the quantification of the effect of low water temperature on rice productivity. Rice production in California is almost entirely situated in the Sacramento Valley, the state's largest watershed. The production area co-occupies a region with the few remaining native salmon (*Oncorhynchus* spp.) fisheries in the state (Mutters et al., 2002, 2003). The standard seeding practice in California is to sow soaked seeds by airplane into fields flooded to a depth of 8 to 13 cm. A permanent flood is maintained except for brief periods when water is lowered for herbicide applications. The water used for irrigation is often diverted from rivers where water temperatures are controlled by releasing water at selected depths from reservoirs. Water temperatures may be sub-optimal for rice production (Mutters et al., 2002, 2003).

Rice grown under flooding in cool climates may be subjected to suboptimal water temperature (T_w) at any stage of the crop cycle. It is commonly observed in northern California that cold water damage reduces rice yields near field intake boxes (Raney et al., 1957). Plants in this

vicinity are delayed in heading, heads do not fill, or maturity is not reached by the end of the normal growing season. When the Shasta Dam was completed in 1945, the temperature of the Sacramento River just below the dam changed suddenly from 16.1 to 7.2°C, and T_w fell almost 3°C at Sacramento, CA, 418 km below the dam (Raney et al., 1957; Raney, 1963). Immediately after this, rice growers found that as much as 5% of their planted hectareage did not mature in time to harvest at the end of the cropping season. The temperature of irrigation water taken from the river more than 160 km below the Shasta Dam was sufficiently low to impact rice growth (Raney, 1963). Before construction of the Oroville Dam, Raney et al. (1957, Raney, 1963) pointed out that this dam could cause the Feather River, from which much rice is irrigated, to become colder during the growing season.

This same phenomenon, a reduction of irrigation water temperature delivered to rice field after the construction of dams, has also been observed in Japan (Inoue et al., 1965). Most Japanese rice fields are transplanted under flooded conditions, and lower T_w is considered an important limiting factor in rice production in many locations of the country (Inoue et al., 1965). The rapid development of hydroelectric power plants after World War II accelerated cold water problems. Japanese scientists have tested several different basin warming designs (Mihara and Onuma, 1955; Mihara et al., 1959a, 1959b) in an attempt to solve this problem.

Although there is a vast literature regarding the effect of air temperature (T_a) at different growing stages of the rice crop (IRRI, 1976) there has been much less work performed at the field level concerning the effects of T_w on currently available rice varieties. Shimono et al. (2002, 2004) found that photosynthesis, growth, and yield are limited more by T_w than by T_a before the mid-reproductive period. Chapman and Peterson (1962) found that at temperatures below 20°C there was a significant reduction in shoot elongation. Hearth and Ormrod (1965) studied the effects of T_w on growth and development of flooded rice seedlings for different California and Texas rice varieties. They found that growth was retarded at 16°C, and that 32°C was the most favorable temperature.

Although there have been several laboratory studies of the effect of water temperature on rice growth, there have been few systematic efforts to measure at the field level the effect of low water temperatures on yield in rice. In addition, those studies that have been done have been performed under fixed T_w conditions, while temperature in a commercial rice field varies during the day. The objective of this study was to evaluate two al-

A. Roel, Graduate Group in Ecology, Univ. of California, Davis, CA 95616 (present address: Instituto Nacional de Investigación Agropecuaria, Treinta y Tres, Uruguay); R.G. Mutters and J.W. Eckert, Univ. of California Coop. Ext., Oroville, CA 95965; and R.E. Plant, Dep. of Agronomy and Range Science and Dep. of Biological and Agricultural Engineering, Univ. of California, Davis, CA 95616. Received 17 May 2004. Rice. *Corresponding author (replant@ucdavis.edu).

Published in *Agron. J.* 97:943–948 (2005).

doi:10.2134/agronj2004.0129

© American Society of Agronomy

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DGPS, differential global positioning systems; IDD, inverse degree days; TNHB, total number of hours below; YR, yield reduction.

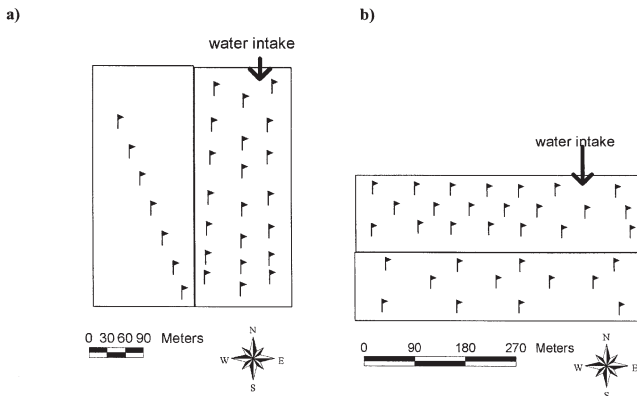


Fig. 1. Sensor deployment in both (a) Field 1 and (b) Field 2. Arrows indicate water intake and flows.

ternative thermal unit models for the effect of low water temperature on yield. One model was based on the total number of hours below a given threshold water temperature and the other was based on the concept of inverse degree days, that is, degree days below a given threshold water temperature threshold. We tested these models over a range of values of T_b from 10 to 25°C to quantify water temperature effects on plant productivity.

MATERIALS AND METHODS

Data Collection

The studies were performed during 2000 and 2001 in two different fields, which will be denoted Field 1 and Field 2. In Field 1, the work was conducted in two adjacent 4.7-ha checks. In Field 2, the work was in two adjacent 5-ha checks. Both fields are located near Richvale, CA (UTM Zone 10, coordinates: E: 613 328 N: 4264 313 and E: 602 316 N: 4372 940; for Field 1 and 2, respectively). Field 1 is located approximately 1 km from the Lake Oroville-Thermalito Afterbay reservoir complex and receives very cold water from this source. Field 2 is located approximately 6 km from the same source and receives water that has been warmed considerably during its passage through the canal system.

The soil survey (Lytle, 1998) of Butte County indicates that soils of the study fields are a mixture of Kimball loam (fine, mixed, active, thermic Mollic Palexeralfs), San Joaquin loam (fine, mixed, active, thermic, Abruptic Durixeralfs), and Brucella loam (fine-loamy, mixed, Ultic Palexeralfs). Medium grain rice cultivar M-202 was sown via air in both fields. The fields were managed by the grower using standard practices for the area (Hill et al., 1992).

Table 1. Values of IDD and TNHB T_b for even values of T_b for every fifth sensor for Field 1, 2001, along with the correlation coefficient across all sensors between the two measures.

Method	Sensor	Threshold T_b , °C							
		10	12	14	16	18	20	22	24
IDD	1	0	-1	-10	-46	-159	-350	-568	-792
IDD	6	-1	-2	-4	-9	-22	-61	-158	-315
IDD	11	-3	-6	-12	-27	-64	-156	-308	-504
IDD	16	-1	-3	-8	-21	-42	-89	-201	-383
IDD	21	-1	-2	-4	-8	-18	-52	-137	-281
IDD	26	-1	-2	-4	-9	-19	-49	-132	-274
Correlation coeff.		-0.94	-0.75	-0.92	-0.96	-0.98	-0.97	-0.95	-0.89
TNHB	1	11	22	40	100	240	774	1563	2151
TNHB	6	25	49	124	245	729	1489	2144	2491
TNHB	11	16	32	107	201	350	867	1809	2457
TNHB	16	9	21	35	74	191	652	1414	1999
TNHB	26	11	24	37	76	192	597	1375	1990

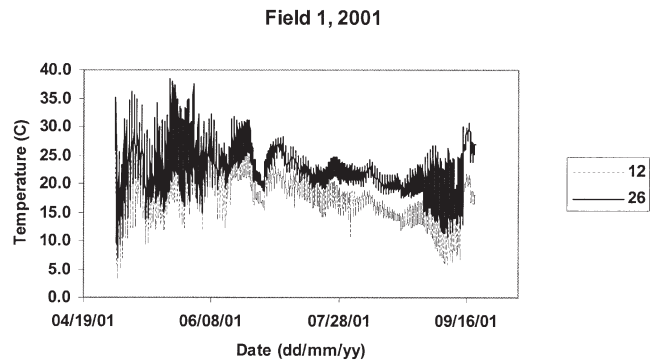


Fig. 2. Temperature record from sensors located in the coldest (Sensor 12) and warmest (Sensor 26) parts of Field 1 in 2001. The pattern from Field 2 was similar except that all temperatures were warmer and oscillations at the end of the season tended to be much smaller.

Data loggers (Hobo H8 Pro, Onset Computer Corp., Bourne, MA) were installed immediately after seeding in a grid or transect pattern in each field (Fig. 1). The data loggers were attached to stakes placed vertically in the field, with the external (water temperature) sensors placed approximately 5 cm below field water level. Water temperatures were measured hourly throughout the growing season. Data logger locations were georeferenced using a backpack differential global positioning systems (DGPS) receiver (Trimble AG 132, Trimble Navigation, Sunnyvale, CA). Data from one sensor in Field 1 in 2001 and two sensors in Field 2 in 2002 were incomplete, so no data from these sensors were used.

Planting dates were 8 May 2001 and 1 May 2002 for Field 1, and 14 May 2001 and 9 May 2002 for Field 2. The periods in which data were recorded were approximately from planting date to date at which the field was drained. These dates were from 1 May to 21 Sept. 2001 and from 27 Apr. to 9 Sept. 2002 in Field 1, and from 25 May to 21 Sept. 2001 and 11 May to 15 Sept. 2002 in Field 2. Data from 29 data loggers were used in both years in both fields. Sensors were removed before harvest. At harvest, yield, yield components, and percent blanking were recorded in the vicinity of each sensor. A sample plot (2.5 by 3.5 m) was harvested with an experimental plot combine at each sensor location. Yield standardized to 14% moisture content and harvest moisture were recorded.

Data Analysis

We tested two models for the effects of water temperature on yield. The first model, which is based on the number of hours that the water temperature is below a given water temperature threshold T_b , is denoted TNHB T_b . The second model

Table 2. Values of IDD and TNHB T_b for even values of T_b for every fifth sensor for Field 1, 2002, along with the correlation coefficient across all sensors between the two measures.

Method	Sensor	Threshold T_b , °C							
		10	12	14	16	18	20	22	24
IDD	1	0	-1	-13	-51	-159	-331	-544	-767
IDD	6	-1	-4	-13	-30	-60	-118	-252	-437
IDD	11	0	-1	-5	-17	-45	-133	-297	-497
IDD	16	-1	-3	-12	-31	-85	-221	-407	-610
IDD	21	-2	-5	-13	-30	-58	-114	-225	-384
IDD	26	-1	-3	-10	-25	-52	-108	-219	-383
Correlation coeff.		-0.77	-0.85	-0.91	-0.93	-0.97	-0.95	-0.92	-0.87
TNHB	1	0	46	248	819	1738	2391	2635	2720
TNHB	6	21	62	160	267	463	1108	2017	2372
TNHB	11	0	25	86	212	563	1597	2250	2536
TNHB	16	18	52	177	308	1138	2061	2335	2514
TNHB	21	21	63	148	257	444	965	1659	2182
TNHB	26	18	44	131	230	442	971	1681	2267

is based on the heat unit concept used in pest management (Zalom, 1983). This measure of accumulated heat is known as physiological time and is measured in degree-days. In pest management 1 degree-day is equal to 1° above a specified temperature threshold during a 24-h period. For this study, instead of using degree-days directly an inverse degree-day concept was used. Inverse degree-days were computed as follows. The inverse degree days on day j , $IDD(j)$, is given by the following:

$$IDD(j) = \sum_{i=1}^{24} (T_{w,i} - T_b)^{-}$$

where $T_{w,i}$ is the water temperature at hour i , and the operation $()^{-}$ is defined as taking the value only if it is negative, that is, for any x ,

$$(x)^{-} = \begin{cases} x & : x \leq 0 \\ 0 & : x > 0 \end{cases}$$

The total IDD are then obtained by summing the daily IDD. Note that by this definition IDD is negative when water temperature is below T_b . The difference between the IDD and the TNHB T_b models is that the former takes into account the magnitude of the difference between T_w and T_b as well as the duration, while the latter is based only on the duration.

We tested a range values for the threshold T_b from 10 to 25°C. This range of temperatures was selected to span the range of values identified in the literature as affecting rice growth during some phenological stage. Yield reduction was computed as the percent of yield loss with respect to the most productive yield location in the field that year using the equation

$$Y_r = 100 \left(1 - \frac{Y_i}{Y_{max}} \right)$$

where Y_r is the percent yield reduction, Y_i is the yield in kg ha^{-1} (corrected to 14% moisture content) at location i , and Y_{max} is the maximum yield measured in the field. The Statistica software package (Statsoft, Tulsa, OK) was used for correlation and linear regression analysis. Following the initial study to determine the best measure, we examined the relationship of yield reduction to this quantity over a range of threshold values. To standardize the model, we evaluated the sums generating IDD and TNHB T_b over a period of 2900 h (i.e., approximately 121 d) for each season and field.

RESULTS AND DISCUSSION

Visual examination of the records showed a pattern that was consistent across three of the field-year combinations and all of the sensors. This pattern was that water temperatures early in the season exhibited a daily oscillation through a wide range of values, ranging from as low as 5°C to values as high as 30°C and in some cases 35°C. This diurnal pattern persisted for about the first 40 d of the season, after which the water temperature settled to a consistent value of approximately 20°C until the end of the season, when somewhat smaller oscillations in temperature resumed (Fig. 2). The damping at midseason was presumably due to the increased thermal mass of the green vegetation. The exception to this pattern was Field 2 in 2001, in which several sensors recorded very large oscillations for about the last 30 d of

Table 3. Values of IDD and TNHB T_b for even values of T_b for every fifth sensor for Field 2, 2001, along with the correlation coefficient across all sensors between the two measures.

Method	Sensor	Threshold T_b , °C							
		10	12	14	16	18	20	22	24
IDD	1	0	-1	-9	-26	-51	-93	-187	-330
IDD	6	0	0	-1	-8	-29	-76	-192	-362
IDD	11	0	-2	-11	-29	-58	-105	-212	-373
IDD	16	0	0	0	-5	-23	-76	-193	-359
IDD	21	0	-2	-11	-28	-53	-99	-201	-353
IDD	26	0	0	0	-3	-20	-82	-208	-377
Correlation coeff.		-0.94	-0.99	-0.99	-0.96	-0.13	0.09	-0.16	-0.63
TNHB	1	3	42	140	251	357	762	1444	1941
TNHB	6	0	7	24	165	348	949	1779	2217
TNHB	11	5	56	164	282	401	863	1670	2110
TNHB	16	0	1	11	124	347	1024	1769	2160
TNHB	21	6	56	156	254	346	880	1556	2010
TNHB	26	0	1	12	99	350	1176	1829	2182

Table 4. Values of IDD and TNHB T_b for even values of T_b for every fifth sensor for Field 2, 2002, along with the correlation coefficient across all sensors between the two measures.

Method	Sensor	Threshold T_b , °C							
		10	12	14	16	18	20	22	24
IDD	1	0	-1	-4	-15	-35	-95	-238	-419
IDD	6	0	0	-2	-10	-29	-85	-195	-352
IDD	11	0	0	-3	-13	-34	-88	-195	-357
IDD	16	0	0	-2	-10	-29	-81	-183	-331
IDD	21	0	0	-2	-8	-25	-72	-160	-297
IDD	26	0	0	-2	-10	-27	-72	-157	-285
Correlation coeff.		-0.20	-0.39	-0.92	-0.96	-0.92	-0.88	-0.89	-0.94
TNHB	1	0	26	72	178	343	1260	2008	2314
TNHB	6	0	7	45	148	344	979	1692	2070
TNHB	11	0	11	67	168	380	961	1664	2151
TNHB	16	0	8	47	146	324	934	1571	1922
TNHB	21	0	5	41	131	297	831	1335	1890
TNHB	26	0	7	48	133	298	810	1248	1843

the record. We do not know the reason for this anomaly, and it may have been an artifact since the affected sensors did not follow any spatial pattern. The data were included in the analysis and had a negligible influence on the results.

Values of IDD and TNHB T_b were highly correlated for all values of T_b except in the field with anomalous behavior, and for the lowest values of T_b in Field 2 in 2002 (Tables 1–4). Examination of the data from this field indicated a different relationship (still linear) in those parts of the field showing late season temperature

oscillations from those that did not. The relation between TNHB T_b and yield reduction (YR) was much less affected by the sensors' anomalous behavior than was that between IDD and YR.

Because the values of IDD and TNHB T_b were so highly correlated except in the one anomalous case, we initially examined the relationship between both measures and YR for this data set. The IDD was not significantly related to YR ($p > 0.05$), whereas the relationship between TNHB 19°C and YR, although poor, was significant. Preliminary examination of other cases revealed that, as expected, there was little difference between TNHB T_b and IDD, but that the former was consistently a slightly better predictor of YR. Based on these preliminary results and the apparently greater robustness of TNHB T_b we dropped IDD from further analysis and focused on TNHB T_b .

Simple linear regression models for the relation between TNHB T_b and YR were separately fit to each field-year combination. Over the range of values of T_b from 10 to 25°C the values of r^2 for the models ranged from 0.01 to 0.83 for Field 1, 2001; from 0.05 to 0.91 for Field 2, 2002; from 0.00 to 0.28 for Field 2, 2001; and from 0.05 to 0.88 for Field 2, 2002 (Fig. 3 and 4). Because the data for Field 1 in both years had an obviously asymptotic behavior (Fig. 3), a model of the form $YR = \exp[-a(b - TNHB \times T_b)]$ was also fit to these data. The exponential model did not improve the fit for the 2001 data ($R^2 = 0.82$) but did for the 2002 data ($R^2 = 0.92$).

Data were then aggregated across all four field-year combinations. A logistic model of the form is as follows:

$$y = y_0 + \frac{ae^{b(t-c)}}{1 + e^{b(t-c)}} \quad [1]$$

where y represents YR and t represents TNHB T_b , was fit to the data for each value of T_b . The value $T_b = 20^\circ\text{C}$ provided the best fit ($R^2 = 0.84$) (Fig. 5). The values of the parameters are $y_0 = 7.65$, $a = 88.34$, $b = 0.0046$, $c = 1506.64$. The nonzero value of y_0 indicates that a three-phase relationship exists between TNHB T_b and YR. Below approximately 400 h of exposure there is a baseline yield reduction independent of exposure duration. This may have been primarily related to factors other than T_w . Between approximately 400 and 2000 h increasing exposure to cold water was associated

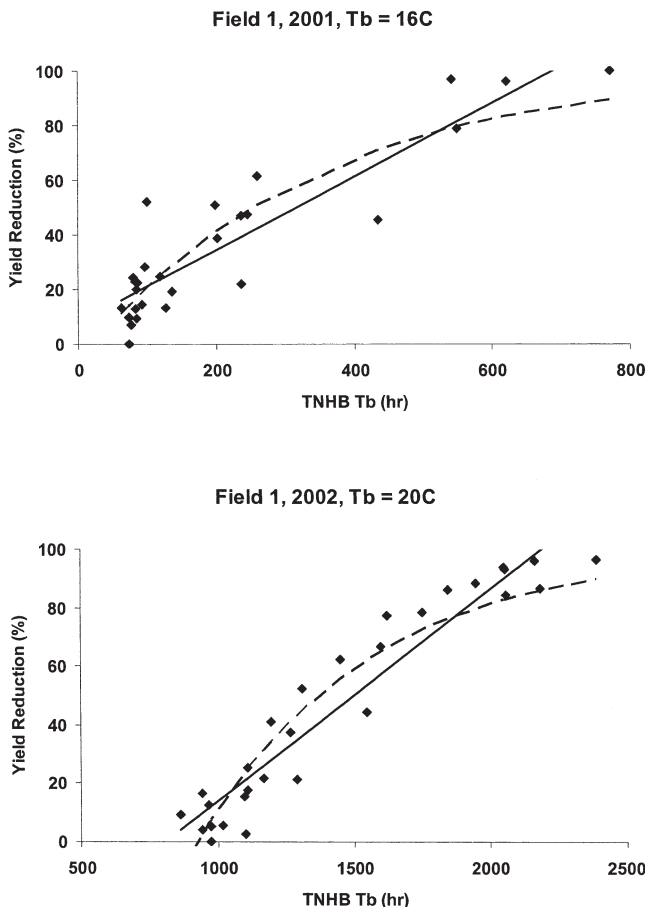


Fig. 3. Plots of the data for Field 1 for the value of T_b that provided the best fit. In each curve the solid line is the simple linear regression and the dashed line is the best fitting exponential model.

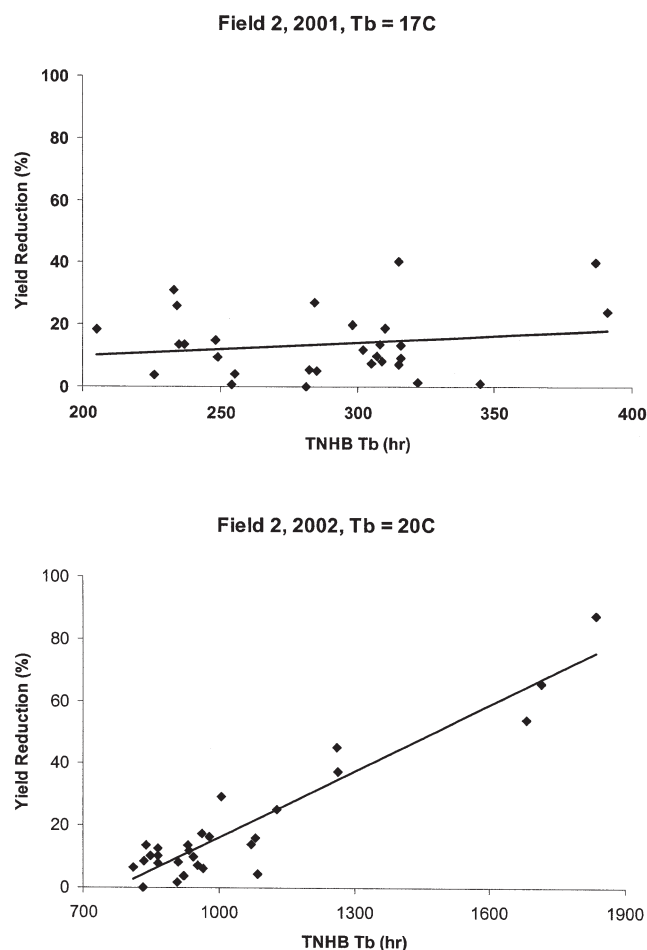


Fig. 4. Plots of the data for Field 2 for the value of T_b that provided the best fit. In each curve the solid line is the simple linear regression.

with increasing yield loss, and at exposures greater than 2000 h yield loss was virtually total.

SUMMARY AND CONCLUSIONS

This study shows that irrigation water in some areas of California rice production is below optimal temperature, as was forecast by Raney et al. (1957) and Raney (1963). The effect of cold water is not uniform across the field but may extend beyond the immediate area of the water inlet. Indeed, visual inspection of the fields indicated that loss of yield due to low water temperature occurred in regions where no visible effect could be seen. There is little difference in predictive capacity between the measures inverse degree-days and total number of hours below a threshold temperature, and indeed the latter is somewhat better. This somewhat unexpected result may be in part due to the fact that the amplitude of the temperature oscillations is relatively constant, as may be seen from Fig. 2. It also indicates that duration of low water temperature is more important than its magnitude.

Our results indicate that under field conditions in California the temperature value 20°C serves as a threshold for yield loss due to cold water effects. At low exposure levels, however, the effect of low water temperature is

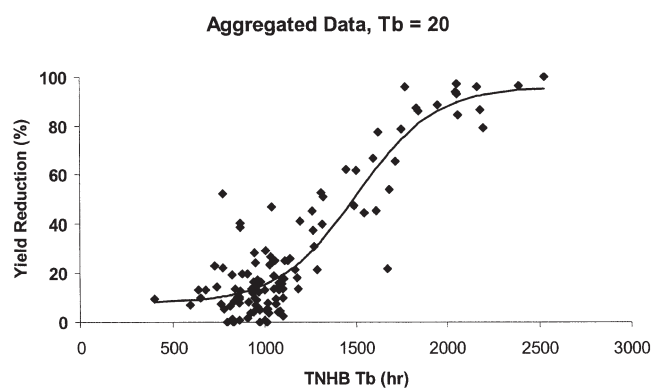


Fig. 5. Plot of the aggregated data for $T_b = 20^\circ\text{C}$ of all field-year combinations. The solid curve is the best fit of the modified logistic equation of the form of Eq. [1] in the text.

not linear. Below about 400 h of exposure low water temperature has little or no effect on yield. The relationship between yield loss and low water temperature in a single field and year could generally be modeled with reasonable accuracy by simple linear regression. Above about 2000 h of exposure crop yield is almost 100% reduced. A modified logistic model provided a good representation for data aggregated across years and fields. This model indicates that a considerable proportion of yield variation (84%) in these two fields can be associated to water temperature effects.

This study indicates that substantial rice yield loss may occur at water temperatures within the range already existing in California irrigation systems. The adjustment of water temperatures to meet environmental needs may therefore affect rice productivity. The present analysis does not explicitly concern itself with time during the growing season at which the crop was exposed to low water temperature. There was, however, an indication (data not shown) that the effect of low water temperature varies depending on when the exposure occurs. This variation should be the subject of future study, particularly to determine strategies of temperature control that provide a balance between rice productivity and environmental benefit.

ACKNOWLEDGMENTS

We are very grateful to the cooperating farmers, Milton Lamalfa and Curt Jossiasen, for allowing us to carry out research on their farms. This research was supported by the California Rice Research Board, by the Instituto Nacional de Investigacion Agropecuaria of Uruguay, and by a William F. Golden Fellowship to A. Roel.

REFERENCES

- Chapman, A.L., and M.L. Peterson. 1962. The seeding establishment of rice under water in relation to temperature and dissolved oxygen. *Crop Sci.* 2:391-395.
- Hearth, W., and D.P. Ormrod. 1965. Some effects of water temperature on the growth and development of rice seedlings. *Agron. J.* 57:373-376.
- Hill, J.E., S.R. Roberts, D.M. Brandon, S.C. Scardaci, J.F. Williams, C.M. Wick, W.M. Canevari, and B.L. Weir. 1992. Rice production in California. Publ. 21498. Univ. of California Division of Agriculture and Natural Resources, Oakland, CA.

- Inoue, E., Y. Mihara, and T. Tsuboi. 1965. Agrometeorological studies on rice growth in Japan. *Agric. Meteorol.* 2:85-107.
- International Rice Research Institute (IRRI). 1976. *Climate and rice*. IRRI, Los Baños, Philippines.
- Lytle, D.J. 1998. *Soil survey of Yuba County, California*. USDA Natural Resource Conservation Service, Washington, DC.
- Mihara, Y., and K. Onuma. 1955. Thermal efficiency of warming ponds for cold irrigation water. *Bull. Natl. Inst. Agric. Sci.* 4:45-66.
- Mihara, Y., Z. Uchijima, and S. Nakamura. 1959a. A study on heat balance of the water-warming channels. *Bull. Natl. Inst. Agric. Sci.* 7:45-67.
- Mihara, Y., Z. Uchijima, S. Nakamura, and K. Onuma. 1959b. A study of heat balance of the water warming ponds. *Bull. Natl. Inst. Agric. Sci.* 7:1-44.
- Mutters, R.G., J.W. Eckert, A. Roel, and R.E. Plant. 2002. Measuring the effect of low water temperature on blanking and grain yield on California rice production [CD-ROM]. Proc. of the 29th Rice Technical Working Group, Little Rock, AR. 24-27 Feb. 2002. Louisiana State Agric. Center, Crowley, LA.
- Mutters, R.G., J.W. Eckert, A. Roel, and R.E. Plant. 2003. Measuring the effect of low water temperature on blanking and grain yield in California rice production [CD-ROM]. Proc. of the 3rd Int. Temperate Rice Conf., Punta del Este, Uruguay. 10-13 Mar. 2003. Instituto Nacional de Investigación Agropecuaria, Montevideo, Uruguay.
- Raney, F.C. 1963. Rice water temperature. *Calif. Agric.* 17(9):6-7.
- Raney, F.C., R.M. Hagan, and D.C. Finrock. 1957. Water temperature in irrigation. *Calif. Agric.* 11(4):19-20.
- Shimono, H., T. Hasegawa, S. Fujimura, and K. Iwama. 2004. Responses of leaf photosynthesis and plant water status in rice to low water temperature at different growth stages. *Field Crops Res.* 89:71-83.
- Shimono, H., T. Hasegawa, and K. Iwama. 2002. Response of growth and grain yield in paddy rice to cool water at different growth stages. *Field Crops Res.* 73:67-79.
- Zalom, F. 1983. Degree-days: The calculation and use of heat units in pest management. Leaflet 21373. Univ. of California Division of Agriculture and Natural Resources, Oakland, CA.