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Cold Injury in Temperate Rice: A Mini Review

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Rice crops in many countries in the world with temperate climate such as Australia (Southern NSW), India (northern areas), Japan, Korea, Nepal, USA (California), etc., where rice is an important crop for national economy, have potential to suffer cold injury. The objective of this mini review is to provide some facts on the effect of cold injury on the physiological processes of rice affecting grain yield, and to demonstrate that a simulation model can be developed and used to predict and forecast yields under cold climate.

In Southern NSW, Australia, rice suffers from cold damage, which can result from low night temperatures during the vegetative (seedling to panicle initiation, PI) as well as reproductive (PI to flowering) stages. However, low night temperatures during the microsporogenesis period (i.e. early pollen microspore stage, from tetrad formation to the time of primary shrinkage of the microspore) from late January to early February when the crop is in PI to booting stage would result in the most damage. Gunawardena., *et al*. [1] reported that in 14% of years, rice crops would be exposed to an average minimum temperature of less than 13^{0}C for 10 days during early pollen microspore stage and this would be expected even when the crop is sown early in the season. Farrell., *et al*. [2], using a yield model based on regression equations, estimated mean rice yield reduction in Australia due to low night temperature during young microspore stage of about 0.68 t/ha/yr, which is equivalent to about $20 M a year.

The range for the critical threshold low temperatures across cultivars for cold damage is between 12^{0}C and 20^{0}C, and the number of days of occurrence of minimum temperatures that each cultivar could tolerate would also vary. Cultivar differences in response to low minimum temperatures have been reported in Australia [3-6]. For example, the critical minimum temperature during the microspore development for var. Amaroo with 20% sterility is 17^{0}C while that for an early-maturing var. HSC55 with 37% sterility is 13^{0}C, and that three consecutive nights of such temperatures or lower would be enough to cause cold injury [5,6]. Developing a cultivar with low temperature threshold is important as the probability of damaging years falls from 45 to 14% with decrease in threshold of Amaroo from 17^{0}C to 13^{0}C [1].

Water temperature at night tends to be as high as 7^{0}C higher than the night air temperature, and the warming effect of water can provide some degree of protection for panicles from the cold night air. For example, Board., *et al*. [7] observed that the location of panicle at meiosis in the short-statured cv. Calrose 76 was 8 cm closer to the water surface than in cv. Calrose and the sterility was lower in Calrose 76 due to the panicles being in a warmer location. Further, deep water can protect young panicles during microspore development, particularly in short-stature cultivars. For example, Reinke [8] reported a grain yield increase from 10.5 to 13.0 t/ha when water depth increased from 5 to 20 cm. Williams and Angus [9] also concluded that full or partial submergence of panicles by deep water (20 cm) at microspore stage allows the use of high nitrogen to produce high yield due to the insulating effect of water.

However, temperature and the thermal stratification of floodwater are also affected by the turbidity of the floodwater. Rose and Chapman [10] reported maximum temperature gradients (upto 1^{0}C/cm) in turbid water, but quite small in clear water, in Darwin (12^{0}33'S; 131^{0}20'E), Northern Australia. The maximum temperatures 1 cm above the soil-water interface in 10 and 30 cm deep clear water were on the average 4.2 and 6.5^{0}C higher respectively than those in turbid water. Chapman [11], also in Darwin, reported that the average maximum temperatures in shallow (10 cm) clear water exceeded 30^{0}C. In deep (30 cm) clear water the maximum temperatures were 1 - 3^{0}C lower, but the mean and minimum temperatures were, respectively, 1 and 2^{0}C higher, than that in clear water. Turbidity reduced temperatures by an average of 2^{0}C in shallow and 4^{0}C in deep water, and for the shallow water, the decrease was 1 - 2^{0}C for mean temperature but generally less than 1^{0}C for minimum temperature.

Humphreys and Barrs [12] also reported that temperatures at soil surface, water surface and in 2.5 cm above the soil surface in shallow (6.5 cm) and deep (13 cm) water fields with clear and turbid water in a red soil were several degrees higher in shallow than in deep clear waters in Western Murray Valley in Australia. Mean daily temperatures at 2.5 cm above the water surface were higher by 1.3^{0}C and at soil surface by 1^{0}C in shallow water than in deep water. In turbid water, temperatures were lower than that in clear water by 0.7 - 0.8^{0}C. In another rice field with a highly dispersive Moulamein clay soil in Denimein also, temperatures at soil surface in turbid water fields were consistently lower than in clear water fields for both deep (10 cm) and shallow (5 cm) water, and were higher by 1 - 3^{0}C in shallow than in deep fields for both clear and turbid water, with clear thermal stratification in the turbid, but lack of stratification in the clear, water. They concluded that the shallow water heats up more during the day than deep water, and thus keeping the water shallow helps provide the higher temperatures favouring more rapid early growth of rice in temperate rice-growing areas of Southern NSW. Condie and Webster [13,14] also reported that shallow water bodies of a few meters depth in inland southeastern Australia are characterized by thermal stratification, which is greater in turbid, than in clear, water bodies.

Growth and development of rice during the early pollen microspore stage is more affected by floodwater or soil surface temperature than ambient air temperature (measured at the standard height of ~1.2 m) as the developing panicle is below the top of the plant canopy and near the soil or floodwater surface, or under the water, and the developing root is under the water. Recent studies have shown that root temperatures may be more important than air or soil temperatures in explaining reduction in spikelet fertility due to cold temperature damage in rice during the microspore stage. For example, Gunawardena., *et al*. [15,16] reported that there was a significant combined effect of average minimum panicle and root temperatures on spikelet sterility, explaining 86% of variation in sterility, and that both the number of engorged pollen grains per anther and engorgement efficiency were determined by both root and panicle temperatures.

Nitrogen (N) management also affects the response of rice to cold injury. High N, under optimum temperatures, increases tillering, panicles/m^2, total number of spikelets per panicle, and panicle height and culm length, but reduces the number of engorged pollen grains per anther, increases spikelet sterility, decreases grain weight, and exacerbates the damage under low temperatures [9,15,17]. Heenan [17] observed that a low constant temperature of 12^{0}C for 4 days during microspore development decreased fertility by 43% with no applied N and by 65% with 150 kg N/ha for cv. Calrose and by 58 and 70%, respectively for cv. Inga. Further, high levels of N applied just before permanent flood (PF) can lead to greater yield loss than when N applied into floodwater at PI [17]. Gunawardena [16] reported that in the absence of applied N, an average minimum temperature of 14^{0}C over 7 days during microspore development resulted in 21% spikelet sterility, which increased to 42% when 150 kg N/ha or more had been applied at the PF or 3-leaf stage. A decrease of 1^{0}C average minimum temperature below 20^{0}C during microspore development increased sterility by 3.2% and 1.3%, respectively, with and without N applied at PF.

Since yield reduction in rice due to cold damage is directly related to disruption of pollen cell meiosis, a simulation model of rice growth and yield would require some description of the timing of this process in relation to the timing of chilling events. The time when pollen cell meiosis occurs will be affected by the cultivar, planting time and developmental responses to temperature and photoperiod. The number of spikelets which could potentially be affected is influenced by the growing conditions of the plant prior to spikelet differentiation and N management. Rice crop models with the ability to simulate the effect of low temperature on rice yield have many potential uses, such as (1) yield predictions and forecasting, (2) evaluation of the tradeoffs between yield and management to save water (e.g. intermittent irrigation, adjustments of sowing date, etc.), (3) investigation of the impact of climate change on yield. A rice model with the inclusion of a cold routine would help predict yield under a range of management practices across years and would thus be useful to the NSW farmers in deciding the management practices regarding the amount and timing of N and water to be applied, water depth to be maintained, and varieties and sowing date to be used. Such a model could also be useful in many temperate countries in the world such as India, Japan, Korea, Nepal, USA (California), etc., where rice is an important crop for their national economy, but the crop has potential to suffer cold injury.

There has been some progress in the development and use of rice models in temperate environments, including in Australia. Using an earlier version (ver. 2.1), Meyer., *et al*. [18] reported large discrepancies between observed and simulated yields of rice, with most discrepancies when low temperatures occurred during early pollen microspore stage. In continuation to that, Godwin., *et al*. [19] developed a chilling injury routine and obtained good agreement between simulated and observed yields for sprinkler irrigation treatments affected by cold damage. That version, however, did not take into account the effects of floodwater temperature and assimilate availability on pollen cell survival throughout the chilling event. Moreover, that version was not tested further against other data sets. Consequently, Timsina., *et al*. [20] developed new floodwater temperature and chilling injury routines and incorporated them into ver. 4.0 of CERES Rice using the most recent understanding of the mechanisms of chilling injury in rice. This new version (ver. 4.0C) improved the ability of the model to simulate rice response to low temperature compared with the earlier versions [21].

To conclude, while this review provides some information on science and modelling of cold injury in rice, more in-depth review and both experimental and modelling work would be required to more accurately predict and forecast crop yields especially under current and future climate change scenarios.

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