Explaining Rice Milling Quality Variation Using Historical Weather Data Analysis

N. T. W. Cooper,[1] T. J. Siebenmorgen,[1,3] P. A. Counce,[2] and J.-F. Meullenet[1]

ABSTRACT

Cereal Chem. 83(4):447–450

Rice quality, specifically head rice yield (HRY), can vary inexplicably from one lot to another, and from year to year. In an effort to correlate air temperatures during various growth stages to HRY, growth staging data expressed in degree day units was used to predict the occurrence of sequential growth stages within a set of 17-year historical data, which included HRY and 50% heading dates for two long-grain rice cultivars, (*Oryza sativa* L) Newbonnet and Lemont, and area weather data. HRY was most strongly affected by the average daily low temperature (or nighttime temperature) during the R8 developmental stage. Lower HRY were associated with high nighttime air temperatures during this stage for both Newbonnet and Lemont. When used as a single variable in a regression model, the nighttime temperature during the R8 developmental stage explained over 25% of the variation in HRY.

Rice quality is largely measured by head rice yield (HRY), which is the mass percentage of rough rice kernels that remain as head rice, or rice that is three-fourths of a kernel length or longer after milling (USDA 1997). As the price of rough rice is determined largely by HRY, it is of economic concern that HRY is maximized. While HRY is determined in part by production practices, HRY can vary inexplicably from year to year and often from field to field, making it difficult for producers to predict income and for processors to maintain a consistent end product.

Variations in growth temperature could be a cause of quality variation. Studies investigating the effects of temperature on kernel development have indicated that higher temperatures during the grain-filling stage of plant development result in a decrease in kernel mass, a decrease in kernel dimensions, and an increase in the number of chalky kernels (Yoshida and Hara 1977; Tashiro and Wardlaw 1991). Lower growth temperatures result in an increase of amylose content in rice cultivars with low amylose content, and in a decrease of amylose content in rice cultivars with high and intermediate amylose content, sometimes changing the cultivar's amylose class, depending on the temperature treatment (Resurreccion et al 1977; Paule et al 1979).

Most research studying the effect of temperature on rice quality has been performed using controlled temperature chambers. This approach is limited in that it does not necessarily reproduce field conditions. It would be useful to use field data to study the effect of temperature on HRY, most particularly to use replicative data that historical data sets can provide. Historical data analyses have shown that growth temperature can affect rice yield (Downey and Wells 1975; Peng et al 2004), however historical data sets have been utilized to estimate the effects of growth temperature on rice quality. As environmental temperatures during grain filling have the most effect on rice starch structure and thereby rice quality (Asaoka et al 1984), perhaps being able to pinpoint these stages of kernel development within a set of historical weather data would provide more information regarding effect of temperature on rice quality.

The staging system of Counce et al (2000) provides a means of estimating reproductive stage within historical weather data. This staging system classifies the vegetative (V) physiological stages of rice plant development by the number of leaves on a rice plant. Reproductive (R) physiological stages are classified by the development of the main stem panicle. In the R0 and R1 stages, panicle initiation and the formation of panicle branches, respectively, are invisible to the naked eye, because these developments occur inside the leaf sheaf. R2 is characterized by the visible formation of a collar on the flag leaf of the main stem. The stage at which the panicle emerges from the stem, which is known as "booting" or "50% heading", is termed R3 in the Counce system. R4, "flowering" or anthesis, occurs when one or more florets on the main stem panicle have reached anthesis. R5 occurs when at least one caryopsis on the main stem starts to fill with starch. The start of the grain-filling stage is termed R6, when at least one caryopsis on the main stem panicle has completely lengthened to the end of the hull. The appearance of one yellow hull and the appearance of one brown hull on the main stem panicle are termed R7 and R8, respectively. The end of maturation is R9, when all of the kernels that reached R6 have a brown hull.

The objective of this study was to analyze a set of historical weather and quality data to determine whether the average low and average high temperatures at individual projected reproductive growth stages were related to HRY.

MATERIALS AND METHODS

HRY Data

A 17-year data set (1983–1999), which included HRY and the number of days to 50% heading for two long-grain cultivars, Newbonnet and Lemont, was compiled using rice produced in field plots at the Rice Research and Extension Center, Stuttgart, AR, following consistent protocols from year to year. At maturity, rice was harvested and dried using 35°C air until the rice reached 12.5% moisture content (MC, wb). HRY was determined by mechanical dehulling (THU, Satake, Tokyo, Japan) 125 g of dried rice to obtain brown rice, then milling the brown rice in a laboratory mill (McGill #2, RAPSCO, Brookshire, TX) for 30 sec. Head rice was then separated from the broken kernels using a sizing device (Seedburo Equipment Co., Chicago, IL). HRY is expressed as the mass percentage of head rice to the original 125 g of rough rice.

Weather Data and Degree-Day Determination

Weather data from 1983 to 1999 was obtained from the USDA weather station at Stuttgart, AR. The data set included the daily high and low temperatures, the two data points necessary to calculate the number of degree days >50°F (DD50). In Arkansas, DD50 is mainly used to estimate the timing of nitrogen fertilizer application and other production practices. DD50 is calculated as

$$\{[(\text{Daily max temp (°F)} + \text{Daily min temp (°F)}) / 2] - 50°\text{F}\} \times 1 \text{ day} \quad (1)$$

---

[1] Graduate assistant, university professor, and associate professor, respectively, Department of Food Science, University of Arkansas, 2650 N. Young Avenue, Fayetteville, AR, 72704.

[2] Professor, Department of Crop Science, University of Arkansas Rice Research and Extension Center, Stuttgart, AR.

[3] Corresponding author. E-mail: tsiebenm@uark.edu

DOI: 10.1094/CC-83-0447

TABLE I
Degree Days to Reach Developmental Stages[a]

Rice	R4	R5	R6	R7	R8	R9
Newbonnet	40	170	252	478	619	992
Lemont	73	138	247	391	674	910

[a] Staging system by Counce et al (2000).

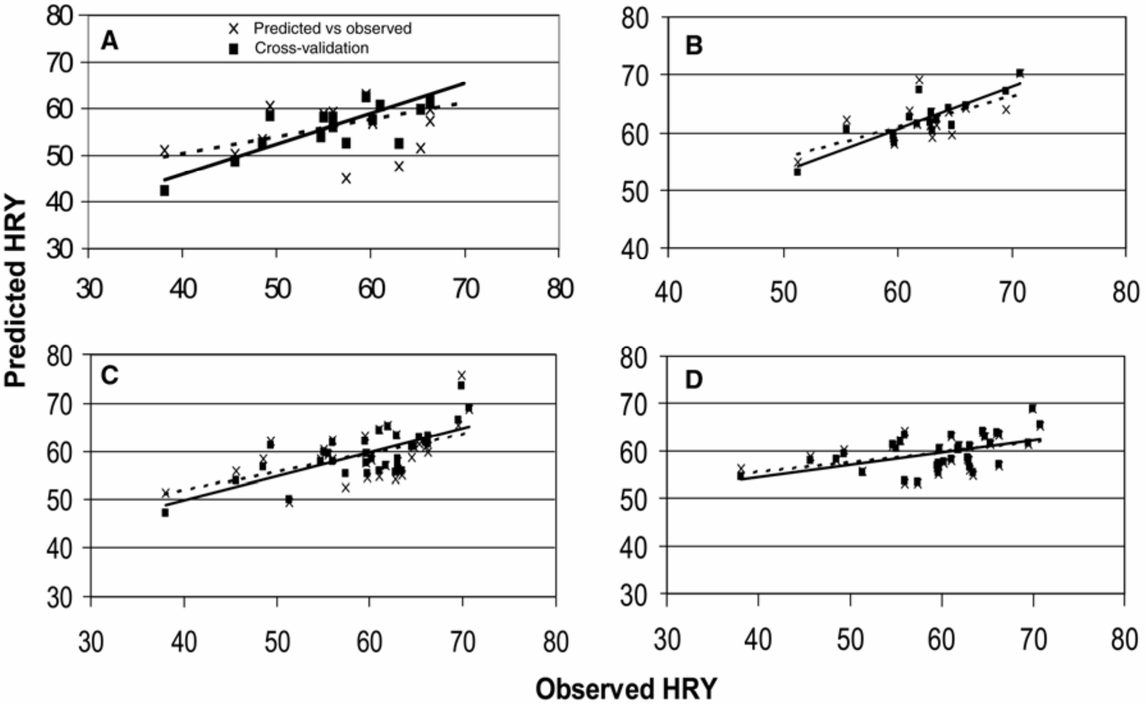

Fig. 1. Predicted vs observed plot, with cross-validation, testing the fit of the regression model correlating the effects of average low and high temperatures at rice developmental stages (Counce et al 2000) with the historical head rice yield (HRY) values of (**A**) Lemont, (**B**) Newbonnet, (**C**) Lemont and Newbonnet combined data, and (**D**) Lemont and Newbonnet combined data.

where daily maximum temperature = 94°F if maximum temperature is >94°F and daily minimum temperature = 70°F if minimum temperature is >70°F.

DD50 describes one day of thermal growing potential based on air temperature (Keisling et al 1984). Equation 1 assumes that the rate of plant development is constant when the daily maximum air temperature is ≥94°F, and when the daily minimum air temperature is ≥70°F.

Estimation of Developmental Stages

The 50% heading date, or R3 stage, was included in the data set, from which point the daily DD50 values were accumulated for each year from 1983 to 1999. Cultivars Lemont and Newbonnet had been previously "staged" according to the procedure of Watson et al (2005). This procedure consists of cultivating plants of a particular cultivar and monitoring the number of degree days necessary to reach each developmental stage. Using the reproductive staging data for Lemont and Newbonnet (Table I), the dates of the start of stages R4 through R8 were estimated for each year and cultivar. The average low temperature and the average high temperature were then calculated for the duration of each growth stage for each year. Harvest date data was not available and thus the duration of R9 could not be determined; therefore, the average high and low temperatures during this stage of development were omitted as variables in the regression analysis.

Statistical Modeling

For all of the 17 years of data, the average low and the average high temperatures during each developmental stage of each cultivar and the HRY data were correlated using partial least squares regression (PLSR) software (Unscrambler, v. 7.5, CAMO, Oslo, Norway). Simply put, HRY was predicted using the average low and high temperatures during the R6, R7, and R8 rice developmental stages. Inclusion of R4 and R5 high and low temperature data had little effect on HRY modeling and the R^2 of the models increased when these variables were excluded. Therefore, R4 and R5 temperatures were removed from the models. PLSR was employed to avoid data over-fitting that would have resulted from least squares regression. Independent variables (i.e., average low and high temperatures at the grain-filling growth stages) were standardized before analysis to give all variables equal possibility to influence the model, regardless of temperature magnitude or variance across years. After simplification, the PLS model can be written as

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 \quad (2)$$

where Y = HRY, β_o = intercept, β_n = regression coefficients of the independent variables, x_1 = average high temperature during R6, x_2 = average low temperature during R6, x_3 = average high temperature during R7, x_4 = average low temperature during R7, x_5 = average high temperature during R8, x_6 = average low temperature during R8.

Model fit was assessed using HRY-predicted versus HRY-observed plots. Predicted values were obtained by determining the β_n values using the entire 17-year data set and then using the model to predict the HRY value for a given year based on the given x values for that year. If the model is accurate, the predicted HRY values should be close to the observed values and should result in

TABLE II
Statistics for Four Models[a]

Model	Primary Components[b]	R^2	RMSEC	R^2val	RMSEP
Lemont only	3	0.651	4.76	0.174	8.20
Newbonnet only	4	0.728	2.33	0.433	3.44
Lemont and Newbonnet	4	0.501	4.93	0.296	5.99
Lemont and Newbonnet R8 low only	1	0.257	6.02	0.167	6.42

[a] Coefficient of determination (R^2); root mean square error of the correlation (RMSEC); coefficient of determination of the cross-validation model (R^2val); root mean square error of the prediction of the validation model (RMSEP).
[b] Number of independent variables (Eq. 2) with significant influence on HRY.

a high R^2 value. The regression model was also cross-validated using full cross-validation, a procedure in which each year's HRY value was removed, one at a time, from the sample set; the regression model was recalculated, and a predicted value was calculated for the removed observation using the new model (i.e., 16 observations instead of 17). The cross-validation technique measured the extent to which a given year's HRY value can be predicted based on a regression model constructed without that year's data point. Additionally, root mean square errors of calibration (RMSEC) and prediction (RMSEP) were computed as estimates of the average prediction error.

RESULTS AND DISCUSSION

Sources of Error in the Data Set

Because the collection of this data occurred over a 17-year period, it is impossible to guarantee that the same personnel cultivated, harvested, dried, and milled samples, thus some error can be expected. Also, the data set did not include a value for harvest MC (HMC). Very high HMC (>22%) can indicate that the rice bulk contains a large amount of immature kernels, many of which do not survive the milling process intact (Bautista and Siebenmorgen 2005), and low HMC indicate a potential for moisture adsorption that promotes fissuring (Siebenmorgen et al 1992). Both of these situations can cause HRY reductions. Therefore, because HMC could not be accounted for in this analysis, one would expect an inherent amount of variability in HRY values.

HRY Regression Analysis

Figure 1A shows a plot of the predicted values of Lemont HRY plotted against the observed values, with model statistics summarized in Table II. The Lemont model explained 65% of the variation in HRY. However, the validation R^2 was 0.174 and the RMSEP was 8.2, meaning that the model might not accurately predict HRY based on temperatures during R6, R7, and R8 of future years. The weighted regression coefficients of the independent model variables were plotted in Fig. 2A, which show the relative influence of each independent variable on HRY. Negative coefficients indicate a reduction, while positive coefficients indicate an increase, in HRY with an increase in a particular independent variable.

Figure 2A indicates that high daily temperatures during the beginning of the grain-filling period (R6) reduced Lemont HRY, while high daily temperatures toward the end of the grain-filling period (R7 and R8) led to an increase in HRY. Overall, the most influential factor on Lemont HRY was the effect of average daily low temperature during R8 (as the nighttime temperature during R8 increased, HRY decreased).

The same analyses performed on Newbonnet data indicate a trend similar to that of Lemont. Figures 1B and 2B show the predicted versus observed plot and the weighted regression coefficient plot, respectively, of the model explaining the effect of daily high and low temperatures during grain filling on Newbonnet HRY. The model statistics (Table II) showed that the independent variables in the model explained 73% of the variation in Newbonnet HRY. The validation R^2 of 0.433 was higher than that of the Lemont model, showing that the temperature variables would be reasonably good predictors of Newbonnet HRY in future years. Figure 2B indicates that, like the HRY of Lemont, high day temperatures during R6 adversely affected Newbonnet HRY, while high day temperatures during R7 and R8 led to an increase in HRY. As in the Lemont analysis, the most influential factor was the high nighttime temperature during R8 that was the most detrimental to HRY.

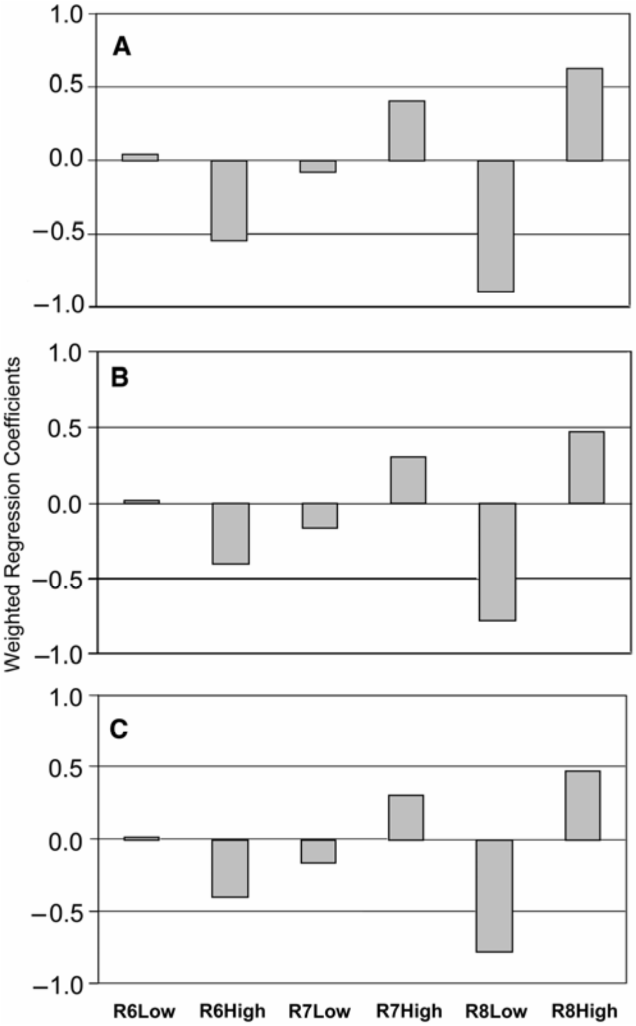

Fig. 2. Plot of weighted regression coefficients when average low (night) and average high (day) temperatures during rice developmental stages (Counce et al 2000). Regression model explaining head rice yield for (**A**) Lemont, (**B**) Newbonnet, and (**C**) Lemont and Newbonnet combined data. R6 begins when at least one caryopsis on the main stem panicle has completely lengthened to the end of the hull, R7 begins with the appearance of one yellow hull, and R8 begins when the appearance of one brown hull on the main stem panicle.

A model was fit to the combined HRY and temperature data of both the Lemont and Newbonnet cultivars (Fig. 1C). The model explained 50% of the variation in HRY, with a validation R^2 of 0.296 (Table II). The regression coefficients reveal the same trend as the model constructed for the individual cultivars (Fig. 2C), in that high daily temperatures at R6 were detrimental to HRY while high day temperatures at R7 and R8 increased HRY. Again, most significant of all was the inverse relationship between average nighttime temperature during R8 and HRY. Alone, the average nighttime temperature during R8 explained 26% of the variation in HRY (Fig. 1D, Table II).

R8 begins when a single kernel on the main stem turns golden in color (Counce et al 2000) and yet main stem kernels account for ≈10% of all of the kernels produced by a rice plant, which may have many tillers that make a considerable contribution to yield (Holloway et al 1995). During R8, all kernels on the main stem panicle, which develops before other panicles on the rice plant, should be at R8, R7, or the end of R6, while the kernels on the tiller panicles could still be at R6 or R5. The effect of temperature at any particular stage of development on HRY would be the collective result of the response of all kernels, including those at previous developmental stages. It follows, therefore, that while the results of this historical data analysis show that high nighttime temperatures during R8 adversely affect HRY, it may actually be the effects of temperatures on kernels at R6 (while the kernel is actively producing starch) that truly affect HRY, as HRY is determined by a composite of individual kernel properties.

High nighttime temperatures could possibly have caused an increase in respiration during the non-daylight hours and subsequently the loss of carbohydrate from the kernel. Peng et al (2004) found that increased nighttime temperatures throughout the growing season were directly correlated to decreased rice crop yield. In a controlled temperature study, Counce et al (2005) found that an increase in nighttime temperatures during R6 through R9 resulted in a decrease in HRY as well as a decrease in the long B chains of amylopectin in rice starch granules. In might follow then, that the high nighttime temperatures could be affecting the rate of starch-filling enzymes, thereby affecting starch structure and kernel strength, and thus HRY.

CONCLUSIONS

The results of this analysis indicate that the nighttime temperatures during the R8 growth stage could have a significant negative effect on HRY. Moreover, high day temperatures during the beginning of grain filling (R6) were detrimental to HRY, while high day temperatures at the end of grain filling (R7 and R8) increased HRY. However, as the staging system of Counce et al (2000) accords a developmental stage to a rice plant based on the status of the most mature kernel on the main stem, the effect of temperature at any particular stage of development on HRY could be the collective result of the response of all kernels still at previous developmental stages.

In the historical data set, the R8 growth stage was estimated to span a period of 12–14 days between mid-August and mid-September. Southern U.S. producers might consider either planting their rice crop earlier in the season, or planting an early-maturing cultivar that would result in the R8 stage of development falling in July, a typically cooler month, which might prevent HRY reductions associated with high temperature nights during grain filling.

ACKNOWLEDGMENTS

We are most grateful to K. Moldenhauer and M. Blocker of the University of Arkansas Rice Research and Extension Center at Stuttgart, AR, for providing the data set used in this analysis.

LITERATURE CITED

Asaoka, M., Okuno, K., Sugimoto, Y., Kawakami, J., and Fuwa, H. 1984. Effect of environmental temperature during development of rice plants on some properties of endosperm starch. Starch 36:189-193.

Bautista, R. C., and Siebenmorgen, T. J. 2005. Milling quality trends with harvest moisture content and the relationship to individual kernel moisture content distribution. Arkansas Rice Research Studies, 2004. AES Research Series 529:364-370.

Counce, P. A., Bryant, R. J., Bergman, C. J., Bautista, R. C., Wang Y.-J., Siebenmorgen, T. J., Moldenhauer, K. A. K., and Meullenet, J.-F. C. 2005. Rice milling quality, grain dimensions, and starch branching as affected by high night temperatures. Cereal Chem. 82:645-648.

Counce, P. A., Keisling, T. C., and Mitchell, A. J. 2000. A uniform, objective and adaptive system for expressing rice development. Crop Sci. 40:436-443.

Downey, D. A., and Wells, B. R. 1975. Air temperatures in the Starbonnet rice canopy and their relationship to nitrogen timing, grain yield, and water temperature. University of Arkansas Agricultural Experiment Station Bulletin 796.

Holloway, G. E., Siebenmorgen, T. J., Counce, P. A., and Lu, R. 1995. Causes of multimodal moisture content frequency distributions among rice kernels. Appl. Eng. Agric. 11:561-565.

Keisling, T. C., Wells, B. R., and Davis, G. L. 1984. Rice management decision aide based on thermal time base 50°F. Arkansas Cooperative Extension Service Computer Technical Bulletin No. 1. Division of Agriculture, University of Arkansas, Little Rock, AR.

Paule, C. M., Gomez, K. A., Juliano, B. O., and Coffman, W. R. 1979. Variability in amylose content of rice. Il Riso 28:15-22.

Peng, S., Huang, J., Sheehy, J., Laza, R. C., Visperas, R. M., Zhong, X., Centeno, G. S., Hkush, G. S., and Cassman, K. G. 2004. Rice yields decline with higher night temperature from global warming. Proc. National Academy of Sciences of the United States of America 101:9971-9975.

Resurreccion, A. P., Hara, T., Juliano, B. O., and Yoshida, S. 1977. Effect of temperature during ripening on grain quality of rice. Soil Sci. Plant Nutr. 23:109-112.

Siebenmorgen, T. J., Counce, P. A., Lu, R., and Kocher, M. F. 1992. Correlation of head rice yield with individual kernel moisture content distribution at harvest. Trans. ASAE 35:1879-1884.

Tashiro, T., and Wardlaw, I. 1991. The effect of high temperature on kernel dimensions and the type and occurrence of kernel damage in rice. Aust. J. Agric. Res. 22:485-496.

USDA. 1997. United States Standards for Rice, revised. Federal Grain Inspection Service: Washington, DC.

Watson, N. T., Counce, P. A., and Siebenmorgen, T. J. 2005. Growth stages of 12 rice cultivars (*Oryza sativa* L.) expressed in DD50 thermal heat units. Arkansas Rice Research Studies, 2004. AES Research Series 529:56-62.

Yoshida, S., and Hara, T. 1977. Effects of air temperature and light on grain filling of an indica and a japonica rice (*Oryza sativa* L.) under controlled environmental conditions. Soil Sci. Plant Nutr. 23:93-107.

[Received January 11, 2006. Accepted April 6, 2006.]