MODELING LONG-GRAIN RICE MILLING QUALITY AND YIELD DURING THE HARVEST SEASON

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ABSTRACT
Three mathematical models were developed to predict percent milled rice (PMR), percent head rice (PHR), and field yield (FY) of long-grain varieties as a function of rice moisture content (m.c.) at harvest. The concept of potential yield was used in the model development. The actual yield was equal to the potential yield minus the yield reduction caused by specific weather conditions. The PMR and PHR models were validated using experimental data collected for three long-grain rice varieties from 1987 to 1990. The potential FY model was validated using the data reported by Morse et al. (1967) and Bal and Ojha (1975). Predicted PMRs compared well with the experimental data with the average prediction errors of less than 1.9 percentage points. The average differences between the predicted and measured PHRs were less than 2.4 percentage points when rice was harvested between 13 and 24% m.c. Large prediction errors (more than 5 percentage points) were obtained in limited cases where rice was harvested at m.c.s greater than 24% or less than 13%. The predicted FY's compared reasonably well with the experimental data by Morse et al. (1967) and Bal and Ojha (1975) with the average errors of 3.5 and 6.8%, respectively.

KEYWORDS. Rice, Milling, Quality, Yields, Harvest, Modeling.

INTRODUCTION

The moisture content (m.c.) at which rice is harvested directly affects milling quality, field yield (FY), and drying costs. Milling quality of rice is represented by percent milled rice (PMR) and percent head rice (PHR). Milled rice, including both whole and broken kernels, is that which remains after the bran has been removed during milling. Head rice denotes milled rice that is comprised of kernels that are three-fourths or more of the original kernel length. The weight of milled rice expressed as a percentage of the rough rice weight is defined as PMR while the weight of head rice as a percentage of the rough rice is defined as PHR. If the effects of rice m.c. at harvest on PMR, PHR, and FY can be quantified, then the economic ramifications of these variables can be analyzed and harvest schedules optimized to maximize economic return to the producer.

Considerable research has been conducted to determine the effects of rice m.c. at harvest on PMR and PHR (e.g., McNeal, 1950; Kester et al., 1963; Morse et al., 1967; Nanjua and De Datta, 1970; Bal and Ojha, 1975; Calderwood et al., 1980; Steffe et al., 1980; Geng et al., 1984; Siebenmorgen et al., 1992). These studies showed that PMR and PHR increase as the rice m.c. decreases during the early maturity stage, as a result of the increase in both kernel dry matter and mechanical strength. After reaching the maximum, PMR normally remains constant and is no longer affected by environmental conditions. However, the environmental conditions will become a predominant factor affecting PHR after rice reaches a certain m.c. level. Drastic reductions in PHR could occur if rice is not harvested at a proper m.c. Because of the susceptibility of PHR to environmental conditions, different harvest m.c.s for obtaining the maximum PHR have been reported for different climatic conditions. In Arkansas, the maximum PHR was obtained when rice was harvested between 15 and 22% m.c.* (McNeal, 1950; and Siebenmorgen et al., 1992). In California, the optimal m.c. for harvesting short-grain rice to obtain the maximum PHR was between 25 and 30% (Kester et al., 1963; Steffe et al., 1980; and Geng et al., 1984). Calderwood et al. (1980) in Texas reported that the maximum PHR occurred when the rice m.c. ranged from 15 to 24%, depending on variety and year. Nanjua and De Datta (1970) in the Philippines reported that the maximum PHR was obtained when the rice m.c. was between 19 and 22% for the dry season and between 18 and 21% for the wet season. Bal and Ojha (1975) in India recommended that rice should be harvested in the m.c. range of 20 to 24% to obtain the maximum PHR.

The reduction in PHR is directly related to the fissuring of rice caused by rapid adsorption of water. Early studies by Stahel (1935) and Craufurd (1962 and 1963) showed that adsorption of water had no or little effect on rice fissuring when rice m.c. was above 15%. This was further confirmed by other researchers (Srinivas et al., 1978; Kamau and Kunze, 1986; Siebenmorgen and Jindal, 1986; Siebenmorgen et al., 1992). Craufurd (1962 and 1963) also reported that the adsorption of water vapor by rice with an

*All moisture contents reported herein are on a wet basis.
initial m.c. above 12% did not cause any fissuring, but the presence of liquid water from dew caused rice to fissure. Chen and Kunze (1983) reported that PHRs for the long-grain variety 'Labelle' and the medium-grain variety 'Brazos' were not reduced when the 10.7% m.c. rice was remoistened until an environmental relative humidity of 92% was used. Siebenmorgen and Jindal (1986) found that PHR for the long-grain variety 'Tebonnet' was reduced by three percentage points when rice with an initial m.c. of 13.1% was exposed to a 95% relative humidity environment. The study by Banaszek and Siebenmorgen (1990) showed that when long-grain rice with an initial m.c. of 12% was exposed to a 90% relative humidity environment, the reduction in PHR was less than two percentage points. These studies indicate that a high relative humidity environment does little damage to head rice if the rice m.c. is above 13%. The reduction in PHR in the field is mainly caused by the adsorption of liquid water by rice with an initial m.c. below 15%.

Few studies have quantified the FY change during the harvest season. Morse et al. (1967) reported that FY for the short-grain variety 'Caloro' increased as the rice m.c. declined to about 20% and then remained constant. Nangju and De Datta (1970) in the Philippines showed that FY for four test varieties in both the wet and dry season increased rapidly from 16 to 28 days after heading (the corresponding m.c. changed approximately from 33 to 22%). Thereafter, the FY remained relatively constant and then decreased steadily. The maximum FY was obtained when the rice m.c. was between 18 and 22%. Similar results were also reported by Bal and Ojha (1975) and Calderwood et al. (1980).

Although numerous experimental results have been reported, no mathematical models have been developed to predict the effects of rice m.c. at harvest on PMR, PHR, and FY. Little research has been done to quantify the influence of weather or environmental conditions on PMR, PHR, and FY.

OBJECTIVES
The overall objective of this research project was to determine the optimal m.c. to harvest long-grain rice to maximize economic return. The specific objectives of this article were to:

- Develop mathematical models for predicting potential PMR, PHR, and FY as a function of rice m.c. at harvest.
- Develop mathematical models for predicting the reductions in PHR and FY for long-grain rice grown under Arkansas climatic conditions.
- Validate the PMR and PHR models using experimental data collected for three long-grain varieties from 1987 to 1990 and the FY model using data from other previous studies.

MODEL DEVELOPMENT
The concept of potential yields was used to develop the actual yield models. Potential yields are defined as the maximum yields that would be attained when no reductions are incurred due to adverse conditions during the harvest season. Here, an adverse condition is referred to as any condition that causes a detrimental effect on yield. For instance, rain might cause a reduction in PHR and, therefore, would be considered an adverse condition. Lodging and shattering are considered adverse conditions because they cause FY losses. Yield reductions normally occur after rice reaches physiological maturity or a certain m.c. level. In the early harvest stage, the actual yield is the same as the potential yield. After this stage, the actual yield is obtained by subtracting the yield reduction caused by the particular adverse condition from the potential yield. Thus, the potential yields are not directly affected by the specific environmental conditions, whereas the yield reductions are highly dependent on environmental conditions.

PERCENT MILLED RICE PREDICTION MODEL
Percent milled rice is directly related to the process of dry matter accumulation during the ripening stage. Ebata and Nagato (1967) and Malabuyoc et al. (1966) found that kernel dry matter increased rapidly within 5 and 20 days after heading during which the kernel m.c. decreased steadily. Thereafter, there was no more accumulation of dry matter and the rice kernels were merely drying. Their results indicate that kernel dry matter either increases or remains constant but does not decrease during the ripening or maturity stage. Likewise, the potential PMR either monotonically increases or remains constant as rice m.c. decreases. Based on these observations and reported experimental trends in PMR (Kester et al., 1963; Nangju and De Datta, 1970; Bal and Ojha, 1975; Calderwood et al., 1980; Steffe et al., 1980; and Siebenmorgen et al., 1992), the following was proposed to model the potential PMR:

\[ PMR_p = A_T \left( 1 - B_T \exp \left( \frac{C_T}{M-M_0} \right) \right) \]  

(1)

Symbols are defined in a list of notations. The parameter \( A_T \) in equation 1 represents the maximum potential PMR. Equation 1 is valid when the m.c. is greater than \( M_0 \). If the m.c. is less than \( M_0 \), then \( PMR_p \) is equated to \( A_T \).

Percent milled rice reflects the relative compositions of rough rice in terms of hull, bran, and endosperm. After rice reaches full maturity, the dry matter of rice components will neither increase nor decrease. The PMR is expected to remain constant and is not affected by environmental conditions. Hence the reduction in PMR due to weather or environmental influence was considered to be zero and the actual PMR was equal to the potential PMR.

PERCENT HEAD RICE PREDICTION MODEL
Potential PHR. During the early ripening stage, PHR increases very rapidly due to the rapid increase in kernel dry matter and mechanical strength (Lu and Siebenmorgen, 1992). When the rice kernel reaches full dimensions and maximum mechanical strength, PHR would also be expected to reach a maximum. After this stage, PHR would remain constant unless some adverse weather condition such as rain is encountered. Therefore it is expected, and
has been shown by many studies (e.g., Kester et al., 1963; Nangiu and De Datta, 1970; Bal and Ojha, 1975; Steffe et al., 1980; Siebenmorgen et al., 1992), that the trend of the potential PHR change is similar to that of PMR. Hence the same exponential function form as that for PMR was used to describe the potential PHR:

$$\text{PHR}_p = A_H \left(1 - B_p \exp \left(\frac{C_H}{M - M_0}\right)\right)$$  \hspace{1cm} (2)

where, $A_H$ represents the maximum potential PHR that can be obtained under ideal weather conditions.

**Percent Head Rice Reduction.** Pre-harvest reduction in PHR is primarily associated with kernel fissuring, which is caused by rapid moisture adsorption. Moisture adsorption of rice can take place under weather conditions such as rain, dew, and high relative humidity air. In Arkansas, rice is normally harvested above 13% m.c. and the relative humidity of air is typically not extremely high at night during the harvest season. Hence, the effects of high relative humidity air on PHR reduction were neglected in view of previous studies by Craufurd (1962 and 1963), Chen and Kunze (1985), Siebenmorgen and Jindal (1986), and Banaszek and Siebenmorgen (1990).

The effects of dew on rice fissuring have been reported by some researchers (e.g., Craufurd, 1962; Srinivas et al., 1978), but the extent to which it affects PHR is not well understood. Dew is primarily a nocturnal phenomenon that occurs when temperatures are low in the daily 24 h time period. The formation of dew at the kernel surface is usually a gradual process. Studies (e.g., Srinivas et al., 1978) have shown that low temperatures generally result in slower formation of fissures and lower proportions of fissured rice kernels. Hence, it can be expected that dew would do less damage to head rice than rain and its effects on PHR reduction would take place at m.c.s lower than 15%. In view of these observations and the fact that rice is normally harvested above 13% m.c. in Arkansas, the effects of dew on PHR reduction were neglected in this study.

The actual PHR was considered equal to the potential PHR when the average rice m.c. was above 18%. After rice m.c. decreased to 18%, the effect of rain on PHR reduction was accounted for. The reduction in PHR caused by rain may depend on a number of factors such as rain intensity and duration. No research has been done to quantify the effects of these factors on PHR reduction. However, studies by Craufurd (1962) and Srinivas et al. (1978) showed that most kernel fissuring took place in a short time period when rice with an initial m.c. lower than 15% was soaked in water. Hence, the effects of each rain event on PHR at a particular m.c. level were modeled to be equal unless the amount of rain was less than 0.3 mm, the lowest limit recorded by weather stations. Head rice reduction for a single rain event was then predicted using the equation developed by Siebenmorgen and Jindal (1986) for soaking in water, which has the following form:

$$\text{HRR} = 1 - \exp \left(-a \exp \left(-bM\right)\right)$$  \hspace{1cm} (3)

where

- $a = 637$
- $b = 0.636$

The actual PHR was then calculated as follows:

$$\text{PHR} = \begin{cases} 
\text{PHR}_p & \text{m.c.} > 18\% \\
\text{PHR}_p \prod_{n=1}^{n_R} (1 - \text{HRR}) & \text{m.c.} \leq 18\% 
\end{cases}$$  \hspace{1cm} (4a)

where $n_R$ is the number of rainfall events occurring after rice m.c. decreased to 18%. Thus, when rice m.c. was above 18%, the actual PHR was directly calculated using equation 4a. After rice m.c. decreased to 18%, the actual PHR continued to follow the relationship given in equation 4a until rain occurred. The head rice reduction caused by rain was calculated using equation 3. The actual PHR after rain was then calculated using equation 4b. This actual PHR remained constant until the next rain occurred. The effect of the second rain event on PHR reduction was again calculated using equation 3. The actual PHR after the second rain was then equal to the actual PHR before rain multiplied by the term $(1 - \text{HRR})$ (eq. 4b). This procedure was repeated for each rain event for the entire harvest season.

**FIELD YIELD PREDICTION MODEL**

**Potential FY.** Since PMR can be interpreted as the ratio of milled rice yield (MRY) to FY, the following expression for the potential FY can be stated:

$$\text{FY}_p = \frac{\text{MRY}_p}{\text{PMR}/100}$$  \hspace{1cm} (5)

The subscript P was dropped from PMR in equation 5 and in the subsequent derivations because the potential PMR is equal to the actual PMR. Since FY is the sum of MRY, bran yield (BY), and hull yield (HY), equation 5 can be rewritten as:

$$\text{FY}_p = \frac{\text{FY}_p - (\text{BY}_p + \text{HY}_p)}{\text{PMR}/100}$$  \hspace{1cm} (6)

Rearranging equation 6 gives:

$$\text{FY}_p = \frac{\text{BY}_p + \text{HY}_p}{1 - \text{PMR}/100}$$  \hspace{1cm} (7)

If it is assumed that the term $(\text{BY}_p + \text{HY}_p)$ is constant over the harvest m.c. range, then equation 7 becomes:

$$\text{FY}_p = \frac{c}{1 - \text{PMR}/100}$$  \hspace{1cm} (8)

Equation 8 shows that under the assumption of constant BY and HY, the potential FY is a function of PMR only. The value of c can be determined if the potential FY and PMR are known at a given harvest m.c. level.
The assumption that the hull and bran yield remain constant over the harvest m.c. range implies that the rate of dry matter accumulation in the hull and bran during maturity in the harvest m.c. range is low compared to that of the endosperm. This inference is justified in view of the experimental results reported by Malabuyoc et al. (1966), in which the hull reached full length and width dimensions within 5 and 12 days after heading, respectively. Thereafter, only the kernel thickness increased, which would be attributed to endosperm development, until 20 days after heading. In addition, the overall trend of increasing PMR with decreasing m.c. during the high m.c. range indicates that the ratio of endosperm to rough rice weight is increasing. This in turn would indicate that the hull and bran component weights remain relatively constant.

**Prediction Error.** The prediction error introduced by the assumption of constant BY and HY will vary depending on the m.c. levels chosen to determine the value of c. If c is evaluated at M = M₀, then the potential FY of rice harvested at a particular m.c. level of Mₘ (Mₘ ≥ M₀) may be approximated by:

\[
FY_M = \frac{BY_M + HY_M}{1 - PMR_M/100}
\]

where the subscripts O and M indicate that the subscripted variables will be evaluated at the respective harvest m.c.s. For clarity the subscript P was dropped from the corresponding variables in equation 9 and in the subsequent derivations. The actual potential FY, as shown in equation 7, would be determined by evaluating c at the m.c. level of Mₘ as follows:

\[
FY_M = \frac{BY_M + HY_M}{1 - PMR_M/100}
\]

From equations 9 and 10, the error introduced by the assumption of constant BY and HY, denoted as Eᵢ, may be estimated as follows:

\[
E_i = \frac{FY_M - FY_M}{FY_M} = \frac{(BY_M + HY_M) - (BY_M + HY_M)}{(BY_M + HY_M)}
\]

Since, from equation 7:

\[
(BY + HY) = FY (1 - PMR/100)
\]

equation 11 can be rewritten as:

\[
E_i = \frac{FY_M (1 - PMR_M/100)}{FY_M (1 - PMR_M/100)} - 1
\]

Denoting:

\[
\alpha = \frac{PMR_M}{PMR_O}
\]

\[
\beta = \frac{FY_O}{FY_M}
\]

where \(\alpha \leq 1\), and \(\beta \geq 1\), equation 13 becomes:

\[
E_i = \frac{\beta (1 - PMR_O/100)}{(1 - \alpha PMR_O/100)} - 1
\]

Suppose that rice is harvested at 24\% m.c., which is usually considered to be the upper limit for harvesting long-grain rice varieties in Arkansas. The value of \(\alpha\), as shown later, will be about 0.95. It is not likely that the potential FY increase will be more than 20\% (\(\beta = 1.20\)) in view of studies by Counce et al. (1990) and Calderwood et al. (1980). If this is the case, then the prediction error in FY, as estimated by equation 16, is about 7.5\% since the value of PMR₀ is normally around 70\%. The actual prediction error would be expected to be smaller than this value because the potential FY increase is likely to be smaller than the 20\% value estimated here. Also, the prediction error in FY will be even smaller if rice is harvested at m.c.s lower than 24\%. Thus, the maximum error expected under the assumption of constant (BY+HY) would be less than 7.5\% and would be expected to be much less at harvest m.c.s less than 24\%.

**Field Yield Reduction.** In the harvest m.c. range, reductions in FY are primarily caused by shattering or lodging. Bird predation or insect invasion can also reduce yields at any stage of harvest. Considerable differences in tendency to shatter exist between varieties. Lodging may be the result of weather conditions, and may be specific to the variety and particular field conditions. Hence accurate prediction of the FY reduction caused by these factors would be very difficult. In this study, an empirical approach was used to estimate FY reduction based on limited experimental data.

Studies by Morse et al. (1967), Nangju and De Datta (1970), Bal and Ojha (1975), Calderwood et al. (1980), and Counce et al. (1990) showed that the actual maximum FY is usually obtained when rice m.c. is between 18 and 25\%. After reaching the maximum, the actual FY normally decreases linearly with time (Calderwood et al., 1980; Bal and Ojha, 1975; Nangju and De Datta, 1970). Based on these observations, the FY reduction (FYᵣ) was modeled as follows

\[
FYᵣ = γN
\]

where

\[
FYᵣ = (FY_{max} - FY)/FY_{max}
\]

FY_{max} = FYₚ at Mₓ where Mₓ corresponds to the maximum actual FY

The expression of FYᵣ in a dimensionless form allows the comparison of data from different harvest seasons without
having to consider FY differences. The constant γ must be determined from experimental data, and its value may vary depending on variety and environmental conditions.

Based on the above discussion, the actual FY was estimated as follows:

\[
FY = \begin{cases} 
FY_p & \text{m.c.} > M_X \\
FY_{\text{max}} (1-FYR) & \text{m.c.} \leq M_X 
\end{cases} \tag{18a} 
\]

\[
FY \leq \text{m.c.} \leq M_X \tag{18b} 
\]

Note that \( M_X \) may be greater than \( M_{P,X} \) where \( M_{P,X} \) is the m.c. at which the maximum \( FY_p \) is obtained, in which case the FY may never reach the maximum value at \( M_{P,X} \).

**PARAMETER DETERMINATION**

The parameters in equations 1 and 2 were determined using a set of experimental data collected in 1989 for the long-grain rice variety ‘Newbonnet’ (Siebenmorgen et al., 1992). This data set covered a m.c. range from 15 to 26%. The entire data set was used to determine the parameters in the potential PMR model since weather conditions were assumed to have no effect on PMR. Only those data with harvest m.c.s above 17.7% were used to determine the parameters in the potential PHR model so that the effects of rain on the PHR data could be eliminated. A nonlinear regression technique (Proc NLIN, SAS, 1988) was used to estimate the parameters. The constant \( M_0 \) was chosen to be 12.0% because this value reflects the lowest m.c. at which rice would normally be harvested. The statistics of the nonlinear regression models for PMR and PHR are summarized in Table 1.

Figure 1 shows the normalized potential PMR, PHR, and FY as a function of average m.c., using the parameter values given in Table 1. The normalized potential PMR and PHR were obtained by dividing both sides of equations 1 and 2 by their respective maximum yield, i.e., the parameter \( A_T \) or \( A_H \). Similarly, the normalized potential FY was obtained by dividing both sides of equation 8 by the term \( c/(1-\text{PMR}^2/100) \). At 24% m.c., the potential PMR, PHR, and FY reached 95, 85, and 90% of the corresponding maximum yields, respectively. The potential PMR, PHR, and FY approached maximum yield at 18% m.c.

The FY reduction rate, \( \gamma \), in equation 17 was estimated using experimental data (Calderwood et al., 1980) for two long-grain varieties ‘Lebonnet’ and ‘Labelle’. Only those data obtained after rice reached maximum FY were used in the regression analysis. Separate regression analyses were first conducted for both ‘Lebonnet’ and ‘Labelle’ rice from each harvest season. The value of \( \gamma \) was found to vary from 0.00614 to 0.00697/day for the ‘Lebonnet’ variety and from 0.00559 to 0.00862/day for the ‘Labelle’ variety. These results indicated that the variation in FY reduction rate was small between the two varieties and among the different harvest seasons. Subsequently, a linear regression analysis was conducted on the pooled data for both ‘Lebonnet’ and ‘Labelle’ rice from all harvest seasons. Figure 2 shows the FY reduction data for both ‘Lebonnet’ and ‘Labelle’ from the 1974 through 1977 harvest seasons. Each data point is the average of four measurements. The pooled FY reduction rate (\( \gamma \)) was 0.00661/day with a standard error of 0.000351/day and an \( R^2 \) value of 0.671. Hence, the rate of FY reduction was 0.661% of the maximum FY per day after rice reached the m.c. level (\( M_X \)) corresponding to maximum FY. It is to be noted that the \( M_Y \) value ranged from 17.9 to 24.8% for ‘Lebonnet’ rice, and from 19 to 22.5% for ‘Labelle’ rice. Counce et al. (1990) also reported a similar \( M_X \) range for ‘Lemont’ rice in Arkansas. Therefore, an overall average value of \( M_X \) in equation 18 may be chosen to be 22%.

**MODEL VALIDATION**

The PMR and PHR models were validated using experimental data obtained in a three-year study conducted at the University of Arkansas, Rice Research and Extension Center at Stuttgart, Arkansas, and a study conducted in 1990 at the Northeast Research and Extension Center at Keiser, Arkansas. Information on the

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**Table 1. Regression analysis results for determining parameters of percent milled rice (PMR, eq. 1) and percent head rice (PHR, eq. 2) models**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>s(A)</th>
<th>s(B)</th>
<th>s(C)</th>
<th>MSE</th>
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<tbody>
<tr>
<td>PMR</td>
<td>68.0</td>
<td>5.2</td>
<td>56.3</td>
<td>0.16</td>
<td>3.16</td>
<td>8.27</td>
<td>0.10</td>
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<tr>
<td>PHR</td>
<td>55.6</td>
<td>12.4</td>
<td>33.1</td>
<td>0.43</td>
<td>6.02</td>
<td>6.63</td>
<td>0.38</td>
</tr>
</tbody>
</table>

* Mean squared error.

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**Figure 2. Field yield (FY) reduction data for ‘Lebonnet’ and ‘Labelle’ rice from 1974 to 1977 (Calderwood et al., 1980) and the fitted regression line.**
TABLE 2. Participation dates and amounts (mm) during the rice harvest seasons at Stuttgart, Arkansas, from 1987 through 1989 and at Keiser, Arkansas, in 1990

<table>
<thead>
<tr>
<th>Year</th>
<th>DOY*</th>
<th>Amount</th>
<th>DOY</th>
<th>Amount</th>
<th>DOY</th>
<th>Amount</th>
<th>DOY</th>
<th>Amount</th>
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<td>244</td>
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<td>251</td>
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<td></td>
<td>246</td>
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<td>244</td>
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<td>244</td>
<td>2.8</td>
<td>254</td>
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<td></td>
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<td>294</td>
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<td>299</td>
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<td>301</td>
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<tr>
<td>1989</td>
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<td>0.9</td>
<td>317</td>
<td>29.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Day of year.

experimental procedure for determining milling results can be found in Siebenmorgen et al. (1992). In the model validation, the parameter A, representing the maximum potential PMR or PHR, was considered as an input value and was determined from milling test data.

Table 2 shows rain information during the harvest seasons from 1987 to 1989 at Stuttgart, Arkansas, and in 1990 at Keiser, Arkansas. In estimating the PHR reduction caused by rain, it was required to know the average rice m.c.s for those days in which there was rain. If no m.c.

measurements were taken, the average rice m.c.s for these particular days were calculated by assuming that the average rice m.c. between two harvest dates changed linearly with time.

Figures 3 to 6 show the comparison of measured and model-predicted PMRs and PHRs for 'Lemont', 'Newbonnet', and 'Tebonnet' varieties from 1987 to 1990. Each data point in figures 3 to 5 is the average of 20 measurements, and each data point in figure 6 is the average of eight measurements. The vertical bars in these figures represent the occurrence of rain events after rice m.c. declined below 18% but do not represent the amount of rain. The horizontal dotted line in figures 3 to 6 represents the 18% m.c. line. Predicted PMRs compared well with the experimental data with the average prediction errors being less than or equal to 1.9 percentage points.

Predicted PHRs compared reasonably well with the experimental data for both 'Lemont' and 'Newbonnet' in 1987 (fig. 3). The average prediction error was 2.2 percentage points for 'Lemont' and 2.4 percentage points for 'Newbonnet' when the rice was harvested between 253 and 295 days of year during which the 'Lemont' rice m.c. changed from 21.5 to 11.1% and the 'Newbonnet' rice m.c. changed from 24.3 to 10.6%. Larger prediction errors were obtained when the rice was harvested at m.c. greater than 27% or after the rice m.c. reached 11%. The experimental data showed that the reduction in PHR at low m.c.s was mainly attributed to
rain. The model predicted the rain influence on PHR with reasonable accuracy.

Measured PHRs for both ‘Lemont’ and ‘Newbonnet’ did not change significantly during the 1988 harvest season (fig. 4), in which the ‘Lemont’ rice m.c. changed from 22.5 to 13.4% and the ‘Newbonnet’ rice m.c. changed from 26.4 to 14.7%. The model underpredicted the PHRs for ‘Lemont’ rice for the last two harvest dates with errors of 6.5 and 12.1 percentage points, respectively. This is likely due to the fact that there was very light rain during the last two harvest dates (Table 2), which may not have fissured as many rice kernels as the model predicted. Contrary to the ‘Lemont’ variety, predicted PHRs for the ‘Newbonnet’ variety compared well with the experimental data (0.7 and 2.8 percentage points difference) for the last two harvest dates. Large prediction errors (15.1 and 5.9 percentage points) were obtained when ‘Newbonnet’ rice was harvested at m.c.s of 26.4% and 24.2% at the two early harvest dates.

The model predicted the PHRs very well for both ‘Lemont’ and ‘Newbonnet’ rice in 1989 (fig. 5). The average prediction errors for ‘Lemont’ and ‘Newbonnet’ were 2.6 and 2.0 percentage points, respectively. The rain effect on PHR reduction was well predicted by the model. However, somewhat larger prediction errors were again obtained when ‘Lemont’ and ‘Newbonnet’ rice were harvested above 24% or below 13% m.c.

In 1990, predicted PHRs compared well with the experimental results for both ‘Lemont’ and ‘Tebonnet’ before the rice m.c. decreased to about 12% (fig. 6). After the 12% m.c. level was reached, dramatic reductions in PHR were measured for both ‘Lemont’ and ‘Tebonnet’. The model also predicted a reduction in PHR, but did not predict as dramatic a PHR reduction as actually occurred. The above results indicate that the PHR model generally performed well when rice was harvested at m.c.s ranging from approximately 13 to 24%. Large prediction errors were obtained in limited cases where rice was harvested at m.c.s greater than 24% or less than 13%. It has been observed that experimental PHRs are more variable at high m.c.s, which could account for some of the prediction error at high m.c.s. As the average rice m.c. decreased to a very low level, the PHR model became more sensitive to m.c. level and small errors in estimating rice m.c. could result in large prediction errors in PHR. In addition, nocturnal dew occurrence might have affected PHR reduction when rice was harvested at low m.c. levels. However, since most long-grain rice in Arkansas is normally harvested between 13 and 24% m.c., the model is not likely to induce significant prediction errors.

Field yield reduction data for long-grain rice were not available and thus the actual FY component of the model could not be validated directly. However, the potential FY model (eq. 8) was validated using the experimental data reported by Morse et al. (1967) for the short-grain variety ‘Calboro’ and by Bal and Ojha (1975) for the medium-grain variety ‘Jayas’. No FY losses were reported by Morse et al. (1967), hence the entire data set was used for the model.
SUMMARY AND CONCLUSIONS

Three models were developed to predict PMR, PHR, and FY as a function of rice m.c. at harvest. The actual yield was obtained by subtracting the yield reduction from the potential yield. The PMR and PHR models were validated using experimental data obtained from 1987 to 1990 for 'Lemont', 'Newbonnet', and 'Tebonnet' long-grain varieties. The potential FY model was validated using experimental data by Morse et al. (1967) and Bal and Ojha (1975).

Predicted PMRs compared well with the experimental results for the four harvest seasons with average prediction errors of less than 1.9 percentage points. The average differences between the predicted and measured PHRs were less than 2.4 percentage points when rice was harvested between 13 and 24% m.c. for the all harvest seasons. Larger prediction errors (more than five percentage points) were obtained in limited cases where the rice was harvested above 24% or below 13% m.c. The relatively poor performance of the PHR model for m.c.s greater than 24% was possibly due to the large variability in experimental PHR data, whereas the large prediction errors for the m.c.s less than 13% appeared to be caused by the sensitivity of the PHR model to m.c. change and the possible dew influence. Predicted FYs compared reasonably well with the experimental data by Morse et al. (1967) and Bal and Ojha (1975) with average errors of 3.5 and 6.8%, respectively.

The models are suitable for predicting PMR, PHR, and FY for long-grain rice grown under Arkansas climatic conditions and can assist producers in scheduling harvest. However, due to the significant influences of environmental conditions, the models need to be verified for long-grain rice grown in other climatic conditions. Also, further research is needed to quantify the effects of dew and rain amount or duration on the PHR reduction so that better predictions in PHR can be obtained for rice harvested at low m.c.s.

ACKNOWLEDGMENTS. The authors wish to thank the Arkansas Rice Research and Promotion Board and Case IH for the financial support of this project.

REFERENCES


**LIST OF SYMBOLS**

- **a, b** parameters in the percent head rice reduction model
- **c** constant in the potential field yield model (kg/ha)
- **A, B, C** parameters in the potential percent milled rice or percent head rice model
- **BY** bran yield (kg/ha)
- **FY** rice field yield (kg/ha)
- **FYR** field yield reduction (decimal)
- **HRR** head rice reduction ratio (decimal)
- **HY** hull yield (kg/ha)
- **M** moisture content, wet basis (%) 
- **MRY** milled rice yield (kg/ha)
- **N** number of days after rice reaches the maximum field yield
- **PHR** percent head rice (%)
- **PMR** percent milled rice (%)
- **γ** field yield reduction rate (day⁻¹)

**SUBSCRIPTS**

- **H** head rice
- **O** the lowest possible harvest moisture content
- **P** potential yield
- **T** milled rice