The Role of Rice Individual Kernel Moisture Content Distributions at Harvest on Milling Quality

R. C. Bautista, T. J. Siebenmorgen, A. Mauromoustakos

Abstract. *The objective of this study was to quantify the effects of rice kernel properties, associated with kernel moisture content (MC) distributions, on milling quality as harvest MC varied. Multiple samples of rice cultivars Bengal, Cypress, and Drew were harvested at various MCs from northeast and southeast Arkansas in 1999 and 2000. Additional sample sets of various rice cultivars were collected in 2004, 2005, and 2006 at various locations in Arkansas, Mississippi, and Missouri. Individual kernel MCs from panicles were measured immediately after each harvest. The percentages of kernels at MC levels >21%, >22%, >23%, >24%, >25%, and >26% and at MCs <12%, <13%, <14%, <15%, <16%, and <17% were quantified at various bulk harvest MCs. The percentages of kernels above various high MC levels increased with harvest MC. The percentages of kernels at different low MC levels and fissured kernels increased with a decrease in harvest MC, once the bulk harvest MC decreased below approximately 18%. Head rice yield reduction (HRYR) increased with increased percentages of both high and low MC kernels. Fissured kernels percentage had a good correlation with HRYR (R^2 = 0.76). Head rice yield reduction in high MC kernels was postulated to be due to immature, high MC kernels; fissured kernels due to rapid moisture adsorption most likely caused HRYR in low MC kernels. Among low MC levels, the percentage of kernels at MCs less than 14% had the strongest correlation to HRYR (R^2 = 0.72), whereas among high MC levels, the percentage of kernels at MCs greater than 22% correlated most strongly with HRYR (R^2 = 0.61). Optimal harvest moisture contents (HMCs) were determined using quadratic equations derived from the percentages of kernels at MCs >22% and <14%. Based on this analysis, optimal HMCs ranged from 18% to 22% for long-grain cultivars, from 19.0% to 20.4% for medium-grain Bengal, and from 17.7% to 19.0% for long-grain hybrid XP723.*

Keywords. *Fissures, Harvest moisture content, Head rice yield, Head rice yield reduction, Milling quality, Rice, Rice individual kernel moisture content.*

Physical properties of individual rice kernels influence post-harvest processing and quality. Head rice yield (HRY), defined as the mass percentage of rough rice that remains as head rice (milled kernels that are at least three-fourths of the original kernel length after complete milling; USDA, 2005), is the most commonly used indicator of rice milling quality. Head rice yields are particularly affected by kernel properties that could be associated with rice kernel moisture content (MC) at harvest. Because there is a premium for head rice relative to brokens, HRY, and thus rice kernel MC, is a direct determinant of economic return. It is thus important to investigate the role of individual kernel MC distributions on milling quality and determine the HMC at which HRYs peak. This effort will benefit breeders, producers, and the rice industry in general by providing a method by which optimal harvest MCs (HMCs) are determined.

Submitted for review in December 2008 as manuscript number FPE 7862; approved for publication by the Food & Process Engineering Institute Division of ASABE in August 2009.

The authors are **Rustico C. Bautista,** Postdoctoral Research Associate, and **Terry J. Siebenmorgen, ASABE Fellow,** University Professor, Department of Food Science, University of Arkansas, Fayetteville, Arkansas; and **Andronikos Mauromoustakos,** Professor, Department of Agricultural Statistics, University of Arkansas, Fayetteville, Arkansas. **Corresponding author:** Terry J. Siebenmorgen, Department of Food Science, University of Arkansas, 2650 N. Young Ave., Fayetteville, AR 72704; phone: 479-575-2841; fax: 479-575-6936; e-mail: tsiebenm@uark.edu.

Optimal Harvest MC

Siebenmorgen et al. (2007) reported that HRY is a quadratic function of harvest MC, which implies that there exists an optimal HMC to maximize HRY. The optimal harvest MC differs depending on cultivar and growing location. Siebenmorgen et al. (2007) reported that in Arkansas, Mississippi, and Missouri, optimal harvest MCs were 18.7% to 23.5% for long-grain cultivars Cypress and Drew and 21.5% to 24.0% for medium-grain cultivar Bengal (all moisture contents are expressed on a wet basis). Chau and Kunze (1982) reported an optimal HMC of 24% to 26% for rice cultivar Brazos in Texas. In California, medium-grain rice HRYs are maximized at 23% to 25% (Geng, 1984). Thompson and Mutters (2006) recommended harvesting rice in California at above 21% MC to prevent HRY reduction.

Individual Kernel MC at Harvest

A consideration in determining optimal HMC is that rice kernels mature asynchronously on the plant and within a single rice panicle (Holloway et al. 1995; Bautista and Siebenmorgen, 2005). Therefore, the bulk MC is only an average of the individual kernel MCs constituting bulk rice from the field. Studies have shown that individual kernel MCs can vary by as much as 10 percentage points (pp) (McDonald, 1967) or 46 pp (Chau and Kunze, 1982) between kernels from

 © 2009 American Society of Agricultural and Biological Engineers ISSN 0001-2351

the bottom of the least mature panicle to the top of the most mature panicles at harvest. Studies have also shown multi-modal individual kernel MC distributions from rice panicles at HMCs greater than 16% (Bautista and Siebenmorgen, 2005; Kocher et al. 1990). Holloway et al. (1995) attributed these multi-modal distributions to the variation in kernel flowering times and subsequent individual kernel MC plateaus during kernel development. Moisture content plateaus were described as periods when MCs remained constant during development and maturation (Yoshida, 1981). Holloway et al. (1995) postulated that when the MCs of all individual kernels are tallied to obtain MC frequency distributions, modes tend to form around the plateau MCs. As harvest MCs decreased as the harvest date was delayed, the high MC modes decreased as the number of kernels with low MCs increased. According to Kocher et al. (1990), kernel MC distributions later in the harvest season were skewed to high MC levels.

Head Rice Yield Reduction and Kernel MCs at Harvest

Lu et al. (1995) and Lu and Siebenmorgen (1995) have shown that significant losses in HRY can be incurred when long-grain rice is harvested at HMCs less than 15% or greater than 22% MC in Arkansas. Above 22% MC, there are large percentages of immature, high MC kernels that are thinner, mechanically weaker, and thus prone to breakage during milling. Below 15% HMC, there is a proliferation of kernel fissuring that is normally caused by rapid moisture adsorption by low MC kernels in the field due to rainfall or exposure to high air relative humidity. The longer that rice at low HMCs is left in the field, the greater the probability that the lower MC kernels will fissure before harvest (Chau and Kunze, 1982).

Rice Critical MCs

A property of rice associated with kernel fissuring, referred to as the rice critical MC (CMC), is defined as that MC below which kernels will fissure when rapidly rewetted. Juliano and Perez (1993) determined CMCs of selected cultivars of tropical rough rice in both dry and wet seasons. Rice cultivar IR42 had a CMC of 16% in both seasons, whereas variety IR60 had a CMC of 14% in the dry season and 12% in the wet season. Siebenmorgen and Jindal (1986) found that CMC levels ranged from 12% to 15%, depending on the cultivar and rewetting environment. With the large variation in kernel MCs within and among panicles at harvest, especially at HMCs below 16%, increasing numbers of kernels reach the CMC for fissures to develop due to rapid moisture adsorption as bulk average harvest MC declines. However, there are also kernels within panicles that are immature (high MCs), which, as stated above, can cause HRYR. It is important to determine the relationships between low MC kernels (kernels that are likely to have fissured) and high MC kernels (kernels that are likely immature) and milling quality across harvest MCs as a means of fundamentally estimating optimal HMCs.

Objectives

This study was conducted to quantify the effects of individual kernel MC distributions, as indicators of the percentage of fissured and immature kernels, on milling quality across HMCs from approximately 26% to 12% for cultivars produced in the U.S. Mid-South rice production region. The study estimated the optimal HMC based on the percentages of high and low MC kernels above and below, respectively, selected MC levels.

Materials and Methods

Panicles of Bengal (medium-grain), Cypress, and Drew (both long-grain) rice cultivars were hand-harvested at the University of Arkansas research and extension centers near Keiser and Stuttgart, Arkansas, at HMCs that ranged from 12% to 24% during the autumns of 1999 and 2000. Additional panicles of medium-grain Bengal, long-grain cultivars Cheniere, Cocodrie, Francis, and Wells, and long-grain hybrid XL723 were collected in 2004, 2005, and 2006 from selected Arkansas, Mississippi, and Missouri farm trials at 12% to 26% HMCs. Table 1 summarizes the HMCs of samples collected. Each sample lot comprised approximately 200 panicles, which yielded at least 2 kg of rough rice.

Immediately after harvest, five panicles were randomly selected from each 200-panicle lot for individual kernel MC measurements. The kernels were stripped by hand, and MCs of 300 kernels were measured using a single-kernel moisture meter (CTR 800E, Shizuoka Seiki, Shizuoka, Japan). The average MC of these 300 kernels was used as the lot HMC. The moisture meter was calibrated with a convection oven (model 1370 FM, Sheldon Mfg. Inc., Cornelius, Ore.) using the method of Jindal and Siebenmorgen (1987) on each harvesting season and showed good agreement (R^2_{1999} = 0.98, R^2_{2000} = 0.97, R^2_{2004} = 0.98, R^2_{2005} = 0.98, and R^2_{2006} = 0.99).

Fissured Kernel Enumeration

Fissured kernels were enumerated in 1999 and 2000 by randomly selecting a second set of five panicles immediately after harvest. The kernels from these panicles were manually stripped, and 200 randomly selected kernels were manually dehulled. The 200 brown rice kernels were spread over the glass top of a fissure inspection light box illuminated by a soft light fluorescent bulb (12 W, 120 V). Brown rice kernels were inspected with a magnifying glass. The fissured kernel percentage was calculated as the number of the 200 kernels that were fissured. The remaining 190 panicles were stripped by hand and the kernels dried to approximately 12% MC in a chamber maintained at 21°C and 56% relative humidity for milling analysis.

In 2004, 2005, and 2006, panicles remaining from those selected for individual kernel MC measurements were mechanically threshed (SBT, Almaco, Nevada, Iowa) to remove the kernels. The rough rice was subsequently dried to 12.5% MC in the same chamber that was used in 1999 and 2000. Two hundred rough rice kernels were then randomly selected and fissured kernels enumerated using the above procedure.

Milling Analyses

The remaining rough rice from each lot was cleaned and used for milling analysis. Two 150 g rough rice samples from each lot were dehulled using a laboratory huller (Rice Machine, Satake Engineering Co., Hiroshima, Japan). The resulting brown rice was milled using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, Tex.) for 30 s. A 1500 g mass was placed on the mill lever arm, 15 cm from the center of the milling chamber. Head rice was separated from brokens

Table 1. Summary of information for rice lots harvested in 1999, 2000, 2004, 2005, and 2006. Peak head rice yield (HRY) and optimal harvest moisture contents (HMCs) were taken from Siebenmorgen et al. (2007).

Year	Cultivar	Grain Type	Location	No. of HMCs; HMC Range (% w.b.)	Peak HRY (%)	Optimal HMC[a] (% w.b.)
1999	Bengal	Medium	Stuttgart, Ark.	6; 12.4 - 22.4	66.3	23.7
			Keiser, Ark.	6; 14.0 - 24.0	68.5	23.8
	Cypress	Long	Stuttgart, Ark.	6; 13.2 - 22.3	66.5	22.1
			Keiser, Ark.	6; 12.8 - 22.0	69.7	19.3
	Drew	Long	Stuttgart, Ark.	7; 12.2 - 23.1	69.0	23.5
			Keiser, Ark.	7; 12.9 - 23.4	70.6	21.0
2000	Bengal	Medium	Stuttgart, Ark.	7; 12.2 - 23.6	69.9	23.0
			Keiser, Ark.	7; 13.1 - 24.0	68.7	21.5
	Cypress	Long	Stuttgart, Ark.	5; 13.7 - 21.6	65.4	21.1
	Drew	Long	Stuttgart, Ark.	5; 14.5 - 24.4	67.1	21.6
			Keiser, Ark.	5; 13.9 - 23.7	69.4	20.3
2004	Bengal	Medium	Brinkley, Ark.	5; 15.9 - 26.5	--[b]	--[b]
			Lodge Corner, Ark.	4; 11.6 - 23.0	67.5	22.4
	Cocodrie	Long	Essex, Mo.	4; 13.5 - 23.9	67.5	19.3
			Newport, Ark.	3; 14.9 - 24.4	--[b]	--[b]
	Wells	Long	Hunter, Ark.	3; 15.2 - 25.7	67.5	21.3
2005	Cheniere	Long	Osceola, Ark.	5; 14.4 - 23.2	66.1	18.8
	Francis	Long	Stuttgart, Ark.	5; 15.5 - 24.4	66.1	18.7
	Wells	Long	Qulin, Mo.	5; 15.4 - 23.7	64.5	19.9
	XL723	Long	Stuttgart, Ark.	6; 14.7 - 20.0	65.2	19.6
			Cleveland, Miss.	5; 12.0 - 23.5	63.8	19.5
2006	Wells	Long	Stuttgart, Ark.	7: 12.0 - 26.9	65.6	21.2
	XL723	Long	Shaw, Miss.	4; 14.2 - 24.7	66.4	20.4
			Stuttgart, Ark.	6; 12.1 - 26.5	66.2	20.1
	Cheniere	Long	Des Arc, Ark.	5; 14.7 - 24.1	65.3	18.7

[a] Optimal HMC corresponds to the peak head rice yield calculated using a quadratic function relating HRY to HMC (Siebenmorgen et al., 2007).
[b] Head rice yields were not statistically related to harvest moisture content.

using a sizing machine (Grainman model 61-115-60, Grain Machinery Manufacturing Corp., Miami, Fla.) with screen size No. 10 (10/64 in.) for medium-grain and No. 12 (12/64 in.) for long-grain cultivars. Head rice yield was then determined as the mass percentage of head rice to the original 150 g of rough rice.

Calculation of Head Rice Yield Reduction

The effects of high and low MC kernels on milling quality were determined using HRYR. Head rice yield reduction for each lot was calculated using the method of Siebenmorgen et al. (2007) as:

$$\text{HRYR}_n = \text{HRY}_{\text{peak}} - \text{HRY}_n \quad (1)$$

where
HRYR_n = HRY reduction for a rice lot (percentage points)
HRY_{peak} = greatest HRY for a rice lot set (table 1) (%)
HRY_n = HRY of a given rice lot (%).

Determination of Critical MC Levels

The percentages of kernels with MCs <12%, <13%, <14%, <15%, <16%, and <17% within a rice lot were used to represent the percentage of fissured kernels that could potentially reduce HRY. The low MC levels encompass the kernel CMCs reported by Lu and Siebenmorgen (1995) and Siebenmorgen and Jindal (1986) wherein at average MCs below 15%, HRYR was observed for rice cultivars harvested in Arkansas. The percentages of kernels with MCs >21%, >22%, >23%, >24%, >25%, and >26% within a rice lot represent the percentage of immature kernels within that lot that could potentially reduce HRY.

The percentages of kernels at these different low and high MC levels were calculated from the individual kernel MC distribution data obtained from each sample lot harvested at different harvest MCs using Microsoft Excel. The computed percentages of kernels less than the various low MC levels of all rice lots were correlated to the percentages of fissured kernels and to the HRYRs for those lots. The percentages of kernels at the various high MC levels were correlated to the HRYR for all rice lots. All correlation analyses were performed using JMP Statistical Discovery version 7.0.1 (SAS Institute, Inc., Cary, N.C.).

Optimal HMC Calculations Based on Individual Kernel MC Distributions

To estimate the optimal HMC for each year/location/cultivar lot, individual kernel MC distributions were utilized as predictors of milling performance. Optimal HMC was calculated for each lot set using quadratic equations generated by plotting the percentages of kernels >22% MC and <14% MC across lot HMCs. The selection of these two MC levels was based on the results of the correlation analysis of the percentage of kernels at high and low MC levels and HRYR. The <14% MC level was most highly correlated to both HRYR and the percentage of fissured kernels (in the case of the low MC levels), and the >22% MC level was most highly correlated to HRYR (in the case of the high MC levels). Using the two equations for each rice lot set, the sums of percentages of kernels >22% and <14% MCs were calculated across HMC; the optimal HMC for each sample lot set was determined as the HMC at which the summed percentage was minimum. The optimal HMCs were then compared to the actual optimal HMCs shown in table 1, which corresponded to the actual peak HRY.

Results and Discussion

Typical rice kernel MC distributions, each from five panicles harvested at a high (22.7%) and low (14.3%) HMC, are shown in figure 1. At an average HMC of 22.7%, the individual kernel MC distribution was multi-modal with an MC range of 14% to 42%. At an average harvest MC of 14.3%, the distribution was unimodal, with the majority of kernels within the 13% to 20% MC range, yet skewed to high MCs. These trends were similar to those reported by Kocher et al. (1990). Such kernel MC distributions could have implications on milling quality, as described previously.

Variability analysis showed significant effects of cultivar ($P < 0.0001$), location ($P < 0.0001$), year ($P = 0.0003$), and HMC ($P < 0.0001$) on HRYR. Thus, variation in HRYR was due to both inherent genetic characteristics and differences in environmental conditions during kernel maturation. With regard to cultivar effects, Cypress generally had the least HRYR; Cypress is known to be resistant to fissuring and has shown stable milling performance across HMCs (Jodari and Linscombe, 1996; Siebenmorgen et al., 2007). Low HRYR variability in 2004 was attributed to generally cooler than normal summer temperatures.

Figure 2 shows how HRYR varied across HMC for all lots indicated in table 1. Head rice yield reduction generally increased as HMC decreased below 20% and also as HMC increased above approximately 22%. Such HRYR can be attributed to the properties associated with kernels in either the low or high MC range of the individual kernel MC distributions.

Relationship of Percentages of High MC Kernels to HRYR

Figure 3 shows the percentages of rice kernels with MCs at >21%, >22%, >23%, >24%, >25%, and >26% plotted against HMC for all rice lots (table 1). Multivariate linear re-

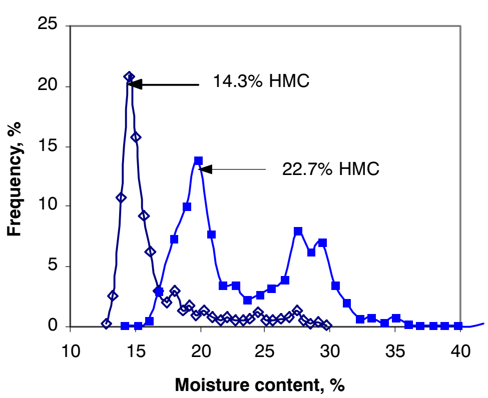

Figure 1. Individual kernel moisture content (MC) distributions within panicles (composite of kernels from five panicles) of Bengal rice at average harvest MCs (HMCs) of 22.7% and 14.3% from Stuttgart, Arkansas, in 1999.

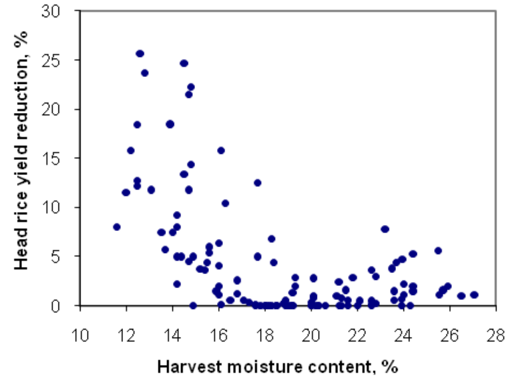

Figure 2. Head rice yield reduction (HRYR) (eq. 1) versus harvest moisture content for all rice lots indicated in table 1. Each data point represents the average HRYR of two milling repetitions for each lot.

gression analysis showed significant differences ($P = 0.001$) in the percentages of kernels at >21%, >22%, >23%, >24%, >25%, and >26% MC at HMCs greater than 16% for all rice lots shown in table 1. At 18% and 22% HMCs, there were 17 and 34 pp difference in the percentage of kernels >21% and >26% MC, respectively. Generally, location and year had no significant effect on the percentage of kernels greater than the integer MC levels of figure 3. Variation in individual kernel MC distribution is affected to a greater extent by the kernel maturation associated with the asynchronous development of kernels on a plant and within a single panicle that could cause kernel-to-kernel MC deviation.

Head rice yield reduction increased above 22% HMC (fig. 2), most likely due to the increased percentage of immature kernels present in the rice bulk. Immature kernels are thin and are mechanically weaker that sound kernels; these kernels usually break when milled, causing a reduction in HRY.

Figure 4 shows the correlations of the percentage of HRYR to the percentage of kernels at >21%, >22%, >23%, >24%, >25%, and >26% MC. Correlation analysis showed that the percentage of kernels in a rice bulk that were >22% MC were most highly correlated to HRYR ($R^2 = 0.61$) compared to the percentages of kernels >21% ($R^2 = 0.56$), >23($R^2 = 0.58$), >24% ($R^2 = 0.57$), >25% ($R^2 = 0.58$), and

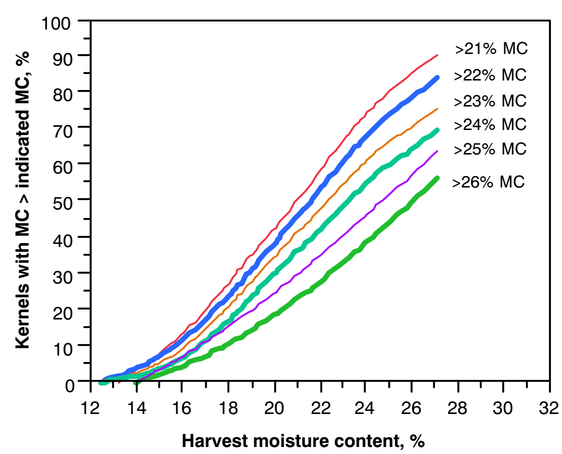

Figure 3. Percentages of kernels with moisture contents (MCs) >21%, >22%, >23%, >24%, >25%, and >26% across average harvest MCs for all lots indicated in table 1. Each curve represents the average percentage of kernels in 300 kernels of rough rice from each HMC lot having MCs greater than the indicated MC.

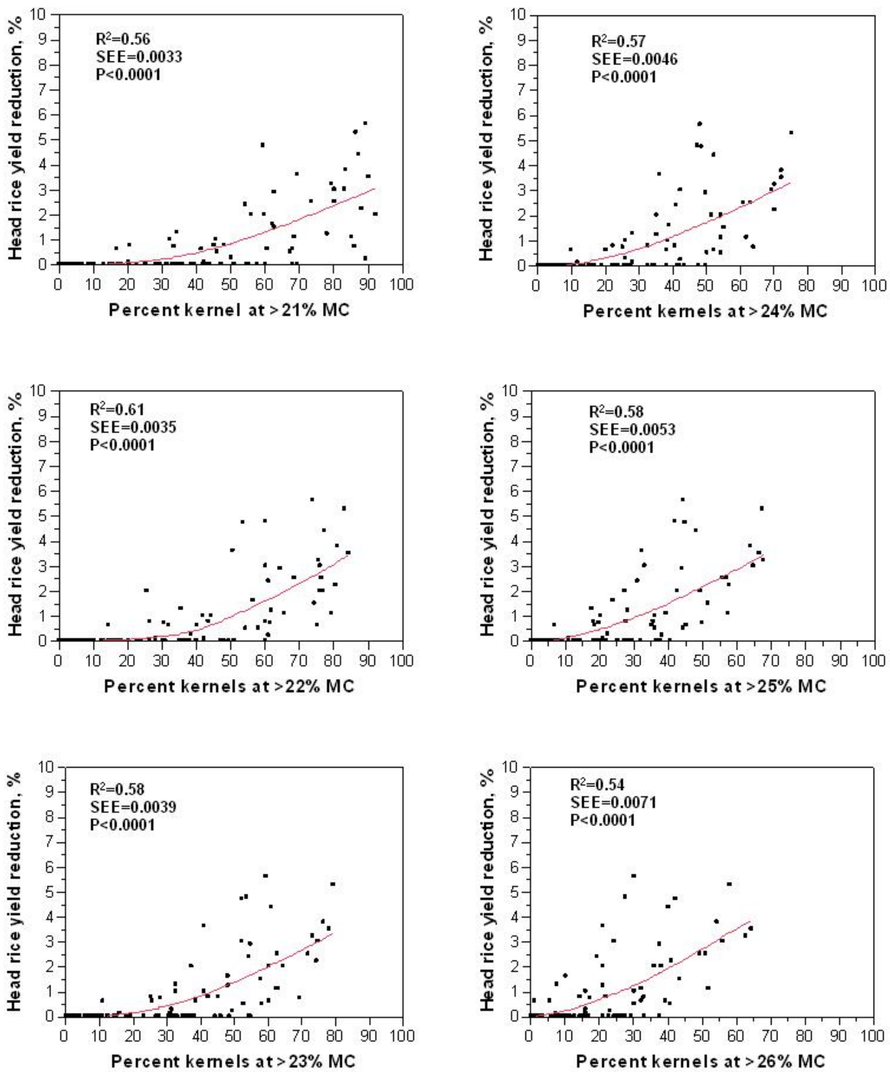

Figure 4. Correlations of the percentage of head rice yield reduction (HRYR) to the percentage of kernels at >21%, >22%, >23%, >24%, >25%, and >26% moisture content (MC) for the rice lots indicated in table 1. Each data point represents the average HRYR of two milling repetitions for each lot.

>26% (R^2 = 0.54) MC. This result corroborates with the results of Lu and Siebenmorgen (1995), who reported that significant loss in HRY was incurred when harvesting rice greater than 22% MC in Arkansas. This result suggests that the percentage of kernels with MCs >22% in bulk rice corresponds to the percentage of immature kernels that would cause HRY reduction; this also suggests that the percentage of kernels >22% MC could be used as a potential gage in relating HRYR to HMC. As was indicated by Siebenmorgen et al. (2007), it is to be noted that a 1:1 mathematical association between HRYR and percentages of kernels >21%, >22%, >23%, >24%, >25%, and >26% could not exist since HRY calculations inherently include the hull and bran masses as part of the denominator base, whereas the percentages of kernels within these high MC levels are based on a direct kernel number percentage.

Relationship of the Percentages of Low MC Kernels to HMC and HRYR

Figure 5 shows the correlations of the percentages of kernels at MCs < 12%, <13%, <14%, <15%, <16%, and <17% to HMC for all lots indicated in table 1. Multivariate linear regression analysis indicated significant differences (P < 0.0001) among percentages of kernels with MCs <12%, <13%, <14%, <15%, <16%, and <17%. Above 18% HMC, there were practically no kernels with MC <12%. However, as HMC decreased to 14%, there was a significant increase in the percentage of kernels with MC <12%. At 20% HMC, kernels with <14% MC averaged approximately 10%, while at 16% HMC, the percentage of kernels at <14% MC averaged approximately 47%. Analysis of variance indicated that location and year had no significant effect on the percentage of kernels with MCs less than the above-mentioned low MC levels across HMC for the lots shown in table 1.

Figure 6 shows the correlation of HRYR to the percentage of kernels at <12%, <13%, <14%, <15%, <16%, and <17% MC. Head rice yield reduction increased as the percentage of low MC kernels increased, as critically low MC kernels are susceptible to moisture adsorption when placed in rewetting conditions, which causes kernel fissuring. Fissured kernels usually break during milling, thus increasing HRYR. Multivariate linear regression analysis showed that the percentage of kernels <14% MC was most highly correlated to the per–

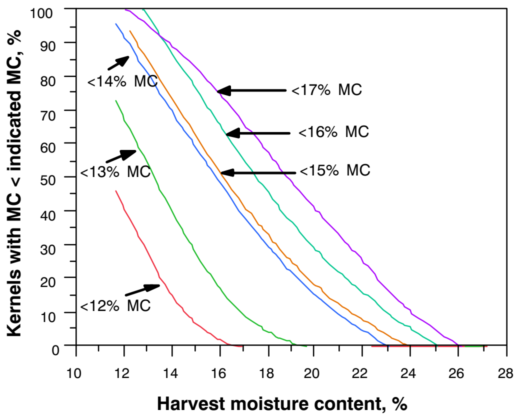

Figure 5. Percentages of kernels at moisture contents (MCs) <12%, <13%, <14%, <15%, <16%, and <17% across average harvest MCs for all rice lots indicated in table 1. Each curve represents the average percentage of kernels in 300 kernels of rough rice from each HMC lot having MCs less than the indicated MC.

centage of fissured kernels with an $R^2 = 0.72$ (SEE = 0.0138 and $P < 0.0001$) (fig. 6).

Relationship Between Percentages of Low MC and Fissured Kernels

Figure 7 shows the relationship between the percentages of fissured kernels and kernels <12%, <13%, <14%, <15%, <16%, and <17% MC for the sample lots indicated in table 1. Multivariate regression analysis showed that the percentage of kernels <14% MC was most highly correlated to the percentage of fissured kernels with an $R^2 = 0.76$ (SEE = 0.0343 and $P < 0.0001$). It is for the greatest correlation of the percentage of kernels at <14% MC to fissured kernels percentage (fig. 7) and HRYR (fig. 6) that the <14% MC level was chosen as the basis for optimal HMC calculations, as discussed in the following section.

Analysis of variance showed that the percentage of fissured kernels at a given HMC was significantly different among cultivars and locations ($P < 0.05$). For example, Cy–

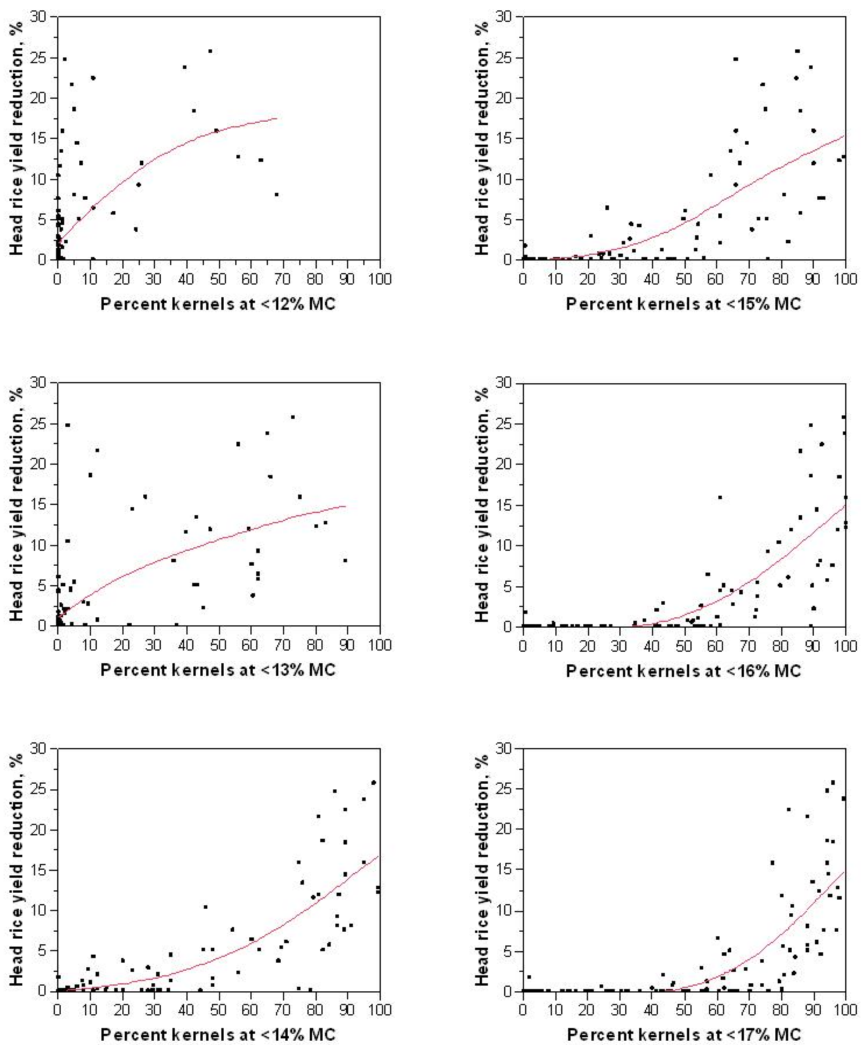

Figure 6. Correlations of the percentage of head rice yield reduction (HRYR) to the percentage of kernels <12%, <13%, <14%, <15%, <16%, and <17% moisture content (MC) for the rice lots indicated in table 1. Correlation results between the percentage of kernels <12%, <13%, <14%, <15%, <16%, and <17% MC and the percentage of HRYR are indicated. Each data point represents the average HRYR of two milling repetitions for each lot.

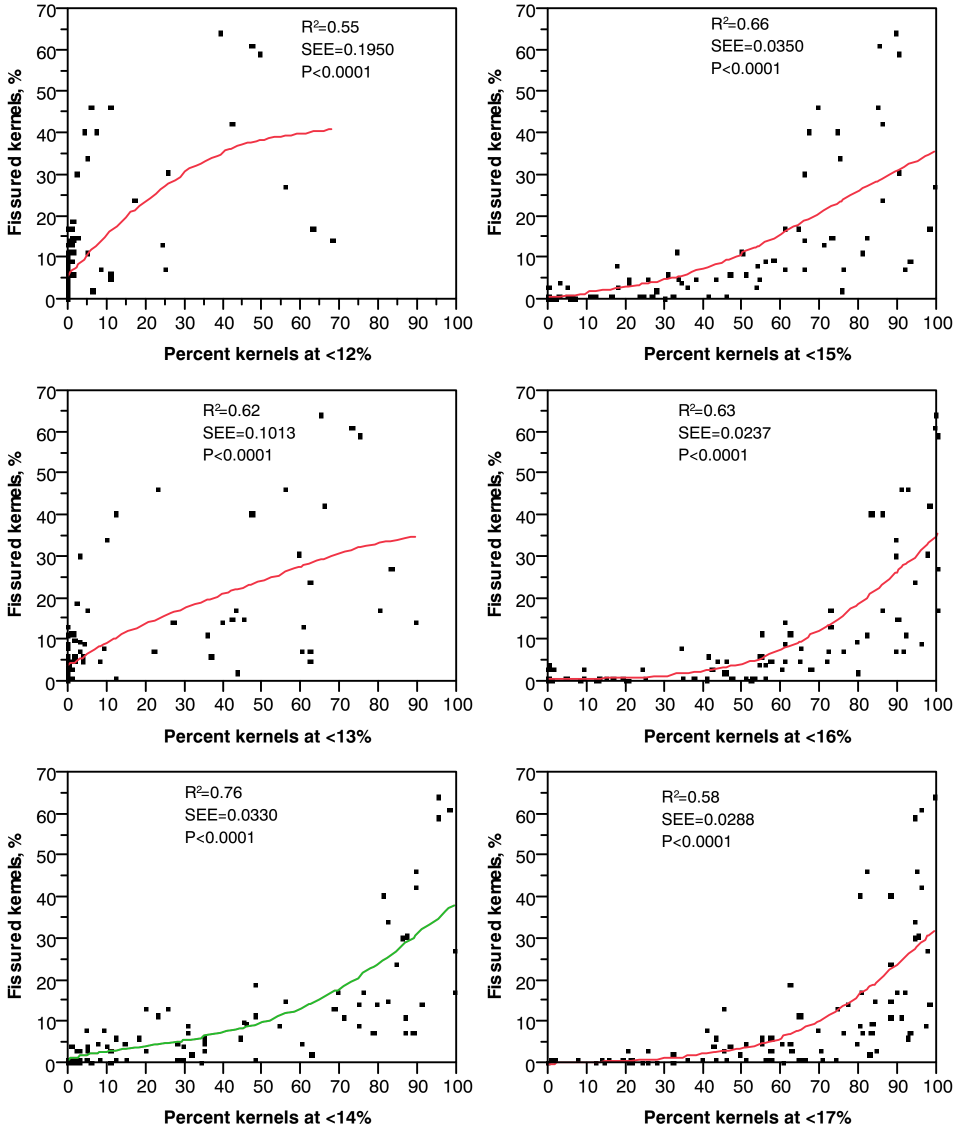

Figure 7. Correlations of the percentage of fissured kernels to the percentage of kernels <12%, <13%, <14%, <15%, <16%, and <17% moisture content (MC) for the rice lots indicated in table 1. Correlation results between the percentage of kernels <12%, <13%, <14%, <15%, <16%, and <17% MC and the percentage fissured kernels are indicated. Each data point represents the percentage fissured kernels in 200 brown rice kernels and the percentage of kernels <MC in 300 kernels for each lot.

press had lower fissuring rates than Bengal and Drew, which had in turn similar fissuring rates. Harvest year did not significantly affect the percentage of fissured kernels, except for 2004, in which fissured kernel effects on HRYR were less dramatic than in 1999, 2000, 2005, and 2006. Variation in environmental conditions could have affected fissuring differences among locations.

Optimal HMC Based on Percentages of Kernels at MCs >22% and <14%

Figure 8 illustrates how the percentages of kernels at MCs >22% and <14% are correlated with HRY across HMC for lots harvested in 1999. Generally, HRY peaked at 18% to 22% HMC and decreased as the percentages of kernels >22% and <14% MC increased. Similar results were observed for the 2000, 2004, 2005, and 2006 lot samples (data not shown).

An approach to determine the HMC at which HRY was maximum was applied by using the percentages of high (>22%) and low (<14%) MC kernels in rice lots across HMC. The percentages of high (>22%) and low (<14%) MC kernels vs. HMC (fig. 8) were described using quadratic functions:

$$\text{Kernels at} > 22\%\ \text{MC} = a_i \cdot \text{HMC}^2 + b_i \cdot \text{HMC} + c_i \quad (> 22\%\ \text{MC curve}) \tag{2}$$

$$\text{Kernels at} < 14\%\ \text{MC} = a_i \cdot \text{HMC}^2 + b_i \cdot \text{HMC} + c_i \quad (< 14\%\ \text{MC curve}) \tag{3}$$

where kernels at >22% MC, kernels at <14% MC, and HMC are in % w.b., and a_i, b_i, and c_i are regression variables. Subscript i refers to the year/location/cultivar lot sets in table 1.

The results of the regression analysis (eqs. 2 and 3) are shown in table 2, including the coefficients of determination for each quadratic equation. The quadratic equations generally described the trends in percentages of kernels at >22% and at <14% MC well, with R^2 values greater than or equal to 0.90.

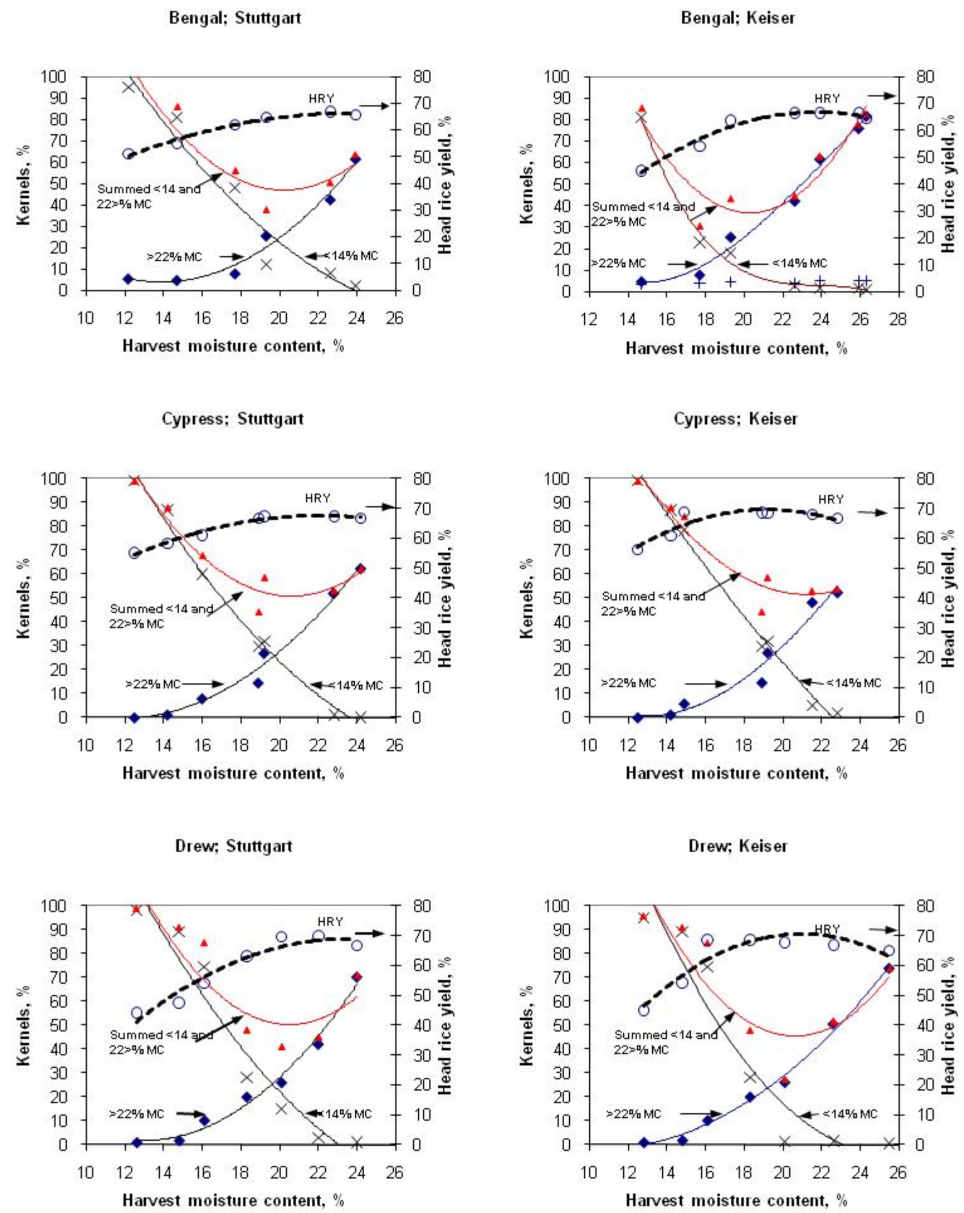

Figure 8. Relationships of percentages of kernels at moisture contents (MCs) >22% and <14%, head rice yields (HRYs), and the summed percentages of <14% and >22% MCs to harvest MCs for lots harvested in 1999 (table 1). Each data point in the MC curves represents the average of 300 kernel MCs from five panicles. Each point in the fissured kernel curves represents the percentage of fissured kernels in 200 brown rice kernels. Each HRY data point represents the average of two milling repetitions for each lot.

From equations 2 and 3, the sum percentages of kernels at >22% and <14% MC were calculated across HMCs for each lot set shown in table 1. Figure 8 also shows the summed percentage of these kernels for 1999 sample lots from Stuttgart and Keiser. The goal was to determine the HMC at which this sum (summed percentages) was minimum, with the hypothesis being that the intersection of the two quadratic curves has the lowest summed percentage of kernels <14% and >22% MC, which would correspond to maximum HRY, and thus optimum HMC.

The results showed that the optimal HMCs obtained using the above procedure (table 2) were generally lower than the optimal HMCs as determined by Siebenmorgen et al. (2007) as shown in table 1. One of the reasons for the lower optimal HMCs obtained using this technique (table 2) is the manner by which the minimum sum percentage of kernels at low and high MC levels was determined. In this study the optimum HMC was based on the minimum sum percentage of kernels at threshold levels of <14% and high >22% MC. The HMC corresponding to the minimum sum percentage of kernels could vary with different combinations of low and high MC threshold levels. These threshold levels could vary slightly with cultivar and location since those independent variables were found to significantly affect fissured kernels percentage at given HMCs.

Optimal HMCs for Bengal were 2.0 to 4.0 pp lower than the optimal HMCs determined by Siebenmorgen et al. (2007). For all long-grain lot sets including XL723, the optimal HMCs obtained were 1.0 to 3.0 pp lower than the optimal HMCs determined by Siebenmorgen et al. (2007). Only 1999 Cypress from Keiser, Arkansas, and 2004 Cocodrie from Essex, Missouri, had 2.3 pp and 0.9 pp, respectively, higher optimal HMCs than reported by Siebenmorgen et al. (2007).

Table 2. Regression results of fitting equations 2 and 3 to each set of cultivar lot sets (table 1).

			Regression Results for Percentage of Kernels at >22% MC				Regression Results for Percentage of Kernels at <14% MC				Optimal
Year	Cultivar	Location	a_i	b_i	c_i	R^2	a_i	b_i	c_i	R^2	HMC[a] (%)
1999	Bengal	Stuttgart, Ark.	0.5551	-15.4210	110.91	0.98	0.3709	-22.028	314.49	0.95	20.2
		Keiser, Ark.	0.4021	-9.8181	62.03	0.99	1.0561	-49.306	573.88	0.97	20.3
	Cypress	Stuttgart, Ark.	0.1959	0.8560	-20.88	0.98	0.2411	-18.350	293.52	0.99	20.0
		Keiser, Ark.	0.3266	-5.2721	13.70	0.97	0.1726	-16.294	279.76	0.99	21.6
	Drew	Stuttgart, Ark.	0.4281	-9.2790	52.58	0.99	0.4274	-25.602	363.04	0.94	20.4
		Keiser, Ark.	0.3096	-6.0310	26.52	0.99	0.6956	-35.556	450.17	0.98	20.6
2000	Bengal	Stuttgart, Ark.	0.8658	-25.3490	186.92	0.98	0.4338	-24.077	326.29	0.98	19.0
		Keiser, Ark.	0.5967	-15.1590	97.56	0.99	1.1794	-51.890	569.16	0.97	19.3
	Cypress	Stuttgart, Ark.	0.6680	-17.5590	116.44	0.99	0.7125	-34.135	408.43	0.95	19.5
	Drew	Stuttgart, Ark.	0.8809	-27.2040	215.64	0.98	1.3507	-61.480	696.69	0.99	19.9
		Keiser, Ark.	0.0099	7.8242	-112.42	0.96	1.2225	-54.370	605.69	0.91	19.8
2004	Bengal	Brinkley, Ark.	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]
	Bengal	Lodge Corner, Ark.	0.0808	1.6849	-29.518	0.98	0.4657	-23.955	307.05	0.95	20.4
	Cocodrie	Essex, Mo.	-0.0551	-6.7744	-77.418	0.93	0.6195	31.812	405.94	0.99	20.2
	Cocodrie	Newport, Ark.	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]	--[b]
	Wells	Hunter, Ark.	0.0775	2.3563	-35.804	0.99	0.9080	-43.918	528.57	0.97	21.1
2005	Cheniere	Osceola, Ark.	0.5820	-14.9220	94.207	0.98	1.0186	42.294	436.67	0.95	18.2
	Francis	Stuttgart, Ark.	-0.0623	10.6332	-138.82	0.99	0.6380	-28.274	311.65	0.90	18.6
	Wells	Qulin, Mo.	0.9920	8.3023	-148.15	0.99	1.2856	-49.388	475.72	0.90	19.5
	XL723	Stuttgart, Ark.	2.6011	-79.0390	600.73	0.96	1.7898	-67.047	629.91	0.97	18.6
	XL723	Cleveland, Miss.	0.4543	-8.9312	40.771	0.97	1.1284	-47.311	487.95	0.99	17.7
2006	Wells	Stuttgart, Ark.	0.3350	-7.4142	38.254	0.90	0.7641	-34.680	386.52	0.90	20.4
	XL723	Shaw, Miss.	0.0384	4.1883	-66.870	0.99	1.0462	-45.158	479.00	0.99	17.4
	XL723	Stuttgart, Ark.	0.3043	-6.0742	27.070	0.99	0.7702	-34.947	389.13	0.98	19.0
	Cheniere	Des Arc, Ark.	0.2061	-2.9201	4.7784	0.98	0.8022	-36.580	411.77	0.98	18.6

[a] The optimal harvest moisture contents (HMCs) for each lot set were determined as the HMC at which the summed percentage of kernels at >22% and <14% MC was minimum.
[b] Head rice yields were not statistically related to harvest moisture content.

Another possible reason for the slight discrepancies in optimal HMCs between tables 1 and 2 is that the approach used by Siebenmorgen et al. (2007) to determine optimal HMCs was to first model HRY versus HMC using a quadratic function, and then determine the optimal HMC at which this quadratic function peaked for each lot set. While the HRY versus HMC functions generally described HRY versus HMC trends well, the trends were not completely characterized by a quadratic function, particularly for high HMCs. This lack of complete fit at high HMCs would generally have caused HRYs to peak at HMCs slightly greater than the true optimal.

It is also possible that the discrepancies in optimal HMCs between the results of this study and that of Siebenmorgen et al. (2007) are caused by the fact that near the optimum HMC, HRY does not change greatly over several percentage points of harvest MC and that other factors such as the varietal characteristics and weather affect the results.

In summary, using the minimum summed percentage of kernels with MCs <14% and >22%, the optimal HMCs ranged from 18% to 22% for long-grain cultivars generally, from 19% to 20% for the medium-grain cultivar Bengal, and from 18% to 19% for the hybrid XP723. These values were generally lower or near the optimal HMC ranges that Siebenmorgen et al. (2007) determined (table 1).

Summary

Percentages of kernels at MCs >21%, >22%, >23%, >24%, >25%, and >26% and kernels at MCs <12%, <13%, <14%, <15%, <16%, and <17% were quantified for various rice lots grown in Arkansas, Mississippi, and Missouri in 1999, 2000, 2004, 2005, and 2006. The low MC percentages were correlated with the percentage fissured kernels and HRYR, and the high MC percentages were correlated with HRYR across HMCs. There was good correlation (R^2 = 0.76) between fissured kernel percentage and HRYR. The percentage of kernels at MCs >22% within lots was most strongly correlated with the HRYR of those lots. The percentage of kernels at MCs <14% within lots correlated well to the percentage of fissured kernels and HRYR. Head rice yield reduction at high HMCs is speculated to be tied to the increasing percentage of immature kernels as HMC increased, whereas at low HMCs, HRYR was linked to the increasing percentage of fissured kernels, most likely due to rapid moisture adsorption by dry rice kernels, as HMC decreased. The percentages of kernels at MCs <14% were highly correlated to fissured kernels percentage and HRYR, and those at MCs >22% were most highly correlated to HRYR. Based on this finding, the optimal HMC was calculated using quadratic equations derived from the percentages of kernels at MCs >22% and <14% across lot HMC. The minimum summed percentages of kernels at MCs >22% and <14% were postulated to indicate the maximum HRY and the corresponding optimal HMC. Optimal HMCs ranged from 18% to 22% for long-grain cultivars, from 19% to 20% for medium-grain Bengal, and from 18% to 19% for hybrid XP723. This method predicted optimal HMC with lower or near the optimal HMCs as reported by Siebenmorgen et al. (2007).

Acknowledgements

The authors wish to acknowledge the financial support of the Arkansas Rice Research and Promotion Board and the corporate sponsors of the University of Arkansas Rice Processing Program.

References

Bautista, R. C., and T. J. Siebenmorgen. 2005. Individual rice kernel moisture content variability trends. *Applied Eng. in Agric.* 21(4): 637-643.

Chau, N. N., and O. R. Kunze. 1982. Moisture content variation among harvested rice grains. *Trans. ASAE* 25(4): 1037-1040.

Geng, S., J. F. Williams, and J. E. Hill. 1984. Harvest moisture effects on rice milling quality. *California Agric.* 38(11/12): 11-12.

Holloway, G. E., T. J. Siebenmorgen, P. A. Counce, and R. Lu. 1995. Causes of multi-modal moisture content frequency distributions among rice kernels. *Applied Eng. in Agric.* 11(4): 561-565.

Jindal, V. K., and T. J. Siebenmorgen. 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. *Trans. ASAE* 30(4): 1185-1192.

Jodari, F., and F. S. Linscombe. 1996. Grain fissuring and milling yields of rice cultivars as influenced by environmental conditions. *Crop Sci.* 36(6): 1496-1502.

Juliano, B. O., and C. M. Perez. 1993. Critical moisture content for fissures in rough rice. *Cereal Chem.* 70(5): 613-615.

Kocher, M. F., T. J. Siebenmorgen, R. J. Norman, and B. R. Wells. 1990. Rice kernel moisture content variation at harvest. *Trans. ASAE* 33(2): 541-548.

Lu, R., and T. Siebenmorgen. 1995. Correlation of head rice yield to selected physical and mechanical properties of rice kernels. *Trans. ASAE* 38(3): 889-894.

Lu, R., T. J. Siebenmorgen, T. A. Costello, and O. Fryar Jr. 1995. Effect of rice moisture content at harvest on economic return. *Trans. ASAE* 11(5): 685-690.

McDonald, D. J. 1967. "Suncracking" in rice: Some factors influencing its development and the effects of cracking on milling quality of the grain. MS thesis. Sidney, Australia: The University of Sydney.

Siebenmorgen, T. J., and V. K. Jindal. 1986. Effects of moisture adsorption on the head rice yields of long-grain rice. *Trans. ASAE* 29(6): 1767-1771.

Siebenmorgen, T. J., R. C. Bautista, and P. A. Counce. 2007. Optimal harvest moisture contents for maximizing rice milling quality of long- and medium-grain rice cultivars. *Applied Eng. in Agric.* 23(4): 517-527.

Thompson, J. F., and R. G. Mutters. 2006. Effect of weather and rice moisture at harvest on milling quality of California medium-grain rice. *Trans. ASAE* 49(2): 435-440.

USDA. 2005. U.S. standards for rice. Washington, D.C.: USDA Federal Grain Inspection Service.

Yoshida, S. 1981. Fundamentals of rice crop science. Manila, The Philippines: International Rice Research Institute.