Optimal Harvest Moisture Contents for Maximizing Milling Quality of Long- and Medium-Grain Rice Cultivars

T. J. Siebenmorgen, R. C. Bautista, P. A. Counce

Abstract. *The objective of this study was to determine the harvest moisture contents (HMCs) at which rice milling quality peaked for various rice lots. Multiple samples per field of cultivars Bengal, Cypress, and Drew were harvested at northeast and southeast Arkansas locations in 1999 and 2000. Additional field sample sets of multiple cultivars were collected in 2004, 2005, and 2006 at various locations in Arkansas, Mississippi, and Missouri. Head rice yields (HRYs) were described by a quadratic equation with HMC as the independent variable. Peak HRYs varied from 63.8% to 70.6%. Optimal HMCs, determined as the MC at which HRY peaked, varied from 18.7% to 23.5% for long-grain cultivars and 21.5% to 24.0% for medium-grain Bengal. The general range of optimal HMCs was 19% to 22% for long-grains and 22% to 24% for medium-grain Bengal. For rice lots with HMCs less than the optimal HMC, the amount of HRY reduction from peak values was strongly correlated to the percentage of fissured kernels at harvest; fissured kernel percentage accounted for 77% of the variation in HRY reduction from peak HRYs.*

Keywords. *Milling quality, Head rice yield, Optimal harvest moisture content, Fissures, Rice.*

Head rice yield (HRY) is a primary measure of milling quality. HRY is 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. Currently, brokens are sold at less than 60% of the price of head rice. Because of this premium for head rice relative to brokens, HRY is a direct determinant of economic return. A number of interrelated factors during growing and processing, including kernel physicochemical properties and environmental conditions, determine rice milling quality.

Role of Harvest Moisture Content in Affecting Rice Quality

Individual kernel physical properties, and the distribution of these properties within a bulk, change as the harvest moisture content (HMC) changes (Bautista and Siebenmorgen, 2005, 2006). Some of this change is due to kernel maturation, but much is due to the influence that MC plays on properties. The bulk MC level and the individual kernel MC distribution at harvest influence milling quality (Siebenmorgen et al., 1998). Additionally, kernel thickness has been shown to impact milling performance; Matthews et al. (1982), Sun and Siebenmorgen (1993), Siebenmorgen et al. (2006) showed the influence of kernel thickness distributions on HRYs. Qin and Siebenmorgen (2005) quantified the effects of HMC and kernel thickness on kernel breaking force distributions; Siebenmorgen and Qin (2005) related kernel breaking force distributions to milling quality.

Kocher et al. (1990) showed that at high HMCs, a significant percentage of kernels in a bulk had much higher moisture contents (MCs) than the bulk average MC. These high MC kernels, generally being less mature, are typically thinner, weaker kernels than the bulk average and are more susceptible to breaking during milling than thicker, non-fissured kernels. Matthews et al. (1982) found that the thickest and thinnest kernel fractions had significantly higher percentages of fissured and broken kernels, respectively, than the intermediate thickness fractions. They postulated that thicker kernels, having lower MCs, were more susceptible to fissuring than thinner kernels due to re-wetting of kernels at MCs below a safe re-wetting threshold.

In addition to milling quality, HMC affects other processing properties. Kester et al. (1963) studied changes in the chemical and physical properties of three short-grain rice cultivars across HMC. They reported that HRY, peak viscosity, water absorption, and milled rice kernel color were highly affected by rice maturity levels. Wang et al. (2004) reported that rice HMC, in addition to cultivar and growing location, affected peak viscosity. Peak viscosity consistently increased as HMC decreased, and the rate of increase varied with cultivar and location. It is speculated that this variation was due to varying distributions of kernel MCs and corresponding maturities.

Optimal Harvest Moisture Content

Rice is normally harvested in Arkansas at 14% to 22% bulk MC (moisture contents are expressed on a wet basis). HRYs are adversely affected by harvesting rice at MCs that are either too high or too low (Siebenmorgen et al., 1992; Jo-

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dari and Linscombe, 1996). Particular emphasis has been placed on the effects of moisture adsorption fissuring by lower MC kernels on HRY reduction (Siebenmorgen and Jindal, 1986; Juliano and Perez, 1993). This work has suggested the existence of an optimal MC at which milling quality peaks.

Chau and Kunze (1982) reported that for cultivar Brazos, the highest HRYs were obtained at 24% to 26% HMC in Texas. They also reported that the longer rice at harvest MC is left in the field, the greater the probability that the lower MC kernels will fissure. Jodari and Linscombe (1996) reported that HMC, rainfall, and humidity affected milling yields of six long-grain and one medium-grain cultivars in a three-year study. They also indicated that fissured kernels increased with a decrease in HMC and were primarily caused by rapid moisture adsorption due to rainfall. Siebenmorgen et al. (1992) showed that significant losses in HRY can be incurred when long-grain rice is harvested at MCs lower than 15% or higher than 22% MC in Arkansas. Geng et al. (1984) cited that the amount of head rice decreased when rice was harvested at low HMCs in California, particularly in very early maturing varieties. Further, Geng et al. (1984) stated that no single curve could adequately represent HRY versus HMC relationships because of inherent cultivar differences and environmental variations. Consequently, it is necessary to quantify HRY versus HMC relationships for various cultivars and environments.

Given the assessment by Geng et al. (1984), the research reported herein was conducted to quantify the HRY versus HMC relationships for cultivars harvested from the USA mid-South rice production region as a means to estimate the HMC at which HRYs peaked. The research was also designed to provide fundamental information explaining HRY reduction. The reported data is part of a larger effort to understand the relationships between rice physicochemical property distributions and post-harvest processing behavior.

Materials and Methods

Panicles of Bengal (medium-grain), Cypress, and Drew (long-grains) rice cultivars were harvested at the University of Arkansas Northeast Research and Extension Center near Keiser, Arkansas, and the Rice Research and Extension Center near Stuttgart, Arkansas, at HMCs from 12% to 24% during 1999 and 2000. Additional panicles of Bengal, and long-grain cultivars Cheniere, Cocodrie, Francis, and Wells, and a long-grain hybrid, XP723, were collected in 2004, 2005, and 2006 from selected Arkansas, Mississippi, and Missouri farm trials at HMCs from 12% to 27%. Table 1 summarizes the lots collected. In 2000, Cypress panicles were not collected at Keiser, Arkansas, because of frost damage.

Each lot comprised at least 200 hand-harvested panicles (approximately 2 kg of grain). Immediately after harvest, five of the 200 panicles were randomly selected from each lot; kernels were stripped by hand from the five panicles and MCs of 300 of these kernels were measured using a single kernel moisture meter (CTR 800E, Shizuoka Seiki, Shizuoka, Japan). The average MC of the 300 individual kernel MCs was used as the lot HMC.

Table 1. Summary of rice lots harvested over the indicated ranges of moisture contents (HMCs).

Year	Location	Cultivar	No. of HMCs; HMC Range (% w.b.)
1999	Stuttgart, Ark.	Bengal	6; 12.4-22.4
	Stuttgart, Ark.	Cypress	6; 13.2-22.3
	Stuttgart, Ark.	Drew	7; 12.2-23.1
	Keiser, Ark.	Bengal	6; 14.0-24.0
	Keiser, Ark.	Cypress	6; 12.8-22.0
	Keiser, Ark.	Drew	7; 12.9-23.4
2000	Stuttgart, Ark.	Bengal	7; 12.2-23.6
	Stuttgart, Ark.	Cypress	5; 13.7-21.6
	Stuttgart, Ark.	Drew	5; 14.5-24.4
	Keiser, Ark.	Bengal	7; 13.1-24.0
	Keiser, Ark.	Cypress	No samples
	Keiser, Ark.	Drew	5; 13.9-23.7
2004	Brinkley, Ark.	Bengal	5; 15.9-26.5
	Lodge Corner, Ark.	Bengal	4; 11.6-23.0
	Hunter, Ark.	Wells	3; 15.2-25.7
	Essex, Mo.	Cocodrie	4; 13.5-23.9
	Newport, Ark.	Cocodrie	3; 14.9-24.4
2005	Osceola, Ark.	Cheniere	5; 14.4-23.2
	Stuttgart, Ark.	Francis	5; 15.5-24.4
	Stuttgart, Ark.	XP723	6; 14.7-20.0
	Cleveland, Miss.	XP723	5; 12.0-23.5
	Qulin, Mo.	Wells	5; 15.4-23.7
2006	Stuttgart, Ark.	Wells	7: 12.0-26.9
	Shaw, Miss.	XP723	4; 14.2-24.7
	Osceola, Ark.	Wells	5; 13.7-24.2
	Stuttgart, Ark.	XP723	6; 12.2-26.8
	Des Arc, Ark.	Cheniere	5; 14.7-24.1

Fissured Kernel Enumeration

Fissured kernels were enumerated in 1999 and 2000 by randomly selecting a second set of five panicles immediately after harvest, manually stripping the kernels from the panicles, and manually dehulling 200 randomly selected kernels. Each of the 200 brown rice kernels was inspected for fissures by placing kernels on the glass top of a fissure inspection box (30 × 20 × 20 cm) constructed of 10-mm thick plywood and featuring a glass top illuminated by a soft light fluorescent bulb (12 W, 120 V). Fissures were observed with a magnifying glass. The fissured kernel percentage was calculated as the percentage of the 200 inspected kernels having at least one fissure. The approximately 190 remaining panicles were stripped by hand and subsequently dried to 12.5% in a chamber in which the air conditions were maintained at 21°C and 56% relative humidity.

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

Milling Analyses

The remaining dried rough rice in each lot was cleaned and used for milling analyses. Two, 150-g 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 using a sizing machine (Grainman Model 61-115-60, Grain Machinery Manufacturing Corp., Miami, Fla.) with screen sizes #10 (4.0 mm, 10/64 in.) for medium-grain and #12 (4.8 mm, 12/64 in.) for long-grain cultivars. Analyses were performed using statistical software (JMP®, 2001).

Results and Discussion

Fissured Kernel Percentages

Figures 1, 2, 3, 4, and 5 show the percentage of fissured kernels from lots harvested in 1999, 2000, 2004, 2005, and 2006, respectively. For all cultivars, fissured kernel percentages increased exponentially as HMC decreased below HMCs of 19% to 22%; however, the rate of increase varied among cultivars. For example, the rate of increase in fissured kernel percentage for Cypress in 1999 from Stuttgart and Keiser was less than that of Bengal and Drew from those locations (fig. 1). Cypress is regarded as a fissure resistant

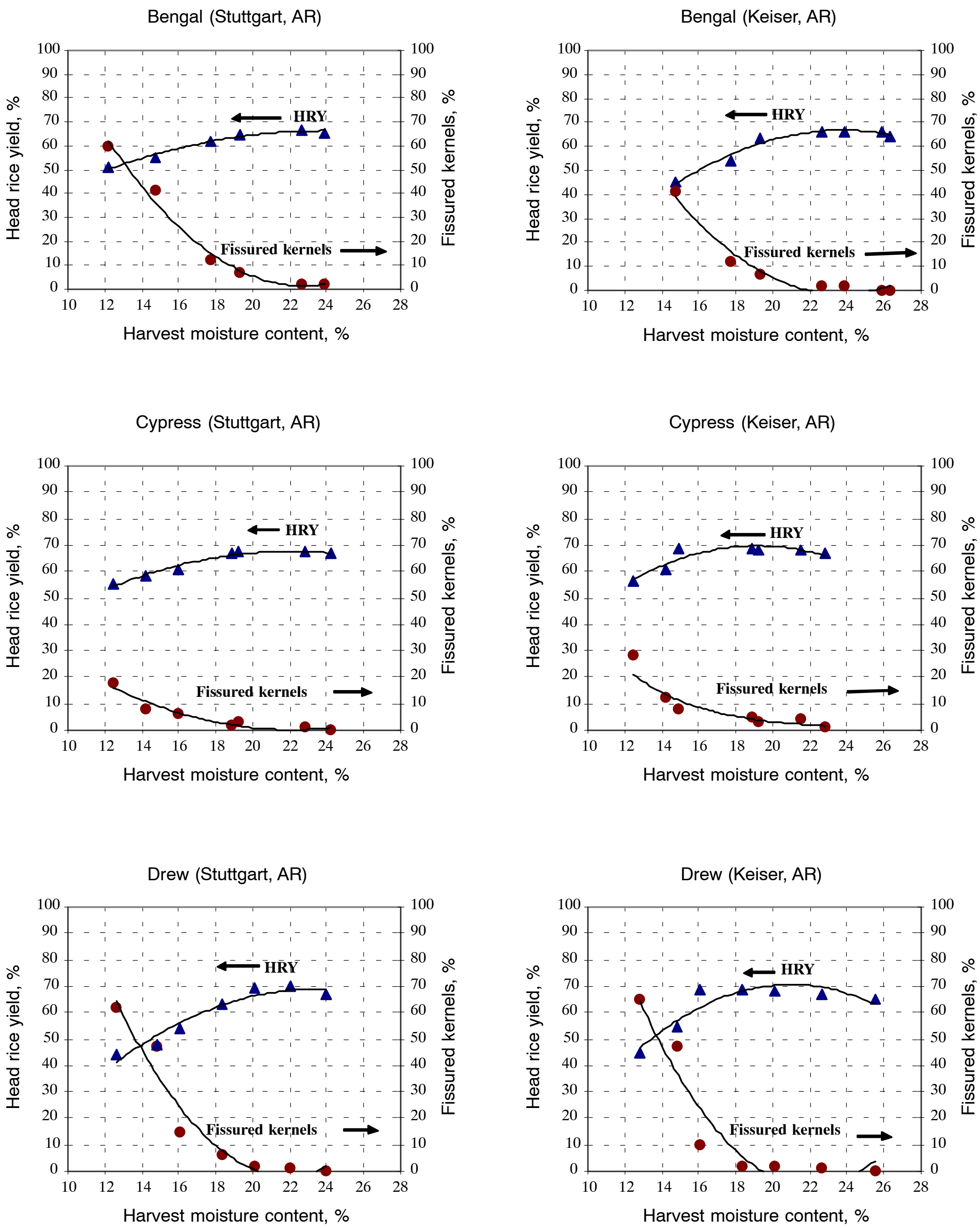

Figure 1. Fissured kernel percentages and head rice yields (HRYs) vs. harvest moisture content for the indicated rice lots harvested in 1999. Each fissured kernel percentage data point represents the percentage of fissured kernels in 200 brown rice kernels. Each HRY data point represents the average of two milling repetitions.

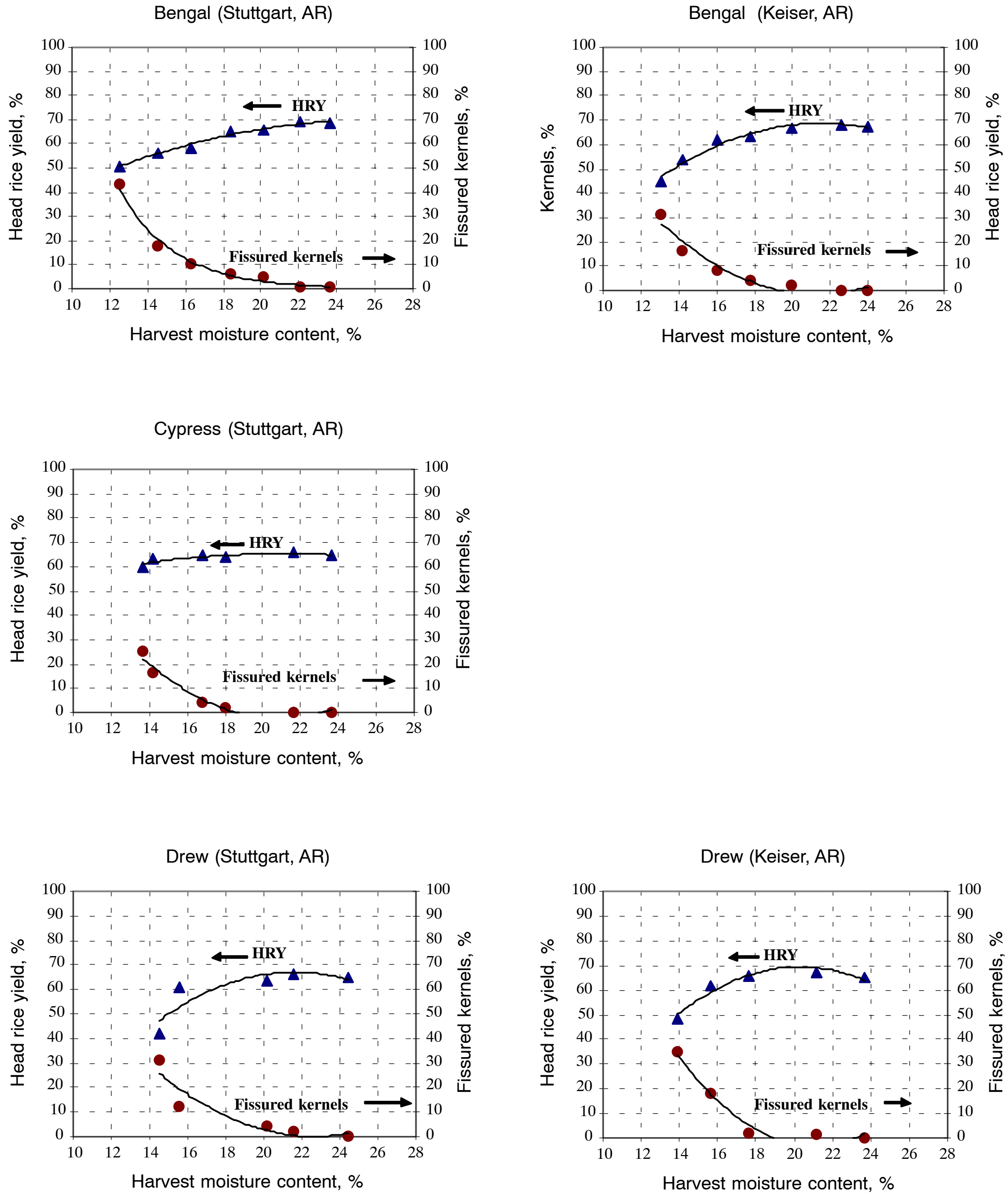

Figure 2. Fissured kernel percentages and head rice yields (HRYs) vs. harvest moisture content for the indicated rice lots harvested in 2000. Each fissured kernel percentage data point represents the percentage of fissured kernels in 200 brown rice kernels. Each HRY data point represents the average of two milling repetitions.

variety (Jodari and Linscombe, 1996) and exemplified this characteristic in 1999 and to a lesser extent in 2000 (fig. 2).

As HMC decreased to 15%, approximately 35% of Bengal and Drew kernels had fissured in 1999 (fig. 1). In 2000, when HMC had decreased to 15%, approximately 15% to 20% of the Bengal and Drew kernels had fissured (fig. 2). Variation in weather during the harvest season could have been responsible for this year to year fissuring level variation. Additionally, year to year variation in production practices and environments could have produced different individual kernel MC distributions that, when exposed to weather conditions during the harvest season, would have caused different fissuring responses (Siebenmorgen et al., 1998).

The primary cause of fissure formation is reasoned to be moisture adsorption by low MC kernels (Kunze and Hall, 1967; Siebenmorgen and Jindal, 1986). Environments causing moisture adsorption could have been produced by rain or high ambient air relative humidity, both of which have been shown to reduce HRYs (Siebenmorgen and Jindal, 1986).

Fewer samples at low HMCs were collected in 2004, 2005, and 2006 (figs. 3, 4, and 5) than 1999 and 2000, yet the percentage of fissured kernels increased similarly with decreases in HMC, albeit at an apparently lower rate. At 15% HMC, the fissured kernel percentage ranged from 5% to 25% in 2004 (fig. 3), 8% to 15% in 2005 (fig. 4), and 5% to 25% in 2006 (fig. 5). It is speculated that fissured kernel

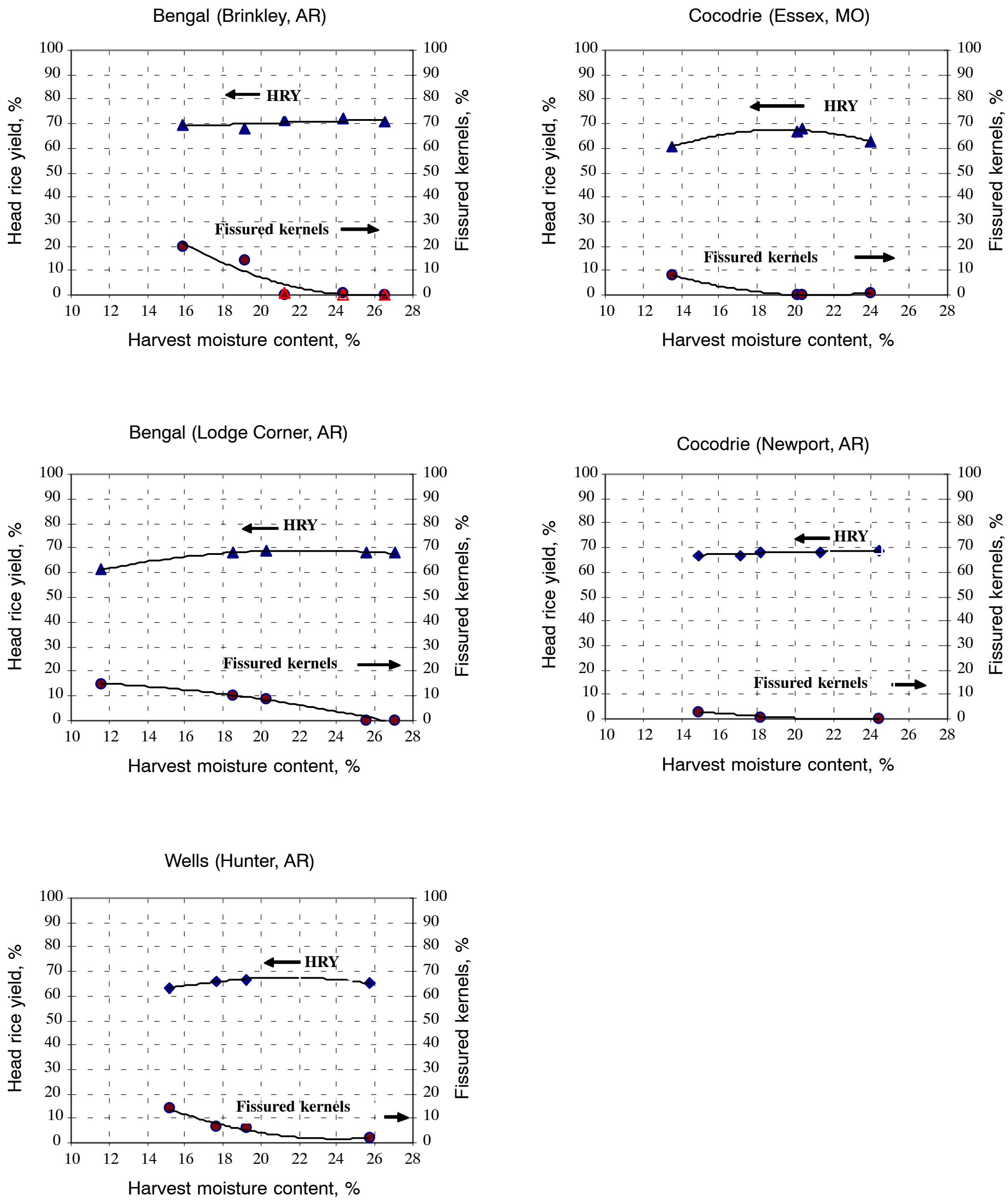

Figure 3. Fissured kernel percentages and head rice yields (HRYs) vs. harvest moisture content for the indicated rice lots harvested in 2004. Each fissured kernel percentage data point represents the percentage of fissured kernels in 200 brown rice kernels. Each HRY data point represents the average of two milling repetitions.

percentages would have exponentially increased as HMCs decreased below 15% MC. A possible source of differences in fissured kernel percentages in 1999 and 2000 versus 2004, 2005, and 2006 was the difference in fissure enumeration procedures. In 1999 and 2000, fissures were counted using hand-stripped kernels immediately after harvest. In 2004, 2005, and 2006, fissures were counted using thresher-stripped kernels after gentle drying. It was assumed that neither procedure would impart damage to produce fissures, but if either would, it is reasoned that the mechanical stripping and subsequent drying would sooner do so, yet the years in which this procedure was used (2004-2006) had lower fissure percentages. Thus, it is presumed that the apparently lower fissure rates in the latter years were due to differences in growing conditions and prevailing weather at each location.

Some cultivars planted in different locations in the same year varied in fissured kernel percentage trends. Such was the case for Bengal in 2004 (fig. 3), which had greater fissured kernel percentages at Brinkley, Arkansas (20% at 16% HMC) than at Lodge Corner, Arkansas (12% at 16% HMC). A similar case held for XP723 at Stuttgart, Arkansas and Shaw, Mississippi in 2006 (fig. 5). The variation is speculated to be due primarily to environmental differences during the harvest period.

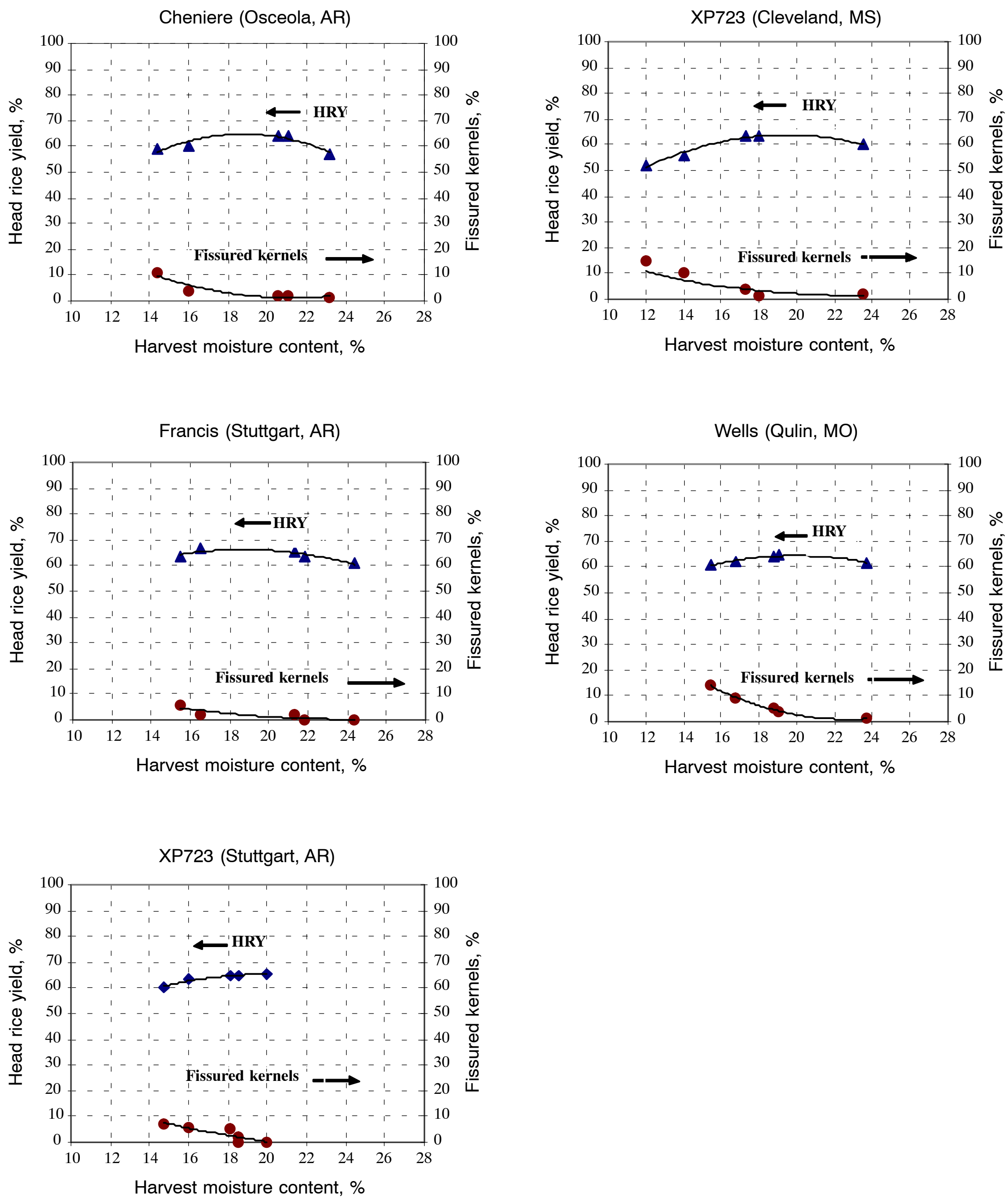

Figure 4. Fissured kernel percentages and head rice yields (HRYs) vs. harvest moisture content for the indicated rice lots harvested in 2005. Each fissured kernel percentage data point represents the percentage of fissured kernels in 200 brown rice kernels. Each HRY data point represents the average of two milling repetitions.

Head Rice Yield Trends

Figures 1, 2, 3, 4, and 5 also show HRY versus HMC data for lots harvested in 1999, 2000, 2004, 2005, and 2006, respectively. Analysis of variance showed a significant difference in HRY as a function of HMC ($P < 0.0001$) for each cultivar except for 2004 Bengal harvested at Brinkley, Arkansas and Cocodrie at Newport, Arkansas (fig. 3).

In 1999 and 2000, the overall HRY versus HMC trends across cultivars showed that the magnitude of HRY reduction at either high or low HMCs was somewhat cultivar dependent, with Cypress generally having the least HRY reduction, particularly in 2000 (fig. 2). Differences in cultivar HRY responses in 2004, 2005, and 2006 were also apparent but not as dramatic as in 1999 and 2000. This could have largely been due to the more limited HMC range in the latter years.

Figures 1 through 5 show that as HMCs decreased from high levels (greater than 22%), HRYs increased. The increase in HRYs can be attributed to the decrease in the percentage of immature kernels at high HMCs. Siebenmorgen and Qin (2005) and Siebenmorgen et al. (2006) showed that the mechanical strength and milling quality of thin, immature kernels was drastically lower than that of thicker, fully mature kernels.

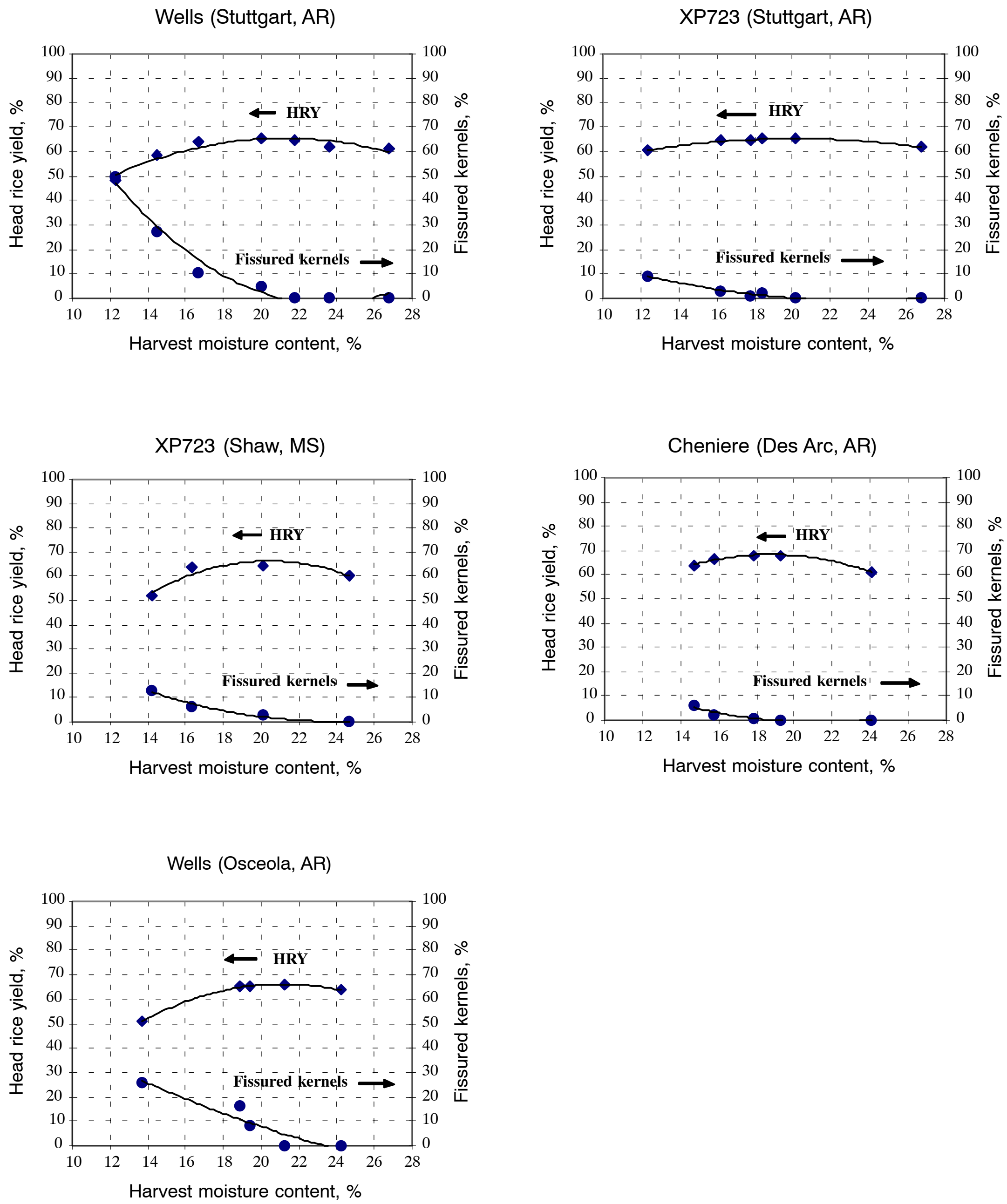

Figure 5. Fissured kernel percentages and head rice yields (HRYs) vs. harvest moisture content for the indicated rice lots harvested in 2006. Each fissured kernel percentage data point represents the percentage of fissured kernels in 200 brown rice kernels. Each HRY data point represents the average of two milling repetitions.

After reaching a peak, HRYs generally decreased as HMC decreased (figs. 1 to 5); the decrease in HRYs was highly correlated with the increase in fissured kernel percentages, as presented below. There was no significant change in 2004 Bengal (Brinkley, Ark.) and Cocodrie (Newport, Ark.) HRYs with HMC. It is noted that the lowest HMC for these Bengal lots was approximately 16% and for Cocodrie, 15%; as such, the effects of moisture adsorption in producing fissures were not evident. Additionally, the 2004 growing season in Arkansas was characterized as having lower than normal ambient temperatures. Counce et al. (2005) and Cooper et al. (2006) have shown that high nighttime air temperatures during kernel development can have deleterious effects on HRYs. Thus, the minimal HRY reductions in 2004 could possibly be due to favorable environmental conditions during kernel development and maturation.

Peak Head Rice Yields and Optimal Harvest Moisture Contents

The HRY versus HMC relationships (figs. 1 to 5) were described using a quadratic function:

$$HRY = a_i \cdot HMC^2 + b_i \cdot HMC + c_i \qquad (1)$$

where HMC is expressed as % w.b. and HRY as %; a_i, b_i, and c_i are regression variables; the subscript i refers to the year/location/cultivar lot sets of table 1.

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

Year	Location	Cultivar	a_i	b_i	c_i	R^2	Opt. HMC[a] (%, w.b.)	Opt. HMC Range[b][c]	Peak HRY[a] (%)
1999	Stuttgart, Ark.	Bengal	-0.1207	5.7325	-1.7553	0.98	23.7	21.7-	66.3
	Stuttgart, Ark.	Cypress	-0.1436	6.3436	-2.4039	0.98	22.1	20.3-23.9	67.7
	Stuttgart, Ark.	Drew	-0.2345	11.0100	-60.2390	0.93	23.5	22.0-	69.0
	Keiser, Ark.	Bengal	-0.2730	12.9800	-87.5030	0.96	23.8	22.4-25.1	66.8
	Keiser, Ark.	Cypress	-0.2800	10.8060	-33.8400	0.82	19.3	18.0-20.6	70.4
	Keiser, Ark.	Drew	-0.3640	15.2540	-89.2060	0.86	21.0	19.8-22.1	70.6
2000	Stuttgart, Ark.	Bengal	-0.1063	5.5248	-1.8773	0.98	23.0	21.0-	69.9
	Stuttgart, Ark.	Cypress	-0.0732	3.0852	32.8430	0.71	21.1	18.5-	65.4
	Stuttgart, Ark.	Drew	-0.3937	17.0080	-116.5800	0.77	21.6	20.5-22.7	67.1
	Keiser, Ark.	Bengal	-0.3068	13.1900	-73.0270	0.96	21.5	20.2-22.8	68.7
	Keiser, Ark.	Drew	-0.4690	19.0460	-123.9600	0.94	20.3	19.3-21.3	69.4
2004	Brinkley, Ark.	Bengal	[d]	[d]	[d]	[d]	[d]		[d]
	Lodge Corner, Ark.	Bengal	-0.0668	2.9983	35.7500	0.93	22.4	19.7-25.2	69.4
	Hunter, Ark.	Wells	-0.1136	4.8420	15.8700	1.00	21.3	19.2-23.4	67.5
	Essex, Mo.	Cocodrie	-0.2151	8.2862	-12.2500	0.97	19.3	17.7-20.8	67.6
	Newport, Ark.	Cocodrie	[d]	[d]	[d]	[d]	[d]		[d]
2005	Osceola, Ark.	Cheniere	-0.3582	13.4440	61.3340	0.81	18.8	17.6-19.9	64.8
	Stuttgart, Ark.	Francis	-0.1735	6.4733	5.7470	0.74	18.7	17.0-20.4	66.1
	Stuttgart, Ark.	XP723	-0.1905	7.4658	-7.9433	0.93	19.6	18.0-21.2	65.2
	Cleveland, Miss.	XP723	-0.2228	8.6679	-20.5300	0.98	19.5	18.0-21.0	63.8
	Qulin, Mo.	Wells	-0.1872	7.4632	-9.8707	0.94	19.9	18.3-21.6	64.5
2006	Stuttgart, Ark.	Wells	-0.1881	7.9834	-19.2540	0.89	21.2	19.6-22.9	65.6
	Shaw, Miss.	XP723	-0.3361	13.7150	-73.5650	0.85	20.4	19.2-21.6	66.4
	Osceola, Ark.	Wells	-0.2710	11.4660	-55.0530	0.99	21.2	19.8-22.5	66.2
	Stuttgart, Ark.	XP723	-0.0814	3.2759	32.3600	0.97	20.1	17.6-22.6	65.3
	Des Arc, Ark.	Cheniere	-0.2524	9.4555	-20.2110	0.99	18.7	17.3-20.1	68.4

[a] The optimal harvest moisture contents (HMCs) and peak head rice yields (HRYs) were calculated using equations 1 and 2.
[b] The Opt. HMC range represents the HMC range corresponding to HRYs within 0.5 pp of the peak HRY.
[c] The upper limit of the HMC range was not listed when the predicted HMC exceeded the highest measured HMC.
[d] Head rice yields were not statistically related to harvest moisture content.

The results of the equation 1 regression analysis are presented in table 2, including the coefficients of determination for each quadratic equation. The quadratic equations generally described the HRY trends well with R^2 values all being greater than 0.70, with most being greater than 0.90.

From these quadratic equations, the HMC at which HRY peaked for each lot set was determined by using the first derivative of equation 1:

$$\frac{\partial HRY}{\partial HMC} = 2 \cdot a_i \cdot HMC + b_i \qquad (2)$$

By setting equation 2 to zero and solving for HMC, the "optimal" HMCs at which HRYs peaked in each lot set were computed. Peak HRYs were calculated as the HRY of equation 1 at the optimal HMC. The peak HRYs and optimal HMCs are listed in table 2. These peak HRYs and optimal HMCs are a manifestation of each cultivar's response to the environment in which it was produced.

Peak HRYs ranged from 63.8% to 70.6%. Because the hulls and bran comprise approximately 30% of the mass of rough rice, the theoretical maximum HRY that can be attained is approximately 70%; slight variations in this value can occur due to variations in the degree to which a rice sample is milled. In 1999, peak HRYs for Keiser Cypress and Drew were near the theoretical maximum, while for the other 1999 lot sets, peak HRYs were 1.0 to 3.7 percentage points (pp) below the 70% level. Similar observations held in 2000 in that the Keiser peak HRYs were near maximum, yet the Stuttgart Cypress and Drew peak HRYs were 4.6 and 2.9 pp below maximum, respectively. The mean of peak HRYs in 2005 (64.9%) was less than those in the other four years of the study.

The reasons for the lower peak HRYs in some lot sets versus others could be due in part to the deleterious effects of high nighttime air temperatures cited by Counce et al. (2005) and Cooper et al. (2006). The hypothesis of these works was that high nighttime air temperatures during the filling stage of kernel development could lead to disruptions in the enzymatic activities responsible for kernel filling, which would result in lower average kernel strengths, and thereby lower HRYs. Because the critical stage for this effect is at kernel filling, the negative effects of high nighttime air temperatures would be manifested if the rice growth stage and high ambient nighttime air temperatures coincided. Thus, ambient environmental conditions, planting dates, and the rate of development for a given cultivar, all determine whether deviations from the theoretical maximum occur. While beyond the scope of this study, efforts are underway to correlate HRY reductions from the theoretical maximum to the incidence of nighttime air temperature levels for each lot set used in this study.

The optimal HMC relative to maximizing HRY varied considerably across cultivar and year. In 1999 at Stuttgart, Bengal HRY peaked at 23.7% HMC, Cypress at 22.1%, and Drew at 23.5%. In 1999 at Keiser, Bengal HRY peaked at 23.8% HMC, Cypress at 19.3%, and Drew at 21.0%. In 2000 at Stuttgart, Bengal HRY peaked at 23.0% HMC, Cypress at 21.1%, and Drew at 21.6%. 2004 Bengal had different optimal HMCs, depending on location; HMC did not affect Bengal HRYs at Brinkley within the HMC range of 16% to 27%, and the optimal HMC for Bengal at Lodge Corner was 22.4%. 2004 Cocodrie harvested at Essex, Missouri, peaked at 19.3% HMC while 2004 Cocodrie at Newport also was not affected by HMC within the HMC range of 15% to 24%. Wells harvested at Hunter in 2004, while not showing large HRY changes with HMC, had an optimal HMC at 21.3%. For 2005, dramatic changes in HRY were observed for samples collected at different HMCs and locations; peak HRYs varied with HMC as follows; Cheniere (Osceola) peaked at 18.8% HMC, Francis (Stuttgart) at 18.7%, XP723 (Stuttgart) at 19.6%, XP723 (Cleveland) at 19.5%, and Wells (Qulin) at 19.9%.

To summarize, the HMCs at which HRY peaked ranged from 18.7% to 23.8%, indicating a fairly wide range. For the long-grain cultivars, the optimal HMC generally fell between 19% and 22%. For medium-grain Bengal, the optimal HMC generally ranged from 22% to 24%.

Jodari and Linscombe (1996) also observed large ranges in optimal HMCs for long- and medium-grain cultivars. They reported optimal HMCs for five long-grain cultivars from 15.1% to 17.9% during 1991 to 1993. For another long-grain cultivar, Lemont, known to be a bold kernel cultivar, the optimal HMC ranged from 17.6% to 20.0% during this three-year period. For Bengal during this period, the optimal HMC range was 17.9% to 23.8%. Jodari and Linscombe reported that the optimal HMC range varied significantly from year to year.

There were large differences across the year/location/cultivar lot sets in the rate at which HRY decreased with HMC from the optimal HMC for a given lot set. The extent of these rate differences can be observed from the curvature of the HRY versus HMC relationships in figures 1 through 5. Mathematically, this can also be observed through the a_i and b_i values of table 2; the larger the absolute values of a_i and b_i, the more curvature the HRY versus HMC relationships will have and thus, the faster HRY will decrease with deviations from the optimal HMC. As a means of practically quantifying these effects, the optimal HMC range is presented in table 2. This range represents the span of HMCs that would produce HRYs within ±0.5 pp of the peak HRYs. This data indicates the "window" for harvesting rice to maintain HRYs reasonably close to the peak HRY for that field. Table 2 indicates that the HMC window generally spanned 2.5 to 3.5 pp, although lesser and greater ranges were observed.

Correlation of Fissured Kernel Percentage to Head Rice Yields

The decline in HRY after a peak was highly correlated with the percentage of fissured kernels for each cultivar (figs. 1 to 5). As a means of explaining HRY reduction at low HMCs, the HRY reduction of a lot from the peak level attainable for a rice lot set was correlated to the fissured kernel percentage for that lot. Head rice yield reduction was calculated as:

$$HRYR_n = HRY_{peak} - HRY_n \tag{3}$$

where

$HRYR_n$ = the HRY reduction for a rice lot, percentage points

HRY_{peak} = peak HRY for a rice lot set (table 2), %

HRY_n = the HRY of a given rice lot, %.

Figure 6 shows the HRYRs and the associated fissured kernel percentages for cultivars harvested in 1999. Data collected in 2000, 2004, 2005, and 2006 showed similar trends (data not shown). In most all cases, an increase in the fissured kernel percentage was associated with an increase in HRYR. It is to be noted that a 1:1 mathematical association between HRYR and fissured kernel percentage could not exist as HRY calculations inherently include the hull and bran masses as part of the denominator base whereas the fissured kernel percentage is based on a direct kernel number percentage. Nevertheless, figure 6 shows a close association between HRYR and percentage of fissured kernels.

As a means of more comprehensively observing this association, figure 7 shows a correlation of HRYR to fissured kernel percentage for all rice lots in this study having HMCs less than the optimal HMC for a given lot set. Fissured kernel percentage accounted for 77% of the variation in HRYR, which is considered good, given the inherent errors associated with manual fissure counting and HRY measurement. This correlation indicates that the fissured kernel percentage should be kept as low as possible to maintain high HRYs. Measures to prevent kernel fissuring include harvesting rice before reaching critical MC levels when kernels are susceptible to fissuring due to rapid moisture adsorption.

Summary

Head rice yield data were described by quadratic relationships with HMC. These relationships were used to estimate both the maximum HRY that could have been attained for a given HRY versus HMC lot set and the HMC at which that maximum HRY occurred. Based on this procedure, the optimal HMCs for maximizing HRYs were found to vary from 18.7% to 23.5% for the long-grain cultivars and 21.5% to 23.8% for the medium-grain Bengal cultivar produced in the mid-South rice producing region. The general ranges of optimal HMCs were 19% to 22% for long-grain cultivars and 22% to 24% for medium-grain Bengal.

The primary cause of HRY reduction as HMC decreased below optimal levels was attributed to moisture adsorption fissuring. The percentage of fissured kernels accounted for 77% of the variation in HRY reduction from the peak HRY that could have been attained for that particular field.

Maximum HRYs varied from 63.8% to 70.6%. Based on recent research, the effects of nighttime air temperatures during kernel development could offer an explanation for this inexplicable variation and merits further, specific investigation.

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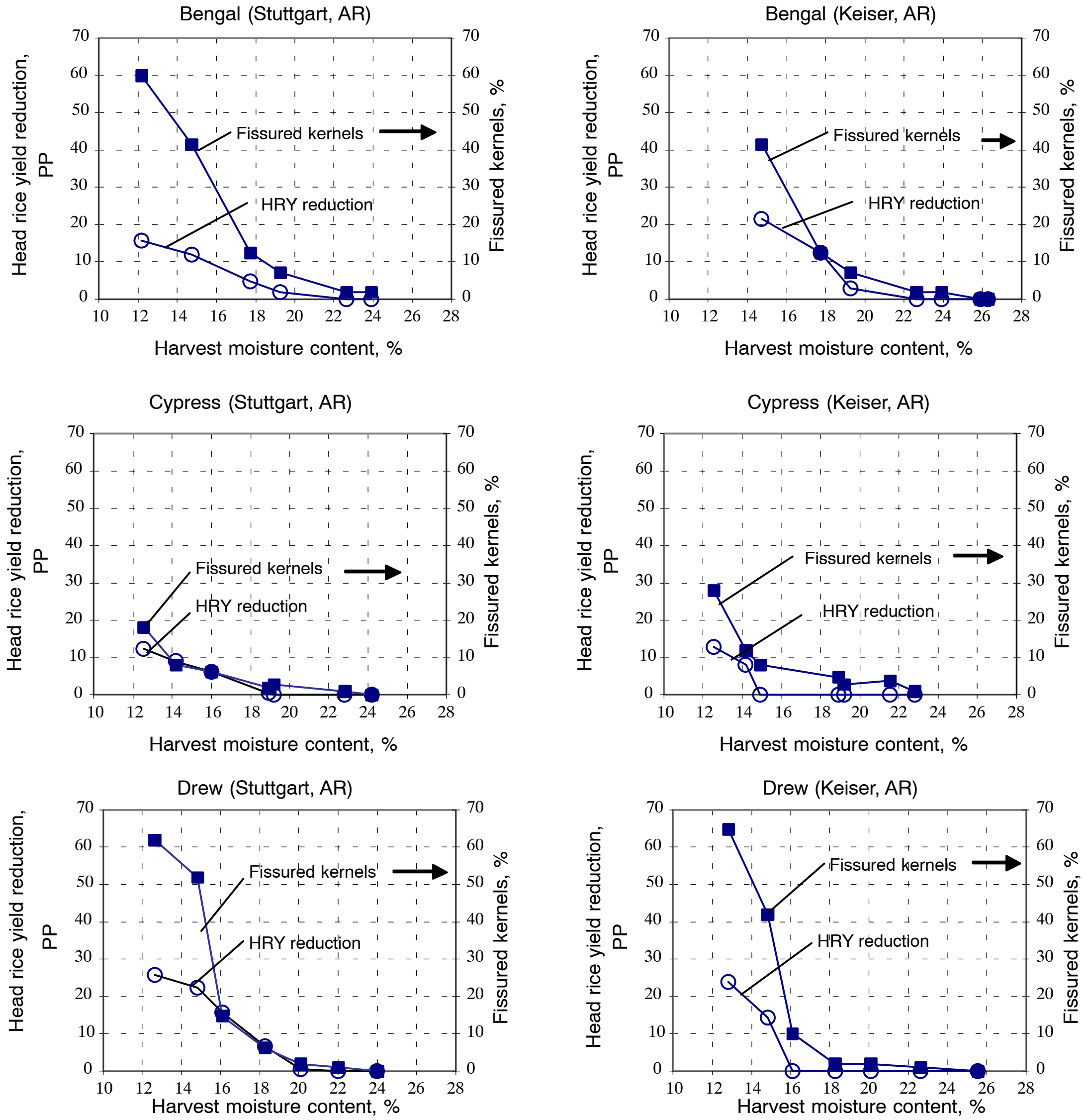

Figure 6. Head rice yield (HRY) reductions and fissured kernel percentages for cultivars harvested at various moisture contents in 1999 from Stuttgart and Keiser, Ark. HRY reduction was calculated as the difference between the peak HRY (table 2) and that at a given harvest moisture content (eq. 3).

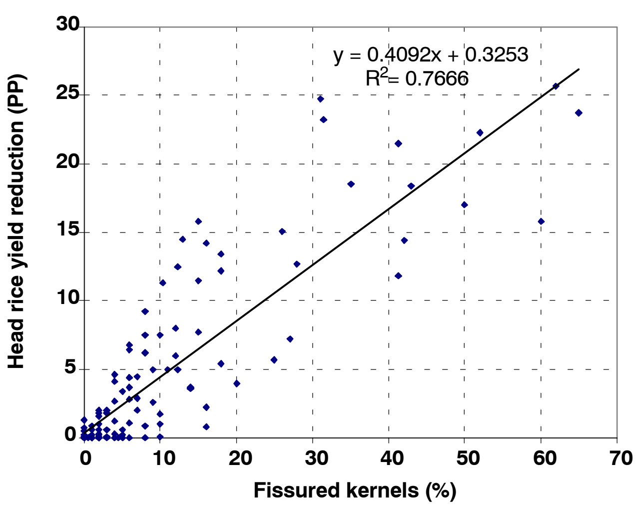

Figure 7. Correlation of head rice yield reduction (eq. 3) to fissured kernel percentage for all rice lots in this study having harvest moisture contents (HMCs) less than the optimal HMC (table 2) for a given lot set.

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