RICE KERNEL DIMENSIONAL VARIABILITY TRENDS

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

ABSTRACT. *Rice kernel dimensions affect the performance of various post-harvest processes. This study assessed variability trends in kernel dimensional distributions of Bengal (medium-grain), Cypress, and Drew (long-grains) rice varieties. Rice was harvested at various stages of maturity from Stuttgart and Keiser, Arkansas during the autumns of 1998, 1999, and 2000. Brown rice kernel dimensions decreased with harvest moisture content [HMC (Moisture contents are expressed on a wet basis)] below 24% HMC. Kernel dimensional distributions were usually single-modal and near normal. Brown rice dimensional variability, expressed by kernel dimensional standard deviation (SD), was significantly affected by HMC and location. Kernel dimensional SD generally was linearly and directly related to HMC. Among kernel dimensions, thickness had the greatest shrinkage with decreasing HMC, followed by length and then width. Among varieties, Bengal had the greatest kernel shrinkage, followed by Drew, and then Cypress.*

Keywords. *Individual kernel dimensions, Length, Width, Thickness, Dimensional variability, Rice kernel, Shrinkage, Rice.*

Uniformity of rice kernel dimensions is very important in that the performance of practically all post-harvest processes (hulling, milling, sizing, puffing, and cooking) is dependent on one or more kernel dimensions. For example, kernel thickness affects fissuring during pre- and post-harvest processes in that thick kernels from a bulk are more susceptible to fissuring than thinner kernels (Jindal and Siebenmorgen, 1994). Fissured kernels usually break during milling and thus reduce milling quality.

Physiologically, the rice caryopsis (the dehulled or brown rice kernel) attains full length (long axis dimension) first, then full width (dorso-ventral or transverse dimension), and finally full thickness (Luh and Luh, 1991). The kernel attains full length by four days after flowering (DAF), maximum width by 14 DAF, and maximum thickness by 21 DAF (del Rosario et al., 1968, as cited by Juliano, 1985). Kernels from a rice panicle or from an entire plant develop and mature asynchronously. Individual kernel moisture content (MC) distributions from panicles are multi-modal, especially at HMCs greater than 16% (Kocher et al., 1990; Bautista and Siebenmorgen, 2005). Holloway et al. (1995) postulated an explanation for these multi-modal MC distributions based on the fact that all kernels do not emerge simultaneously and that individual kernel MC profiles throughout development contain plateaus at which MC does not change appreciably. Anthesis or flowering generally starts at the top of the panicle and ends at the bottom; the process of flowering can occur over a period of 15 days (Luh and Luh, 1991). Jongkaewwattana et al. (1993) showed that kernel size and rate of filling decreased from the upper to the lower parts of the panicle for six short-, medium- and long-grain cultivars.

FACTORS AFFECTING KERNEL DIMENSIONS

Beyond the kernel-to-kernel development differences within panicles, it is also believed that kernels are affected by other factors during the filling process that could cause dimensional variation. These factors include diseases, the environment during kernel development, and production management practices such as fertilizer and irrigation applications. Candole et al. (2001) reported the negative effects of two common production diseases in rice, blast and sheath blight, on the physical properties of kernels. Rough rice kernels from blast-infected panicles were 7 to 10 percentage points drier and 10% thinner than kernels from blast-free panicles. There were similar negative effects of sheath blight infection on kernel thickness. Another factor influencing kernel dimensional distributions is nighttime temperature during kernel development. A controlled environment growth chamber study showed that rice plants exposed to high nighttime temperature during kernel development produced a greater number of thinner and empty kernels at harvest; this corresponded to a significant head rice yield reduction (HRY) (Counce et al., 2005). Hoshikawa (1993) showed that higher temperatures at the ripening stage of early-planted rice affected brown rice kernel shape and size.

KERNEL THICKNESS AND ITS RELATIONSHIP TO KERNEL MC AND MECHANICAL STRENGTH

Among kernel dimensions, thickness has been most successfully tied to other kernel properties. Kernel thickness has been related to kernel MC. Wratten et al. (1969) showed that the average thickness of rough rice kernels decreased as MC decreased. Wadsworth et al. (1982) reported that for medium-grain (var. Nato) and long-grain (vars. Lebonnet and Labelle) rice, the average MC difference between thick and thin fractions ranged from 0.6 to 3.5 percentage points with the thin fractions having greater MC. Wadsworth et al. (1982)

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stated that kernel thickness could be an effective basis for separating rice kernels so that the MC variation within the fractionated portions would be greatly reduced; thus possibly improving rice drying and milling quality.

Kernel thickness has been related to milling quality. Kunze and Hall (1967) found that bold rice kernels [rice type with kernels whose length:width ratio ranges from 1.1 to 2.0 (IRRI, 1966)] were more susceptible to fissuring than slender kernels. Matthews et al. (1982) speculated that thicker kernels, having lower MC, were more susceptible to fissure occurrence. Thicker kernels when exposed to rapid moisture adsorption creates moisture gradient in the kernel that produces stress in the kernel that cause kernel fissuring. Sun and Siebenmorgen (1993) found that the thickest and thinnest kernel fractions from samples had significantly higher percentages of fissured and broken kernels, respectively, than the intermediate thickness fractions. Thinner kernels, generally being less mature and of lower mechanical strength, are more susceptible to breakage than thick kernels during milling. Wadsworth et al. (1982) and Matthews et al. (1982) reported higher percentages of fissured kernels among thicker kernel fractions.

Siebenmorgen and Qin (2005) reported significant correlations between brown rice kernel thickness and breaking forces as determined using a three-point bending test. They reported that the breaking forces of brown rice kernels were not significantly related to kernel width or length. Sun et al. (2002) also showed a strong contribution of thickness in predicting kernel breaking force.

Kernel Thickness and Chemical Composition

Wadsworth and Matthews (1986) studied the chemical composition of rice associated with the thickness of kernels; higher protein, lipid, fiber, and ash contents were found in the thinner compared with thicker kernels. Studies conducted in 2003 of thickness-fractionated rice showed higher protein and total lipid contents for thin, followed by medium, and thick brown rice kernels (Siebenmorgen and Bautista, 2005).

The above-mentioned works have indicated the existence of kernel size variability and the importance of kernel dimensional distributions, especially thickness, in affecting milling and functional properties. However, little work has been done to systematically quantify the variation in individual kernel dimensions for various varieties of rice grown in various locations and across years. This study was thus conducted to measure trends in kernel dimensions as affected by these variables. Results of this study will provide fundamental information on kernel dimensional variability trends to be used as a reference for improving rice kernel dimensional property and variety selection for end-use processing.

Materials and Methods

Panicles of rice varieties Bengal (medium-grain), Cypress and Drew (long-grains) were collected from foundation seed fields at the University of Arkansas research and extension centers near Keiser and Stuttgart, Arkansas, at HMCs that ranged from about 12% to 24% during the autumns of 1998, 1999, and 2000 (table 1). In 2000, only Bengal and Drew samples were collected from Keiser because of frost damage to Cypress. Each sample comprised 20 panicles collected by hand at approximately two percentage point increments in MC decline. Ten of the 20 panicles were selected randomly for kernel dimension measurements. The remaining 10 panicles were used for kernel MC measurements. A single kernel moisture meter (CTR 800E, Shizuoka Seiki Co., Ltd., Fukurui City, Shizuoka, Japan) was used to measure the kernel MCs of 300 kernels randomly selected from stripped kernels from the 10 panicles immediately after harvest (Bautista and Siebenmorgen, 2005). The individual kernel MC meter was calibrated and showed good correlation ($R^2 = 0.98$) with MCs determined by drying at 130°C for 24 h in a forced air oven.

Table 1. Summary of samples collected at various harvest moisture contents (HMCs) for Bengal, Cypress, and Drew rice from Keiser and Stuttgart, Arkansas, in 1998, 1999, and 2000.

Year	Variety	Location	Number of HMCs; HMC Range (%)
1998	Bengal	Keiser	7; 12.1 – 24.1
		Stuttgart	6; 12.7 – 24.6
	Cypress	Keiser	6; 11.0 – 22.3
		Stuttgart	7; 12.6 – 23.4
	Drew	Keiser	6; 12.1 – 23.0
		Stuttgart	7; 12.6 – 24.5
1999	Bengal	Keiser	6; 14.0 – 22.4
		Stuttgart	5; 14.1 – 22.4
	Cypress	Keiser	6; 12.8 – 22.0
		Stuttgart	6; 13.2 – 22.3
	Drew	Keiser	7; 12.9 – 23.4
		Stuttgart	7; 12.2 – 23.1
2000	Bengal	Keiser	6; 12.0 – 24
		Stuttgart	6; 12.0 – 23.6
	Cypress	Keiser	No samples
		Stuttgart	5; 13.7 – 22.6
	Drew	Keiser	6; 13.9 – 23.7
		Stuttgart	5; 14.5 – 24.4

An image analysis system (RIA IA, Satake Co., Higashi-Hiroshima City, Hiroshima, Japan) was used to measure individual rough and brown rice kernel dimensions. Five panicles were randomly selected and prepared for rough rice kernel dimensional measurements and another five panicles for brown rice measurements, with the kernels from each panicle measured and grouped separately. The number of kernels on a panicle varied from 40 to 200. The image analyzer was calibrated with a standard deviation of ±0.01 mm for length and width, and ±0.015 mm for thickness prior to testing.

Kernels were stripped from panicles and cleaned by hand. Any empty kernels and foreign matter were discarded. To produce brown rice, kernels were dehulled manually using tweezers. Extreme care was observed in dehulling each kernel to avoid damage to the bran or the endosperm. Brown rice dimensional measurements were indicative of the kernel dimensions devoid of the air spaces that could be present within a rough rice kernel. For this reason, analysis of brown rice kernels was given more emphasis. After sample preparation, rice kernels were placed onto the feeding device of the image analyzer, which individually positioned kernels onto an illuminated screen where two cameras captured kernel images. Kernel orientation was controlled by a feeding guide that aligned each kernel as they were positioned on top of the imaging screen. The first camera captured images of the kernel from the top view for kernel length and width measurements, while the second camera captured images of the kernel from the side view to measure thickness. Images were then digitized and analyzed to calculate kernel dimensions. Statistical analyses were performed using JMP® (JMP® ver. 5, SAS Institute, Cary, N.C.) with kernel dimensions as dependent variables and years, and location as the independent variables. For each variety, analysis of variance and effect tests were performed to address the effect of the independent variables on kernel dimensions.

Results and Discussion

Kernel Dimensional Distributions and Shrinkage at Harvest

Figure 1 shows the individual brown rice kernel dimensional distributions from panicles of Bengal, Cypress, and Drew harvested at Stuttgart in 1998; two HMCs were selected

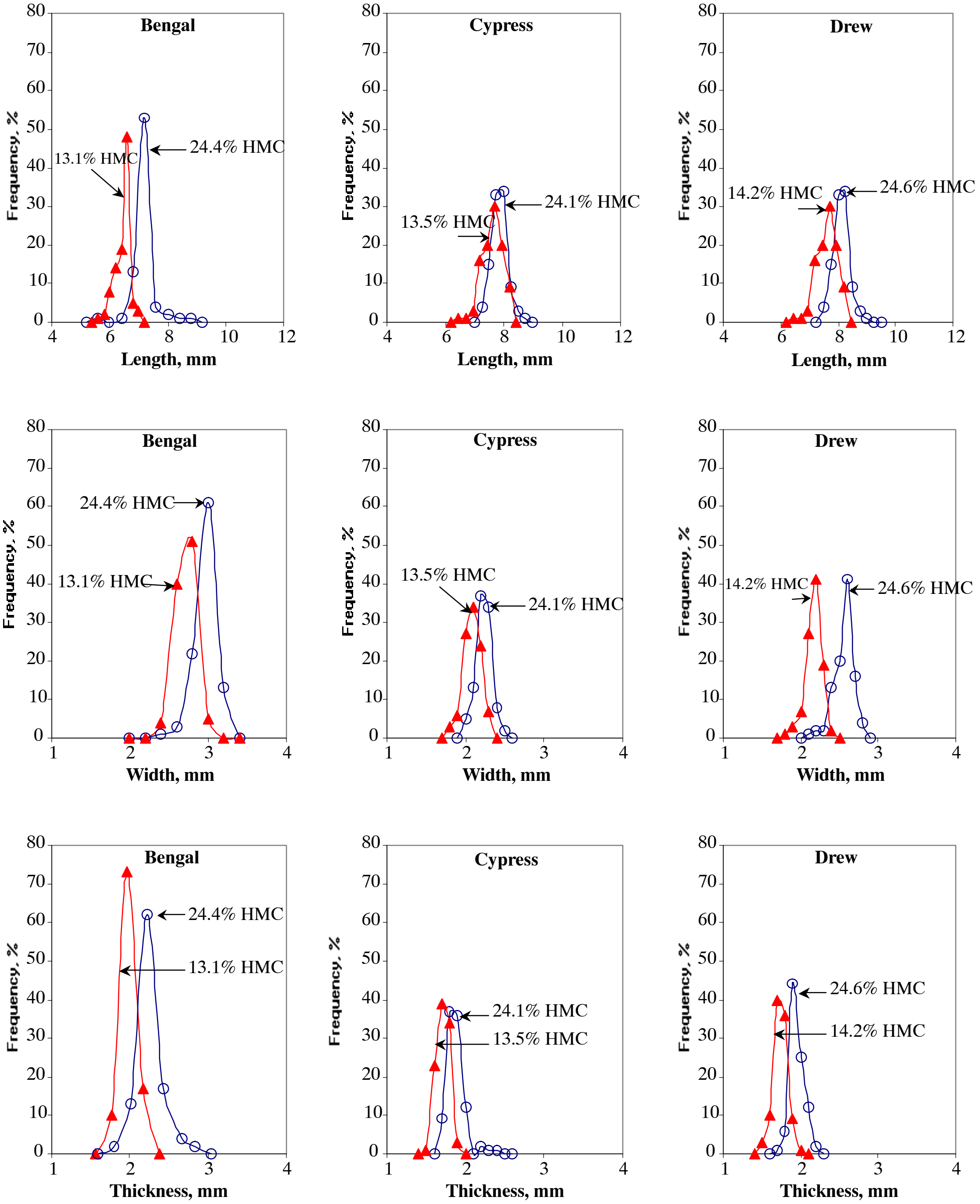

Figure 1. Individual brown rice kernel dimensional distributions for rice varieties Bengal, Cypress, and Drew harvested at the indicated harvest moisture contents (HMCs) at Stuttgart, Arkansas, in 1998. Each curve represents pooled kernel dimensions from five panicles.

representing high (22% to 24%) and low (13% to 15%) MCs. The individual brown rice kernel dimensional distributions for all varieties were single-modal and were generally near normal as analyzed using the Shapiro-Wilk normality tests (JMP ver. 5, SAS Institute). Modes for Bengal width and thickness were usually greater than for Cypress and Drew.

For all varieties, kernel dimensions were affected by HMC as shown by a mode shift in the distributions to smaller kernel dimensions as HMC decreased, figure 1. This is also shown in figure 2, which illustrates changes in the average kernel dimensions with HMC for Bengal, Cypress, and Drew in 1998, 1999, and 2000 at Stuttgart, Arkansas. Figure 2 shows that the average kernel dimension decreased as HMC decreased. The reductions in dimensions presented in figures 1 and 2 represent the shrinkage that kernels incurred while drying on panicles in the field.

As shown in figure 2, the rate of kernel dimensional change with HMC varied among varieties and years. The average length of Drew kernels reduced faster with changes in HMC in 2000 than 1998 and 1999. For Bengal, the average kernel length declined faster in 1999 and 2000 than in 1998. Kernel width shrinkage rates for Cypress and Drew were similar for all years; Bengal had less kernel width shrinkage in 2000 than in 1998 and 1999. Kernel thickness

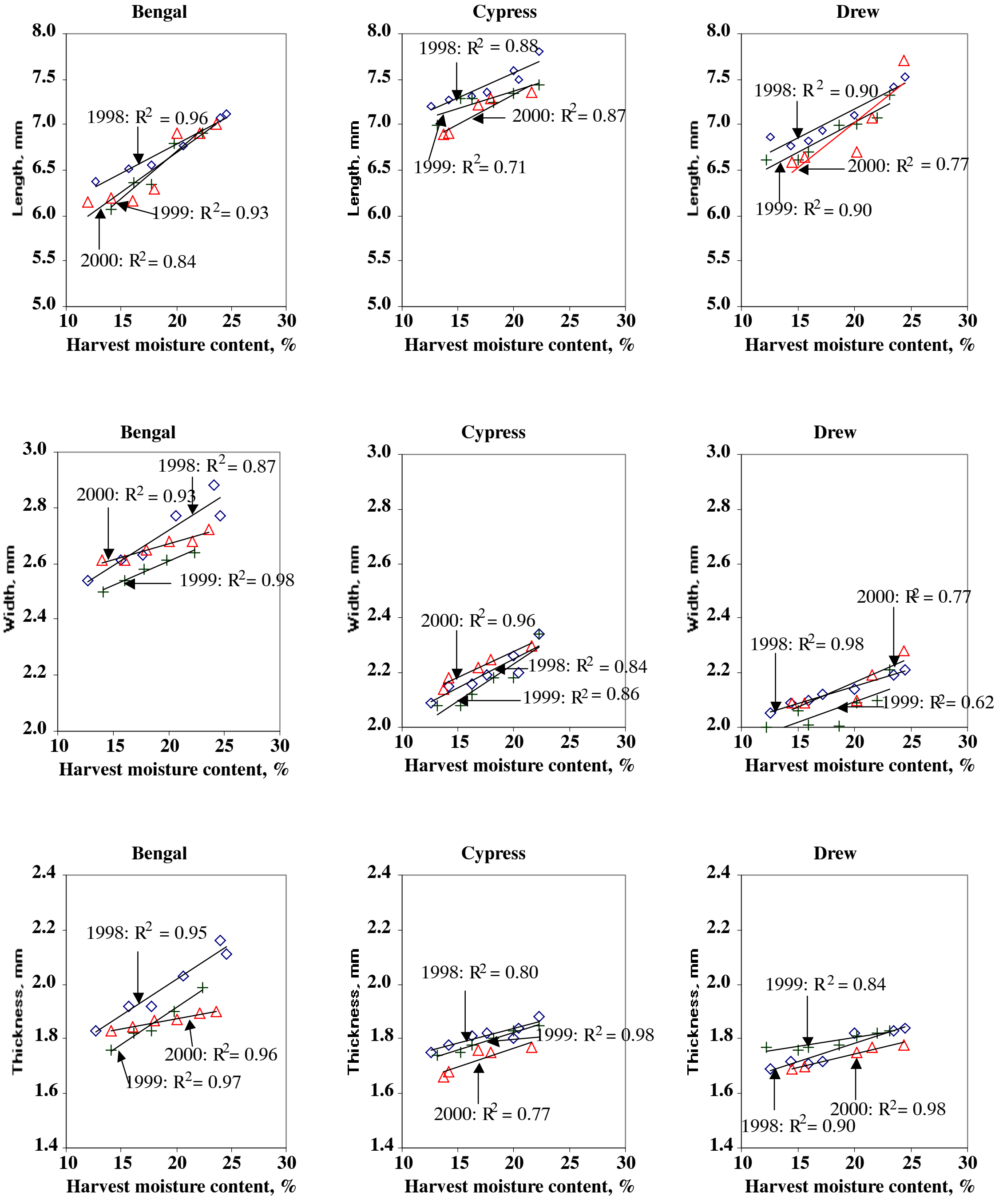

Figure 2. Average brown rice kernel dimensions for rice varieties Bengal, Cypress, and Drew harvested in 1998, 1999, and 2000 at Stuttgart, Arkansas. Each data point represents the average of kernel dimensions from five panicles.

shrinkage rates with HMC followed a similar trend as width shrinkage in that Cypress and Drew shrinkage rates were similar for all years while Bengal thickness shrinkage with HMC was less in 2000 than in 1998 and 1999.

Based on average kernel dimensions among varieties, Bengal (medium-grain) had the shortest, widest and thickest kernels (fig. 2). Cypress and Drew (long-grains) had similar kernel dimensions, but Cypress had slightly longer kernels than Drew at any given HMC for all years. The average kernel lengths for all varieties tended to be greater in 1998 than in 1999 and 2000. The average kernel width for Bengal was greater in 1998 than 1999 and 2000 at HMCs greater than

Table 2. Regression equations, coefficient of determination (R^2) and standard error of estimates (SEE) of brown rice kernel dimensions (length, width, and thickness) as a function of harvest moisture content (HMC) for rice varieties Bengal, Cypress, and Drew harvested in 1998, 1999, and 2000 at Keiser and Stuttgart, Arkansas.

			Regression Equation/R^2/SEE		
Year	Variety	Location	Length (L, mm)	Width (W, mm)	Thickness (T, mm)
1998	Bengal	Stuttgart	L=0.0644HMC+5.7124 R^2=0.96 SEE=0.0680	W=0.0251HMC+2.1028 R^2=0.76 SEE=0.0503	T=0.0262HMC+1.4909 R^2=0.95 SEE=0.0309
		Keiser	L=0.0407HMC+5.4958 R^2=0.91 SEE=0.0610	W=0.01041HMC+2.5525 R^2=0.62 SEE=0.074	T=0.0208HMC+1.5808 R^2=0.90 SEE=0.0353
	Cypress	Stuttgart	L=0.0359HMC+6.7438 R^2=0.65 SEE=0.1870	W=0.0211HMC+1.8265 R^2=0.844 SEE=0.060	T=0.0106HMC+1.6243 R^2=0.80 SEE=0.057
		Keiser	L=0.0304HMC+6.2731 R^2=0.96 SEE=0.0340	W=0.0063HMC+2.1182 R^2=0.73 SEE=0.0300	T=0.0052HMC+1.6281 R^2=0.60 SEE=0.0227
	Drew	Stuttgart	L=0.0318HMC+7.0174 R^2=0.78 SEE=0.0840	W=0.0124HMC+1.9025 R^2=0.98 SEE=0.0416	T=0.0137HMC+1.5114 R^2=0.90 SEE=0.0224
		Keiser	L=0.0225HMC+6.6651 R^2=0.81 SEE=0.0480	W=0.0015HMC+2.16 R^2=0.64 SEE=0.0246	T=0.0163HMC+1.4212 R^2=0.96 SEE=0.0152
1999	Bengal	Stuttgart	L=0.1027HMC+4.6417 R^2=0.93 SEE=0.0106	W=0.0273HMC+2.1195 R^2=0.64 SEE=0.0750	T=0.0269HMC+1.3743 R^2=0.97 SEE=0.0178
		Keiser	L=0.0674HMC+5.1567 R^2=0.98 SEE=0.0390	W=0.0119HMC+2.3575 R^2=0.56 SEE=0.0445	T=0.0174HMC+1.5467 R^2=0.81 SEE=0.0354
	Cypress	Stuttgart	L=0.0383HMC+6.5939 R^2=0.71 SEE=0.0911	W=0.0273HMC+1.684 R^2=0.86 SEE=0.0401	T=0.0064HMC+1.6849 R^2=0.76 SEE=0.0132
		Keiser	L=0.0328HMC+6.5843 R^2=0.94 SEE=0.0326	W=0.012HMC+1.9263 R^2=0.57 SEE=0.0403	T=0.0137HMC+1.5594 R^2=0.73 SEE=0.0319
	Drew	Stuttgart	L=0.0655HMC+5.7139 R^2=0.90 SEE=0.0928	W=0.0133HMC+1.8658 R^2=0.64 SEE=0.0429	T=0.0087HMC+1.628 R^2=0.97 SEE=0.0072
		Keiser	L=0.0488HMC+6.0788 R^2=0.98 SEE=0.0305	W=0.0049HMC+2.0684 R^2=0.75 SEE=0.0274	T=0.0108HMC+1.5995 R^2=0.89 SEE=0.0156
2000	Bengal	Stuttgart	L=0.0862HMC+4.9652 R^2=0.84 SEE=0.1730	W=0.0155HMC+2.4404 R^2=0.93 SEE=0.0126	T=0.0111HMC+1.6474 R^2=0.91 SEE=0.0142
		Keiser	L=0.023HMC+5.9787 R^2=0.74 SEE=0.0624	W=0.0149HMC+2.3545 R^2=0.72 SEE=0.0432	T=0.0056HMC+1.7349 R^2=0.57 SEE=0.0223
	Cypress	Stuttgart	L=0.0646HMC+6.0407 R^2=0.77 SEE=0.0912	W=0.0189HMC+1.899 R^2=0.96 SEE=0.0148	T=0.0138HMC+1.4908 R^2=0.77 SEE=0.0277
		Keiser	No samples	No samples	No samples
	Drew	Stuttgart	L=0.0984HMC+5.047 R^2=0.77 SEE=0.2588	W=0.0032HMC+2.0717 R^2=0.78 SEE=0.0687	T=0.005HMC+1.6262 R^2=0.70 SEE=0.0293
		Keiser	L=0.0274HMC+6.2703 R^2=0.78 SEE=0.0670	W=0.0109HMC+1.9182 R^2=0.97 SEE=0.0928	T=0.0116HMC+1.4663 R^2=0.93 SEE=0.0150

16%. For Cypress, wider kernels were observed in 2000 than 1998 and in 1999. Bengal brown rice kernels were thicker in 1998 than in 1999 and 2000 at all HMC levels. For Drew, the average kernel thickness was greater in 1999 than in 1998 and 2000. Average kernel dimensions were thus affected by year and speculated to be affected by the environment, possibly the ambient temperature during kernel development. For instance, Watson et al. (2005) showed that nighttime, or daily average low, temperatures during kernel filling had a significant effect on kernel thickness.

AVERAGE BROWN RICE KERNEL DIMENSIONS VS. HMC

Table 2 shows the regression equations, including the corresponding coefficients of determination and the standard error of estimates, of average brown rice kernel dimensions versus HMC for Bengal, Cypress, and Drew. Analysis of variance showed significant differences in brown rice kernel length slope across year (P = 0.05), location (P = 0.02), and year and location interaction (P < 0.05). The slopes within each variety for brown rice kernel width were significantly different across variety (P = 0.02) but not different across year and location. The slope values for brown rice kernel thickness were affected by year (P = 0.05), location (P = 0.05), and year and location interaction (P = 0.001).

Figure 3 shows an example of the growing location effect on kernel dimensions and dimensional change with HMC in 1998. Average brown rice kernel length was greater for samples harvested at Stuttgart than Keiser for all varieties across HMC, which is supported by the higher linear regression equation intercept values for Stuttgart in table 2. However, Bengal and Drew brown rice kernels were wider at Keiser than Stuttgart across HMC; this same trend held for

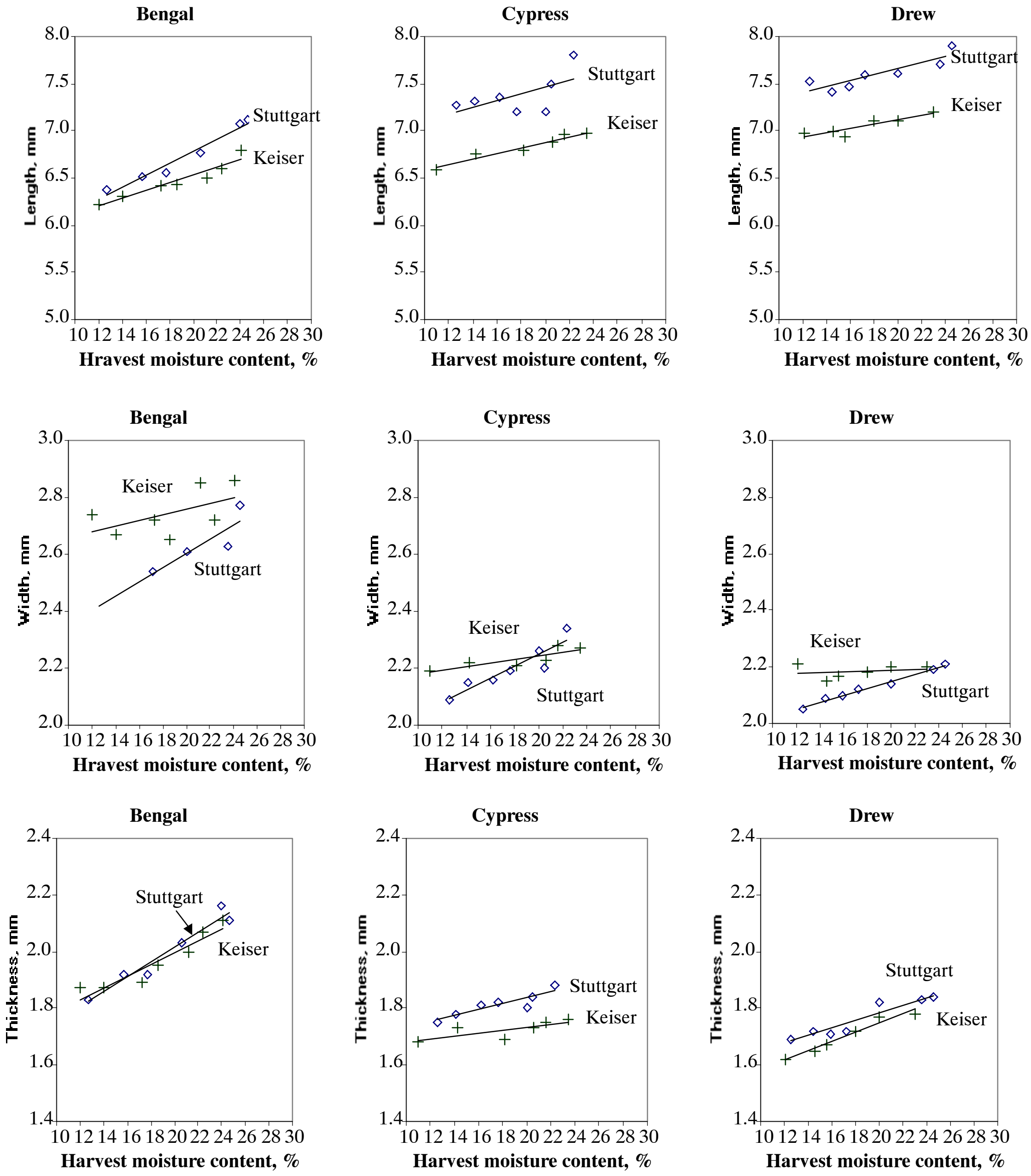

Figure 3. Average brown rice kernel dimensions for rice varieties Bengal, Cypress, and Drew harvested at Stuttgart and Keiser, Arkansas, in 1998 at various harvest moisture contents. Each data point represents the average kernel dimensions from five panicles.

Cypress samples below an HMC of 19%. Thicker kernels were measured for Cypress and Drew at Stuttgart than at Keiser across HMC; there was no significant difference in Bengal kernel thickness between Stuttgart and Keiser samples. Similar to 1998, the average brown rice kernel length for Bengal and Cypress was greater at Stuttgart than Keiser in 1999; however; Drew had similar kernel length at both locations in 1999. Bengal had wider kernels at Stuttgart than Keiser but the inverse was true for Drew; Cypress had similar kernel width at both locations. Similar to 1998, Cypress had thicker kernels at Stuttgart than at Keiser in 1999; but Bengal and Drew had similar thicknesses for both

Table 3. Regression equations, coefficient of determination (R^2), and standard error of estimates (SEE) of rough rice kernel dimensions (length, width, and thickness) as a function of harvest moisture content (HMC) for rice varieties Bengal, Cypress, and Drew harvested in 1998, 1999, and 2000 at Keiser and Stuttgart, Arkansas.

			Regression Equation/R^2/SEE		
Year	Variety	Location	Length (L, mm)	Width (W, mm)	Thickness (T, mm)
1998	Bengal	Stuttgart	L=0.013HMC+8.06 R^2=0.73 SEE=0.0427	W=0.0008HMC+3.0616 R^2=0.0462 SEE=0.0204	T=0.0156HMC+1.77 R^2=0.922 SEE=0.0243
		Keiser	L=0.016HMC+7.8612 R^2=0.84 SEE=0.035	W=0.0065HMC+2.9945 R^2=0.81 SEE=0.0152	T=0.0167HMC+1.7505 R^2=0.92 SEE=0.0233
	Cypress	Stuttgart	L=0.0015HMC+9.0517 R^2=0.67 SEE=0.0241	W=0.0011HMC+2.4925 R^2=0.25 SEE=0.00083	T=0.0056HMC+1.8034 R^2=0.4769 SEE=0.0261
		Keiser	L=0.0039HMC+8.6934 R^2=0.76 SEE=0.0104	W=0.024HMC+2.197 R^2=0.94 SEE=0.0289	T=0.0021HMC+1.889 R^2=0.69 SEE=0.0064
	Drew	Stuttgart	L=0.0023HMC+8.9835 R^2=0.38 SEE=0.0109	W=0.0049HMC+2.3446 R^2=0.64 SEE=0.0193	T=0.0054HMC+1.74 R^2=0.41 SEE=0.0335
		Keiser	L=0.0297HMC+8.133 R^2=0.38 SEE=0.193	W=0.0109HMC+2.16 R^2=0.51 SEE=0.0538	T=0.0074HMC+1.6698 R^2=0.68 SEE=0.0265
1999	Bengal	Stuttgart	L=0.0238HMC+7.8266 R^2=0.64 SEE=0.0098	W=0.0036HMC+2.8914 R^2=0.46 SEE=0.019	T=0.0507HMC+1.6579 R^2=0.83 SEE=0.011
		Keiser	L=0.0298HMC+7.7467 R^2=0.96 SEE=0.0233	W=0.0213HMC+2.6615 R^2=0.89 SEE=0.0293	T=0.0462HMC+1.8595 R^2=0.82 SEE=0.0863
	Cypress	Stuttgart	L=0.0118HMC+8.761 R^2=0.97 SEE=0.0098	W=0.0028HMC+2.432 R^2=0.65 SEE=0.0088	T=0.0043HMC+1.89 R^2=0.81 SEE=0.00903
		Keiser	L=0.0029HMC+8.984 R^2=0.16 SEE=0.0284	W=0.0081HMC+2.3896 R^2=0.94 SEE=0.0082	T=0.0034HMC+1.823 R^2=0.53 SEE=0.0133
	Drew	Stuttgart	L=0.0145HMC+8564 R^2=0.97 SEE=0.0120	W=0.0075HMC+2.2996 R^2=0.96 SEE=0.0069	T=0.0098HMC+1.67 R^2=0.87 SEE=0.0175
		Keiser	L=0.0206HMC+8.43 R^2=0.65 SEE=0.0716	W=0.0054HMC+2.302 R^2=0.80 SEE=0.0128	T=0.0287HMC+1.437 R^2=0.31 SEE=0.0204
2000	Bengal	Stuttgart	L=0.0094HMC+8.097 R^2=0.66 SEE=0.031	W=0.0068HMC+2.9211 R^2=0.28 SEE=0.0502	T=0.00146HMC+1.8439 R^2=0.86 SEE=0.0268
		Keiser	L=0.0105HMC+8.1075 R^2=0.7808 SEE=0.0224	W=0.0109HMC+2.8705 R^2=0.98 SEE=0.0052	T=0.009HMC+1.9749 R^2=0.86 SEE=0.0145
	Cypress	Stuttgart	L=0.039HMC+8.114 R^2=0.86 SEE=0.065	W=0.0046HMC+2.3778 R^2=0.42 SEE=0.0249	T=0.0055HMC+1.7694 R^2=0.93 SEE=0.0072
		Keiser	No samples	No samples	No samples
	Drew	Stuttgart	L=0.00412HMC+8.2761 R^2=0.88 SEE=0.0734	W=0.0099HMC+2.2635 R^2=0.78 SEE=0.0263	T=0.0051HMC+1.687 R^2=0.92 SEE=0.0075
		Keiser	L=0.0278HMC+8.259 R^2=0.97 SEE=0.0203	W=0.0124HMC+2.278 R^2=0.96 SEE=0.0117	T=0.0097HMC+1.6286 R^2=0.95 SEE=0.0108

locations. In 2000, Bengal and Drew had slightly wider kernels at Stuttgart than at Keiser.

Average Rough Rice Kernel Dimensions vs. HMC

Table 3 shows the regression equations, and associated coefficients of determination and standard error of estimates, of average rough rice kernel dimensions versus HMC for the three rice varieties from the two locations and three harvest years. Regression coefficients of determinations for rough rice were lower than for brown rice because data points were so scattered associated to higher dimensional variability measurement due to presence of awn in some in rough rice kernels and none on the others. Although the coefficients of determinations were low, there is some value in using the equation slope in analyzing dimensional trends for rough rice. There was an apparent decrease in all kernel dimensions with HMC but the difference was not significant as indicated by the slope values of kernel length, width, and thickness. The calculated slopes also indicated a smaller kernel size reduction or kernel shrinkage as HMC decreased for all varieties across harvest years and locations compared to brown rice.

Generally, across location, year, and HMC, Bengal rough rice length was 20% to 24% greater then Bengal brown rice, Cypress 19% to 21%, and Drew 16% to 23%. Bengal rough rice was 13% to 15% wider than Bengal brown rice, Cypress 14% to 16%, and, Drew was 12% to 14%. Bengal rough rice was 10% to 16% thicker than Bengal brown rice, Cypress 8% to 11%, and Drew 6% to 8%. The hull and the void space between the caryopsis and the hull constituted the differences in kernel dimensions between rough and brown rice.

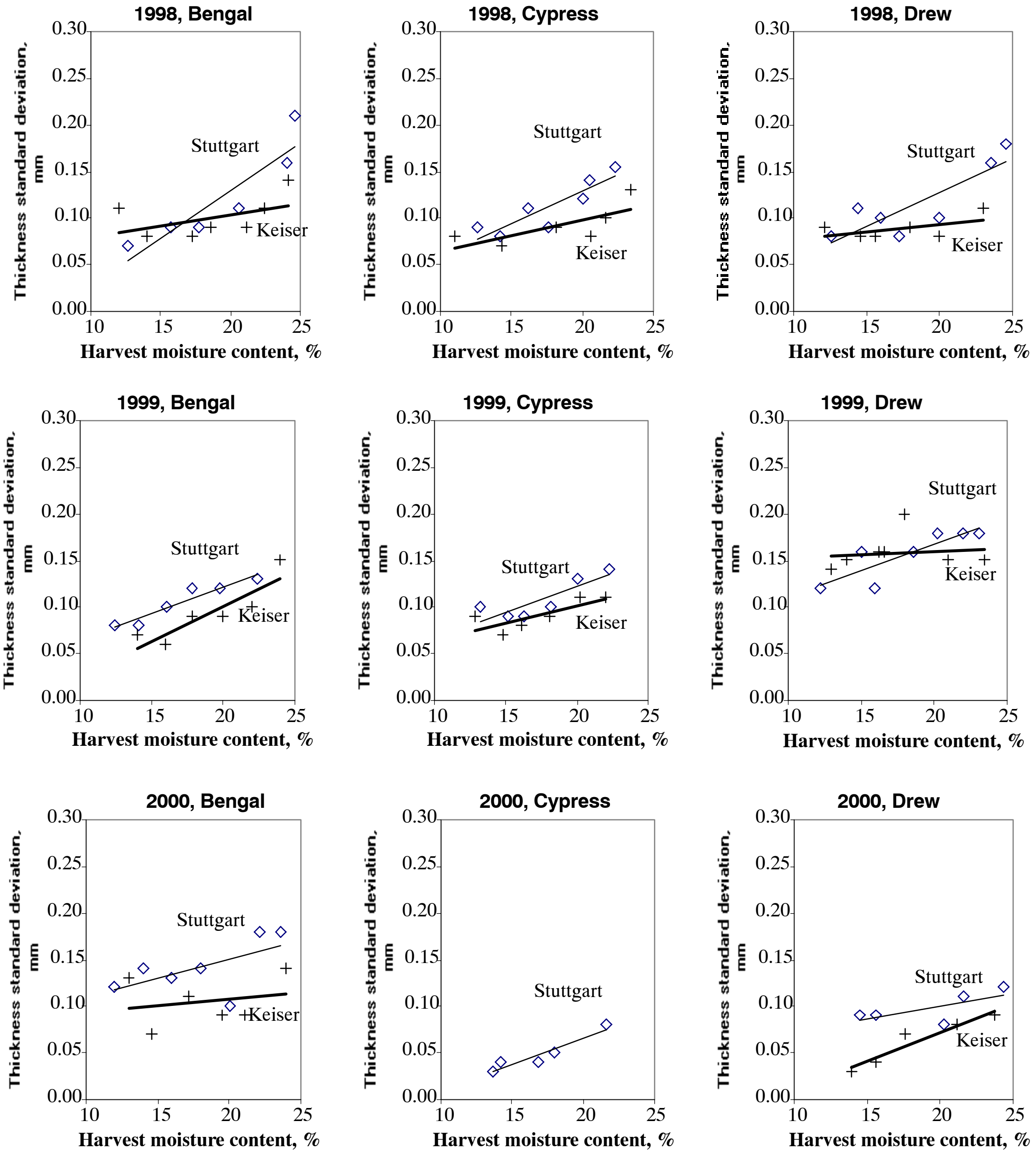

Figure 4. Individual brown rice kernel thickness standard deviations for rice varieties Bengal, Cypress, and Drew harvested at Stuttgart and Keiser, Arkansas in 1998, 1999, and 2000 at various harvest moisture contents. Each data point represents the thickness standard deviation from five panicles.

BROWN RICE KERNEL DIMENSIONAL VARIATION

Standard deviation provides a measure of the individual kernel dimensional variation from the mean. Individual brown rice kernel thickness SDs are shown in figure 4 for all varieties harvested at Stuttgart and Keiser in 1998, 1999, and 2000. Kernel thickness SD was given emphasis over length and width SDs due to kernel thickness being significantly correlated to breaking force as found by Siebenmorgen and Qin (2005). Kernel thickness SD was directly and linearly related to HMC for both locations. Location had a significant effect on brown rice kernel thickness SDs (P = 0.001); Bengal, Cypress, and Drew thickness SDs were as great or greater at Stuttgart than at Keiser for all years.

The generally lower kernel thickness SDs for Keiser samples could imply an advantage in milling performance. Siebenmorgen and Qin (2005) indicated that samples harvested from Keiser in 2001 had more uniform kernel thickness and breaking force distributions than did Stuttgart samples; it was also shown that Keiser samples had consistently higher HRYs than rice harvested from Stuttgart. Thus, for whole grain processing, such as breakfast cereals, if uniformity of kernel dimension is of high importance Cypress grown in Keiser, Arkansas, would be a good choice for this purpose because of its lower dimensional variability.

There was no significant difference in width SDs across location; however, there were apparent trends of slightly higher SDs at Stuttgart (data not shown). In general, for all varieties, there was greater variation in kernel dimensions from Stuttgart than Keiser, except for Drew kernel length where Stuttgart samples had lower SDs than that of Keiser. Environmental factors could contribute to the variation in kernel dimensions across locations. Hoshikawa (1993) indicated that phosphorus content and temperatures during kernel development of japonica rice significantly affected the biosynthesis of rice starch. Hoshikawa (1993) and Counce et al. (2005) showed that kernel development was hampered by low or high nighttime temperatures during kernel filling.

KERNEL SHRINKAGE DURING FIELD DRYING

Brown rice kernel length, width and thickness shrinkage rates were calculated using the average initial kernel dimension at a given HMC and after drying in the field to approximately 12% MC as follows:

$$\begin{aligned}&\text{Shrinkage rate} = \\ &\quad(\text{Kernel dimension at HMC} \\ &\quad - \text{Kernel dimension at HMC}_{12}) \\ &\quad \div (\text{Kernel dimension at HMC}) \times 100\ \%\end{aligned} \tag{1}$$

where 1) kernel dimension at *HMC* refers to the kernel dimension (length, width or thickness) at any HMC as predicted by the regression equations of table 2, and, 2) kernel dimension at HMC_{12} refers to the kernel dimension (length, width or thickness) at 12% HMC as predicted by the regression equations of table 2.

Figure 5 shows brown rice kernel shrinkage rates for Bengal, Cypress, and Drew harvested in 1998 at Stuttgart at

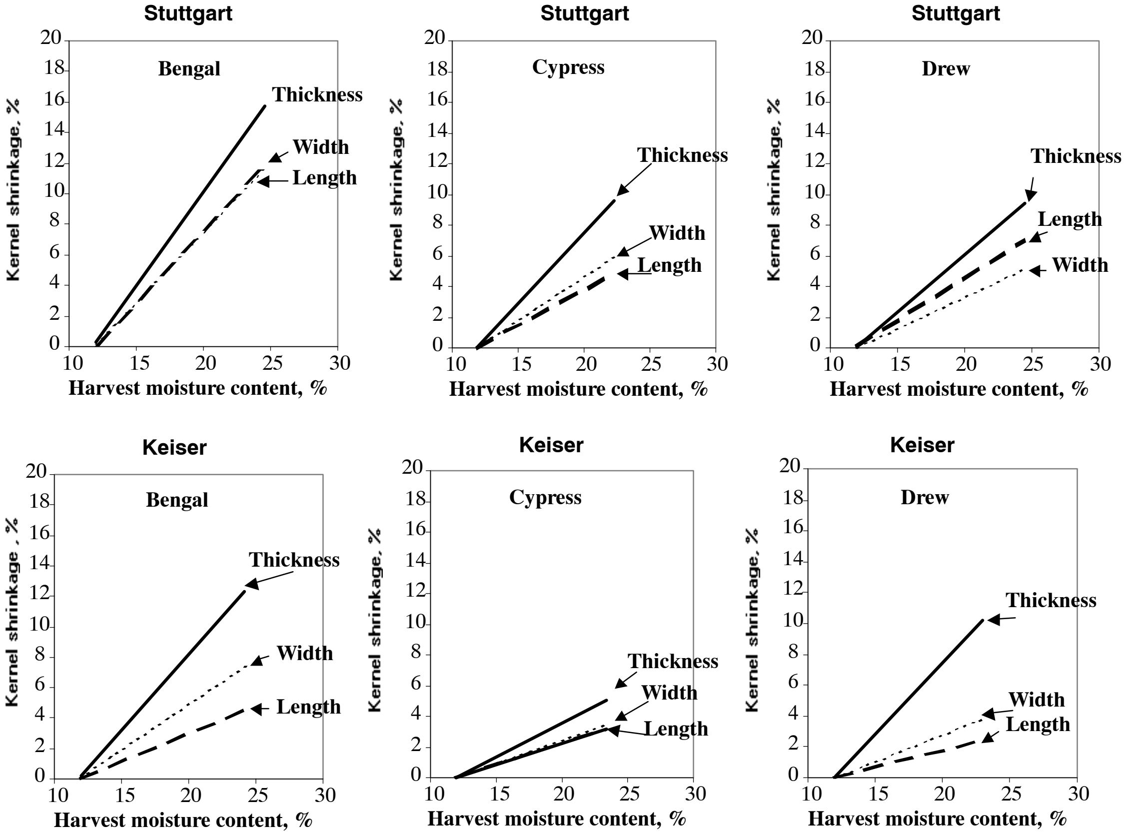

Figure 5. Average brown rice kernel dimensional shrinkage due to moisture content change for rice varieties Bengal, Cypress, and Drew harvested at different moisture contents at Keiser, Arkansas, in 1998. Each data point represents the average shrinkage of kernels as calculated using equation 1 and regression equations from table 2.

different HMC levels. Figure 5 indicates the amount of shrinkage a kernel incurred through field drying from any HMC to 12% HMC. The kernel dimensional shrinkage rates in all years were greatest in the thickness dimension, followed by the width and then the length. These results corroborated the findings of Sun et al. (2002) that shrinkage was greater in kernel thickness than in length and width. Figure 6 shows trends in kernel thickness shrinkage for 1998, 1999, and 2000 at Stuttgart and Keiser. Bengal had consistently greater kernel thickness shrinkage rates at Stuttgart than at Keiser across years. Cypress followed a similar trend except in 1999, where thickness shrinkage was greater at Keiser than Stuttgart. For Drew, kernel thickness shrinkage was greater at Stuttgart than at Keiser in 1999 and 2000. Among varieties, Bengal had the greatest kernel thickness shrinkage.

CONCLUSIONS

The following conclusions were derived from this study:

- Kernel dimensional distributions were usually single-modal and near normal.
- For all varieties, the average kernel dimensional change with HMC varied across year and location. All average kernel dimensions decreased as HMC decreased.
- Kernel dimensional variation, as expressed by SD, decreased linearly with HMC. Growing location had a significant effect on individual kernel dimensional variation.

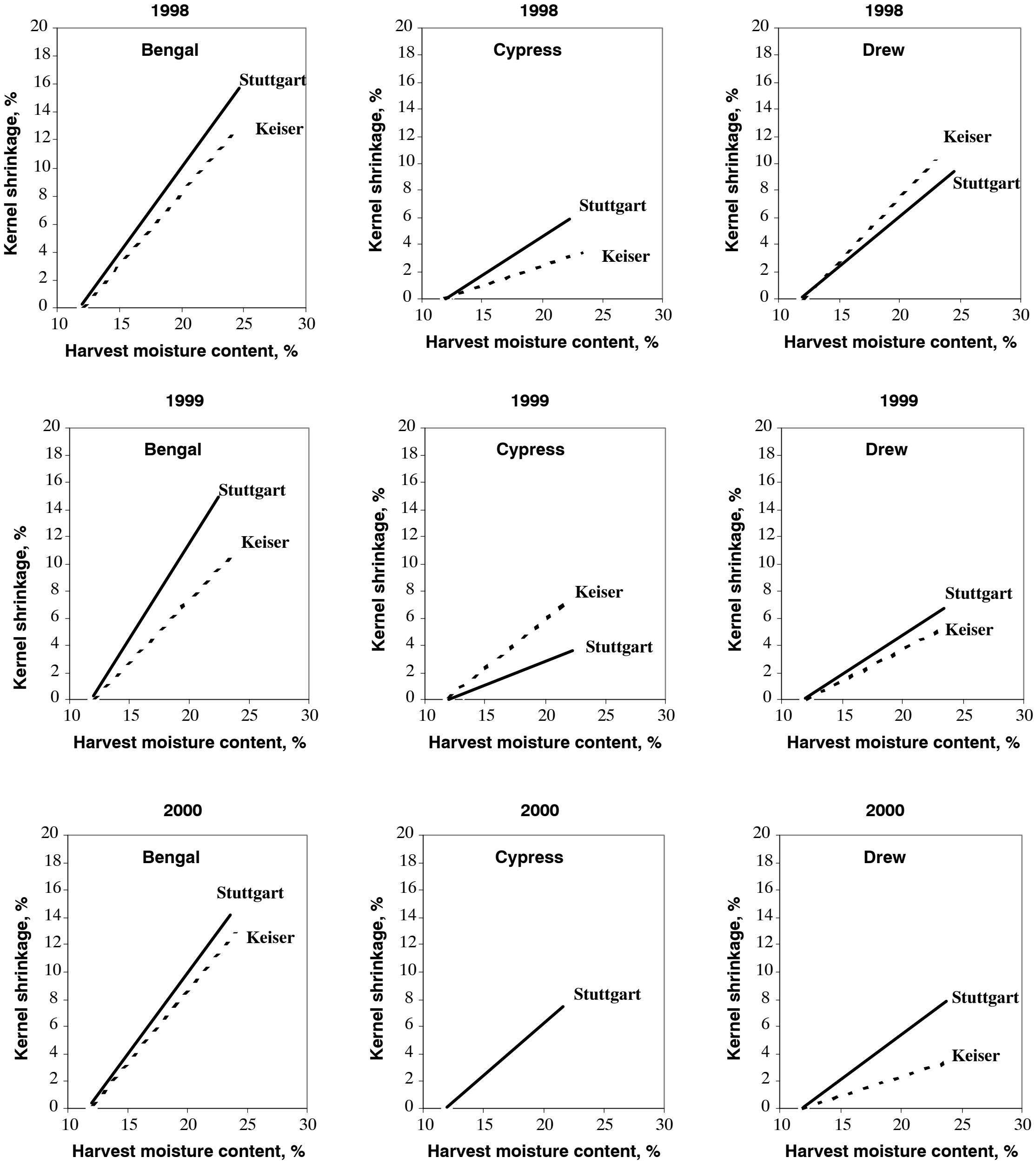

Figure 6. Average brown rice kernel thickness shrinkage due to moisture content change for rice varieties Bengal, Cypress, and Drew harvested at different moisture contents (HMCs) at Keiser, Arkansas, in 1998, 1999, and 2000. Each data point represents the average thickness shrinkage of kernels as calculated using equation 1 and regression equations from table 2.

- Kernel shrinkage values linearly decreased with HMC; medium-grain Bengal had greater shrinkage than long-grain Cypress or Drew. Among kernel dimensions, shrinkage rates in all years were greatest in the thickness dimension, followed by the width and then the length.

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