Estimating the Economic Value of Rice (*Oryza Sativa* L.) as a Function of Harvest Moisture Content

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Abstract. *The net value (NV) of rice, as affected by drying costs and milling quality changes associated with harvesting rice at various moisture contents (MCs), was studied using a five-year data set comprising eight cultivars harvested over a range of MCs from 11 southern U.S. locations. A quadratic relationship was used to characterize the change in NV across harvest MC (HMC); this relationship was due to the progressively-increasing fee structure for commercial drying costs and the quadratic nature of head rice yield (HRY) changes with HMC. A sensitivity analysis revealed that as the price of brokens increased, there was a slight decrease in the HMC at which NV was maximized. Relative to the price of brokens, the optimum HMC was not influenced by fluctuations in head rice price. At a given HMC, the NV of a rice bulk increased with the price of brokens, and the extent of the increase was heavily influenced by the HRY versus HMC relationship. In all instances, the optimal HMC to maximize HRY ($HMC_{opt\text{-}HRY}$) was greater than the HMC corresponding to the maximum NV ($HMC_{opt\text{-}NV}$). When HMC, NV and HRY were plotted regardless of cultivar, location, or harvest year, the MC at which HRY was maximized was 21.7% whereas the MC at which NV was maximized was 18.5%, representing a 3.2 percentage point difference between $HMC_{opt\text{-}HRY}$ and $HMC_{opt\text{-}NV}$.*

Keywords. *Rice, Head rice yield, Net economic value, Drying cost, Milled rice value.*

Determining the appropriate time to harvest is a crucial decision for rice producers. Upon maturity, the average moisture content (MC) and the distribution of individual kernel MC distributions vary dramatically depending on environmental conditions (Bautista and Siebenmorgen, 2005). These MC changes can correspond to milling quality changes. For example, if the harvest date is delayed and the rice field MC is allowed to decrease to ≤15% (all moisture contents have been expressed on a wet basis), there is a risk that environmental humidity could cause dry kernels to rapidly absorb moisture, which causes fissuring (Kunze and Prasad, 1978; Siebenmorgen and Jindal, 1986). Rice kernel fissuring would then result in low head rice yields (HRYs), the mass percentage of rough rice kernels that remain as head rice [milled kernels that are ≥75% in length of an intact rice kernel after complete milling (USDA, 2005)]. As rice is sold primarily as head rice, HRY is a key determinant of rice quality and therefore the value of rice. Broken rice, which is typically ground and sold as flour, is currently valued at 60% to 80% of head rice (USDA, 2007). At high harvest MCs (HMCs), HRY can also decrease, as the percentage of immature kernels increases with HMC. These immature kernels are typically thin and weak, and thus increasingly prone to breaking during milling (Siebenmorgen and Qin, 2005; Siebenmorgen et al., 2006; Bautista et al., 2007).

Though there are other factors that can affect HRY, including combine cylinder speeds (Dilday, 1989), grain drying regimens (Schluterman and Siebenmorgen, 2007), and the presence of foreign matter, HMC is one of the foremost properties that indicate HRY potential. Optimal HMCs for maximizing HRYs vary with cultivar and location. In the mid-Southern United States, Siebenmorgen et al. (2007) recommended harvesting long-grain cultivars at MCs of 19% to 22% and medium-grains at MCs of 22% to 24%, while in California, Mutters and Thompson (2006) recommended harvesting medium-grains at greater than 21%. To a producer, it might seem logical to harvest at high MCs, when the rice is at the recommended HMC for maximizing HRY. However, high HMCs result in high drying charges. Drying charges are typically applied on a progressively-increasing scale based on the HMC of a rice lot.

It is vital to rice producers and to cooperatives to determine the most economical MC at which to harvest rice, taking into consideration drying costs and potential pre-harvest milling quality changes. Mutters and Thompson (2006), with a two-year data set of California medium-grain rice, reported that some of the HRY loss that resulted from harvesting at low MCs was counter-balanced by lower drying costs to the producer, leading to a minimal loss of rice economic value. In California, rewetting in the field occurs mostly during conditions of heavy dew, when cool temperature conditions are coupled with relative humidity conditions that fluctuate diurnally (Mutters and Thompson, 2006). These conditions are different than those of the

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rice-growing regions of the Southern United States, where hot, humid weather is common during the harvest season and significant damage due to rewetting usually occurs during rain events (Kunze and Prasad, 1978). Lu et al. (1995), using a modeling system to predict HRY, determined that the maximum economic return was obtained when rice was harvested at approximately 19% MC. The use of actual HRY and related HMC values would avoid the ambiguity associated with predictive modeling.

Siebenmorgen et al. (2007) presented rice milling quality data that were collected over five years from multiple locations and cultivars over a range of HMCs, from which optimal HMCs for maximizing HRY were determined. That study provided actual trends in HRY values, from which the gross economic value of rice throughout a harvest season can be determined. The objective of the study herein was to determine the net economic value of rice, accounting for milling quality changes and drying charges associated with harvesting rice at various MCs. From the relationship between economic value and HMC, the optimal HMC for maximizing the net value (NV) of bulk rice was quantified.

Materials and Methods

Rice Samples

The milling quality data set from Siebenmorgen et al. (2007) was utilized to meet the objectives of this study. During 1999, 2000, 2004, 2005, and 2006, a total of 139 rice lots of Bengal (medium-grain cultivar), Cypress, Drew, Cheniere, Cocodrie, Francis, Wells (long-grain cutivars), and XP723 (long-grain hybrid), were collected from various locations across the rice-growing regions of Arkansas (seven locations), Missouri (two locations) and Mississippi (two locations). Each rice field, which was either a research or a farm trial plot of at least 0.2 ha, was sampled four to seven times during each harvest season to collect rice at HMCs ranging from 12% to 27%. Table 1 summarizes the sample lots that were collected.

Harvest, Drying, and Milling

At least 200 randomly-chosen panicles (approximately 2 kg of grain) of each sample lot were hand-harvested using a sickle. The HMC of each lot was determined at the time of harvest as the average MC of 300 individual kernels stripped from five randomly-selected panicles using a single-kernel moisture meter (CTR 800E, Shizuoka Seiki, Shizuoka, Japan).

After HMC determination, kernels were removed from the remaining panicles by either hand-stripping (1999 and 2000) or by mechanical threshing (2004, 2005, and 2006) (SBT, Almaco, Nevada, Iowa). Mechanical threshing is more aggressive than hand-stripping, and thus could be reasoned to impart more stress to kernels, possibly reducing HRY. However, Siebenmorgen et al. (2007) noted that fissure counts were actually lower in the mechanically-threshed samples than in the hand-stripped samples of that study,

Table 1. Summary of 139 rice lots from which data were used for this study. When head rice yield (HRY) was plotted against harvest moisture content (HMC), a parabolic relationship resulted for each year/location/cultivar lot.[a]

Year	Location	Cultivar	Harvest Moisture Contents (%, w.b.)							HRY_{opt} (%)[b]	$HMC_{opt\text{-}HRY}$ (%)[b]	R^2
1999	Keiser, Ark.	Bengal	14.7	17.7	19.3	22.6	23.9	25.9	–	67.1	24.2	0.97
		Cypress	12.5	14.2	14.9	18.9	19.2	21.5	22.8	69.7	19.2	0.82
		Drew	12.8	14.8	16.1	18.3	20.1	22.6	25.5	70.6	21.0	0.86
	Stuttgart, Ark.	Bengal	12.2	14.7	17.7	19.3	22.6	23.9	–	66.3	23.8	0.98
		Cypress	12.5	14.2	16.0	18.9	19.2	22.8	–	67.9	22.5	0.97
		Drew	12.6	14.8	16.1	18.3	20.0	22.0	24.0	69.0	23.4	0.93
2000	Keiser, Ark.	Bengal	13.1	14.2	16.0	17.8	20.0	22.6	24.0	68.7	21.5	0.96
		Drew	13.9	15.6	17.6	21.2	23.7	–	–	69.4	20.3	0.94
	Stuttgart, Ark.	Bengal	12.5	14.5	16.3	18.4	20.1	22.1	23.6	69.9	26.0	0.98
		Cypress	13.7	14.2	16.8	18.0	21.6	23.6	–	65.4	21.1	0.71
		Drew	14.5	15.6	20.2	21.6	24.4	–	–	67.1	21.6	0.77
2004	Essex, Mo.	Cocodrie	13.5	20.1	20.3	23.9	–	–	–	67.6	19.2	0.97
	Hunter, Ark.	Wells	15.2	17.6	19.2	25.7	–	–	–	67.5	21.3	1.00
	Lodge Corner, Ark.	Bengal	11.6	18.5	20.3	25.5	27.1	–	–	69.1	22.4	0.99
	Newport, Ark.	Cocodrie	14.9	17.1	18.2	21.3	24.4	–	–	69.3	32.8	0.82
2005	Cleveland, Miss.	XP 723	12.0	14.0	17.3	18.0	23.5	–	–	63.8	19.5	0.98
	Osceola, Ark.	Cheniere	14.4	16.0	20.6	21.1	23.2	–	–	64.8	18.8	0.81
	Qulin, Mo.	Wells	15.4	16.8	18.8	19.0	–	–	–	63.0	18.7	0.46
	Stuttgart, Ark.	Francis	15.5	16.5	21.3	21.8	24.4	–	–	67.1	18.7	0.76
		XP 723	14.7	16.0	18.1	18.5	18.5	20.0	–	69.7	19.6	0.93
2006	Des Arc, Ark.	Cheniere	14.7	15.8	17.9	19.3	24.1	–	–	70.6	18.7	0.99
	Osceola, Ark.	Wells	13.7	18.9	19.4	21.2	24.2	–	–	66.3	21.2	1.00
	Shaw, Miss.	XP723	14.2	16.3	20.1	24.7	–	–	–	67.9	20.4	0.85
	Stuttgart, Ark	Wells	12.3	14.5	16.7	20.0	21.8	23.6	26.8	69.0	21.2	0.89
		XP723	12.4	16.2	17.8	18.4	20.1	26.8	–	68.7	20.1	0.97

[a] This data was reported by Siebenmorgen et al. (2007).

[b] The peak of each curve corresponded to the optimum HRY (HRY_{opt}) and the HMC at which HRY was optimized ($HMC_{opt\text{-}HRY}$). The coefficient of determination, R^2, indicates how well HRY and HMC were correlated.

although that observation may have been confounded due to the increased number of low HMC samples harvested in 1999 and 2000, which may have had an increased amount of fissuring due to rewetting in the field. Following threshing, the samples were dried to 12.5% MC in a chamber in which air conditions were maintained at 21°C and 56% relative humidity. Once dry, each rice lot was cleaned (Kicker Grain Tester, MidContinent Industries, Inc., Newton, Kans.), sealed in a Ziplock™ bag, and stored at 4°C until milling was performed.

Samples were removed from storage and, while still sealed in bags, were allowed to equilibrate to room temperature for approximately 24 h. The husks were removed from two duplicate 150-g samples from each lot using a laboratory huller (Rice Machine, Satake Engineering Co., Hiroshima, Japan). The resultant brown rice was milled for 30 s using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, Tex.); pressure was applied to the milling chamber using a 1.5-kg mass placed on the mill lever arm, 15 cm from the centerline of the milling chamber. Excess bran was then removed from the samples using an aspirator (Grain Blower, Seedburo Equipment Co., Chicago, Ill.), after which the milled rice was weighed. The milled rice yield (MRY) was recorded as the mass percentage of milled rice to the original mass of rough rice (150 g). Head rice was then separated from brokens using a sizing device (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. Head rice yield was determined as the mass percentage of the original 150 g of rough rice that remained as head rice. The results of each duplicate were averaged before subsequent statistical and cost analyses were conducted.

Cost Analyses - Drying Charges

In the US rice industry, rice is traded based on its "dry" mass, commonly taken as the mass at 12.5% MC. The pricing unit typically used is the cwt, or hundredweight, which is equal to 100 lb (avoirdupois, US), or 45.36 kg. However, drying charges in the United States are typically applied based on the number of "green," or freshly harvested, bushels. A bushel is a unit of volume equal to 1.25 ft^3 (0.03524 m^3 or 35.24 L). The conventional technique involved in the computation of the number of green bushels of incoming, non-dried rice is to assume a bulk density of 45 lb/bu (577 kg/m^3) (Henderson and Perry, 1976). Drying charges were calculated according to equation 1.

$$DC = \frac{M_G}{BD} \cdot DF \tag{1}$$

where

DC = drying charge ($)

M_G = mass of green rough rice at a given HMC (lb or kg)

BD = bulk density of rough rice, conventionally taken as 45 lb/bu or 577 kg/m^3

DF = drying fee ($/bu or $\$/m^3$)

In this study, the drying fee (DF) schedule was assumed to be progressive with the MC of the rice bulk. Table 2 presents the drying fee schedule that was used in this study, which approximates values incurred or applied in the state of Arkansas. Some rice producers choose to dry their crop prior to transportation to a commercial rice mill. However, the cost of this practice was unavailable at the time this study was conducted; therefore, on-farm drying costs were not considered in the calculations.

Table 2. Drying fee schedule that was used to compute drying charges (eq. 1).

Harvest Moisture Content (MC) (w.b.)	Drying Fee ($)
≤ 13.5% MC	0.25/bu
13.6% to 18.9% MC	0.30/bu
19.0% to 21.9% MC	0.35/bu
≥ 22.0% MC	0.50/bu

Cost Analyses - Net Value

Freshly-harvested rice is dried to approximately 12.5% MC for long-term storage and milling throughout the year. To compute the economic value of dried rice, M_G must first be adjusted to 12.5% MC according to equation 2.

$$M_D = \frac{M_G}{\left(\frac{100-12.5}{100-HMC}\right)} \tag{2}$$

where

M_D = mass of dry rice after adjusting to 12.5% MC (lb or kg) [In order to convert to more commonly traded units, the M_D units of pounds (lb) must be divided by 100 to convert to hundredweight (cwt), or kilograms (kg) by 1000 to convert to metric tons (t)]

HMC = moisture content of undried rice (%)

After hull and bran removal, milled rice is separated into head rice and brokens fractions. The gross values of head rice and brokens were calculated by equations 3 and 4, respectively.

$$GV_{HR} = (M_D) \cdot HRY \cdot P_{HR} \tag{3}$$

$$GV_{BR} = (M_D) \cdot (MRY - HRY) \cdot P_{BR} \tag{4}$$

where

GV_{HR} = gross value of head rice ($)

GV_{BR} = gross value of brokens ($)

M_D = mass of dry rice after adjusting to 12.5% MC (cwt or t)

P_{HR} = price of head rice ($/cwt or $/t)

P_{BR} = price of brokens ($/cwt or $/t)

HRY = mass proportion of rough rice remaining as head rice after milling (decimal)

MRY = mass proportion of rough rice remaining as milled rice (head rice + brokens) (decimal)

The gross value of a mass of dried rice (GV_{Rice}) was taken as the sum of GV_{HR} and GV_{BR}; in so doing, the value of hulls and bran was omitted from the equations for the purposes of this study. The NV of rice was calculated according to equation 5.

$$NV = GV_{Rice} - DC \tag{5}$$

where

NV = net value of rice ($)

The approach used in this analysis was to establish a basis of comparison as 1 cwt (100 lb), the most commonly-used trade unit in the rice industry, at 12.5% MC. As such, for each of the 139 sample lots analyzed in this study, a base M_D amount of 1 cwt was assumed and, using this standardized base unit, the M_G at the HMC of each lot was calculated from the one cwt base using equation 2. For example, if a sample HMC were 18.0%, the M_D of 1 cwt would correspond to a M_G of 106.7 lb (2.37 green bushels or 0.0835 m^3). At 18.0% MC, a drying fee of $0.30/bu would have applied, based on the drying fee schedule listed in table 2, which would equate to a drying charge of $0.71, essentially $0.71/cwt of dried rice. After milling, if the sample had a MRY of 70% and a HRY of 60%, one cwt of dry rough rice would produce 0.7 cwt of milled rice, of which 0.6 cwt would have been head rice and 0.1 cwt brokens. If the price of head rice were $16.50 /cwt and the price of brokens were 60% of the value of head rice, according to equations 3 and 4, the GV_{Rice} would total $10.89. By subtracting the drying costs, the NV, through equation 5, would equal $10.18/cwt of dried rice. In this manner, the NV of each of the 139 year/location/cultivar/HMC sample lots was calculated. Head rice yield and NV values were regressed against HMC using statistical software (JMP 7, SAS Institute, SAS Institute, Cary, N.C.).

As a means of comparing the effect of commodity price on the NV of rice, a sensitivity analysis was conducted. To examine the effect of fluctuations in the price of brokens, the head rice price was set at $18.00/cwt while the price of brokens was assumed to be 60%, 70%, or 80% of the price of head rice. To examine the effect head rice price fluctuation, the price of brokens was set at 70% of the price of head rice while the price of head rice was assumed to be $16.50, $18.00, or $19.50/cwt, based on USDA (2007).

Results and Discussion

The underlying trend between HRY and HMC for all year/location/cultivar sample lots was a second-order correlation, caused by two HRY-reducing factors, as described by Siebenmorgen et al (2007): moisture adsorption in the field at low HMCs, and the presence of weak, immature kernels at high HMCs. The HRYs and HMCs of each year/location/cultivar sample set were well correlated, with R^2s ranging from 0.46 to 1.00 (table 1). The peak of each quadratic HRY versus HMC regression line corresponded to the optimal HRY (HRY_{opt}), as described by Siebenmorgen et al. (2007), and the associated HMC, which will be hereafter abbreviated $HMC_{opt\text{-}HRY}$. The peak of each NV versus HMC regression line corresponds to the optimal NV (NV_{opt}) and the optimal HMC at which NV is maximized ($HMC_{opt\text{-}NV}$). The $HMC_{opt\text{-}HRY}$ differed depending on cultivar, year, and location. Due to the drying cost structure, the HMC at which HRY was greatest was not necessarily the HMC at which the NV was maximized.

Net Value Sensitivity Analysis

While HRY and HMC were well correlated within each year/location/cultivar sample set using a quadratic equation, the rate at which HRY changed with HMC varied. Depending on year, location, and cultivar, HRY usually decreased rapidly at low HMCs; however, for some sample sets, the HRY did not respond as drastically. To demonstrate the effects of these varying HRY versus HMC patterns on the net value of rice, it was necessary to choose several examples that would illustrate the NV changes due to these patterns.

Parabolic HRY vs. HMC Relationship

Figure 1 shows the relationship between NV, HRY, and HMC for Wells rice harvested in 2006 from Osceola, Arkansas. The corresponding tabular values of NV_{opt} and $HMC_{opt\text{-}NV}$ for all sample sets used in this study are given in tables 3-5. For the five samples collected at this location during this year, HMCs ranged from 13.7% to 24.2% with HRYs ranging from 51.1% to 63.9%. A quadratic relationship existed between HRY and HMC, with the peak of the regression line corresponding to a HRY_{opt} of 66.3%, which would have been achieved if the rice had been harvested at an $HMC_{opt\text{-}HRY}$ of 21.2% (table 1). However, the peaks of the NV regression lines indicate that in order to achieve NV_{opt}, Wells rice from Osceola, Arkansas during 2006 would have had to have been harvested at lower MCs, from 18.0% to 19.2% ($HMC_{opt\text{-}NV}$), depending on the price of head rice and brokens (tables 3-5).

The NV curves in figure 1 were developed assuming a head rice price (P_{HR}) of $18.00/cwt and brokens prices (P_{BR}) of 60%, 70%, and 80% of the head rice price. As the price of brokens increased, the peaks of the NV vs HMC curves shifted towards lesser HMCs. For this sample set, the $HMC_{opt\text{-}NV}$ decreased from 19.1% HMC at 60% brokens value, to 18.7% and 18.1% HMC at 70% and 80% brokens values, respectively (fig. 1 and table 4). However, though the price of brokens (P_{BR}) varied a total of $3.60/cwt, from $10.80/ cwt to $14.40/cwt (60% and 80%, respectively, of the head rice price of $18.00/cwt), NV_{opt} increased a total of only $0.29/cwt, from $11.76/cwt at 60% value, to $12.05/cwt at the 80% value (table 4).

At higher HMCs, the NV versus HMC regression lines decreased at a greater rate than the HRY versus HMC curve due to progressively-increasing drying fees incurred when high HMC rice is delivered to a commercial drier. The shape of the NV curves show that as the price of brokens increased from 60% to 80% of the value of head rice, there was little difference in NVs at higher HMCs due to the correspondingly

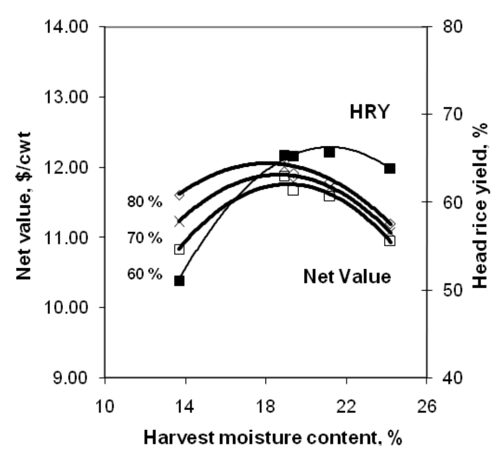

Figure 1. Net value (eq. 5) and head rice yield (HRY) (■) of Wells rice harvested from Osceola, Arkansas in 2006. Net value was calculated assuming that head rice had a value of $18.00/cwt, and brokens had values of 60% (□), 70% (x), or 80% (◇) of the head rice value. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

Table 3. Summary of optimal net values (NV_{opt}) and corresponding optimal harvest moisture contents ($HMC_{opt\text{-}NV}$) of the 25 year/location/cultivar sample sets that were used for this study, as calculated from the NV vs. HMC quadratic regression equations.[a]

			$HMC_{opt\text{-}NV}$ (%, w.b.)			NV_{opt} ($/cwt)			$NV_{14\%HMC}$ ($/cwt)[b]		
Year	Location	Cultivar	60%	70%	80%	60%	70%	80%	60%	70%	80%
1999	Keiser, Ark.	Bengal	21.8	21.1	19.9	10.43	10.56	10.70	9.25	9.76	10.28
		Cypress	17.8	17.5	17.2	11.03	11.08	11.15	10.60	10.76	10.92
		Drew	19.5	19.1	18.4	11.00	11.06	11.14	10.15	10.49	10.82
	Stuttgart, Ark.	Bengal	19.4	18.7	17.8	10.50	10.64	10.79	10.09	10.36	10.63
		Cypress	18.7	18.1	17.3	10.54	10.62	10.71	10.18	10.38	10.58
		Drew	20.5	19.9	19.0	10.69	10.80	10.93	9.73	10.14	10.54
2000	Keiser, Ark.	Bengal	19.5	19.0	18.2	10.79	10.88	10.98	9.98	10.33	10.68
		Drew	19.2	18.9	18.5	10.76	10.79	10.83	9.64	9.97	10.30
	Stuttgart, Ark.	Bengal	19.4	18.5	17.4	10.54	10.66	10.80	10.09	10.37	10.65
		Cypress	17.8	17.5	17.1	10.45	10.53	10.60	10.25	10.38	10.50
		Drew	20.5	20.3	20.1	10.53	10.59	10.66	8.84	9.21	9.58
2004	Essex, Mo.	Cocodrie	17.6	17.5	17.3	11.01	11.12	11.23	10.62	10.79	10.96
	Hunter, Ark.	Wells	18.2	17.6	16.8	10.86	10.98	11.10	10.64	10.84	11.03
	Lodge Corner, Ark.	Bengal	17.2	16.0	14.1	10.91	11.00	11.12	10.85	10.98	11.12
	Newport, Ark.	Cocodrie	17.0	16.8	16.6	11.06	11.16	11.27	10.97	11.09	11.20
2005	Cleveland, Miss.	XP 723	17.1	16.6	15.8	10.37	10.50	10.64	10.16	10.38	10.60
	Osceola, Ark.	Cheniere	17.7	17.5	17.2	10.46	10.54	10.63	9.87	10.08	10.28
	Qulin, Mo.	Wells	16.5	16.0	15.6	10.51	10.67	10.85	10.30	10.55	10.77
	Stuttgart, Ark.	Francis	18.1	18.0	18.0	10.73	10.82	10.90	10.24	10.36	10.48
		XP 723	17.9	17.7	17.4	10.58	10.69	10.79	10.19	10.37	10.57
2006	Des Arc, Ark.	Cheniere	17.7	17.5	17.3	10.97	11.04	11.13	10.53	10.68	10.82
	Osceola, Ark.	Wells	19.0	18.6	18.0	10.71	10.85	10.98	9.97	10.31	10.64
	Shaw, Miss.	XP723	18.9	18.5	18.1	10.60	10.70	10.80	9.81	10.11	10.42
	Stuttgart, Ark.	Wells	18.8	18.2	17.4	10.60	10.74	10.89	10.21	10.48	10.76
		XP723	15.6	14.4	12.8	10.64	10.78	10.94	10.62	10.78	10.94

[a] Table values were calculated using a head rice price of $16.50/cwt and brokens prices of 60%, 70%, and 80% of the head rice price.
[b] The $NV_{14\%HMC}$ values represent the NVs of the rice if it had been harvested at 14% HMC.
Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

high HRYs and thus the relative absence of broken kernels. At lower HMCs there were lower HRYs and thus an increased mass of brokens, causing the NV curves to separate. Therefore, an increase in the price of brokens had a more pronounced effect at lower HMC ranges.

From figure 1 and table 4, the consequences of delayed harvesting caused by logistics or equipment limitations can be quantified. If the Wells rice had been harvested at 14% HMC ($NV_{14\%HMC}$) as opposed to $HMC_{opt\text{-}NV}$, there would have been a $0.82/cwt loss if the price of brokens had been at 60% of the head rice price, and $0.59/cwt and $0.38/cwt at 70% and 80% values, respectively. As the price of brokens decreases, the NV of the rice bulk at lower HMCs is greatly affected, but at higher HMCs, the price of brokens had little effect on NV, owing to the relative absence of brokens at the higher HMCs.

Figure 2 shows the effect of a change in head rice price, assuming that the brokens price was equal to 70% of the head rice price. With increased head rice price, the $HMC_{opt\text{-}NV}$ increased by only 0.1 percentage points, from 18.6% to 18.7% HMC corresponding to a head rice price of $16.50 and $19.50/cwt, respectively. Moreover, the price of head rice did not dramatically affect the reduction in NV between harvesting at low HMCs and harvesting at $HMC_{opt\text{-}NV}$. The difference between $NV_{14\%HMC}$ and NV_{opt}, for a 70% brokens price, was $0.54/cwt at $16.50/cwt head rice price (table 3), $0.59/cwt (table 4) at $18.00/cwt, and $0.65/cwt at $19.50/cwt head rice price (table 5).

Declining HRY vs. HMC Relationship

Figure 3 (and table 4) shows the relationship between NV, HRY, and HMC for medium-grain rice cultivar Bengal grown in Stuttgart, Arkansas in 2000, assuming a head rice price of $18.00/cwt. For the seven samples collected, HMCs ranged from 12.5% to 23.6% with HRYs between 51.0% and 68.4%. Head rice yields decreased dramatically as HMC decreased, but did not correspondingly decrease at the higher HMCs as with the parabolic relationship example (fig. 1). According to the HRY versus HMC regression equation, the $HMC_{opt\text{-}HRY}$ would have been 26.0% with a corresponding HRY_{opt} of 69.9% (table 1). If samples had been collected with a greater range of HMCs, the $HMC_{opt\text{-}HRY}$ may have been closer to the expected range of 22% to 24% (Siebenmorgen et al., 2007).

The NV versus HMC curves in figure 3 were developed assuming a head rice value of $18.00/cwt and broken rice values of 60%, 70%, and 80% of the head rice value. As in the parabolic relationship example (fig. 1), the NV did not change as dramatically as did HRY at either end of the MC range (fig. 3), due to the drying fee structure. When the value of the brokens was 60% of the head rice price, the $HMC_{opt\text{-}NV}$

Table 4. Summary of optimal net values (NV_{opt}) and corresponding optimal harvest moisture contents ($HMC_{opt\text{-}NV}$) of the 25 year/location/cultivar sample sets that were used for this study, as calculated from the NV vs. HMC quadratic regression equations.[a]

Year	Location	Cultivar	$HMC_{opt\text{-}NV}$ (%, w.b.)			NV_{opt} ($/cwt)			$NV_{14\%HMC}$ ($/cwt)[b]		
			60%	70%	80%	60%	70%	80%	60%	70%	80%
1999	Keiser, Ark	Bengal	21.9	21.2	20.2	11.48	11.61	11.76	10.14	10.70	11.26
		Cypress	17.8	17.6	17.3	12.10	12.16	12.22	11.62	11.80	11.97
		Drew	19.6	19.3	18.6	12.08	12.15	12.22	11.13	11.49	11.86
	Stuttgart, Ark.	Bengal	19.6	19.0	18.1	11.53	11.68	11.84	11.06	11.36	11.66
		Cypress	18.8	18.3	17.5	11.57	11.65	11.75	11.16	11.38	11.59
		Drew	20.6	20.0	19.2	11.75	11.86	12.00	10.67	11.11	11.55
2000	Keiser, Ark.	Bengal	19.6	19.1	18.4	11.85	11.94	12.06	10.94	11.33	11.71
		Drew	19.3	19.0	18.6	11.81	11.83	11.88	10.58	10.94	11.30
	Stuttgart, Ark.	Bengal	19.7	18.7	17.6	11.58	11.69	11.84	11.06	11.37	11.67
		Cypress	17.9	17.6	17.2	11.46	11.54	11.63	11.25	11.38	11.52
		Drew	20.6	20.4	20.2	11.56	11.63	11.70	9.70	10.11	10.52
2004	Essex, Mo.	Cocodrie	17.7	17.5	17.3	12.07	12.18	12.30	11.64	11.82	12.01
	Hunter, Ark.	Wells	18.3	17.8	17.0	11.92	12.04	12.17	11.67	11.88	12.09
	Lodge Corner, Ark.	Bengal	17.5	16.2	14.4	11.97	12.06	12.17	11.89	12.03	12.17
	Newport, Ark.	Cocodrie	17.0	16.8	16.5	12.13	12.24	12.36	12.04	12.17	12.29
2005	Cleveland. Miss.	XP 723	17.2	16.7	15.8	11.38	11.51	11.67	11.14	11.37	11.62
	Osceola, Ark.	Cheniere	17.7	17.5	17.2	11.47	11.56	11.66	10.83	11.05	11.28
	Qulin, Mo.	Wells	16.4	16.1	15.6	11.52	11.71	11.90	11.32	11.56	11.82
	Stuttgart, Ark.	Francis	18.1	18.0	18.0	11.77	11.86	11.95	11.24	11.39	11.52
		XP 723	18.0	17.8	17.5	11.61	11.72	11.84	11.18	11.39	11.60
2006	Des Arc, Ark.	Cheniere	17.7	17.6	17.4	12.03	12.12	12.20	11.55	11.71	11.87
	Osceola, Ark.	Wells	19.1	18.7	18.1	11.76	11.90	12.05	10.94	11.31	11.67
	Shaw, Miss.	XP723	18.9	18.6	18.1	11.63	11.74	11.85	10.77	11.10	11.43
	Stuttgart, Ark.	Wells	18.9	18.4	17.5	11.64	11.79	11.95	11.19	11.49	11.79
		XP723	15.8	14.5	12.9	11.67	11.82	11.99	11.64	11.82	11.99

[a] Table values were calculated using a head rice price of $18.00/cwt and brokens prices of 60%, 70%, and 80% of the head rice price.
[b] The $NV_{14\%HMC}$ values represent the NVs of the rice if it had been harvested at 14% HMC.
Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

was 19.7% with a corresponding NV_{opt} of $11.58/cwt (table 4). As the value of brokens increased to 70% and 80% of that of head rice, the NV_{opt} increased only slightly, to $11.69 and $11.84/cwt, respectively. However, the HMC necessary to reach NV_{opt} decreased to 18.7% and 17.6%, respectively.

Similar to the parabolic example (fig. 1), the $NV_{14\%HMC}$ was more affected by the price of brokens than NV_{opt}. The $NV_{14\%HMC}$ decreased a total of $0.61/cwt, from $11.67/cwt at 80% brokens value, to $11.37 and $11.06/cwt at 70% and 60% values, respectively, at a head rice price of $18.00/cwt (table 4). Table 4 also indicates that the difference between $NV_{14\%HMC}$ and NV_{opt} was similarly affected. If the Bengal rice had been harvested at 14% HMC as opposed to HMC_{opt}, there would have been a $0.52/cwt loss if the price of brokens had been at 60% of the head rice price, and losses of $0.32/cwt and $0.17/cwt at 70% and 80%, respectively.

Figure 4 shows the effect of a change in head rice price, assuming that the brokens price was equal to 70% of the head rice price. With the change in head rice price, the $HMC_{opt\text{-}NV}$ was 18.5%, 18.7%, and 18.9% at $16.50, $18.00, and $19.50/cwt, respectively (tables 3-5). As in the parabolic relationship example (fig. 2), the price of head rice did not dramatically affect the reduction in NV associated with harvesting at low HMCs. The difference between $NV_{14\%HMC}$ and NV_{opt} was $0.29/cwt at $16.50/cwt, to $0.32/cwt at $18.00/cwt, and $0.38/cwt at $19.50/cwt head rice price, when the brokens price was 70% that of head rice.

Static HRY vs. HMC Relationship

Figure 5 (and table 4) shows the relationship between NV, HRY, and HMC for long-grain cultivar Cypress grown in Stuttgart, Arkansas in 2000, assuming a head rice price of $18.00/cwt. Head rice yield did not drastically change with HMC, but instead remained relatively static with only a 4.8 difference in HRY throughout the harvest season. This sample set comprised six rice samples harvested between 13.7% and 23.6% MC with corresponding HRYs between 60.0% and 64.8%, and a HRY_{opt} of 65.4% at a $HMC_{opt\text{-}HRY}$ of 21.1% HMC (table 1). Though it is more common that HRY decreases with decreased HMC, it has been reported that, for some years and locations, low HMCs do not necessarily relate to low HRYs (Qin and Siebenmorgen, 2005; Siebenmorgen et al., 2007). This could be due to the absence of a rain event or high relative humidity during the late harvest period, thus water adsorption and subsequent kernel fissuring would not have occurred in the field. Additionally, it has been shown that some rice cultivars, specifically Cypress, are particularly resistant to fissuring due to field water absorption (Berrio and Cuevas-Perez, 1989; Jodari and Linscombe, 1996).

As with figures 1 and 3, the NV versus HMC regression lines in figure 5 were developed assuming a head rice value of $18.00/cwt and broken rice values of 60%, 70%, and 80% of that of head rice. As a result of the fairly stable HRYs, the shape of the NV curves did not change appreciably with the

Table 5. Summary of optimal net values (NV_{opt}) and corresponding optimal harvest moisture contents ($HMC_{opt\text{-}NV}$) of the 25 year/location/cultivar lots that were used for this study, as calculated from the NV vs. HMC quadratic regression equations.[a]

Year	Location	Cultivar	$HMC_{opt\text{-}NV}$ (%, w.b.) 60%	70%	80%	NV_{opt} ($/cwt) 60%	70%	80%	$NV_{14\%HMC}$ ($/cwt)[b] 60%	70%	80%
1999	Keiser, Ark.	Bengal	22.0	21.4	20.4	12.53	12.66	12.82	11.04	11.64	12.25
		Cypress	17.9	17.7	17.3	13.16	13.23	13.30	12.64	12.83	13.02
		Drew	19.7	19.4	18.7	13.16	13.23	13.31	12.11	12.50	12.90
	Stuttgart, Ark.	Bengal	19.8	19.2	18.3	12.57	12.73	12.90	12.03	12.36	12.68
		Cypress	19.0	18.5	17.7	12.60	12.69	12.79	12.14	12.38	12.61
		Drew	20.8	20.2	19.3	12.81	12.93	13.07	11.61	12.09	12.56
2000	Keiser, Ark.	Bengal	19.7	19.3	18.5	12.91	13.01	13.13	11.90	12.32	12.73
		Drew	19.3	19.0	18.6	12.85	12.89	12.92	11.52	11.91	12.30
	Stuttgart, Ark.	Bengal	19.9	18.9	17.8	12.62	12.74	12.89	12.03	12.36	12.69
		Cypress	18.0	17.7	17.3	12.47	12.56	12.66	12.24	12.39	12.53
		Drew	20.6	20.5	20.3	12.60	12.67	12.75	10.58	11.02	11.46
2004	Essex, Mo.	Cocodrie	17.8	17.6	17.4	13.14	13.26	13.38	12.66	12.86	13.05
	Hunter, Ark.	Wells	18.5	18.0	17.1	12.98	13.11	13.25	12.70	12.92	13.16
	Lodge Corner, Ark.	Bengal	17.7	16.5	14.6	13.03	13.12	13.24	12.93	13.09	13.24
	Newport, Ark.	Cocodrie	17.1	16.8	16.6	13.20	13.32	13.44	13.09	13.24	13.37
2005	Cleveland. Miss.	XP 723	17.3	16.8	15.9	12.38	12.53	12.70	12.11	12.37	12.64
	Osceola, Ark.	Cheniere	17.8	17.5	17.3	12.48	12.58	12.68	11.79	12.04	12.28
	Qulin, Mo.	Wells	16.4	16.0	15.6	12.55	12.74	12.95	12.32	12.59	12.87
	Stuttgart, Ark.	Francis	18.1	18.1	18.1	12.81	12.91	13.01	12.24	12.39	12.54
		XP 723	18.1	17.9	17.5	12.64	12.76	12.89	12.17	12.39	12.62
2006	Des Arc, Ark.	Cheniere	17.7	17.6	17.4	13.09	13.19	13.28	12.57	12.74	12.92
	Osceola, Ark.	Wells	19.2	18.7	18.1	12.80	12.95	13.11	11.91	12.30	12.70
	Shaw, Miss.	XP723	19.0	18.7	18.2	12.67	12.78	12.91	11.72	12.09	12.44
	Stuttgart, Ark.	Wells	19.0	18.5	17.7	12.68	12.83	13.01	12.18	12.50	12.82
		XP723	16.0	14.8	13.0	12.70	12.85	13.04	12.66	12.85	13.03

[a] Table values were calculated using a head rice price of $19.50/cwt and brokens prices of 60%, 70%, and 80% of the head rice price.
[b] The $NV_{14\%HMC}$ values represent the NVs of the rice if it had been harvested at 14% HMC.
Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

price of brokens, compared to the previously exemplified sample sets. While HRY for this sample set was at a maximum at 21.1% HMC, figure 5 and table 4 show that NV was at maximum at 17.9%, 17.6%, and 17.2% HMC at 60%, 70%, and 80% brokens values, respectively; thus a HMC difference of at least 3.2 percentage points when considering the optimization of NV rather than HRY. The NV_{opt} varied by a total of only $0.17/cwt due to the change in brokens values, from $11.46/cwt, to $11.54 and $11.63/cwt, at 60%, 70%, and 80% brokens values, respectively (table 4).

The $NV_{14\%HMC}$ did not vary as much as the previous examples of the parabolic and declining HRY versus HMC relationships. The $NV_{14\%HMC}$ changed a total of $0.27/cwt

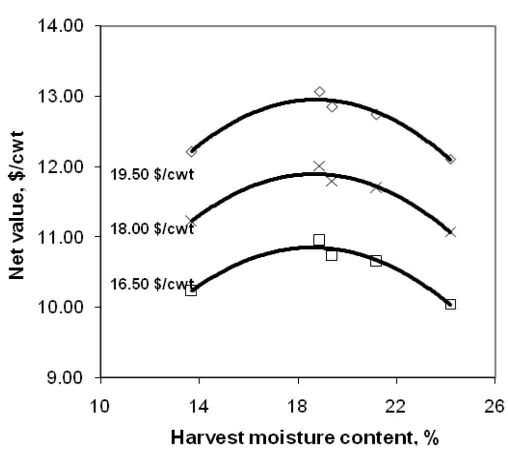

Figure 2. Net value (eq. 5) of Wells rice harvested from Osceola, Arkansas in 2006, as affected by changes in the price of head rice [$16.50/cwt (□), $18.00/cwt (x), or $19.50/cwt (◇)] assuming that the price of brokens was equal to 70% of the head rice price. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

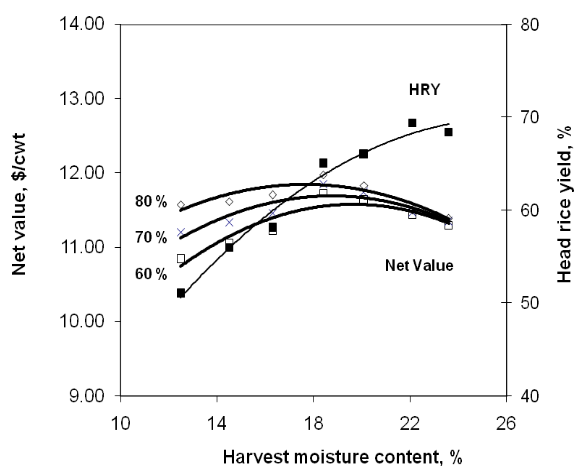

Figure 3. Net value (eq. 5) and head rice yield (HRY) (■) of Bengal rice harvested from Stuttgart, Arkansas in 2000. Net value was calculated assuming that head rice had a value of $18.00/cwt, and brokens had values of 60% (□), 70% (x), or 80% (◇) of the head rice value. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

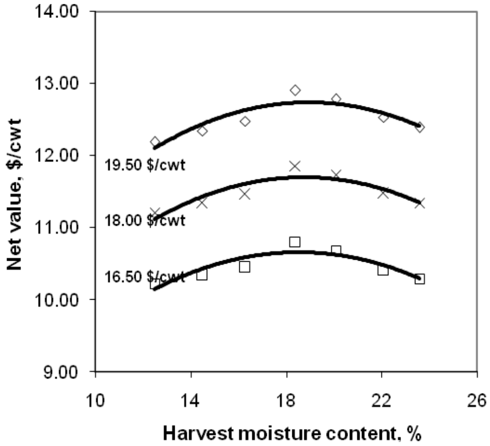

Figure 4. The net value (eq. 5) of Bengal rice harvested from Stuttgart, Arkansas in 2000, as affected by changes in the price of head rice [$16.50/cwt (□), $18.00/cwt (x), or $19.50/cwt (◇)] assuming that the price of brokens was equal to 70% of the head rice price. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

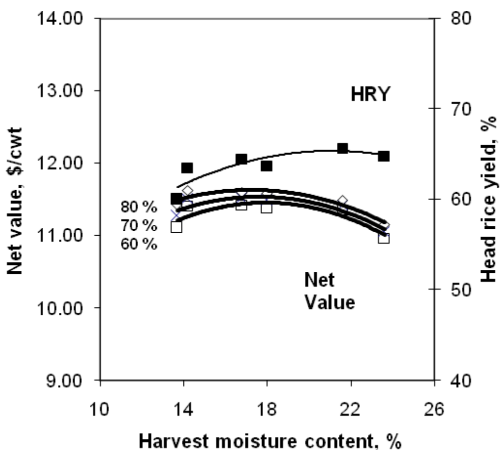

Figure 5. Net value (eq. 5) and head rice yield (HRY) (■) of Cypress rice harvested from Stuttgart, Arkansas in 2000. Net value was calculated assuming that head rice had a value of $18.00/cwt, and brokens had values of 60% (□), 70% (x), or 80% (◇) of the head rice value. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

with the changes in brokens values, from $11.25/cwt to $11.52/cwt at 60% and 80% brokens values, respectively (table 4). The difference between $NV_{14\%HMC}$ and NV_{opt} was small relative to the parabolic and the declining HRY versus HMC relationships. If the rice had been harvested at 14% MC as opposed to HMC_{opt}, there would have been a $0.21/cwt loss if the price of brokens had been at 60% of the head rice price, and $0.16/cwt and $0.11/cwt at 70% and 80%, respectively (table 4).

Figure 6 shows the effect of a change in head rice price, assuming that the brokens price was equal to 70% of the head rice price. With the change in head rice price, the $HMC_{opt\text{-}NV}$ did not change appreciably, at 17.5%, 17.6%, and 17.7% at $16.50, $18.00 and $19.50/cwt, respectively (tables 3-5). As with the parabolic (fig. 2) and declining (fig. 4) HRY versus HMC relationships, the difference between NV_{opt} and $NV_{14\%HMC}$ did not change appreciably with the change in head rice price, with the difference between $NV_{14\%HMC}$ and NV_{opt} being $0.15/cwt at $16.50/cwt head rice price (table 3), $0.16/cwt at $18.00/cwt (table 4), and $0.17/cwt at

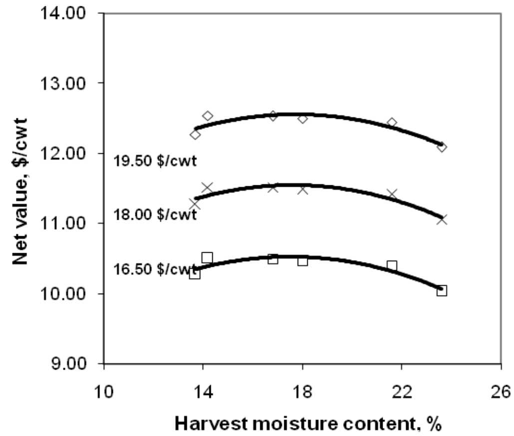

Figure 6. The net value (eq. 5) of Cypress rice harvested from Stuttgart, Arkansas in 2000, as affected by changes in the price of head rice [$16.50/cwt (□), $18.00/cwt (x), or $19.50/cwt (◇)] assuming that the price of brokens was equal to 70% of the head rice price. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

$19.50/cwt head rice price (table 5) when the brokens price was 70% of head rice.

Cultivar Trends

When HRYs and NVs were pooled according to cultivar and plotted against HMC, regardless of year and location, variability was introduced into the data sets, thus decreasing the degree of correlation (as indicated by the decreased R^2 values) between HRY and HMC, as well as NV and HMC (fig. 7) (data shown only for $18.00/cwt and 70% brokens value as a means of concept illustration). The greatest degree of correlation between HRY versus HMC was found for Drew, as indicated by an R^2 of 0.805. The weakest correlation between NV and HMC was found for Bengal, indicated by an R^2 of 0.213, showing that by pooling location and harvest year, a large amount of variability was introduced into the data sets. All cultivars but Cocodrie and Francis showed dramatic decreases in HRY with decreasing HMC. Cocodrie and Francis cultivars exhibited flatter regression lines associating HRY with HMC, possibly due to fewer data points taken at very low (<14%) MCs.

Assuming a head rice price of $18.00/cwt and a brokens price of 70% of that of head rice, the $HMC_{opt\text{-}NV}$ of all long-grain cultivars, except for Drew, was between 17.1% and 18.4% (fig. 7). The $HMC_{opt\text{-}NV}$ of Drew was 19.7%, which was equal to that of the medium-grain cultivar Bengal. The NV_{opt} of all cultivars fell between $11.63 and $11.86/cwt, except for that of Cocodrie, whose NV_{opt} reached $12.20/cwt. These cultivar differences may be attributed to differences in HRY levels, but Cocodrie has been reported to have higher milled rice total and surface lipids than other rice cultivars typically grown in the mid-Southern United States (Siebenmorgen et al., 2007) and thus the greater NVs for Cocodrie may have been a product of laboratory milling and degree of milling issues.

Figure 8 shows the relationships between NV, HRY, and HMC when all 139 lots used in this study were pooled. The differences in the shapes of the individual HRY versus HMC curves introduce variability and thus the lower coefficient of determination (R^2 of 0.527) between HRY and HMC when all sample lots of all years, locations, and cultivars were pooled. The NVs in figure 8 were calculated using a head rice

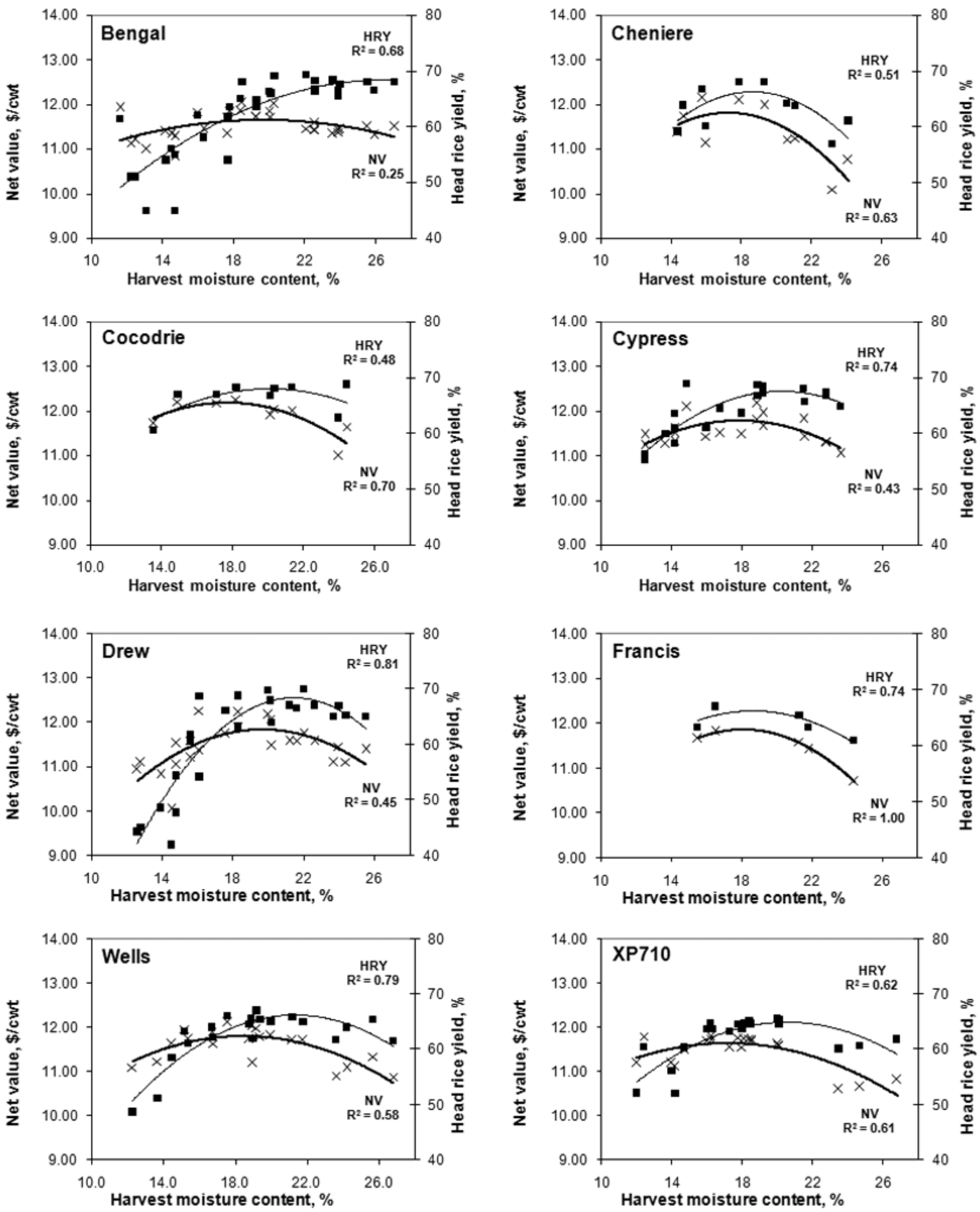

Figure 7. Correlations between pooled head rice yields (HRYs) (■) and net values (NVs) (×) vs. harvest moisture content (w.b.) data of eight cultivars harvested from the locations and dates indicated in table 1. The NV curves were developed assuming a head rice price of $18.00/cwt and a brokens price of 70% of the head rice price.

price of $18.00/cwt and a brokens price of 70% of the head rice price. The HRY versus HMC regression line indicated that HRY reached a maximum of 66.6% at a corresponding $HMC_{opt\text{-}HRY}$ of 21.7%. However, the peak of the NV versus HMC curve corresponded to a NV_{opt} of $11.73/cwt and a corresponding $HMC_{opt\text{-}NV}$ of 18.5%. The 3.2 percentage point difference between the HMC needed to maximize HRY and the HMC needed to maximize NV reflects the effect of a progressively increasing drying fee schedule.

Conclusions

The NV of rice, as affected by drying costs and milling quality changes associated with harvesting rice at various MCs, was studied using a five-year data set comprising 139 sample lots of eight cultivars harvested over a range of HMCs from 11 locations in the Southern United States. Quadratic relationships characterized the change in HRY and NV across HMCs. A sensitivity analysis revealed that as the price of brokens increased, the $HMC_{opt\text{-}NV}$ at which NV was maximized decreased. When HMC, NV, and HRY were plotted regardless of cultivar, location or harvest year,

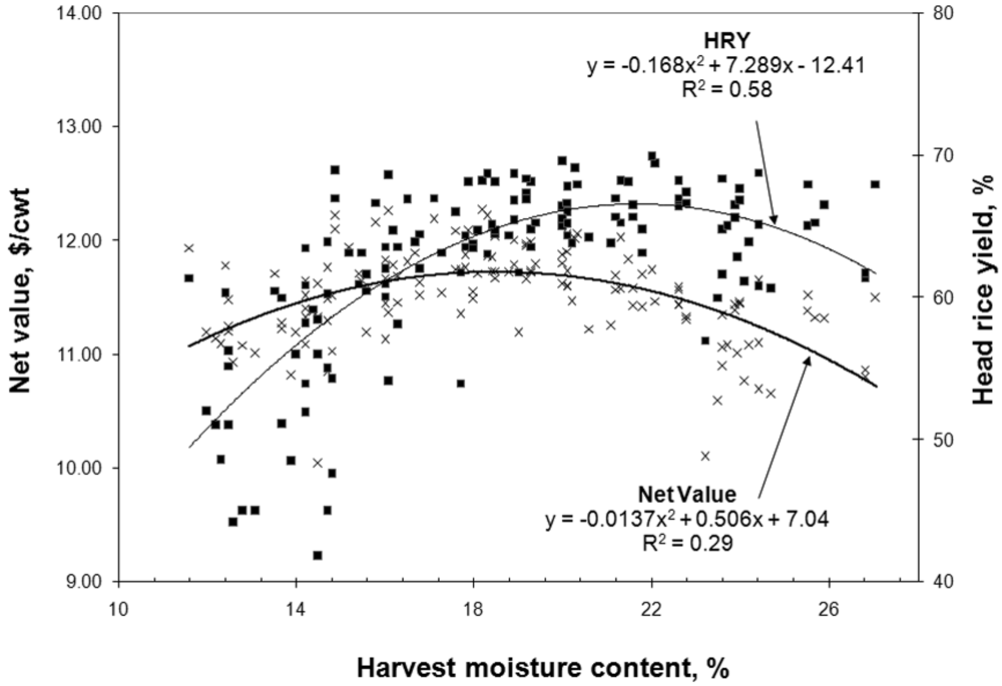

Figure 8. Head rice yield (HRY) (■) and net value (×) vs harvest moisture content correlations of all 139 samples (table 1) used in this study. This graph was developed assuming a head rice value of 18.00 $/cwt and a brokens value of 70% of the head rice value. Drying charges were calculated per equation 1 using the drying fee structure detailed in table 2.

theHMC at which HRY was maximized was 21.7% whereas the HMC at which NV was maximized was 18.5%, representing a 3.2 percentage point difference between $HMC_{opt\text{-}HRY}$ and $HMC_{opt\text{-}NV}$.

The HRY versus HMC curve for Bengal did not decrease at the higher HMCs as it did for long-grain cultivars. The $HMC_{opt\text{-}HRY}$ and the $HMC_{opt\text{-}NV}$ of the Bengal curves differed by a great amount (26.5% and 19.7% HMC, respectively). It is evident that more complete HRY versus HMC data is needed for medium-grain cultivars in the Southern United States in order to more accurately assess the effect of HMC on NV. A study of this sort may involve the collection of samples across a wide range of HMCs, from 12.5% to 30% for example, to fully develop the NV versus HMC curve.

Additional future work should include an investigation of the NV of rice calculated using other drying fee structures that exist in Arkansas and in other rice-producing states. Comparisons could then be made of the differences between NV_{opt} and the NV found when harvesting at HMCs to maximize HRY ($HMC_{opt\text{-}HRY}$). It may be possible to develop different drying cost structures that would bring the $HMC_{opt\text{-}NV}$ value closer to that of $HMC_{opt\text{-}HRY}$. Such a study would require quantifying the relative cost of the head rice that is lost by harvesting at $HMC_{opt\text{-}NV}$ versus that at $HMC_{opt\text{-}HRY}$.

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