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Biomass production and allocation in rice with implications for straw harvesting and utilization

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Abstract

Variability in straw quantity and quality can have critical impacts on biomass industries. To generate better information on this variability for rice residues, trials with eight common California rice cultivars were planted at multiple sites for the 1999 and 2000 seasons. Straw yields averaged 11.2 Mg ha^{-1} in 1999 and 8.5 Mg ha^{-1} in 2000 with a consistent range of 2–3 Mg ha^{-1} between the highest and lowest yielding varieties at each site. Straw-to-grain ratios were also higher in 1999 averaging 1.50 kg kg^{-1} with high variability while in 2000 they were a more typical 1.04 kg kg^{-1} with little difference by site or variety. The length of the pre-heading period was the strongest indicator for straw yield. Each one day increment in the length of the time to 50% heading resulted in an additional 8.4 kWh m^{-2} of solar energy and 0.2 Mg ha^{-1} of straw production at an efficiency slightly over 1%. Average stem weight ranged from 1.3 to 2.6 g and increased stem weight corresponded to higher yield but lower stand density. Harvested straw yield is also strongly affected by cutting height with a non-linear distribution resulting in nearly half of the straw biomass occurring in the lower third of the plant. Forty percent of biomass was in the internode sections of the stem, 53% in leaf and sheath, 4% in nodes and 3% in the panicle (excluding hull and seed). Stem (culm) fraction decreases and leaf fraction increases from the base of the plant to the panicle. Since many properties vary by botanical fraction, height of cut influences both the yield and composition of the straw. The ability to predict the amount and composition of the biomass material allows for greater control in the design and mobilization of the harvesting system.

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1. Introduction

Information on biomass yields by variety, along with variability due to site and growing season is important for utilization of agricultural residues. Biomass utilization systems require accurate yield data and some estimate of variability for design purposes. Currently, this information is limited and insufficient for engineering uses. For the rice straw industry in California, most of this information to date has been provided by monitoring commercial baling operations. Such studies have shown large variations

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ranging from 3 to 9 Mg ha^{-1} in yield [1–3]. Yield variations are difficult to account for and are anecdotally attributed to effects of variety, season, location, stubble height, equipment losses, and other effects [4]. To understand harvesting and handling losses, there is a need for baseline yield information for variety, location, season and cutting height.

Grain yield information is often used for estimating available straw. Grain yield is readily available for crops on a regional level and is usually measured on the field level by the harvester. Dependable straw-to-grain factors become critical for estimating available biomass after grain harvest. Based on baling operations, harvested straw-to-grain ratios for modern California cultivars have been measured in the range of 0.3–0.5 [1], but these do not account for the biomass remaining in the field behind the baler. In terms of available straw, it is commonly accepted that most modern semi-dwarf rice varieties yield a 1:1 straw-to-grain ratio (total straw to total rough-rice, both dry basis) while traditional tall varieties yield even more straw with ratios greater than 2 [5]. A biomass availability study from 1982 reported straw-to-grain ratios for California rice at 1.35 but did not specify by type or variety [6]. A more detailed California study over multiple varieties, sites and seasons showed the effect of fertilization rate on grain and straw production [7].[1] The experiments were conducted from 1976 to 1985 and included 5 locations and 9 modern semi-dwarf cultivars. At typical fertilization rates of 135–225 kg-N ha^{-1} straw yield ranged from 6 to 11 Mg ha^{-1} and straw-to-grain ratios ranged from 0.7 to 1.8 across the study. At maximum grain yield, average straw-to-grain ratio was 1.08 at a fertilization rate of 167 kg-N ha^{-1}. At higher fertilization rates grain yield declined while straw production continued to increase. From these results it can be shown that for a given grain yield the straw yield can be double-valued depending on whether the rice is above or below optimum fertilization.

Other conditions can affect the of straw-to-grain ratio but there is little detailed information on the range or frequency of these occurrences. For example, if significant sterility (seed blanking) occurs due to climate, there can be a loss in grain yield without much effect on straw or perhaps even an increase in straw. Diseases including sheath spot and stem rot are known to reduce grain yield but whether straw yield shows a corresponding reduction remains uncertain. The application of unity straw-to-grain ratio in these cases may fail to predict the available straw. Knowledge of potential straw yield is important because inadequate equipment can be mobilized for harvesting within the short time frame available, or idle time can increase with excess equipment. Both effects contribute to higher costs.

Field losses of straw in harvesting depend in part on the distribution of mass in the plant. Changes in cutting height near the base of the plant may have a disproportionate effect on the biomass yield. Mass in each botanical fraction also varies with height. Culm fraction decreases and leaf sheath and leaf blade increase upwards along the stem. Physical and chemical properties of the culm, nodes, leaf sheaths, leaf blades and panicle are different and the changes in composition along the stem create opportunities for selective control in harvesting specifically for desirable properties. Many studies have shown that the leaves of rice straw have twice the silica concentration of the internode culm [8–13]. Other differences observed include higher cellulose content in the culm [9], higher protein content in the leaves [9,10], and higher lignin content in the culm [8]. None of the studies showed a great deal of variation between leaf sheath and blade. Properties of nodes and panicles typically are intermediate to those of leaf and stem. Overall mass fractions have been reported in the range of 25–35% leaf blade, 30–40% leaf sheath, and 30–40% culm. The linear distribution of these fractions along the stem was not found in the literature.

A trial study to examine the biomass yields of several common California rice cultivars was begun in 1999. The main objective of this study was to understand how yield and properties are affected by variety, location, season, botanical fraction, and other conditions of growth. Understanding and controlling for these variables can be critical to the long-term viability of biomass industries. The methodology presented here is not unique to rice straw and can readily be applied to other agricultural residues.

The wide range of varieties chosen represented a large share of the rice production in California

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[1] In order to match the present study, straw yield data from [7] was increased by 10%. The harvesting method employed was likely to leave some unmeasured stubble in the field estimated to be 10% on average.

during the previous year [14]. Early maturing varieties account for most of the crop because of the higher reliability of favorable weather with an earlier harvest. Medium grain Japonica varieties account for 83% of the California acreage with M202 and M204 representing 57% and 11%. Short grains are increasing in importance with 12% of the California rice crop. Of these, the sweet rice, CM101, accounts for 4% of the crop and S102 another 1.5%. The different agronomic requirements of other Japanese short grain varieties of importance to California, for example Akitacomachi (3%) and Koshihikari (2%), precluded their inclusion in this study. Long grains are a smaller share of production (3%), with mostly L204 and a small amount of the newer variety L205. Late maturing varieties such as M401 and the newer M402 target a premium quality rice market and make up 6% of the state crop.

2. Materials and methods

Experimental plots for both 1999 and 2000 were planted next to annual Statewide Rice Variety Trials conducted in the Sacramento Valley through a collaborative industry and university research effort. Two field sites were chosen for the six early varieties (CM101, L204, L205, M202, M204, and S102) in Colusa and Yuba Counties (Fig. **??**). At the Colusa county site the soil is moderately alkaline Willows clay typical of the west side of the growing region. The temperate rice varieties grown in the region require the intense sun of the summer growing season and warm nighttime temperatures. At the eastern site in Yuba County, soil is a fine, mixed Kimball loam, hermic mollic palexeralfs. Greater distance from the ocean typically results in temperatures on the east side of the valley to be higher than the west side. The late varieties (M401, M402) were grown in Glenn and Sutter Counties during 1999. Glenn County is in the northwestern area of rice production and has similar soil conditions to Colusa County. The Sutter County site is near the Sutter bypass (a flood control structure for the Sacramento River) with moderate weather and clay soils. For the 2000 trials the late varieties were not included because of the difficulty of managing a separate site; however, two additional early varieties (M102, M205) were added to the Colusa and Yuba County sites. At all sites the land had previously been in continuous rice monoculture typical of California rice production.

Fig. 1. Map of northern California and the Sacramento Valley indicating trial sites located within the principal rice growing counties of the state.

Plot layouts were created using a randomized complete block design with 4 replicates per experiment, blocked based on distance from the flood-water inlet. These plots were established within a commercial field of an equal maturing variety (M202 for the early trials and M401 for the late trials). Each plot measured 3 m × 6 m and was hand sown at seed rates of 167 kg ha^{-1}. All of the trials were subject to the fertilization and weed control regimens of the participating grower. Nitrogen was applied at 180 –210 kg ha^{-1}. The 2000 Yuba trial, for example, was fertilized with 112 kg ha^{-1} N as aqueous ammonia, 224 kg ha^{-1} of starter (16% N, 20% P, 0% K) and 168 kg ha^{-1} potassium chloride (muriate of potash). The crop was top-dressed twice with ammonium sulfate at a rate of 112 kg ha^{-1}. Total nitrogen was 204 kg ha^{-1}. The 2000 Colusa county trial was fertilized with 141 kg ha^{-1} N as aqueous ammonia, 195 kg ha^{-1} of starter (14.7% N, 40% P, 21% K, 10% S) and top dressed with 140 kg ha^{-1} ammonium sulfate. Total nitrogen was 205 kg ha^{-1}. Fertilization practices were similar for the 1999 trials and are typical for California rice grown in these regions.

Plots were harvested with a SWECO (Sutter, CA) 324 rice plot harvester cutting 2.3 m × 6 m swaths from each plot at a measured height from ground level (usually 10 cm). The combine was allowed to thresh and clean until rough rice was thoroughly separated. Straw and chaff were deposited in a container attached to the rear of the combine at the discharge of the straw walkers. The grain was weighed, sampled for moisture and deposited in the grain tank. The straw container was closed and weighed and then straw samples collected for analysis. Straw yield was adjusted for any deviations in cutting height using the mass distribution analysis described later.

Straw samples were immediately sealed in plastic bags and cooled over ice until received at the laboratory. Moisture content was determined in accordance with ASAE Standard S358.1 (24 h in air at 105°C). Whole plant samples were also collected from each plot, placed in plastic bags on ice, and stored at $-10°$C until air-dried to equilibrium moisture content on a drying table. Ten randomly selected plant samples from each plot were measured for length, weighed, and divided into components: grain, panicle, node, internode, and leaf. Component length and weight were measured. Node lengths were fixed at 5 mm by design of the cutting apparatus.

3. Results and discussion

For early rice, the 1999 Colusa and the 2000 Yuba trials were harvested late (Table **??**) resulting in greater crop lodging and low grain moisture (20–22% is optimum at harvest) at these sites. This has no effect on straw yields and straw-to-grain ratios as little plant growth occurs in the late season and the panicles retain most of their grain even to low moistures. The number of days to 50% heading is a measure of the maturity rate of the crop and is longer on average for the 1999 crop. The late trials show a characteristic increase in time to heading and maturity with the Sutter site longer than the Glenn site for 1999. Seedling vigor was lowest for 1999 Yuba and 1999 Sutter. These sites also had the lowest grain yields in 1999, a result attributed to low nighttime temperatures during critical heading stages. Straw yields remained high, indicating greater vegetative growth even with low seed production.

Straw yields for individual trials ranged from 7.0 to 13.6 Mg ha^{-1} with a global average of 9.7 Mg ha^{-1} (Table **??**). Strong season by site interactions appear for straw yield. In 2000 there was very little difference between average yield with both sites at about 8.5 Mg ha^{-1} while there was a large difference in 1999 with Colusa at 10.4 Mg ha^{-1} and Yuba at 12.1 Mg ha^{-1}. The data for each season were analyzed separately with a two-factor randomized block model for site and variety. For early varieties the 1999 yields show a significant effect of site ($p = 0.0007$) and variety ($p = 0.0168$) while 2000 yields only show significant differences by variety ($p < 0.0001$) but not by site ($p = 0.33$). Clearly 1999 showed a regional effect of higher straw yields on the east side of the growing region (Yuba and Sutter sites). Late varieties showed this significant site difference ($p < 0.0001$) but no significant variety difference between M401 and M402. For early varieties both seasons revealed similar rankings for yield by variety with M204, L204, L205 and M202 being the higher yielding varieties and S102 and CM101 lower yielding in straw. Of the new varieties planted in 2000, M205 proved to be higher yielding than all others at both sites while M104 fell within the lower yielding group. Mean differences by site and variety are shown in Table **??** using LSD tests with $\alpha = 0.05$.

Straw-to-grain ratios (dry basis) ranged from 0.81 to 2.29 with an average of 1.27 (Table **??**). As with straw yields, straw-to-grain ratios also showed high interaction between season and site. In the 2000 season, straw-to-grain ratios were all near unity for both sites while in 1999 they averaged 1.16 for the Colusa site and a much higher 1.87 for the Yuba site. Low grain yields and high straw yields for certain varieties in 1999 are responsible for the high ratios on the east side of the growing region, particularly at the Yuba site. The late varieties also followed this trend with an average straw-to-grain ratio of 1.13 for Glenn and 1.96 for Sutter. For straw-to-grain ratios, the 1999 trials show strong effects of both site ($p < 0.0001$) and

Table 1
Agronomic and harvest summary for 1999 and 2000 rice straw variety trials

Variety trial (year, type, site)	Total days to harvest	Days to 50% heading	Avg. seedling vigor (1–5)	Avg. plant height (cm)	Avg. crop lodging (%)	Avg. straw moisture (% db)	Avg. grain moisture (% db)	Avg. straw yield (Mg ha^{-1})	Avg. grain yield (Mg ha^{-1})
1999, Early, Colusa	158	95	4.2	90	32	60.8	13.8	10.4	8.9
1999, Early, Yuba	148	102	2.8	91	1	66.9	19.3	12.1	6.6
1999, Late, Glenn	160	114	4.8	93	1	64.6	19.5	8.7	7.7
1999, Late, Sutter	170	118	3.9	92	1	63.9	20.8	12.7	6.5
2000, Early, Colusa	155	88	3.9	96	64	66.8	19.0	8.6	8.4
2000, Early, Yuba	170	87	4.0	88	22	59.5	13.1	8.4	7.9

Yields are reported at zero moisture.

Table 2
Straw yields (Mg ha^{-1} dry basis) for 1999 and 2000 rice straw trials with means by variety, site and season

Early varieties	Colusa 1999	Yuba 1999	Colusa 2000	Yuba 2000	Season mean		Site mean[a]		Overall mean[a]
					1999	2000	Colusa	Yuba	
M204	11.7	13.6	9.1	9.1	12.6a	9.1ab	10.4	11.3	10.9
L204	11.2	12.7	9.4	8.4	11.9a	8.9b	10.3	10.5	10.4
L205	10.8	12.2	8.7	8.3	11.5ab	8.5bc	9.8	10.3	10.0
M202	10.2	12.2	8.8	9.1	11.2abc	8.9b	9.5	10.7	10.1
S102	9.6	10.9	7.0	7.6	10.3bc	7.3d	8.3	9.3	8.8
CM101	8.7	11.1	7.2	7.7	9.9c	7.5d	7.9	9.4	8.7
M205			10.1	9.5		9.8a	10.1	9.5	9.8
M104			8.3	7.4		7.8cd	8.3	7.4	7.8
Mean[b]	*10.4*a	*12.1*b	*8.6*a	*8.4*a	*11.2*	*8.5*	*9.3*	*10.0*	*9.7*
Late varieties	Glenn 1999	Sutter 1999			Season mean		Site mean[a]		Overall mean[a]
					1999	2000	Glenn	Sutter	
M401	9.0	12.9			10.9a		9.0	12.9	10.9
M402	8.4	12.6			10.5a		8.4	12.6	10.5
Mean	*8.7*a	*12.7*b			*10.7*		*8.7*	*12.7*	*10.7*

[a] Site and overall means are shown for reference but were not statistically evaluated due to strong site by season interaction.
[b] Means with same letter for each category are not significantly different by Tukey's test with $\alpha = 0.05$.

variety ($p < 0.0001$) while the 2000 trials show only a weak effect of variety ($p=0.0391$) and no significant effect of site ($p = 0.14$). The late trials show significance by site only ($p < 0.0001$) with no statistical difference between M401 and M402. Strong differences between high ratio varieties (M204, L204, and L205) and low ratio varieties (M202, CM101, and S102) apparent during 1999 did not recur during 2000, making less obvious any trends for the early varieties.

Results for 1999 and 2000 are quite different in terms of straw and grain production. For modern semi-dwarf varieties, expected ratios of straw to grain production are nearly 1:1 at optimum levels of fertilization [5–7]. All of the varieties grown in 2000 are near this 1:1 line, but for many of the 1999 varieties the ratios are considerably higher (Fig. **??**). For 1999

Table 3
Straw-to-grain ratios for 1999 and 2000 rice straw trials

Early varieties	Colusa 1999	Yuba 1999	Colusa 2000	Yuba 2000	Season mean		Site mean[a]		Overall mean[a]
					1999	2000	Colusa	Yuba	
M204	1.55	2.14	0.99	1.07	1.84a	1.03ab	1.27	1.60	1.43
L204	1.22	2.22	1.08	1.15	1.72a	1.12a	1.15	1.68	1.42
L205	1.42	2.29	1.08	1.16	1.85a	1.12a	1.25	1.72	1.49
M202	0.96	1.64	0.95	1.04	1.30b	0.99b	0.95	1.34	1.14
S102	0.95	1.31	1.04	0.96	1.13b	1.00b	1.00	1.13	1.06
CM101	0.89	1.45	1.06	1.01	1.17b	1.03ab	0.97	1.23	1.10
M205			1.02	1.07		1.04ab	1.02	1.07	1.04
M104			0.96	1.01		0.99b	0.96	1.01	0.99
Mean[b]	*1.16*a	*1.84*b	*1.02*a	*1.06*a	*1.50*	*1.04*	*1.08*	*1.39*	*1.24*
Late varieties	Glenn 1999	Sutter 1999			Season mean		Site mean[a]		Overall mean[a]
					1999	2000	Glenn	Sutter	
M401	1.13	2.00			1.56a		1.13	2.00	1.56
M402	1.13	1.92			1.52a		1.13	1.92	1.52
Mean	*1.13*a	*1.96*b			*1.54*		*1.13*	*1.96*	*1.54*

[a] Site and overall means are shown for reference but were not statistically evaluated due to site by season and variety by season interactions.

[b] Means with same letter for each category are not significantly different by Tukey's test with $\alpha = 0.05$.

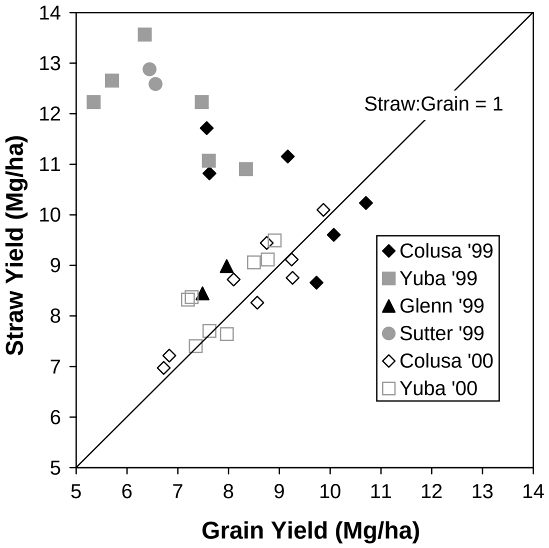

Fig. 2. Grain and straw yields for the 1999 and 2000 trials.

using grain yield to predict straw yield would have had poor success. In some cases a 1:1 ratio would have predicted less than half of the actual available straw.

Other factors affect the relative amounts of straw and grain produced by the rice plant. Fertilization has been shown by other researchers to affect straw-to-grain ratio [7]. Nitrogen fertilization rate has been used to predict grain, straw, and total above ground biomass yield and the resulting straw-to-grain ratio (Fig. ??). The latter steadily increases from 0.72 to 1.26 with nitrogen fertilization rates from 0 to 235 kg-N ha^{-1}. At 167 kg-N ha^{-1} and maximum grain yield, average straw-to-grain ratio is 1.08. At higher fertilization rates grain yield declines while straw production continues to increase. Straw yield is then double-valued in grain yield as is straw-to-grain ratio (Fig. ??). For these trials fertilization was constant for the two seasons at each site so fertilization does not directly explain the differences seen, although N levels were relatively higher compared to crop requirements for the cooler year.

Weather is the primary factor causing differences in straw yield and partitioning between straw and grain for the two seasons. Cool evening temperature during early seed formation is the likely cause of

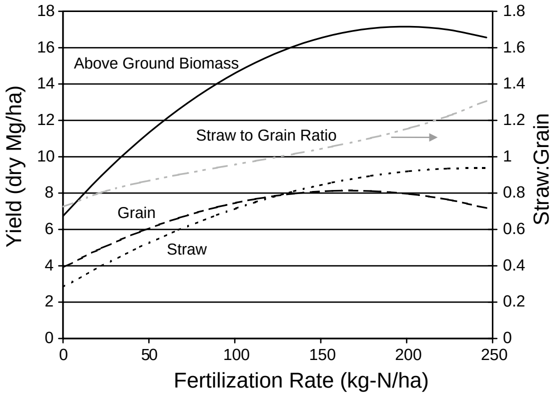

Fig. 3. Total biomass production and the proportion of straw and grain as influenced by fertilization. Yield relationships were developed for California modern semi-dwarf cultivars by Roberts et al. [7].

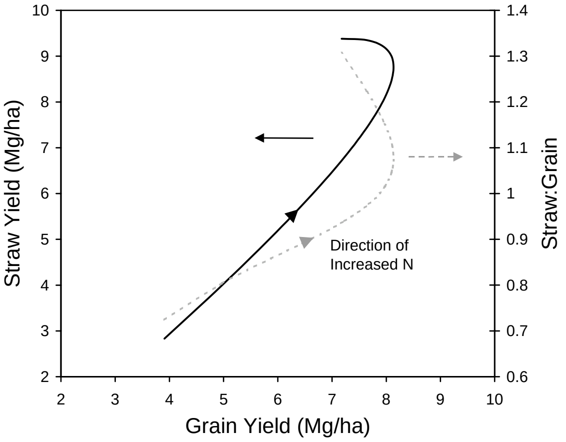

Fig. 4. Straw yield and straw:grain at varying grain yield and fertilization (data from Roberts et al. [7]).

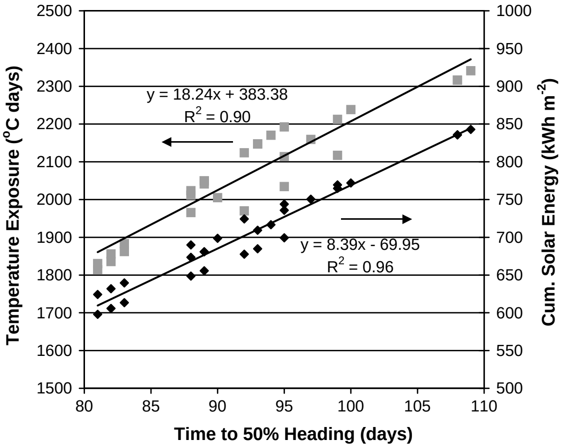

Fig. 5. Temperature exposure and cumulative solar energy for days to 50% heading (early varieties).

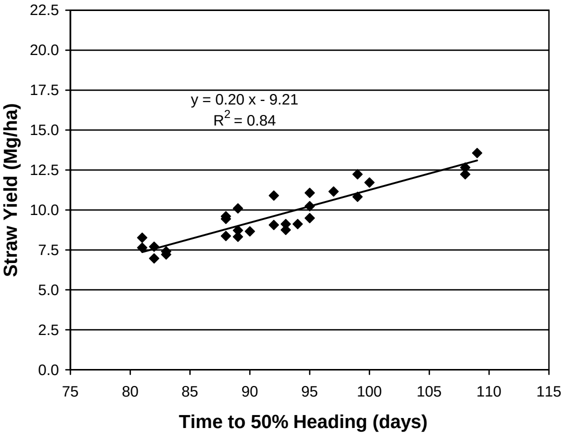

Fig. 6. Straw yield with days to 50% heading (early varieties).

some sterility and extended pre-heading periods for 1999. Weather data during this period (first 90 days) showed that 1999 had 13 and 21 days with lows below 10°C for Colusa and Yuba while 2000 had only 7 and 9 days. Even though nighttime temperatures were low, overall temperature exposure and solar energy were nearly equal between seasons and sites. Highly correlated with heading date were both temperature exposure ($r^2 = 0.90$) and solar energy ($r^2 = 0.96$) (Fig. **??**). Each day heading date was extended resulted in an increase of 18°C d of temperature exposure and 8.4 kWh m^{-2} of additional solar energy. Straw production primarily takes place during this period. Post inflorescence the dominant biomass accumulation occurs in the seed. A longer time to heading provides a longer period for straw production. The number of days to 50% heading was measured in the field and ranged from 81 to 109 days for the early varieties that typically require an average of 90 days. Time to 50% heading showed a strong linear relationship with straw yield (Fig. **??**) independent of variety ($r^2 = 0.84$). Each day heading was extended increased straw production by 0.2 Mg ha^{-1}. The conversion efficiency of solar

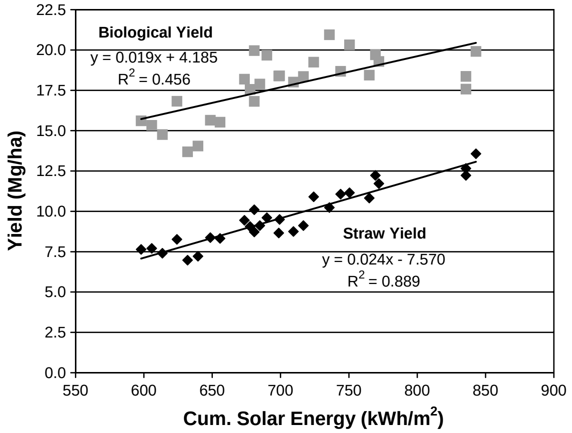

Fig. 7. Straw and biological yield for cumulative solar energy to 50% heading.

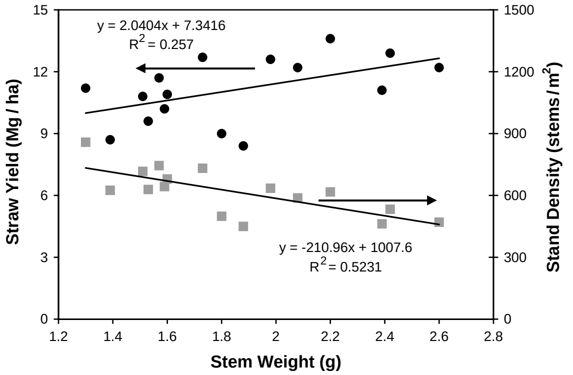

Fig. 8. Straw yield and stem density as related to mean stem weight.

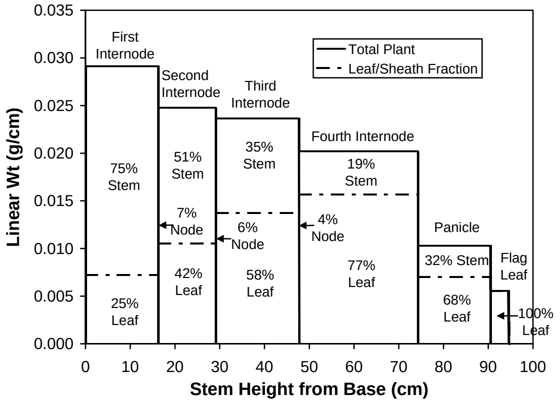

Fig. 9. Linear weight by internode section for California rice straw from stems harvested during 1999 trials. The length, linear weight, and stem, leaf and node fractions are enumerated for each internode section. Node fractions fall within the first 0.5 cm of the internode and arrows denote their locations. Stems were harvested above the first node (root node) and the small panicle node was counted as part of the stem.

energy to straw biomass slightly exceeds 1%. Solar energy to the date of heading was the strongest indicator of straw yield ($r^2 = 0.89$) (Fig. ??). The total biological yield (grain and straw) shows a much weaker relationship because grain yield is affected by low temperatures and other weather factors during head formation and by conditions post-heading.

Randomly selected whole plants from each variety had average stem lengths (root node to panicle tip) ranging from 81 to 97 cm (Table ??). Differences among varieties were significant. Rice straw stem weights were between 1.3 and 2.6 g. Individual plant weights were greatest for the Yuba and Sutter sites that also had the highest yields, suggesting shoot weight rather than stand density largely dictated biomass yield. Stand density is negatively correlated ($r^2 = 0.52$) while straw yield is positively correlated with stem weight ($r^2 = 0.26$) (Fig. ??). Stem density for each variety was estimated from straw yield and mean stem weight and ranged from 500 to 700 stems m^{-2}.

A harvest yield model was developed from the weight distribution along the stem. Leaf (including sheath) and culm by internode, node, and panicle weights were determined for each stem. Although node locations vary between varieties, there were only small varietal differences in weight distribution and overall height. Data for all early varieties were therefore aggregated to create the rice stem model illustrated in Fig. ??. The yield model (Fig. ??) relates factional yield (y, % of maximum) at a given cutting height (h, cm) above ground level:

$$y = 0.0061h^2 - 1.6597h + 100 \qquad r^2 = 0.995. \tag{1}$$

Fifty percent yield is obtained at a height of 34 cm, meaning that half of the straw biomass is in the first third of the shoot height. Eq. (??) can be used along with machinery capacity and other data to make economic decisions on harvesting and stubble cutting (e.g. swathing) operations.

Table 4
Stem data and estimated stem density for subsamples taken from 1999 rice straw trials

Location	Variety	Stem data			
		Length (cm)	Weight (g dry)	Yield (Mg ha^{-1})	Stem density (stems m^{-2})
y trials	*Type mean*	*90.4*	*1.79*	*11.2*	*647*
Colusa	M204	90.8	1.57	11.7	745
	L204	80.8	1.30	11.2	858
	L205	85.3	1.51	10.8	717
	M202	95.0	1.59	10.2	643
	S102	92.5	1.53	9.6	629
	CM101	93.5	1.39	8.7	625
	Site mean	*89.6*	*1.48*	*10.4*	*703*
Yuba	M204	90.8	2.20	13.6	617
	L204	81.8	1.73	12.7	732
	L205	91.0	2.60	12.2	470
	M202	94.5	2.08	12.2	588
	S102	91.5	1.60	10.9	680
	CM101	97.0	2.39	11.1	462
	Site mean	*91.1*	*2.10*	*12.1*	*591*
Late trials	*Type mean*	*92.6*	*2.02*	*10.7*	*529*
Glenn	M401	94.0	1.80	9.0	499
	M402	92.5	1.88	8.4	450
	Site mean	*93.3*	*1.84*	*8.7*	*474*
Sutter	M401	92.8	2.42	12.9	533
	M402	91.3	1.98	12.6	635
	Site mean	*92.0*	*2.20*	*12.7*	*584*

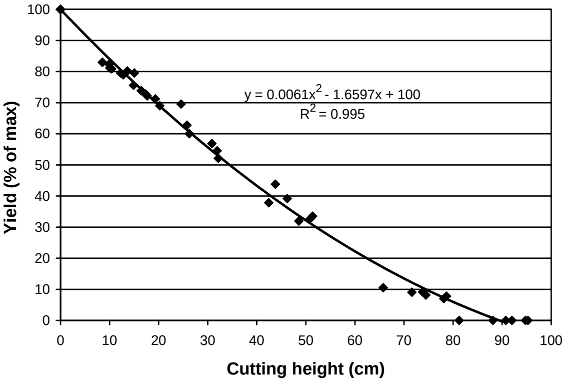

Fig. 10. Straw yield fraction (% of maximum yield) for cutting height above the ground. Mean cumulative weights at each node ($n = 5$–6 nodes) to the tip of the panicle are plotted for each early variety.

Another effect of varying cutting height is that of changing the mix of botanical fractions in the harvested straw. Relative amounts (as dry weight percentages) of leaf, internode, node and panicle based on the cutting height of the straw are modeled as shown in Fig. ??. When cutting the plants at ground level, the straw is about 53% leaf and sheath, 40% internode culm, 4% node and 3% panicle. At 30 cm the fractions are 69% leaf and sheath, 22% internode, 4% node and 5% panicle, showing an increase in leaf fraction and a large reduction in internode culm. This has a significant impact on the composition and structural properties due to differences between leaf and internode. For example, other work has suggested that the silica concentration in leaves is nearly 3 times that in culm. Straw taken at 30 cm is likely to have higher silica concentration than that taken at ground level, an important consequence for industrial uses preferring overall lower silica concentration. The same would

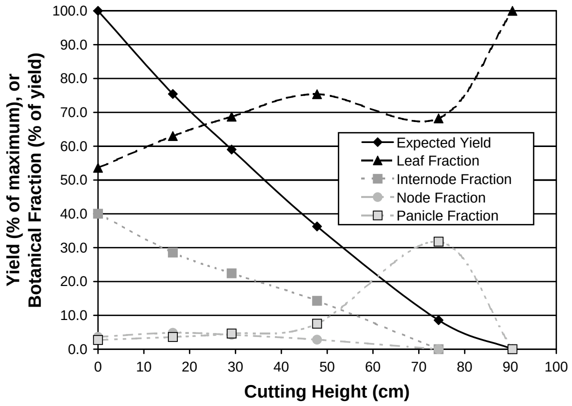

Fig. 11. Expected yield and botanical fractions for rice straw based on in-field cutting height. Each data point represents an average node location (composite of early varieties).

apply to other chemical and structural components that vary by botanical fraction.

4. Conclusions

These rice straw trials show consistent variety differences in straw yield across locations and seasons. The typical range from lowest to highest yield was 2.5 Mg ha^{-1} although the average straw yield was higher in 1999 (11.2 Mg ha^{-1}) than 2000 (8.5 Mg ha^{-1}). The 1999 trials also revealed a strong difference by site while the trials during 2000 showed no statistically significant site differences. Grain yield proved to be a poor indicator for straw yield across the study. In 2000, with normal grain yields, the potential straw-to-grain ratio was near unity with slight variety differences. In 1999 when grain yields were low for some varieties, straw yields increased above average values leading to elevated straw-to-grain ratios. Estimates of straw yields based on grain yields alone are therefore subject to considerable potential error. If 1:1 ratios are assumed for all seasons, gross under-prediction of available straw may occur in years with lower than normal grain yields. Fertilization can also affect straw-to-grain ratio, further compounding the use of grain yield alone as a predictor of straw yield. An over-fertilized crop can produce more straw for the same grain yield as an under-fertilized crop.

Superior indicators of straw yield emerge from these results. Increased straw yield was weakly related to greater stem weight, although greater stem weight indicated decreased stand density. By far the strongest predictor for straw yield was number of days to 50% heading and cumulative solar energy to the heading date. Delay in the establishment of grain increases straw production. Each additional day to heading resulted in an additional 18°C d of temperature exposure, 8.4 kWh m^{-2} of additional solar energy, and 0.2 Mg ha^{-1} straw yield. The range of nearly 30 days to heading accounted for over 6 Mg ha^{-1} difference in straw yield for early varieties. Continuing work with additional seasons and sites will be needed to examine the validity of this predictor. Heading date is commonly tracked by growers. This information is available more than 50 days prior to rice harvest and consequently is useful for planning and efficiently mobilizing straw harvesting equipment. The use of heading date to predict yield may also apply to other agricultural residues and energy crops.

Harvested straw yield is non-linearly affected by stem cutting height. Weight per unit length varies from 0.030 g cm^{-1} at the base to 0.020 g cm^{-1} near the top of the shoot. The stem and leaf weight fractions change dramatically, being 75% stem and 25% leaf at the base and 19% stem, 77% leaf at the panicle. Overall yield and the yields of stem, leaf, node, and panicle fractions can be determined based on the height at which the straw is cut. Straw cut at ground level (giving maximum available straw) will have a composition of about 40% internode, 53% leaf, 4% node, and 3% panicle. The same crop cut at 30 cm will yield 58% of the available straw with a composition of 22% internode, 69% leaf, 4% node and 5% panicle. Since properties vary considerably by botanical component, the overall mean properties of the product biomass will vary with cutting height. Future work will identify how other properties vary with botanical fraction and with height. Cutting practices and novel harvesting and separation techniques might be employed to optimize the properties of the straw for particular end uses.

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