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Straw to Grain Ratio Equation for Combine Simulation

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Abstract

Purpose: The ratio of straw to grain mass as a function of cutting height affects combine efficiency and power consumption and is an important input parameter to combine simulation models. An equation was developed to predict straw to grain ratios for wheat as a function of cutting height. **Methods:** Two mass functions, one for straw and one for grain, were developed using regression techniques and measured data collected in west Texas during the summer, and used to predict the straw to grain ratio. **Results:** Three equations were developed to facilitate the simulation of a combine during wheat harvest. Two mass functions, one for straw and one for grain, were also developed; a quadratic equation describes the straw mass with an R^2 of 0.992. An S-shaped curve describes the mass function for grain with an R^2 of 0.957. An equation for straw to grain ratio of wheat was developed as a function of cutting height. The straw to grain ratio has an R^2 value of 0.947. **Conclusions:** In all cases, the equations had R^2 values above 0.94 and were significant at the 99.9 percent probability level (alpha = 0.001). Although all three equations are useful, the grain mass and straw to grain ratio equations will have direct application in combine simulation models.

Keywords: Combines, Harvesting, Simulation, Straw to grain ratio, Cutting heights

Introduction

Over 80% of human diet is provided by seeds from fewer than a dozen plant species. These seed crops must be harvested either by hand or machine. According to Quick and Buchele (1978), harvest becomes “the most important event on Earth every year.” In much of the world, harvesting machines have replaced hand harvest because of efficiency and timeliness in harvesting. Harvesting machines affect both the quantity and quality of grains harvested.

The first step in grain harvesting is commonly called reaping. Reaping is a combined cutting and gathering process. Both straw and grain are gathered in order to obtain a high percentage of the available grain. The combine, a combination of reaper, thresher, and separator, has a header, which controls the height of cut and thus controls the straw to grain ratio of the material to be processed during threshing. Usually, crops are cut just low enough to recover all or nearly all of the heads. When large machines with wide headers are used, a minor change in elevation at the drive wheels can cause major changes at the ends of the header. These fluctuations change the straw to grain ratio. If the header or a part of the header cuts above the grain, major cutting losses will occur. If the header is operated too low, a high straw to grain ratio will result and cause low threshing and separation efficiency and increased power requirements. A study is needed to evaluate the interaction of crop variability and cutting height on combine performance. The distribution of grain and straw with height from the ground is important information to evaluate cutting loss, straw to grain ratio, and combine performance. An understanding of the grain and straw distribution with height should lead to more optimum combine design and operation.

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The power consumption and the torque variation in combine harvesting increase with feed rate and the "lumpiness" in the feeding stream, which comes from the non-uniformity of field conditions and variation of cutting height (Arnold and Lake 1964). The feed rate decreases as cutting height increases, but the possibility of grain loss also increases as cutting height increases. The goal is to optimize both the design and operation of harvesting machinery. Information on the variation of the plant height and the straw to grain ratio (SGR) as affected by the cutterbar height will provide variable field data needed to predict power consumption and grain loss in the harvesting process. Unfortunately, most of the published research work was conducted with constant straw to grain ratios without regard for the relationship between SGR and power or SGR and grain losses in the field.

The objective of this research is to develop an equation to predict the straw to grain ratio of wheat as a function of cutting height. The equation is needed to provide input data to a combine simulation model (Gregory and Fedler 1987), which is used to teach design and operation alternatives in an undergraduate machinery class. The simulation model also can be used as a research tool in the development of better harvesting machines both in the United States and in developing countries.

Materials and Methods

Two work tasks were conducted to measure the grain and straw distribution as a function of height from the soil surface. The final task was to develop an equation to predict the straw to grain ratio with height.

Experimental procedure

Measurements were conducted to determine the variation of plant height and length of grain heads for wheat grown in west Texas. Straw and grain masses were also measured as a function of height from the soil surface.

Six wheat fields were chosen from two different locations in west Texas. One field was non-irrigated and located near Lubbock. The other five fields were irrigated long-term fertilizer rate test plots on the Texas A&M Experimental Station at Halfway, Texas. Five small sampling plots one meter in length for one row were randomly harvested from each field. The complete plant was harvested, bagged, and brought back to the laboratory for further analysis. Field sampling was performed after physiological maturity but before normal harvesting. Physiological maturity occurs when the crop starts to change color from green to yellow. In the laboratory, plant height and spike length were measured for each plant. Starting at the base of the plant, the stem of the plant was cut in segments 5 cm in length. All plants from each plot were combined to form the plot sample. Each length segment was dried and then weighed to determine the dry mass with height. After drying, the samples containing grain were threshed by hand and the grain separated from the straw. Both the grain and straw were weighed individually. This procedure was repeated for all samples.

Analysis

Three equations were developed as a function of cutting height: one for straw mass, one for grain mass, and one for the straw to grain ratio. All equations were developed empirically by fitting the best functional relationship to measured data.

The two individual mass functions were superimposed to obtain a prediction function for the straw to grain ratio. The R^2 and the significance level of each equation were evaluated with the measured data using the computer program MERV (Gregory and Fedler 1986). Individual results are presented in the next section.

Results and Discussion

Plant height, spike length, and grain weight

Table 1 shows the crop properties data for each field sampled. The effect of field treatments are compared in Tables 2, 3, and 4. Generally, but not always, treatment differences were small and not significant. As shown in Figure 1, spike length increases as plant height increases. Spike weight also increases as plant height increases (Figure 2).

Mass function for straw

The distribution of straw mass in the plant as a function of height to maximum height is shown in Figure 3. The straw mass per unit length decreases near the top of the plant; otherwise, straw mass is almost uniformly distributed with height.

The fraction of uncut straw mass as a function of the ratio of cutting height to plant height is shown in Figure 4.

Table 1. Means, standard deviations, and coefficients of variation of crop characteristics for each field

		Non-irrigated	Irrigated				
			Nitrogen application rate (kg/ha-yr)				
			135	180	225	270	315
Grain Head Length	Mean	4.46	4.96	4.99	5.01	5.00	5.28
	Std Dev.	1.53	1.21	1.34	1.27	1.40	1.26
	CV	0.34	0.24	0.27	0.25	0.28	0.24
Grain Head Weight	Mean	0.45	0.41	0.42	0.40	0.48	0.44
	Std Dev.	0.23	0.22	0.23	0.20	0.26	0.25
	CV	0.50	0.54	0.53	0.50	0.54	0.56
Plant Height	Mean	37.77	50.25	48.12	53.25	49.03	55.37
	Std Dev.	8.24	9.12	8.31	7.83	9.17	8.24
	CV	0.22	0.18	0.17	0.15	0.19	0.15

Table 2. Effect of field treatment on plant height

	Irrigated				
	Nitrogen application rate (kg/ha-yr)				
	135	180	225	270	315
Irr. N = 135	-	**	**	-	**
Irr. N = 180		-	**	-	**
Irr. N = 225			-	**	-
Irr. N = 270				-	**
Irr. N = 315					-

** 99% significance level
\- Non-signification
N Nitrogen application

Table 3. Effect of field treatment on spike length

	Irrigated				
	Nitrogen application rate (kg/ha-yr)				
	135	180	225	270	315
Irr. N = 135		-	-	-	**
Irr. N = 180			-	-	**
Irr. N = 225			-	-	-
Irr. N = 270				-	**
Irr. N = 315					-

** 99% significance level
\- Non-signification
N Nitrogen application

A second-order polynomial equation fits the data points with an R^2 of 0.992:

$$Ystraw = 1.481*X - 0.445*X^2 \quad (1)$$

Table 4. Effect of field treatment on plant weight

	Irrigated				
	Nitrogen application rate (kg/ha-yr)				
	135	180	225	270	315
Irr. N = 135	-	-	-	-	-
Irr. N = 180		-	-	-	-
Irr. N = 225			-	**	-
Irr. N = 270				-	-
Irr. N = 315					-

** 99% significance level
\- Non-signification
N Nitrogen application

Where, Ystraw = fraction uncut straw (uncut straw mass/total straw mass)
X = cutting height ratio (cutting height/maximum plant height)

Although equation (1) fits the measured data well, it is not perfect. The fraction of uncut straw mass becomes 100 percent at 93 percent of maximum cutting height. When equation (1) is used, a mass percentage of 100 should be used for height ratios above 93 percent. The error associated with this incorrect boundary condition is less than 1.5% and usually can be neglected.

Equation (1) can be used to estimate residue material available for erosion control, a need defined by Douglas et al. (1989), or to estimate forage available for harvest for animal feed, a need suggested by Raheja et al. (1983).

Mass function for grain

A mass function for grain was also developed relating

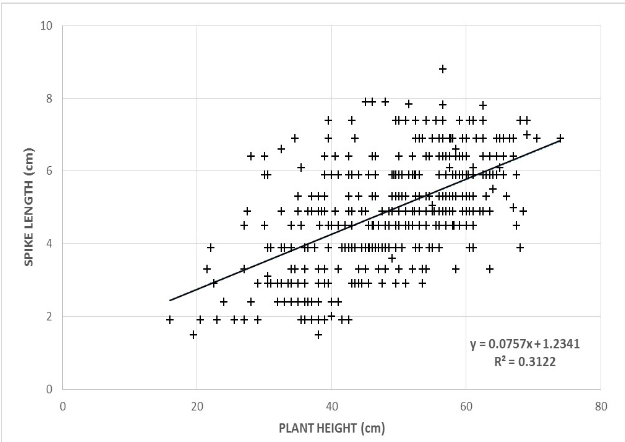

Figure 1. Variation of spike length with plant height.

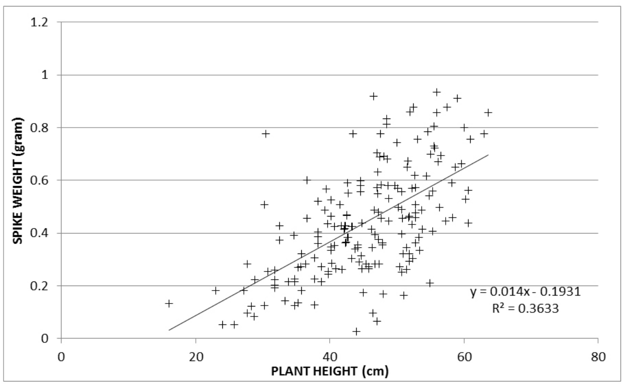

Figure 2. Variation of spike mass with plant height.

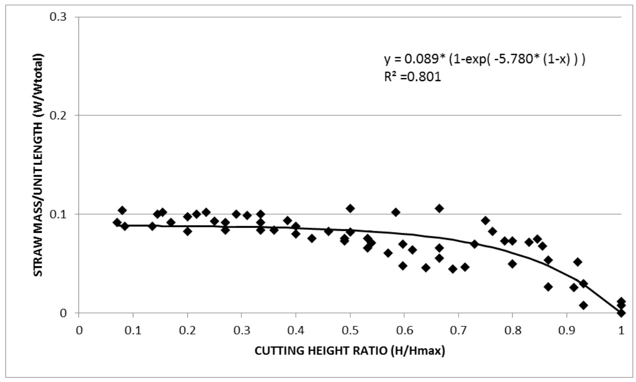

Figure 3. Variation of straw mass per unit length with cutting height ratio.

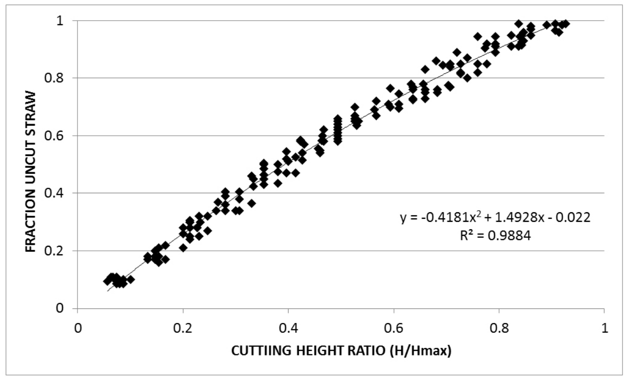

Figure 4. Effect of cutting height ratio on fraction of uncut straw.

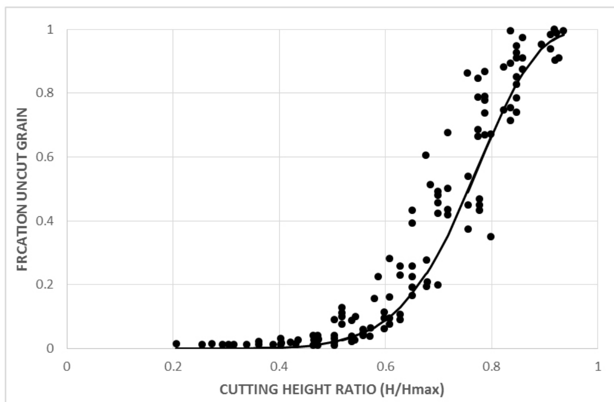

Figure 5. Cumulative uncut grain fraction as a function of the cutting height ratio.

the fraction of uncut grain (Ygrain) to the cutting height ratio. The fraction of uncut grain is defined as the fraction of total grain weight below the cutting height. The measured grain mass of each plant segment was accumulated according to the plant height to obtain the cumulative grain weight. An S-shaped curve with the inflection point at the center of the average spike describes the cumulative grain weight distribution (Figure 5). The following equation fit the data with an R^2 of 0.957 and was highly significant (alpha = 0.001):

$$\text{Ygrain} = \text{l} - \text{EXP}(-28.8\text{A}69*(\text{l} - \text{EXP}(-0.502907*(\text{X} - 0.06)))*(\text{X} - 0.06)**6.972042) \quad (2)$$

Where, Ygrain = fraction of uncut grain (uncut grain weight/total grain weight)
X = cutting height ratio (cutting height/maximum plant height)

Major cutting losses during grain harvest come from uncut grain. The developed mass function for grain can be used to calculate cutting loss directly by using the cutting height ratio.

The cutting loss of a combine with a wide cutterbar would be a function of the mean height of cut, slope of the cutterbar, and cutterbar length. The cutting height ratio can be expressed anywhere along the cutterbar as

$$X = [Havg + Sin\theta^*(L/2 - D)] \ / \ Hmax \qquad (3)$$

Where, Hmax = maximum plant height
Havg = mean height of cutterbar
θ = angle of cutterbar relative to ground
L = length of cutterbar
D = distance from high end of cutterbar

Replacing X in equation (2) with the value from equation (3) and integrating or summing over all distances D gives the average cutting loss of a combine. Because of the difficulty in integration, it is recommended that equations (2) and (3) be used together with a summation procedure.

Straw to grain ratio

A prediction function for straw to grain ratio was obtained by superimposing the two straw and grain mass models. The resulting function fit the measured data very well up to 80% of the total plant height (Figure 6). The model is defined as

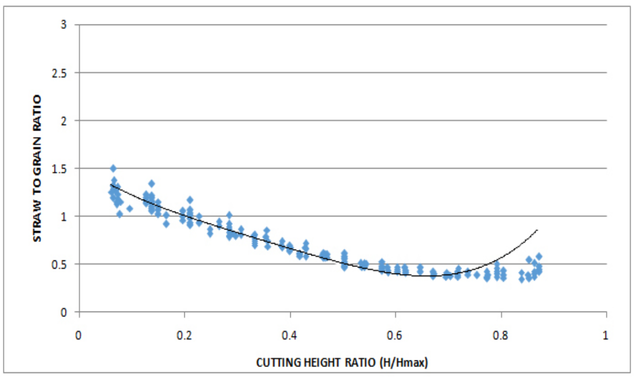

Figure 6. Effect of cutting height ratio on straw to grain ratio.

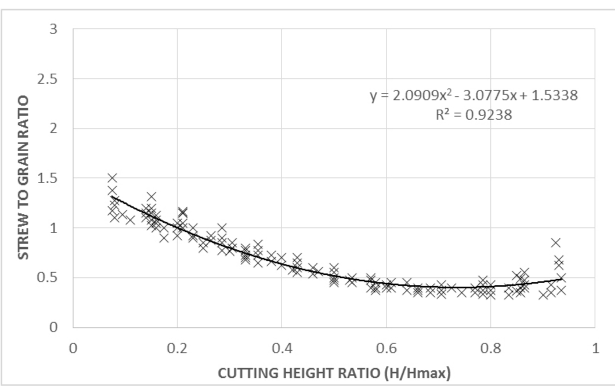

Figure 7. Alternative equation and straw to grain ratio data.

$$Ysg = (1 - Ystraw)/(1 - Ygrain)^*SGzero \qquad (4)$$

Where, Ysg = straw to grain ratio
Ygrain = fraction of uncut grain
Ystraw = fraction of uncut straw
SGzero = straw/grain ratio at zero cutting height

Cutting heights above 80% of maximum height give erroneous results; therefore, equation (4) should not be used above 80% of maximum height.

A second prediction function for straw to grain ratio was obtained by curve fitting with a second-order polynomial:

$$Ysg = 1.493 - 2.964^*X + 1.894^*X^2 \qquad (5)$$

An R^2 of 0.947 was obtained (Figure 7). The problem of unrealistic boundary condition for high cutting heights is avoided with equation (5).

The straw to grain ratio expressed in equation (5) is also affected by the variation in the mean height and slope of the cutterbar. The value from equation (3) can be used for the X in equation (5). An average straw to grain ratio can be obtained by integration of equation (5) from 0 to L.

$$Ysg\ avg = 1.493 - 2.964^*Havg/Hmax + 1{\bullet}894^*(Havg^2 + Sin^2\theta^*L^2/12)/Hmax^2 \qquad (6)$$

Where, Ysg avg = average straw to grain ratio

Conclusions

Three equations were developed to simulate a combine during wheat harvest. Two mass functions, one for straw and one for grain, were also developed; a quadratic equation describes the straw mass with an R^2 of 0.992. An S-shaped curve describes the mass function for grain with an R^2 of 0.957. An equation for the straw to grain ratio of wheat was developed as a function of cutting height. The straw to grain ratio had an R^2 value of 0.947. In all cases equations were significant at the 99.9% probability level (alpha = 0.001). Although all three equations are useful, the grain mass and straw to grain ratio equations will have direct application in combine simulation models.

Conflict of Interest

The authors have no conflicting financial or other interests.

Achnowledgement

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