ON-COMBINE SENSING TECHNIQUE FOR MAPPING STRAW YIELD WITHIN WHEAT FIELDS

D.S. Long

J.D. McCallum

Columbia Plateau Conservation Research Center
USDA-ARS
Pendleton, Oregon

D.R. Huggins

Land Resources and Water Conservation Research Unit
USDA-ARS
Pullman, Washington

ABSTRACT

Straw from production of wheat is available for conversion to bioenergy. However, not all of this straw is available for conversion because a certain amount must be returned to the soil for conservation. County and state-wide inventories do not account for variation within farm fields. In this study, a technique is described that applies information from on-combine crop sensors into estimation of straw yield across fields. Straw yield could be predicted to within 350 kg ha^{-1} ($R^2 > 0.90$) using grain yield, grain protein, and crop height as regression estimators. When validated in the field, the straw yield model provided a modest fit to the data ($R^2 = 0.58$). Further testing and development is needed to improve this technique and draw conclusions.

Keywords: wheat straw, biomass, mapping,

INTRODUCTION

Wheat straw offers a tremendous supply of raw material for conversion to biofuel. However, many studies have recognized the critical role that crop residue plays in preventing soil erosion and maintaining soil organic carbon levels (Barber 1979, Reicosky et al. 2002, Wilhelm et al. 2007). For example, Banowetz et al. (2008) used the USDA-NRCS Soil Conditioning Index to calculate the amount of straw from grass and wheat required to maintain soil quality and found that 1.03 Mt of straw were available from a total of 2.24 Mt produced in the Pacific Northwest states of Idaho, Washington, and Oregon.

Figures for straw production should be regarded as indicative since they are based on areal units of whole states and counties. In reality, great variation in the yield of straw occurs within farm fields depending on differences in soils, slopes, and other biophysical factors. Site-specific information on the distribution of straw within-fields is needed to determine where sufficient straw is available for removal or soil conservation.

One approach to obtaining measurements of site-specific straw yield is to directly sense the mass flow of straw within the cutting, feeding, or threshing units of a combine. Schueller et al. (1982) measured the direct force applied to the cross auger of the header required to move the straw to the feeder unit and found no correlation between drive chain tension and straw flow. In contrast, the torque on the feeder elevator drive chain and the speed of engine were both correlated with straw flow. Missotten (1996, 1998) estimated straw flow, achieving a maximum error rate of 10%, by measuring the deflection of a sprocket pushed against the drive chain of the feeding unit elevator.

Alternatively, Engel et al. (2003) demonstrated that multiple regression models that include factors for grain yield, grain protein, and crop height provide indirect estimates of the straw yield of hard red spring wheat. The rationale for considering grain protein was that it is a good postharvest indicator of N nutrition adequacy and its presumed correlation with straw N (Engel et al. 1999). These workers envisioned the use of grain yield monitors, grain protein sensors, and crop height sensors on combine harvesters to predict straw productivity across farm fields. At the time, a sensor was not in place that could accurately measure and map the protein concentration of grain from a combine during harvest.

In this paper, we illustrate the use of maps of grain yield, protein, and crop height to predict straw yield with results from wheat fields in northeastern Oregon. Focus is on sensing from the combine because of ability to obtain site-specific measurements during harvest. In addition, we illustrate how this information might be applied into determining how much straw is available for energy use and soil protection.

ON-COMBINE MAPPING TECHNIQUE

Straw Yield Models

We developed a straw production model based on the results from a spring wheat nitrogen-water gradient experiment conducted in 2008 on Ritzville silt loams near Echo, Oregon (45.7305ºN, -119.0542ºW). A sprinkler irrigation system was used to create three levels of productivity termed: low, intermediate, and high water regimes. In the low water regime, wheat received 87-mm of rainfall during the growing season (Feb.-Jun.). The intermediate regime received this rainfall plus 46–mm of irrigation during the vegetative growth period. In the high regime, wheat received this rainfall plus 133-mm of irrigation during vegetative and reproductive growth. Within each regime, five hard red spring wheat cultivars (Jefferson, Hank, Hollis, Westbred 926, and Tara 2002) and one soft white spring cultivar (Alpowa) were seeded in factorial combination with five nitrogen rates for a total of 90 plots (6×5×3 regimes = 90).

Crop height was measured as the average distance between the ground and top of spikes, and was approximated by sighting along a string pulled taunt between two diagonal corners of a rectangular plot (1.82×4.67 m). The grain was harvested in each plot using a small combine, and the resulting grain was weighed for yield determination. Straw yields were determined by collecting and weighing the straw exiting the combine during harvesting. Analysis for grain N was undertaken on ground subsamples of grain by means of the dry combustion analysis. Grain protein was computed by multiplying the N concentration by 5.7 and correcting to a moisture content of 12%.

The 2008 water gradient experiment produced a wide range in straw yield (1220 kg ha^{-1} to 4684 kg ha^{-1}, data not shown). Straw yield to grain yield ratios varied from 0.81 to 2.12 and increased from high, intermediate, and low water regimes. Across the experiment, on average, Tara 2002 yielded the most straw per unit of grain yield (1.57) followed by Westbred 926 (1.32), Hank (1.23), Hollis (1.19), Jefferson (0.87), and Alpowa (0.84) (Table 1).

Table 1. Mean values of grain yield, straw yield, and crop height for spring wheat cultivars in the water gradient experiment at Echo, OR.

Cultivar	Grain Yield	Grain Protein	Crop Height	Straw Yield	Straw/Grain Ratio
	kg ha^{-1}	mg g^{-1}	cm	kg ha^{-1}	
Hollis	1930	162.0	67.9	2290	1.19
Westbred 926	1762	176.7	54.6	2322	1.32
Jefferson	2671	154.5	60.9	2326	0.87
Hank	1937	172.4	58.7	2378	1.23
Alpowa	2853	133.6	59.0	2384	0.84
Tara 2002	1751	179.9	60.9	2745	1.57

Straw yields were significantly related to grain yield ($R^2 > 0.82$) across all cultivars and were predicted with good precision (standard error <560 kg ha^{-1}) by linear regression (Table 2). Including grain protein into a regression model consistently yielded better estimates of straw yield as indicated by improvement in standard errors. Inclusion of a regression term for crop height in a prediction model showed little further improvement in prediction accuracy. The crop height coefficient shows the most change among varieties, ranging in value from 5 to 64 kg ha^{-1} cm^{-1}. The regression coefficients for grain yield and protein are much closer in value to each other across the models. The single model for Alpowa was then used to predict the straw yield of all other varieties (Fig. 1). This “general purpose” model has a slope of 1.0, intercept near zero, and reasonable correlation ($r^2 = 0.84$).

Table 2. Regression equations, coefficient of multiple determination (R^2), and standard error (SE) for predicting straw yield in the 2008 experiment with spring wheat.

Model	Equation†	R^2	SE
	All Cultivars (n=90)		

1	SY = 970 + 0.67GY	0.82	560
2	SY = -2676 + 0.93GY + 18.9GP	0.91	406
3	SY = -3751 + 0.83GY + 17.7GP + 24.4CH	0.92	391
	Jefferson (n=15)		
1	SY = 293 + 0.76GY	0.98	190
2	SY = -647 + 0.82GY + 5.07GP	0.99	174
3	SY = -2992 + 0.64GY + 4.81GP + 46.9CH	0.99	148
	Hank (n=15)		
1	SY = 1148 + 0.63GY	0.82	542
2	SY = -3840 + 1.0GY + 24.8GP	0.97	243
3	SY = -4267 + 0.96GY + 23.9GP + 11.3CH	0.97	252
	Hollis (n=15)		
1	SY = 812 + 0.77GY	0.87	399
2	SY = -366 + 0.81GY + 6.77GP	0.89	385
3	SY = -645 + 0.79GY + 6.47GP + 5.4CH	0.89	402
	Westbred 926 (n=15)		
1	SY = 433 + 1.07GY	0.97	264
2	SY = -1729 + 1.2GY + 11.0GP	0.98	214
3	SY = -3797 + 0.87GY + 6.19GP + 64.1CH	0.99	155
	Tara 2002 (n=15)		
1	SY = 909 + 1.05GY	0.95	352
2	SY = -1862 + 1.1GY + 14.88GP	0.96	324
3	SY = -4019 + 0.95GY + 13.83GP + 42.86CH	0.96	318
	Alpowa (n=15)		
1	SY = 317 + 0.72GY	0.94	395
2	SY = -2664 + 0.92GY + 18.2GP	0.98	186
3	SY = -3047 + 0.86GY + 17.2GP + 11.3CH	0.99	192

† SY = straw yield (kg ha^{-1}), GY = grain yield (kg ha^{-1}), GP = grain protein (mg g^{-1}), and CH = crop height (cm).

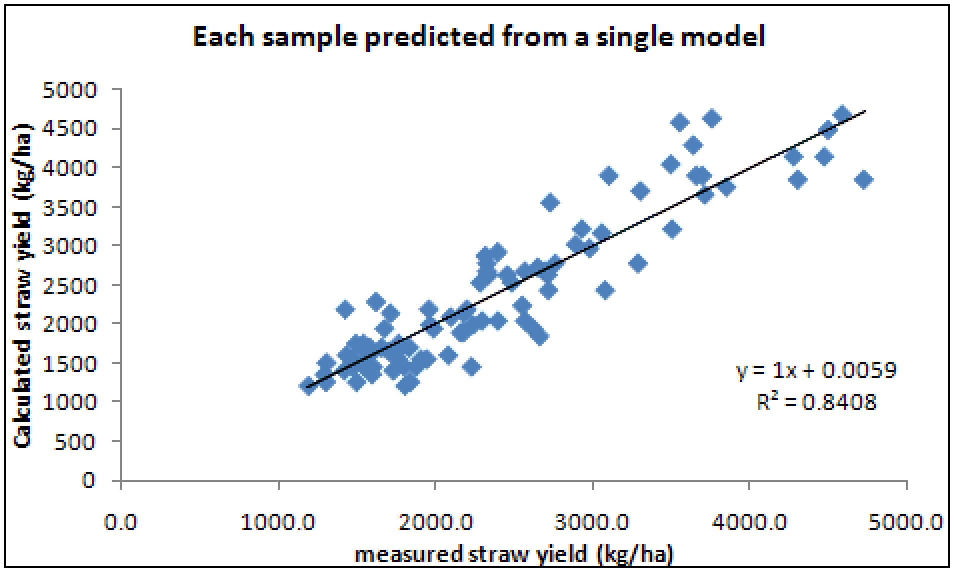

Figure 1. Relationship between predicted and measured values of straw yield with regression line for Alpowa model.

To determine whether any model can be used across cultivars, the observed values of each cultivar were correlated with the predicted values derived from each model (Table 3). Except for Hollis, each model predicted the straw yield of another cultivar well as indicated by $r^2 > 0.90$ and standard errors of prediction <350 kg ha^{-1}. Due to the good performance between different cultivars, which included a soft white wheat variety and four hard red wheat varieties, we believed that the models for Alpowa, Jefferson, and Westbred 926 could accurately predict straw yield.

Table 3. Values of r^2 and standard errors for correlation between the measured values of a cultivar versus the predicted values for the model of the same cultivar and a different cultivar.

Predictor Model	Measured Cultivar						
	Alpowa	Hank	Hollis	Jefferson	Tara	Westbred	Ave.
	regression coefficient (r^2)						
Alpowa	0.987	0.983	0.968	0.971	0.983	0.970	0.977
Hank	0.961	0.970	0.892	0.900	0.937	0.898	0.926
Hollis	0.855	0.822	0.891	0.887	0.878	0.887	0.870
Jefferson	0.963	0.963	0.987	0.991	0.985	0.991	0.980
Tara	0.959	0.953	0.958	0.960	0.964	0.960	0.959
Westbred	0.952	0.933	0.983	0.991	0.984	0.991	0.972

Table 3. Continued.

Predictor Model	Measured Cultivar						
	Alpowa	Hank	Hollis	Jefferson	Tara	Westbred	Ave.
	standard error						
Alpowa	177	205	282	269	207	272	235
Hank	262	232	431	415	332	418	348
Hollis	422	464	370	376	390	376	400
Jefferson	276	361	163	136	175	136	208
Tara	310	332	313	306	292	307	310
Westbred	288	380	194	143	186	143	222

Model Validation

In 2009, the relationship between measured and predicted straw yield was validated within an irrigated field of soft white winter wheat in Oregon. Straw yield, grain yield, protein, and crop height were measured in 30 micro-plots (1-m^2). The soft white wheat regression model for Alpowa was applied to these data to predict straw yield. Three data points were erroneous and had to be removed. A modest correlation was found between observed and predicted values of straw yield (r^2 = 0.58, Fig. 2). This preliminary result indicates that other factors may have influenced straw yield in this wheat field. One explanation for finding only a modest correlation is that micro-plots were too small to represent the average crop variability. Further work is needed before conclusions can be drawn about the utility of yield and protein data to predict straw yield.

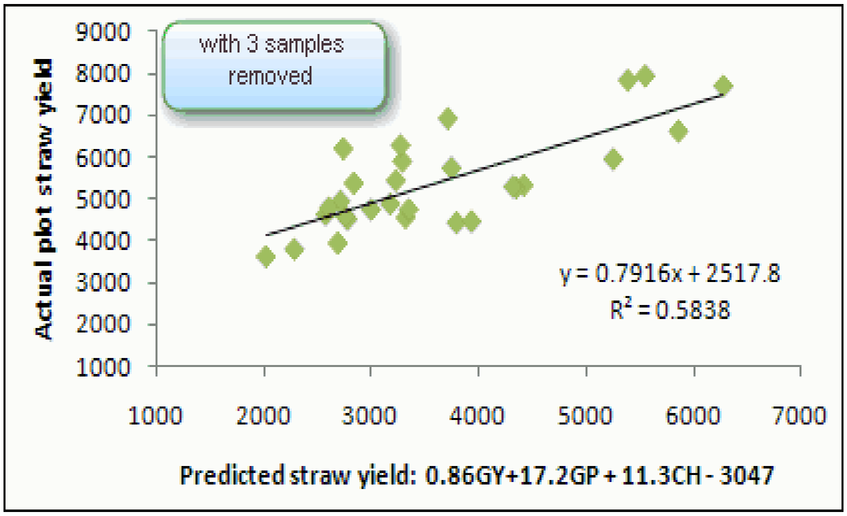

Figure 2. Relationship between measured and predicted values of straw yield that were obtained from a soft white winter wheat field in Oregon and the straw yield model for Alpowa soft white spring wheat.

Field Mapping

A Case IH 1470 combine was equipped with a mass flow yield monitor (AgLeader YM2000), optical protein sensor (Textron Systems ProSpectra Grain Analyzer), ultrasonic height sensor (Pepperl+Fuchs, type UC 2000-30GM-IU-V1), and GPS receiver (Novatel SMART-V1G). The ProSpectra instrument is a near infrared reflectance spectrometer designed for measuring the grain protein concentration of wheat during harvest with a combine (Long et al., 2008). A notebook computer and the DeLight instrument control software for the ProSpectra instrument (DSquared Development, LaGrande, OR) was configured to simultaneously record the protein, yield, and height data; utilize the regression equation to arithmetically combine the data streams; and compute and map straw yield estimates (Fig. 3). The AgLeader YM2000 monitor has an export serial port enabling logging of the yield data stream to an external notebook computer. Communication between each sensor and the controller of the notebook computer was established using the Universal Serial Bus.

In 2009, we applied the Alpowa model to on-combine mapping of the straw yield of soft white winter wheat. The tested fields were irrigated fields with three 20-ha (50-ac) circular pivots and an adjacent rectangular field with lateral wheel line. The center pivot broke down, stalled, and over watered in one field position, which enabled us to use that watering anomaly as a reference point. Grain protein and grain yield values are color coded on the maps in Figures 4 and 5. What is most interesting about this field is the middle pivot with lower protein and higher yield where the pivot line stalled versus higher protein and lower yield in the remaining water-starved areas. In addition, a straw yield map was computed using the Alpowa model and grain yield, grain protein, and crop height as inputs (Fig. 6) and was generated in real-time during actual combine harvest of the four fields.

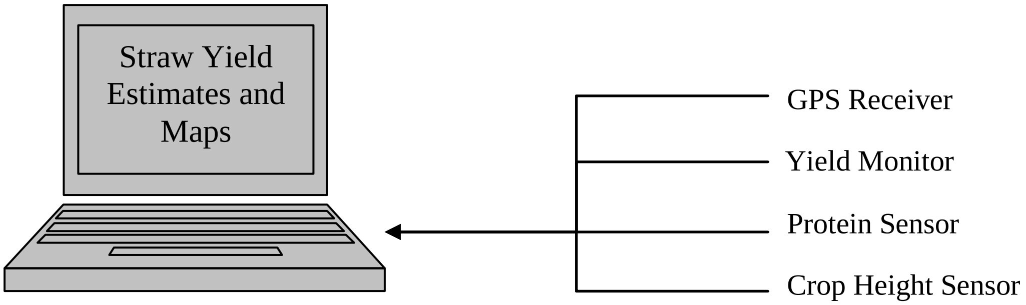

Figure 3. Four sources of data used for computing and mapping estimates of straw yield on a combine harvester.

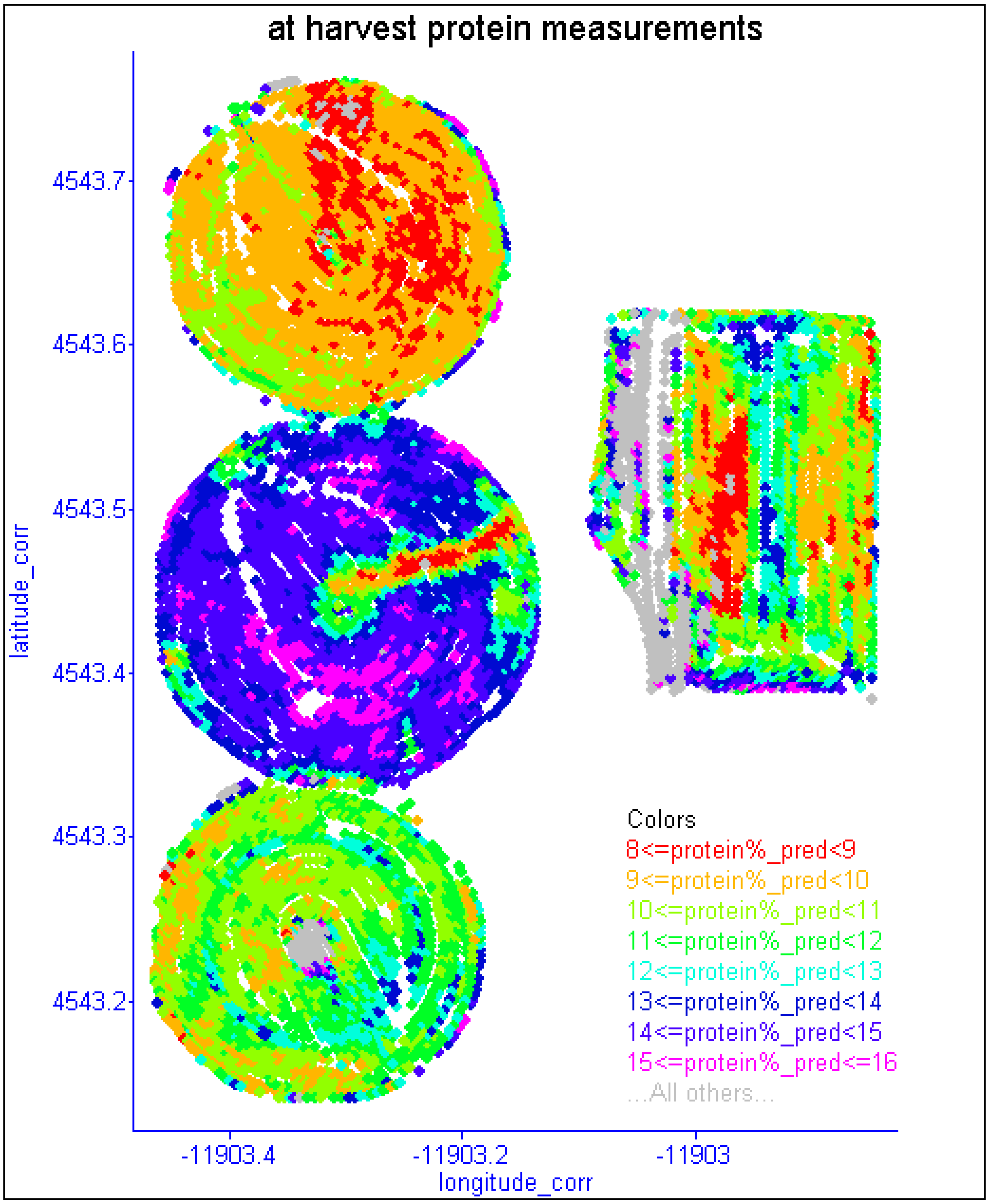

Figure 4. Map of grain protein concentration as measured with the ProSpectra grain analyzer. Longitude and latitude have been corrected for the approximate 12-s delay between the GPS position of the combine and the instrument sensing the grain.

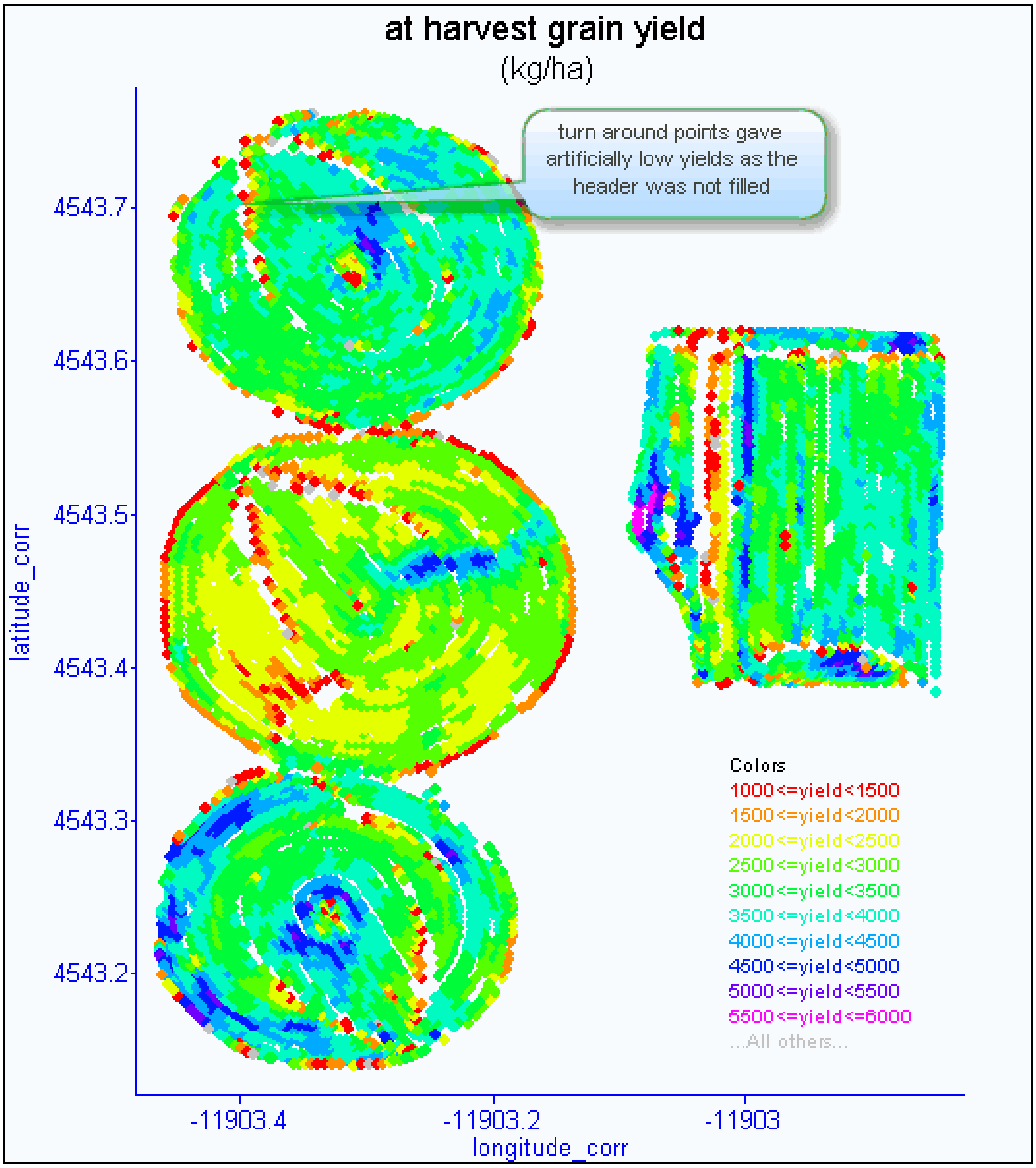

Figure 5. Map of grain yield as measured with the AgLeader 2000 monitor. The middle pivot shows high yield around the area where the pivot had stalled. The V-shaped areas of apparent low yield are areas where the combine was turned around and did not maintain a full header of crop.

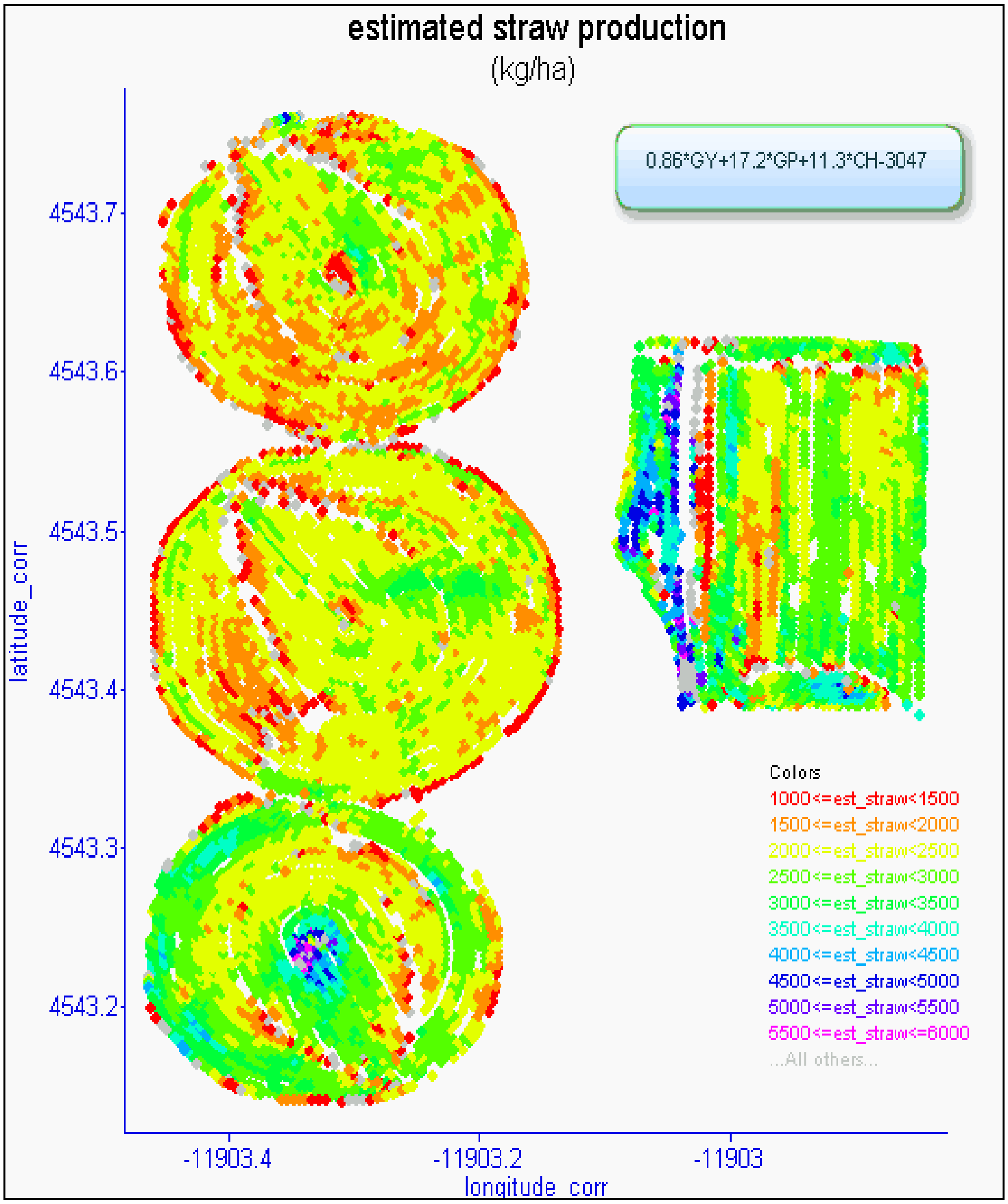

Figure 6. Map of straw yield generated in real-time on the combine during harvest using measurements of grain yield, grain protein, and crop height.

Citing evidence from long-term experiments, Horner et al. (1960) and Rasmussen et al. (1980) showed that annual additions of about 1,200 kg carbon ha^{-1} yr^{-1}, or 3,000 kg residue ha^{-1} yr^{-1}, would be needed to maintain soil organic carbon at current levels in the lower rainfall region (<28 cm annual precipitation) where winter wheat-summer fallow is practiced within the inland Pacific Northwest. Thus, the map in Figure 7 shows areas where the straw yield is in excess of the 3,000 kg residue ha^{-1} needed to maintain soil carbon. Conceptually, straw within the areas shown in green and blue could be removed for use as a feedstock for biofuels.

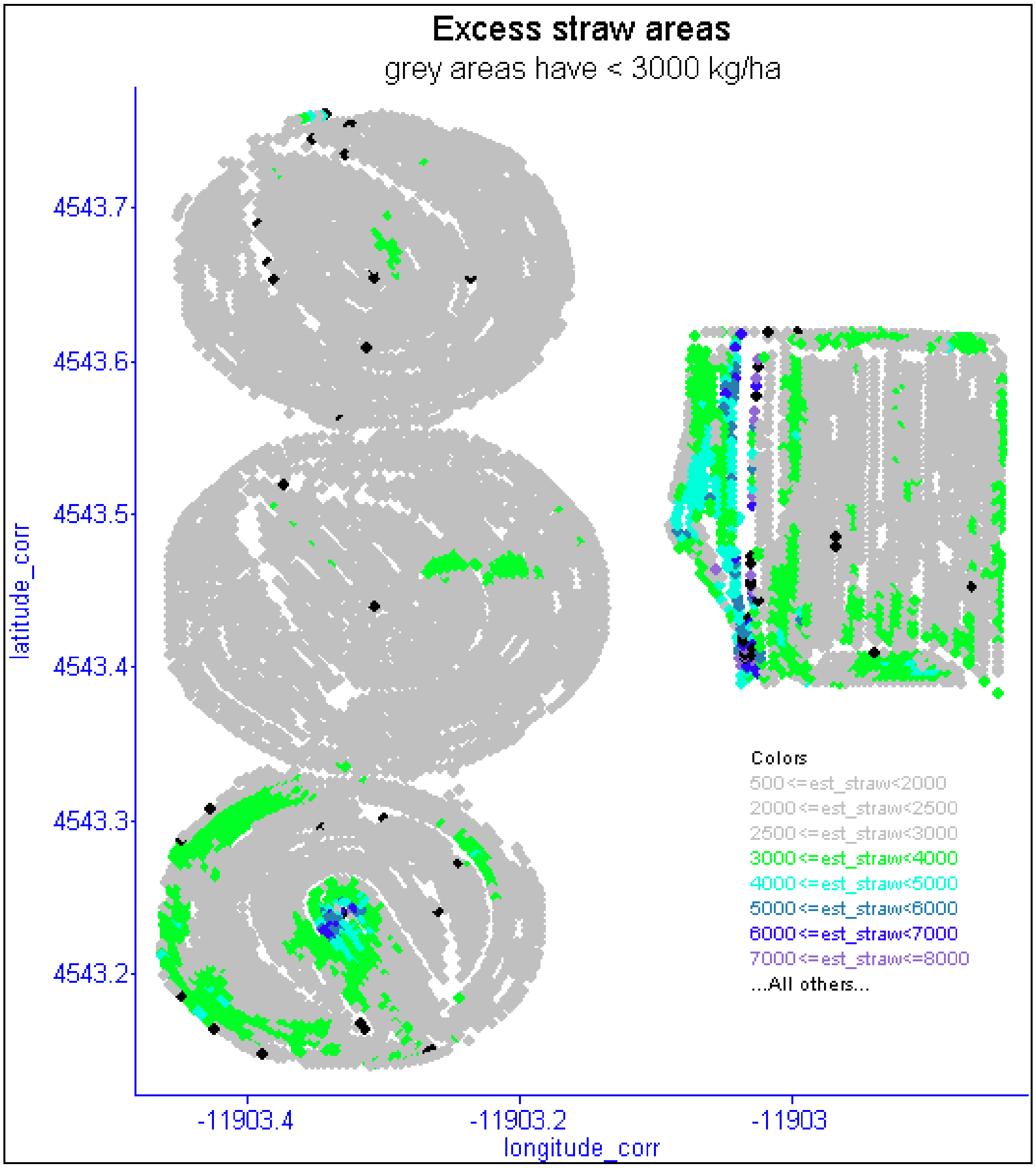

Figure 7. Map of excess straw that could be removed for use as a feedstock for biofuel. Black spots are unusable values due to extraneous yield, protein, or crop height values.

CONCLUSIONS

The preliminary results show that straw yield can be estimated from maps of grain yield and grain protein on the combine during harvesting. The straw yield maps might prove useful for determining in farm fields where excess crop residue could be removed as a feedstock for bioenergy production. In 2010, work will further develop and test this proposed mapping technique so that meaningful conclusions can be made about its accuracy and utility.

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