

# Optical-Mechanical System for On-Combine Segregation of Wheat by Grain Protein Concentration

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## ABSTRACT

Grain segregation by grain protein concentration (GPC) may help growers maximize revenues in markets that offer protein premiums. Our objective was to develop an on-combine system for automatically segregating wheat (*Triticum aestivum* L.) by GPC during harvest. A multispectral optical sensor scans the grain as it is conveyed by the combine's grain bin-filling auger. Light from the optical probe is transmitted through a fiber optic cable to a spectrometer, which determines the spectral characteristics of the grain. This information is processed by the instrument control software that is programmed to calculate GPC from a chemometric model. The continuous GPC output is simultaneously fed to a binary computer algorithm for triggering a logic circuit and operating a mechanical diverter valve that diverts the grain into either one of two bins. Field tests of the system were conducted during harvest of hard red spring wheat using a Case IH 1470 combine modified with front and rear bins. Front and rear bins were compared in terms of the mean and frequency distribution of the optically sensed GPC. In addition, the grain in each bin was manually sampled and tested in the laboratory for GPC. Results showed that it is possible to use the GPC measured by an optical sensor to effectively control a mechanical diverter valve for routing the grain into one of two bins on a combine. An advantage of this approach is that prior knowledge of harvesting zones is not required.

**G**RAIN PROTEIN CONCENTRATION is an important factor that determines the value of various cereal crops with premiums paid for high quality grain that meets the specific requirements of end users. In the United States, for example, brewers offer price premiums for malting barley (*Hordeum vulgare* L.) <math>120\text{ g kg}^{-1}</math> (12%) GPC and millers may offer price premiums for soft white wheat <math>95\text{ g kg}^{-1}</math> GPC. For the dark northern spring (DNS) subclass of hard red spring wheat, a premium is typically added to the price for each <math>2.5\text{ g kg}^{-1}</math> change in GPC above a standard GPC of <math>140\text{ g kg}^{-1}</math> whereas a discount is subtracted for each <math>2.5\text{ g kg}^{-1}</math> in protein below this standard. For instance, premiums were U.S.\$2.57  $\text{Mg}^{-1}$  above <math>140\text{ g kg}^{-1}</math> whereas discounts were U.S.\$3.30 to U.S.\$5.87  $\text{Mg}^{-1}$  below <math>140\text{ g kg}^{-1}</math> (14 June 2013 exporter bids for DNS wheat, Pacific Northwest Grain Market News, [www.ams.usda.gov/mnreports/lswpnwgrain.pdf](http://www.ams.usda.gov/mnreports/lswpnwgrain.pdf)). Analogous pricing structures exist in other grain-producing countries.

Wheat protein varies significantly with position on a single head with greatest GPC at the base and least at the top (Bramble et al., 2002). Protein variability also occurs at larger scales within fields due to site-specific differences in soil fertility (Delin, 2004), topography (Fiez et al., 1994), plant available water

(Stewart et al., 2002), and previous year's cropping inputs (Long et al., 2008). However, growers tend to bin the grain together that is produced in a farm field based on an assumption that the wheat is homogenous. Conventional harvesting systems, which mix the grain together, lessen the ability of growers to capture premiums for high protein grain found in DNS wheat fields.

By segregating grain by protein concentration, growers might be able to maximize revenues in markets that offer protein premiums. Thylén and Rosenqvist (2002) assumed that grain could be segregated either on the combine, hauling vehicles, or on-farm grain drier. They found that the size of protein premiums and magnitude of within-field GPC variability influenced the scale of production needed to cover equipment costs. Stewart et al. (2002) found that segregating durum wheat into two batches would have increased profits by AU\$34  $\text{ha}^{-1}$  over conventional harvesting. Meyer-Aurich et al. (2008) investigated site-specific N fertilization and grain segregation for different price structures that varied as a function of GPC. Grain segregation, which isolated and sold valuable grain at higher prices, increased marginal returns by €50  $\text{ha}^{-1}$  (U.S.\$67  $\text{ha}^{-1}$ ) over that of conventional harvesting. Martin (2012) found that revenue gains from segregating grain by GPC on the combine would vary with size of a price step in a price schedule with potential profits of more than U.S.\$0.02  $\text{kg}^{-1}$  for soft white winter wheat grown in Oregon.

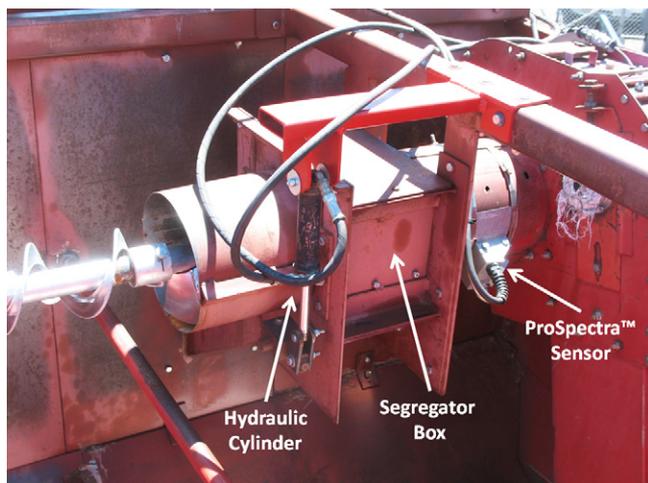
Whole grain analyzers based on the near infrared (NIR) spectroscopic techniques pioneered by Norris (1964) have been developed for combine harvesters and used for continuous in-line measurement of GPC across fields (Maertens et al., 2004; Long et al., 2008). These systems are reported to be accurate in

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**Abbreviations:** DNS, dark northern spring; DCV, directional control valve; GPC, grain protein concentration; I/O, input/output; NIR, near infrared; PC, personal computer; SECV, standard error of cross validation.



**Fig. 1. ProSpectra sensor, segregator box, and hydraulic cylinder of the grain segregator mounted on the grain bin-filling auger in the bulk tank of a Case International Harvester 1470 combine.**

the field to within  $5.7 \text{ g kg}^{-1}$  GPC for winter wheat (Maertens et al., 2004),  $6.6 \text{ g kg}^{-1}$  for hard red spring wheat (Long and Rosenthal, 2005),  $3.1 \text{ g kg}^{-1}$  for soft white winter wheat (Long et al., 2008), and  $4.5 \text{ g kg}^{-1}$  for Australian hard spring wheat (Whelan et al., 2009).

On-combine NIR sensing is capable of identifying the areas of lower or higher quality grain, which creates an opportunity to automatically segregate wheat by GPC while harvesting. Higher quality grain in certain areas of a field could be segregated from lower quality grain in other areas to take advantage of price premiums paid for lower or higher GPC. However, no reports have been found in the literature describing on-combine systems that are capable of grain segregation. The objective of this project was to design and fabricate an on-combine grain segregator that senses GPC and automatically segregates the harvested grain into two batches of low or high quality.

## SYSTEM DESCRIPTION

The on-combine grain segregator system consists of a spectrometer, hydraulic-mechanical diverter valve, and electrical control system. The spectrometer measures the spectral reflectance of the grain stream and uses this information to predict the GPC. The diverter valve is mounted on the combine's grain bin-filling auger and routes the grain into a rear bin or a front bin depending on whether the GPC is above or below a certain threshold value. The control system consists of a notebook personal computer (PC), input/output (I/O) interface, and relay box. The notebook PC acquires data from the spectrometer, determines if the grain is above or below the threshold, and sends instructions to the mechanical diverter valve by means of the I/O interface.

### Spectrometer

For sensing the GPC, the combine was equipped with the ProSpectra grain analyzer (Fig. 1; Textron Systems, Wilmington, MA), which is capable of obtaining continuous measurements of the GPC of a grain stream (Long et al., 2008). This in-line spectrometer measures diffuse reflectance spectra at  $0.5 \text{ nm}$  intervals over a wavelength range from  $600$  to  $1100 \text{ nm}$ . The

device uses a silicon detector array of 1024 elements that can be thermally stabilized over a wide range of ambient temperatures ( $-30^{\circ}$ – $50^{\circ}\text{C}$ ). A tungsten light emitting bulb, reference shutter, and sapphire window are integrated into the sensor probe. A fiber optic pickup cable transmits the reflected light between the probe and detection sensors in the spectrometer unit.

Spectral reflectance ( $R'$ ) and apparent absorbance ( $A'$ ) are related in accordance with the following equation:

$$A' = \log(1/R') \quad [1]$$

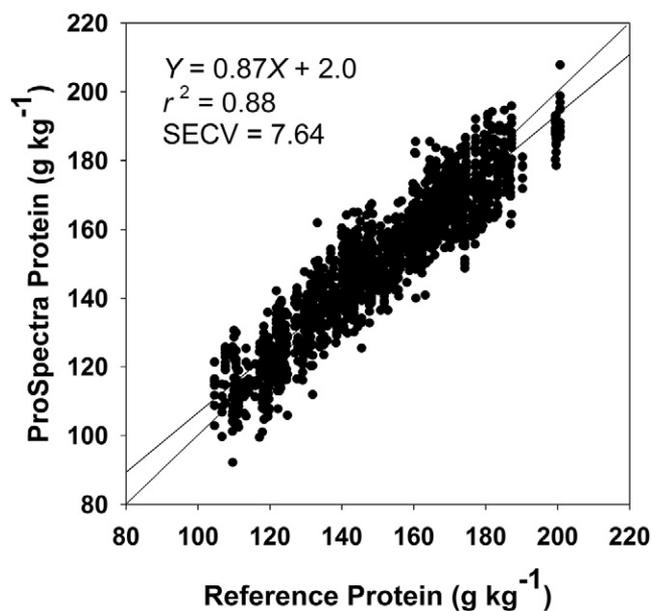
where  $R'$  is sample reflectance of the grain. Grain must flow past the sensor's aperture so that spectra taken within each scan interval adequately represent the reflectance properties of the grain kernels to NIR light, which vary with chemical composition, distribution of protein within the endosperm, and orientation. During operation, a 100% reflectance reference scan is taken every 15 min to adjust the baseline value of the sensor's output.

### Sensor Calibration

Dark northern spring wheat (cultivar Jefferson) grain samples ( $n = 208$ ) from 5 yr (2007–2011) of N fertility trials in northeastern Oregon were used to calibrate the instrument before installation on the combine. Subsamples of this grain had been ground in a Udy Mill before N determination using an automated dry combustion instrument (Flash 1112 Series EA, Thermo Finnigan, Milan, Italy). Protein concentrations were calculated by multiplying dry combustion N by 5.7. Calibration involved connecting the instrument to an apparatus consisting of a cylindrical chamber (300 mL volume) with a circulating impeller. Grain was placed in the cylinder and the axial impeller pushed the grain past the sensor probe to simulate grain flow found within an auger. The instrument control software D2ProSpectra (Textron Systems) was used to operate the spectrometer from the PC and record the diffuse reflectance spectra of the grain flowing past the sensor head. Interested readers may wish to consult Long et al. (2008) for further details on the grain circulating apparatus and calibrating the ProSpectra sensor for use on a combine.

After spectra were acquired, the standard normal variate transformation was used to reduce baseline drift and remove the multiplicative interference of scatter and particle size, and the wavelength axis was averaged in blocks of four pixels (2 nm). A calibration equation for GPC was computed using the partial least squares (PLS) method. Chemometric modeling was implemented by means of the spectroscopic analysis software DeLight (DSquared Development, La Grande, OR). An eight latent variable PLS calibration model was built using spectral data as the independent variables and the GPC as the dependent variable. Final GPC was validated using "leave-one-out" sample cross-validation in which a single sample from the original data set is predicted from the remaining samples and repeating this process for each sample in the data set (Stone, 1974). The coefficient of simple determination ( $r^2$ ) and standard error of cross validation (SECV) were used to evaluate the accuracy of the instrument.

The 1680 scans from 208 grain samples used to calibrate the ProSpectra sensor exhibited a wide range in GPC with minimum and maximum values of  $106$  and  $206 \text{ g kg}^{-1}$ . Predicted protein values, obtained with the instrument mounted to the grain circulating apparatus, exhibited good agreement



**Fig. 2. Scatter plot of the relationship between predicted grain protein concentration by the ProSpectra sensor and reference grain protein concentration by laboratory dry combustion.**

with reference protein values (Fig. 2). The SECV ( $7.64 \text{ g kg}^{-1}$ ) compares unfavorably with values obtained for laboratory NIR whole grain analyzers (SECV = 2.8 to  $3.6 \text{ g kg}^{-1}$ , Williams, 1987). Nonetheless, a high level of variance in reference protein values was explained ( $r^2 = 0.88$ ). Ability to predict protein is further indicated by the lack of bias and a slope near unity. These results suggest that on-combine NIR optical sensing is potentially useful for measuring the protein concentration of DNS wheat in a flowing stream and segregating by GPC.

### Mechanical Diverter Valve

The grain segregator was built onto a Case IH model 1470 combine harvester with a model 810 grain head and standard  $6.3 \text{ m}^3$  (180 bu) bulk grain tank. Mechanical components of the segregator include stock hydraulic reservoir, hydraulic pump, pressure relief valve, directional control valve (DCV), hydraulic motor, lift auger, hydraulic cylinder, mechanical diverter valve, chute, and front and rear bins (Fig. 3). Two grain bins were created by installing a metal dividing bulkhead between the unloading augers in the bottom of the bulk tank (Fig. 4). The bulkhead was constructed of thin steel plate, 3 mm thick, and was supported by a frame of square steel tubing that was bolted to the inside of the bulk tank. When positioned vertically, the bulkhead gave a front bin capacity of approximately  $1.9 \text{ m}^3$  and a rear bin capacity of  $4 \text{ m}^3$ . Our two-bin design is based on Sivaraman et al. (2002) who mathematically modeled optimal grain blending and segregation strategies by protein concentration for hard red winter wheat. They found that most of the benefit of grain segregation may be achieved with only two bins resulting in two distinct batches of grain.

The system was designed to divert the grain stream using the diverter valve housed within the segregator box (Fig. 1 and 3). In 2008, a 12-V electrical linear actuator (model TMD01-1906-12, Duff-Norton, Charlotte, NC) with 30 cm stroke and 45 kg capacity was used for opening and closing the diverter valve. When the diverter valve is closed (i.e., “flow-through” mode) the grain is

conveyed by the combine’s grain bin-filling auger into the rear bin (Fig. 5A). When the diverter valve is open (i.e., “divert position”), the conveyed grain discharges off the auger and is routed through a rectangular opening (21 cm wide by 12.5 cm high) of the diverter valve (Fig. 5B). The material falls into an inclined discharge chute and passes through the steel bulkhead to the bottom of the vertical lift auger mounted in the front bin (Fig. 4). The vertical auger is vertically positioned to lift the grain above the level of the front bin so that it can be filled from the top.

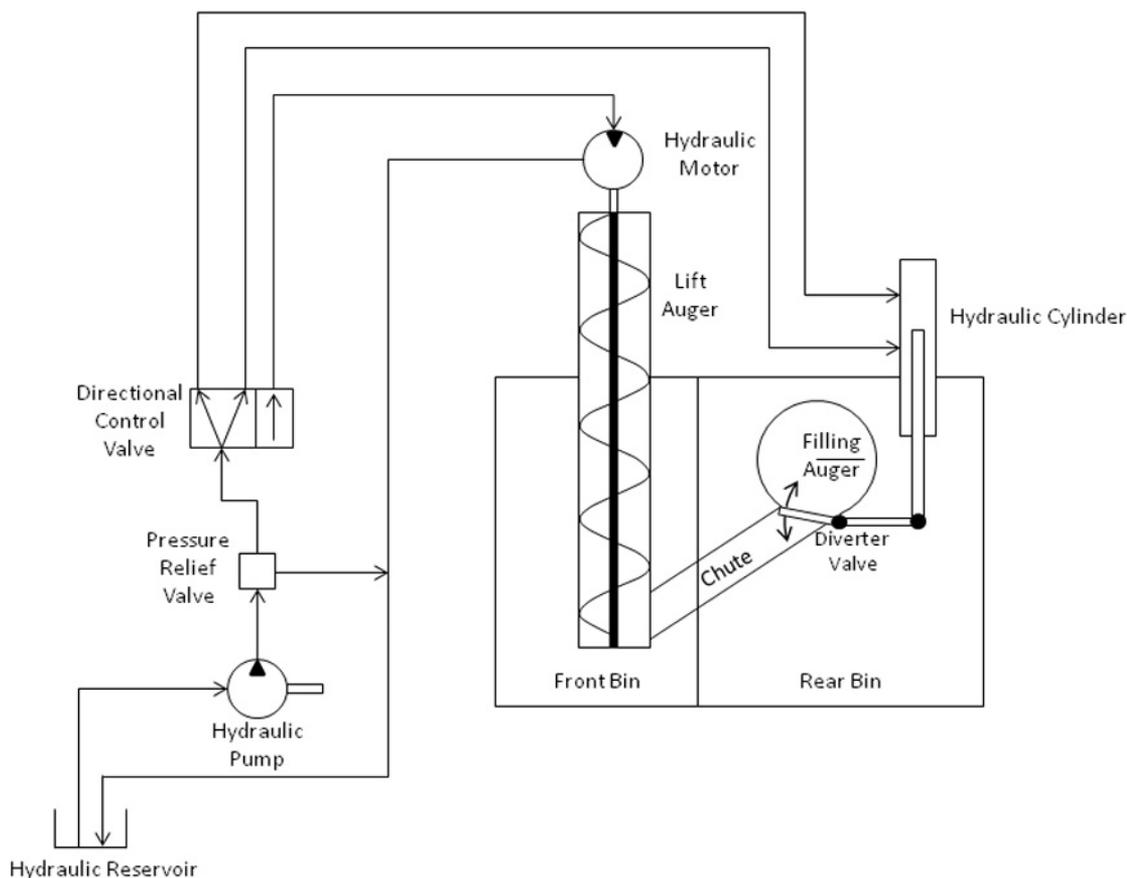
In 2011, the electrical actuator was replaced with a double acting hydraulic cylinder that could more rapidly and completely close the diverter valve against the flowing grain within the auger (Fig. 1). A separate, fixed displacement hydraulic pump, belt driven by the combine’s threshing system (Fig. 6), was installed that provided enough flow to operate the hydraulic cylinder and turn the vertical lift auger at the correct speed. The double acting hydraulic cylinder, controlled by the two-position, solenoid operated DCV (Fig. 4), powered the diverter valve and diverted grain in the same way as described above for the electrical actuator. Mounting the ProSpectra sensor and the segregator box together on the combine’s grain bin-filling auger minimized the phase delay ( $<1 \text{ s}$ ) between the sensed GPC and response of the hydraulic cylinder.

### Electrical Control Unit

Electrical components of the unit for controlling the grain segregator included the spectrometer unit, notebook PC, I/O interface, relay box, and DCV (Fig. 7). The PC was connected to the spectrometer and used to acquire all spectra. Each scan of the grain used a 30 ms exposure to keep the instrument below saturation. One hundred scans were averaged over a measurement period of about 3 s corresponding to a measurement rate of 0.3 Hz. The combine travelled at a speed of about  $1.8 \text{ m s}^{-1}$  and so a 3 s data collection period gave a data collection distance of approximately the combine’s header width of 7.3 m.

A GPS receiver (SMART-V1, Novatel, Inc., Calgary, AB, Canada) with  $<1 \text{ m}$  positional accuracy and a mass flow yield monitor (YM2000, AgLeader Technology, Ames, IA) were also connected to the system (Fig. 7). Values from these sensors were read through serial ports of the spectrometer and PC, and attached to the spectral data before saving. Using location information obtained from the GPS receiver, grain protein and grain yield maps of the wheat field were created simultaneously during harvest. The GPC was calculated using the same data reduction (averaging over wavelengths and repeat scans and an SNV transform) as used in the model development and multiplied (dot product) by the model to predict GPC.

The D2ProSpectra software is programmable to support RS232 communications and has a set of commands for complete control of I/O channels. The GPS connection is built into the spectrometer and the software programmed to read the yield from the YM2000’s RS232 data interface. These values were attached to each spectrum acquired. For the output, software was programmed to send a signal to route the grain to a “common” quality bin if GPC was less than a threshold value or to a “high” quality bin if GPC was greater than or equal to a threshold value. The software has three user set variables, a choice of bin for high quality grain and two thresholds: *low threshold* and *high threshold*. The use of two thresholds allowed



**Fig. 3. Schematic of the mechanical portion of the grain segregator.**

for a hysteresis to ignore short-term fluctuations of GPC near the threshold value and continue sending the grain to the current bin being used unless there was a large change. The following algorithm compares the sensed GPC with each threshold value and keeps track of the position of the diverter valve to determine which bin to send the grain:

1. If GPC is less than the *low threshold* value and diverter valve is set to the bin for high quality grain.

2. Then switch diverter valve to the bin for common quality grain.
3. Else, if GPC is greater than the *high threshold* value and diverter valve is set to the bin for common quality grain.
4. Then switch diverter valve to the bin for high quality grain.

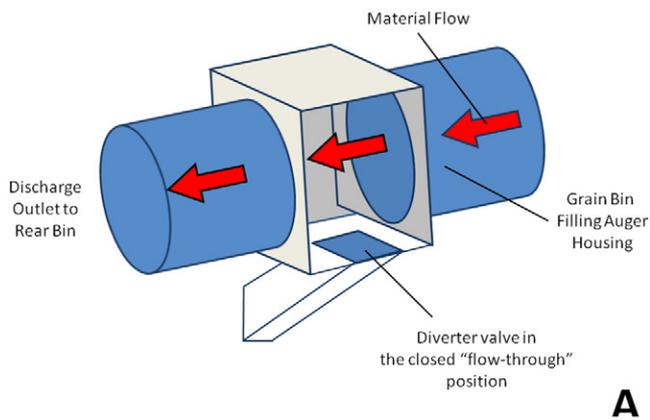
The bi-positional signal generated by the instrument control software was communicated via the serial communication port to an I/O interface (model DRC-10, DSquared Development). Within its metal enclosure, the relay box (Koza Instrument Co., La Grande, OR) houses a computer connector for communication with the I/O interface and two electrical relays. The I/O interface allows the computer's low amp 5 v digital signal to switch and hold in a high or low analog state. The relay box converts the low current 5 v signal to a high amperage 12 v output state thereby allowing for PC-based switching of the relays and control of the DCV of the hydraulic system. An electrical schematic of the relay box is available from the corresponding author by request.

### Field Testing and Data Analysis

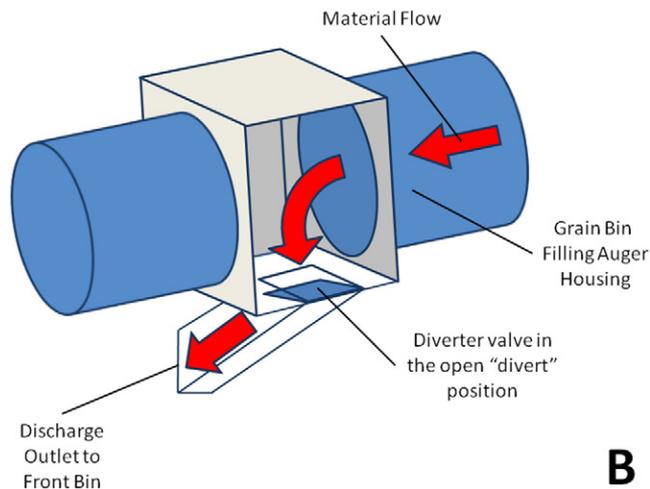
Preliminary field testing began in 2008 within a circular 20.2 ha (50 acre) DNS wheat field near Echo, OR (45°43.4' N, -119°3.3' W), having a center pivot irrigation system. The electrical linear actuator was being used to open and close the diverter valve. A test involved noting the average GPC value as the grain was sensed along a linear harvest transect across low yielding and high yielding areas of the field that resulted from variability in applied irrigation water. With the *low threshold*



**Fig. 4. Top of the Case International Harvester I470 combine with steel bulkhead dividing the bulk tank into a front and rear bin, vertical auger for lifting grain into the front bin, and hydraulic directional control valve.**



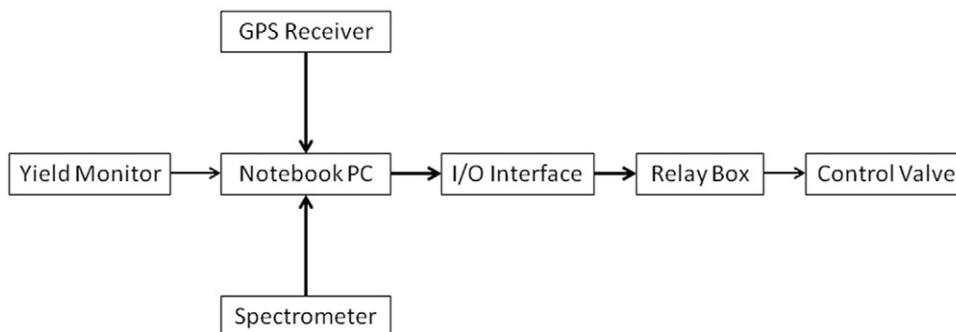
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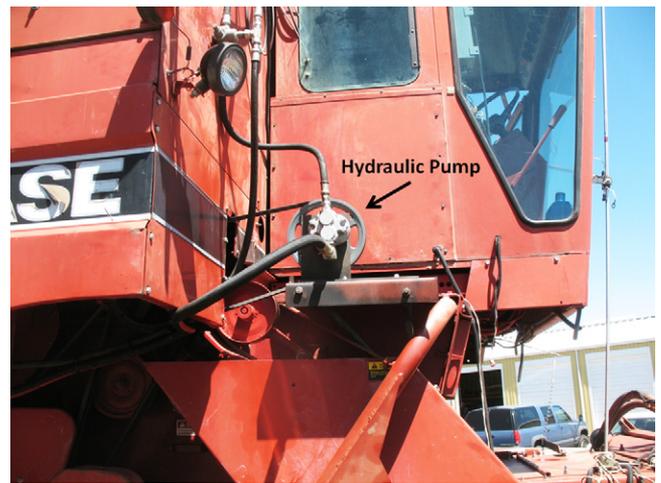
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**Fig. 5.** Cut away diagram of the grain segregator system showing the diverter valve in the up, or “flow-through” position, so that grain discharge is to the (A) rear bin and valve in the down, or “divert” position, so that grain discharge is to the (B) front bin.

set  $0.5 \text{ g kg}^{-1}$  below this average value and the *high threshold*  $0.5 \text{ g kg}^{-1}$  above this value, the system segregated the grain during a second pass of the combine, which was adjacent to the first transect. After the last pass, a grain probe sampler was manually inserted into each bin to obtain a 350-g sample, which was analyzed for GPC by laboratory dry combustion analysis. The front and rear bins could then be compared in terms of their difference in the GPC.



**Fig. 7.** Block diagram of the electrical system consisting of yield monitor, GPS receiver, spectrometer, notebook personal computer (PC), input/output (I/O) interface, relay box, and directional control valve.

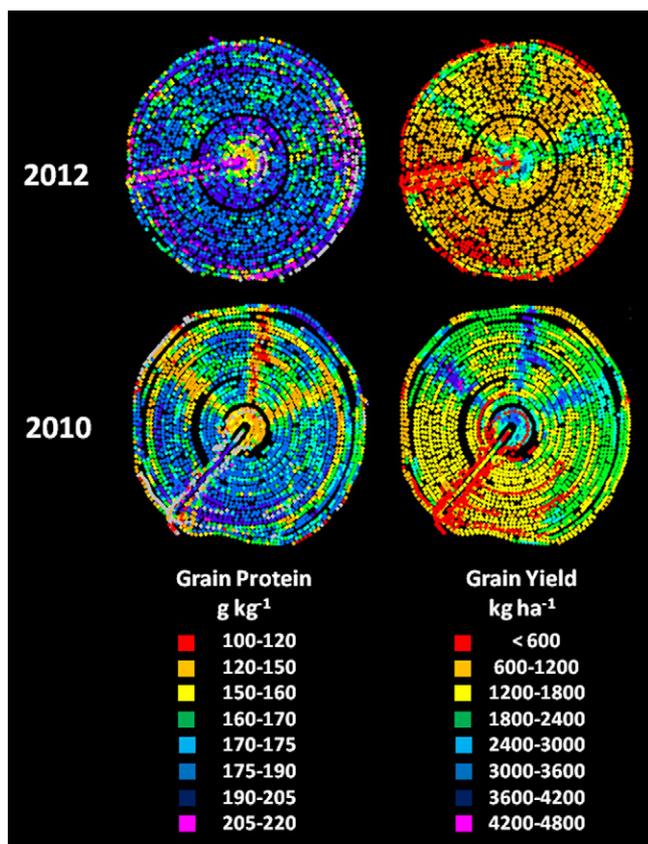


**Fig. 6.** Fixed displacement hydraulic pump used to power the lift auger and double acting cylinder.

In 2010, there were three areas in the field that radiated outward from the center where the irrigation pivot had stalled and over-watered (Fig. 8, blue colored areas of the 2010 grain yield map). These radial areas had relatively high grain yield and were associated with lower GPC (orange and red colored areas of 2010 grain protein map). Final testing of the improved system, which included the hydraulic cylinder, was undertaken in 2012 with the goal of segregating the large-scale variability in GPC seen in previous years. The segregator ran during combine harvest, which was undertaken in a circular pattern. The D2ProSpectra software was programmed to route the relatively low protein grain from the overwatered radial areas into the small front bin. Grain subsamples (ca. 800 g) were periodically collected from each bin during harvesting and tested for protein by laboratory dry combustion analysis. Mean difference in laboratory measured GPC between the front and rear bins was tested for significance ( $P < 0.05$ ) using two tailed Student's *t* test for unequal sample sizes. Mean difference in on-combine measured GPC between the front and rear bins was statistically contrasted in the same way.

## RESULTS AND DISCUSSION

In 2008, Jefferson DNS wheat averaged  $2000 \text{ kg of grain ha}^{-1}$  and  $165 \text{ g of protein kg}^{-1}$  of grain in the 20.2 ha field. Values of GPC for low and high categories were similar for tests 1 to 4,



**Fig. 8. Maps of grain protein concentration and grain yield of dark northern spring wheat in a 20.2-ha irrigated field near Echo, OR, in 2010 and 2012.**

which were conducted in field areas where crop differences were modest and operated over short distances (Table 1). Tests 5 to 7 were conducted in field portions where a strong difference in crop biomass and yield manifested over relatively long distances and proteins were widely separated. Based on our experience, the segregator operated well between field areas that differed in the amount of irrigation water applied and exhibited strong differences in grain yield and GPC. Segregation was more effective if the crop variability was large in amplitude over long distances as opposed to being small in amplitude over short distances.

In 2012, all of the components installed in the segregator worked as designed without failure. During harvest, little fugitive grain was observed being conveyed by the grain bin-filling auger into the rear bin with the segregator switched to the front bin. Likewise, no grain was conveyed by the vertical auger into the front bin with the segregator switched to the rear bin.

**Table 1. Protein concentration of grain in front and rear bins and their difference as determined by laboratory dry combustion analysis of manually collected samples in 2008.**

Test	Front bin	Rear bin	Difference
	g kg <sup>-1</sup>		
1	174.2	170.1	4.1
2	178.0	177.4	0.6
3	180.2	174.0	6.2
4	180.7	180.0	0.7
5	174.7	153.6	21.1
6	177.6	150.6	27.0
7	174.9	164.0	10.9

These visual observations indicated that the hydraulic cylinder was fully opening and closing the diverter valve.

Jefferson wheat averaged  $800 \pm 400$  kg of grain ha<sup>-1</sup> and  $186.4 \pm 18.9$  g of protein kg<sup>-1</sup> of grain in the field. The relatively low grain yield and high GPC were the result of drought conditions. Differences in GPC between the radial areas seen in previous years and the rest of the field were less apparent in 2012 (Fig. 8, green colored areas of 2012 grain protein map) despite strong differences in grain yield that remained (Fig. 8, green and blue colored areas of 2012 grain yield map). Threshold values were set  $0.5$  g kg<sup>-1</sup> apart to accommodate the modest GPC variability and were adjusted up or down with local changes in average GPC to create more opportunities for the segregator to trigger.

Based on on-combine measurements, an overall difference in GPC of about  $21$  g kg<sup>-1</sup> was sensed between the front and rear bins (Table 2). In comparison, the difference in GPC was about  $16$  g kg<sup>-1</sup> for laboratory analysis of grain samples. On-combine optical measurements of GPC were from 2 to 5% greater than laboratory measurements indicating slight upward bias in sensor readings. Segregator performance was further evaluated by means of the frequency distribution of the protein concentration of the grain that was diverted into each bin as determined by on-combine NIR spectroscopy (Fig. 9). Results show that much of the grain classified as low GPC was correctly routed to the front bin and vice versa. However, there is substantial overlap between both grain lots, which may have resulted from the 3-s data collection interval causing the diverter valve to open and close in response to the protein concentration of grain, much of which had already passed the valve. This overlap may also have resulted from the relatively large error of the ProSpectra sensor and the fact that we adjusted the threshold values during harvesting to collect sufficient grain in each bin.

The SECV of the ProSpectra instrument is within the standard deviation of GPC in the field ( $7.6$  vs.  $18.9$  g kg<sup>-1</sup>) and thus one would expect that the segregator could capture some of the variability in GPC in the field. Indeed, the segregator sorted the grain into two batches of relatively low or high protein despite the modest field differences in GPC and the relatively large instrument error. In 2010, grain yield and GPC had shown more spatial variability in this particular field, which likely would have enhanced our ability to segregate the grain.

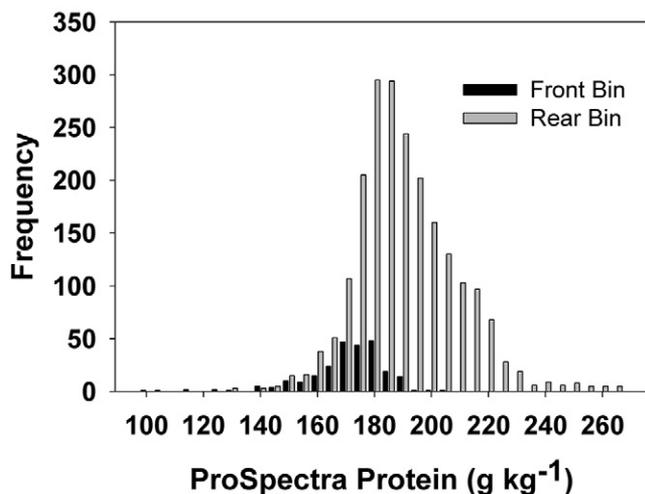
## SUMMARY AND CONCLUSIONS

An on-combine grain segregation system consisting of a spectrometer, hydraulic-mechanical diverter valve, control system, and two bins was developed for automatically segregating a flowing grain stream into concentrations of lower

**Table 2. Numbers of observation (n) and mean protein concentration of grain in front and rear bins and their difference as determined by on-combine optical sensing and laboratory analysis of manually collected samples in 2012.**

Bin	On-combine		Laboratory		
	n	Mean†	n	Mean†	
		g kg <sup>-1</sup>		g kg <sup>-1</sup>	
Front	249	166.9a	16	163.6a	
Rear	2128	187.8b	17	179.2b	
Difference		20.9		15.9	

† Mean values denoted by the same letter in a column are not significantly different at  $P < 0.05$ .



**Fig. 9. Frequency distribution of on-combine sensed grain protein concentration between front and rear bins.**

or higher protein during an actual harvest. The control system collected and processed data from the spectrometer and used this information to hydraulically control a diverter valve that routed the grain into one of two bins. The system performed as designed, with no hardware failures during a field test in 2012. Grain protein measurements with the optical sensor were more accurate in the laboratory than in the field with overestimation of GPC <5%. Combine harvesters currently are not designed to segregate grain by protein concentration, but the results of this research are sufficiently encouraging to suggest that this concept is possible. An advantage of this approach is that prior knowledge of harvesting zones is not required.

Interested readers may wish to consult Martin et al. (2013) for further information on the potential of on-combine grain segregation to increase economic returns. A software (e.g., “Grain Segregation Profit Calculator”) has been developed for calculating the cutoff value to use for segregating wheat into two batches such that prices received for average protein levels in the two batches maximize profit. The grain price schedule, and mean and standard deviation of GPC are input to the software for determining the cutoff value. Growers may not have the mean and standard deviation in advance of harvest, but this information might be acquired by cutting a single pass across a field with a combine equipped with a yield monitor and grain quality sensor.

Though useful, this study employed the ProSpectra spectrometer with a silicon detector that was limited to a spectral range <1100 nm. This instrument is no longer available and has been superseded by a new generation of field spectrometers with indium gallium arsenide (InGaAs) detectors giving improved spectral resolution and sensitivity into the mid-infrared (<1650 nm). Preliminary testing of such an instrument (Polytec model PSS 1721) gave excellent results with hard red spring wheat ( $r^2 = 0.98$  and  $SECV < 2.8 \text{ g kg}^{-1}$ , relative to analysis by combustion, Long and McCallum, unpublished data, 2013). Therefore, the Polytec instrument apparently may give more precise protein readings, but will be more expensive than the older ProSpectra instrument (U.S.\$30,000 vs. U.S.\$15,000).

Future work can be undertaken to evaluate the newer instrumentation for robustness in the field, further improve the ability to segregate grain on the combine, and determine if on-combine grain segregation can cover costs of the sensing technologies.

## ACKNOWLEDGMENTS

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