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Net Returns from Segregating Dark Northern Spring Wheat by Protein Concentration during Harvest

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ABSTRACT

In-line, optical sensing has been developed for on-combine measurement and mapping of grain protein concentration (GPC). The objective of this study was to estimate changes in costs and net returns from using this technology for segregation of the dark northern spring (DNS) subclass of hard red wheat (*Triticum aestivum* L.) by GPC. Site-specific GPC and yield data were obtained from 21 DNS wheat fields in northern Montana over 11 yr (1994–2004). Several hundred measurements of GPC were obtained within each field by means of whole grain spectroscopy. A calculator was built to predict the best economic point at which to segregate grain into two bins and define the protein level and quantity of each volume of grain. Partial budget analysis was used to estimate net returns and determine if segregating wheat was more profitable than bulking wheat in one bin. Segregation consistently increased the value of each megagram of grain if the GPC of a field was below the upper limit of a price schedule and also did not coincide with a price step. Added income was insufficient to offset costs of segregation based on 21-yr (1994–2014) average market prices. Costs could be offset in years when prices were sharply higher than average 21-yr prices. These results suggest that grain segregation may be profitable under certain conditions. Further refinements to the technique are needed to reduce equipment costs and benefit the producer.

Core Ideas

- New optical sensors are potentially useful for segregating grain by protein content during harvest.
- Segregating grain may increase profitability if added income exceeds added costs.
- Profits are possible under the right circumstances.

Grain protein concentration is a primary factor contributing to favorable milling, baking, and dough handling properties of hard red spring wheat (Graybosch et al., 1993). Since high GPC is preferred by buyers of this grain, growers receive a higher price for DNS subclass of hard red spring wheat with GPC at or above 130 g kg^{-1} (13%). For example, prices for DNS wheat were US$161.34 to $174.94 Mg^{-1} for grain with 130 g kg^{-1} protein, $176.04 to $184.86 Mg^{-1} with 140 g kg^{-1} protein, and $183.39 to $190.74 Mg^{-1}with 150 g kg^{-1} protein (7 Apr. 2016 elevator cash prices at Great Falls, MT; http://www.ams.usda.gov/mnreports/bl_gr110.txt). Premium pricing is used by the U.S. wheat industry to encourage growers to maximize protein and provide the grain quality desired by buyers.

Different truckloads of wheat delivered to the elevator can vary in GPC resulting from farm-to-farm differences in crop varieties, growing season conditions, and cultural practices. Within-field differences in plant available water (Campbell et al., 1997; Stewart et al., 2002) and soil fertility (Fiez et al., 1994; Delin, 2004) contribute additional variation. By collecting the grain together in one bin, traditional grain harvesting and handling methods ignore this variability. Segregation by GPC has been used to improve the quality of the collection at the elevator (Le Bail and Markowski, 2004), on the farm (Thylén and Rosenqvist, 2002), and on a combine harvester (Long et al., 2013). Bench analyzers, based on the near infrared (NIR) spectroscopic techniques pioneered by Norris (1964), are typically used to measure protein in grain samples at the elevator. Specialized NIR sensors have been designed to be mounted on combine harvesters and used to obtain continuous in-line measurements of GPC across farm fields (Maertens et al., 2004; Long et al., 2008). On-combine segregation during harvesting is considered in this paper.

Schlecht et al. (2004) identify the farm as the ideal place for grain segregation because it is the earliest point in the supply chain. In Australia, Stewart et al. (2002) found that segregating durum wheat into two batches would have increased profits by AUS$34 ha^{-1} over conventional harvesting. In Germany, Meyer-Aurich et al. (2008) determined that grain segregation, which isolated and sold valuable grain at higher prices, increased marginal returns by €50 ha^{-1} over conventional

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Abbreviations: DNS, dark northern spring; GPC, grain protein concentration; NIR, near infrared.

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harvesting. Martin et al. (2013) used long-term DNS wheat prices to estimate the effect of a stepped price function on the potential gain in value per unit quantity of grain. For a two-bin segregation system, grain segregation of DNS wheat could potentially increase marginal returns by as much as \$2.94 Mg^{-1} for GPC between 120 and 160 g kg^{-1}. Using nonlinear programming to identify grain segregation strategies that would optimize dollar returns, Miao and Hennessy (2015) estimated that growers would be willing to pay up to \$9.31 Mg^{-1} (\$0.308 bu^{-1}) to segregate DNS wheat by protein concentration during harvest.

Discontinuous, stepped price schedules are commonly used in the U.S. marketplace to specify the dollar value of wheat with incremental changes in GPC. The price remains the same between small increments of GPC, but then changes to the next price when a price step is reached. Segregation by GPC can exploit the stepped nature of the price schedules. Profitability is enhanced either by removing an amount of lower protein wheat thereby increasing the value of the remaining bulk or by removing from the bulk an amount of higher protein wheat that can be sold at a premium price while maintaining the bulk price. Initially, grain sold at a premium price is small when mean GPC is well below a price step. However, further increases in the marginal return are possible as the mean approaches a price step from below before disappearing at the price step (Martin et al., 2013). In contrast, conventional harvesting, which mixes the grain together, ensures that the price of each load of grain brought to the elevator will be based on the bulk GPC.

An optical-mechanical system for automatically segregating wheat by GPC during harvest has been constructed for a Case IH 1470 combine and is described in detail by Long et al. (2013). Sivaraman et al. (2002) found that the benefits of grain segregation could be achieved with only two bins. Accordingly, the combine's bulk tank (4.9 Mg [180 bu]) is divided into a large, rear bin (3.81 Mg) and a small, front bin (1.09 Mg). During operation of the system, a multispectral optical sensor (ProSpectra grain analyzer, Textron Systems, Wilmington, MA) scans the grain as it is conveyed by the combine's grain tank-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 (D2ProSpectra, Textron Systems) that is programmed to calculate GPC from a chemometric model. The continuous GPC output is used to activate an electrical relay which operates a mechanical diverter valve that diverts the grain into one bin or the other depending on whether the GPC is above or below a selected cutoff value.

ALGORITHM FOR DETERMINING OPTIMUM CUTOFF VALUE

Martin et al. (2013) developed the web-based Grain Segregation Profit Calculator (GSPC) to compute the optimum cutoff value to use for segregating wheat into two bins such that prices received for average protein levels in the two bins maximize the marginal return. The GSPC uses the field mean GPC ($\overline{x}$) and standard deviation (s) to define the frequency distribution of the GPC, which is assumed to be normal. Values for $\overline{x}$ and s would be obtained in advance of segregation by harvesting along a test strip across the field.

For a series of protein values x over part of a distribution, the mean protein in the corresponding bin is computed from the normal distribution. The mean below a cutoff protein value, p, can be calculated from the relationship:

$$\int_{-\infty}^{p} xN(x)dx = -N(p) \quad [1]$$

where $N(x)$ is the normal frequency distribution and x is the protein value. Using an arbitrary cutoff value, the mean protein and quantity of grain that would be in each bin are calculated based on the normal distribution. The marginal return is computed for each bin over each possible cutoff value. The optimum cutoff value is selected that is associated with the maximum profitability.

Figure 1 shows the marginal returns (calculated using the MS-Excel program described in a following section) for cutoff values from 110 to 170 g kg^{-1} when $\overline{x}$ = 139.5 g kg^{-1} and s = 7.5 g kg^{-1}. In this conceptual example, the cutoff value that maximizes the marginal return falls on a GPC of 125.55 g kg^{-1}. Without grain segregation, the entire load of grain would have a mean GPC of 139.5 g kg^{-1} and the value would be \$3.67 Mg^{-1} lower than the next price step of 140 g kg^{-1} where added value is given to DNS wheat for high protein (Table 1). With segregation, a small amount of low protein ($\overline{x}$ = 122.63 g kg^{-1}) grain is removed and sold at discount while the bulk is boosted to >140 g kg^{-1} and sold without discount. The weighted discount from grain segregation is ≤\$0.78 Mg^{-1} and thus the marginal return is the difference between with and without segregation, or \$2.89 Mg^{-1}.

No studies have been published in the western United States that investigated whether on-combine segregation by GPC is profitable on a per hectare basis. The objective of this study was to estimate changes in costs of grain handling logistics and expected net revenues from on-combine grain segregation by protein concentration. A partial budget analysis was conducted utilizing long-term market prices, and grain quality and yield data from DNS wheat fields in northern Montana.

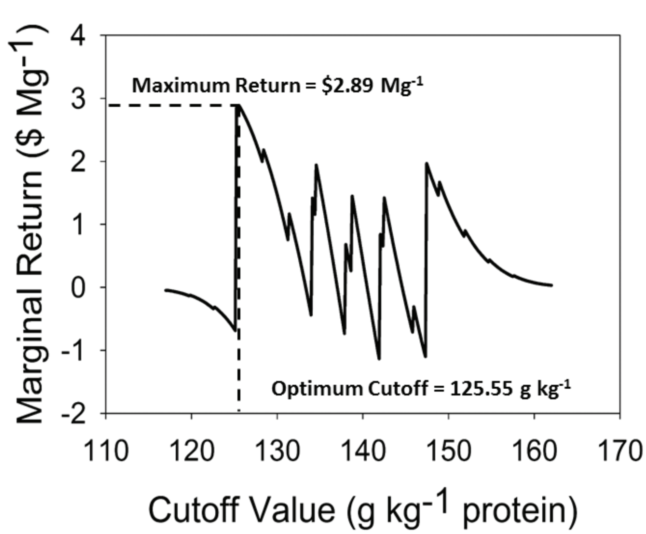

Fig. 1. Marginal returns from segregation of grain into two bins of low and high protein concentration for a wide range of cutoff values.

MATERIALS AND METHODS

Dryland Wheat Production System

Many dryland wheat farms in northern Montana comprise from 15 to 20 quarter sections (972–1296 ha) of land. Alternate wheat–fallow is the predominant cropping system with 50% of farmland in production each year. Therefore, the economic analysis of this study was based on a 1215 ha (3000 acre) farm in a 50:50 wheat–fallow rotation with 607.5 ha of land in wheat production. On average, 55% of the wheat is DNS wheat (334.1 ha) with the remainder winter wheat (273.4 ha) based on county-level sample surveys conducted by the USDA-National Agricultural Statistics Service between 1994 and 2015 (Montana, north central ag district, available at http://quickstats.nass.usda.gov/, verified 22 Dec. 2015). During this period, average yield was 1982 kg ha^{-1} for DNS wheat and 2589 kg ha^{-1} for winter wheat. Therefore, average annual per farm production was 662.2 Mg (24 338 bu) for DNS wheat and 707.8 Mg (26 012 bu) for winter wheat based on long-term USDA-NASS data records. The analysis is applicable to 0.8 M ha of cropland in Major Land Resource Area 52 (Brown Glaciated Plains, NRCS, 2006) of Montana where annual precipitation is mostly 255 to 430 mm.

Table 1. Estimates of grain protein concentration (GPC), fraction of grain, discount, and weighted discount with and without segregation for the example of dark northern spring wheat with mean GPC of 139.5 g kg^{-1} and standard deviation 7.5 g kg^{-1}.

Item	Mean GPC	Fraction	Discount†	Weighted discount
	g kg^{-1}		——— $ Mg^{-1} ———	
		Without grain segregation		
	139.50	1.000	–3.67	–3.67
		With grain segregation		
Large bin	140.05	0.969	0.00	0.00
Small bin	122.63	0.031	–25.08	–0.78

† Based on average 16-yr (1994–2009) market quotes at Portland, OR, for dark northern spring wheat.

Grain Protein and Yield Data

To include differences due to geographic variation, grain protein and yield data were obtained from 21 DNS wheat fields for large dryland farms in five counties of northern Montana over an 11-yr period (1994–2004, Table 2). Site-specific yield data were obtained using combines equipped with an Ag Leader YM2000 yield monitor and Novatel SMART-V1 GPS receiver. While the intention was to obtain a similar number of GPC measurements as yield measurements, this was not possible because an on-combine NIR sensor was not commercially available during

Table 2. Field number, year, latitude, longitude, growing season precipitation (percent of long-term in parentheses), mean and standard deviation (SD) of grain yield (GY), and mean, SD, and skew (S) of grain protein concentration (GPC) for 21 dark northern spring wheat fields in northern Montana.

Field no. site	Year	Latitude	Longitude	Precipitation	GY Mean	GY SD	GPC Mean	GPC SD	S†
				mm	— Mg ha^{-1} —		— g kg^{-1} —		
1	1994	48°50′02″ N	–109°54′49″ W	143 (97%)	2.41	0.38	142.1	21.2	–4.27
2	1995	48°39′46″ N	–110°59′30″ W	322 (210%)	3.71	0.78	108.7	16.9	0.03
3	1996	48°39′46″ N	–110°59′30″ W	117 (76%)	0.92	0.53	153.3	16.1	–4.17
4	1996	48°47′44″ N	–110°03′40″ W	147 (92%)	1.04	0.2	136.6	8.2	–2.95
5	1997	48°28′31″ N	–110°29′56″ W	201 (125%)	2.78	0.29	154.7	7.0	–0.69
6	1997	48°19′54″ N	–110°04′58″ W	181 (91%)	2.59	0.28	152.6	8.4	9.12
7	1997	47°27′39″ N	–111°00′59″ W	242 (125%)	4.56	0.60	135.1	7.9	–11.48
8	1998	48°09′00″ N	–110°17′08″ W	198 (100%)	2.25	0.38	146.0	8.4	–2.17
9	1998	48°31′43″ N	–109°55′55″ W	182 (117%)	2.10	0.44	135.3	9.6	0.02
10	1998	48°25′51″ N	–107°35′28″ W	200 (105%)	2.86	0.53	138.9	9.3	2.22
11	1999	48°25′51″ N	–107°35′18″ W	228 (120%)	3.74	0.35	147.5	8.9	–2.09
12	1999	47°27′36″ N	–111°01′00″ W	157 (81%)	1.77	0.22	129.2	7.3	–1.63
13	2000	48°31′42″ N	–109°55′55″ W	126 (81%)	1.94	0.35	167.1	7.0	–22.69
14	2000	48°25′44″ N	–107°35′27″ W	148 (78%)	2.36	0.36	159.8	12.3	–10.55
15	2000	48°25′55″ N	–107°34′49″ W	148 (78%)	2.55	0.57	141.50	13.0	3.84
16	2001	48°31′47″ N	–109°56′57″ W	144 (92%)	1.06	0.28	171.9	9.5	6.49
17	2001	46°41′43″ N	–110°29′57″ W	134 (70%)	0.83	0.18	158.8	12.0	–1.07
18	2003	48°24′05″ N	–107°47′18″ W	140 (74%)	2.04	0.59	141.4	20.4	2.33
19	2003	48°25′37″ N	–107°35′38″ W	140 (74%)	2.38	0.67	176.0	10.3	–5.21
20	2004	48°23′02″ N	–107°46¢17″ W	145 (76%)	3.71	0.81	144.3	13.3	–0.67
21	2004	48°25′55″ N	–107°34′50″ W	145 (76%)	2.70	0.46	152.6	11.4	–8.36

† Skew divided by standard error of skew, which normalizes for sample size. Any S < 1.96 has a 95% confidence interval that it was drawn from a normal distribution.

this period. Instead, several hundred measurements of GPC were obtained by means of whole grain NIR analysis (Foss Infratec 1226) of grain samples. Laboratory NIR analysis has been found to be accurate to within 3 g kg^{-1} GPC (Casada and O'Brien, 2003) vs. on-combine sensing, which is reported to be <5.0 g kg^{-1} (Long et al., 2008). The sampling tool was a 1 L capacity metal cup used to manually sample approximately 850 g of grain flowing from the combine's grain bin-filling auger. A sample was collected every 60 s, but the period was intensified to 30 s when variability in local terrain conditions increased in complexity. Samples were sealed in plastic bags and labeled by writing the Coordinated Universal Time (UTC) of collection on the bag. The UTC values could then be used to geo-register a sample in the field when matched with the yield monitor data, which included the UTC and GPS coordinates of each data record. Grain protein (n < 500) was under sampled with respect to grain yield (n < 30 000) in any field.

Partial Budget Analysis

The economic impact of adopting grain segregation technology was determined using partial budget analysis. Partial budgeting is an approach used to determine the economic returns from changing to a new management or production practice from the one currently used (Swinton and Lowenberg-DeBoer, 1998). The components of a partial budget include those that either reduce profitability by increasing costs or decreasing income, or enhance profitability by decreasing costs or increasing income (Table 3). Increased costs include greater grain handling costs and costs for equipment and labor whereas the increased income comes from the enhanced market value of the segregated grain. Subtracting the sum of increased costs and decreased income from the sum of increased revenue and reduced costs provides the expected change in net income from grain segregation. A partial budget was constructed for each field and the results were treated as a separate case study.

Table 3. Components of partial budget of costs and services for implementing on-combine grain segregation (adapted from Tao et al., 2010).

Partial budget	
Alternative: Implementing grain segregation	
Increased costs	Increased Income
Additional truck	Value of segregated grain
Combine unloading	
Segregator calibration	
Grain protein sensor	
Segregator hardware	
On-board computer	
Interest on equipment	
Reduced income	Reduced costs
None	None
A. Total added costs and reduced income	B. Total added income and reduced costs
Expected change in net income (B – A)	

Estimating Increased Costs

The total cost (TC) of implementing on-combine grain segregation for a field was calculated as:

$$TC = C_S + C_C + C_P + C_T + C_I + C_U + C_L + C_O \quad [2]$$

where C_S is the cost of constructing the grain segregator, C_C is the cost of purchasing the onboard PC, C_P is the cost of purchasing a grain protein sensor, C_T is the cost of purchasing an additional truck, C_I is the cost of interest on acquiring the equipment, C_U is the cost of added time to unload the combine's second bin, C_L is the cost of calibrating the grain segregator, and C_O is the cost of operating the additional truck. It was assumed that a combine harvester was owned, but would be modified with the two-bin, optical-mechanical grain segregator described by Long et al. (2013). Material costs of C_S are estimated at \$10,000 and include hydraulic hose, hydraulic pump, hydraulic motor, auger, unloading auger clutches, directional control valve, analog to digital signal converter, and relay box; and labor to fabricate metal parts and assemble these components. An on-board computer (C_C, \$120) and grain protein sensor with instrument control software (C_P, \$14 000) are also required. Fixed costs also included \$5000 for purchase of a used, single axle truck (C_T) in good condition for hauling high quality grain from the field to an existing central, on-farm storage bin.

Equipment was depreciated using the straight line method which subtracts a 20% salvage value from the purchase price and divides this difference by the number of productive years. All equipment was assumed to have a useful life of 7 yr except the on-board computer, which was 5 yr. Opportunity cost (C_I) accounted for interest on investment of these equipment items and was calculated at an annual rate of 7.14%. Fixed costs of C_S, C_C, C_P, C_T, and C_I were spread over the 607.5 ha of land in wheat production.

The added unloading cost (C_U) is given by:

$$C_U = t_u \times c_o/a \quad [3]$$

where t_u is extra hours required to unload the two bins; c_o is an operating cost of \$110 h^{-1} for fuel, lubrication, repair, and maintenance and includes the operator's labor (\$15 h^{-1}); and a is total field area in hectares. Extra time to unload the combine (t_u) was computed:

$$t_u = n_u \times t \quad [4]$$

where n_u is the number of additional unloadings and t is the time between unloading the first bin and the second bin, which was assumed to be 2 min with allowance for complete emptying of the unloading auger, switching to the second bin, and moving to a second truck for hauling segregated grain. Number of additional unloadings from the combine (n_u) was given by:

$$n_u = n_w - n_o \quad [5]$$

where n_w is the total number of unloadings with the segregation equipment installed and n_o is the total number without. Number of unloadings with segregation equipment (n_w) equaled the total grain yield times the percentage of grain yield segregated into the rear bin divided by a capacity of 3.81 Mg. Without segregation equipment, number of unloadings (n_o) was the field's total yield divided by the 4.9 Mg capacity of the combine's stock tank.

The cost of obtaining values for $\overline{x}$ and s within a test strip (C_L) as needed to calibrate the grain segregator was estimated from:

$$C_L = t_l \times c_o \quad [6]$$

where t_l is the time to harvest the test strip and c_o is the operating cost of the combine. The extra time for the test (t_l) was computed:

$$t_l = a/r \times 0.03 \quad [7]$$

where a is total field area, r is harvest rate at 3.645 ha h^{-1} typical of a rotary combine with 7.3 m (24 ft) header, and 0.03 is percentage of field allocated to the test strip. A general addition of 3% harvest time was used as an estimate to cover going over any area twice.

Operating costs of the additional truck (C_O) equaled

$$C_o = c_l + c_r + c_s + c_m \quad [8]$$

where c_l is liability insurance at \$300 yr^{-1}, c_r is vehicle registration at \$30 yr^{-1}, c_s is servicing at \$350 yr^{-1}, and c_m is repair and maintenance at \$1000 yr^{-1}. Insurance, registration, servicing, and repair and maintenance were considered as fixed costs spread over the total land in production. Costs for tires and fuel were not considered because the total amount of production did not change. Labor for driving the second truck was also not considered because of the ability to transport the grain and return to the field before the combine refills itself with more harvested grain and further unloading is needed.

Estimating Increased Revenue

Cash prices for DNS wheat were obtained from the Montana Wheat and Barley Committee (Great Falls, MT). Marginal returns to yield were based on average daily cash prices at Great Falls in each year from 1994 to 2014. Grain prices (\$ bu^{-1}) are reported by whole percentage of GPC, but local elevators pay to the nearest 0.25% GPC with premiums applied between 14 and 16%, and discounts between 12 and 14%. Linear interpolation was used to construct prices for quarter percentages within the range of known whole percentages. Between 2011 and 2014, 76% of DNS wheat produced in the United States was exported through Portland, OR (U.S. Wheat Associates, 2015). Local Montana elevator prices are Portland prices adjusted for a rail freight cost of about \$48 Mg^{-1} (\$1.30 bu^{-1}) from the shipping origin. An MS-Excel spreadsheet calculator was programmed for calculating the cutoff value to segregate grain into two on-combine bins (small bin or large bin) and maximize the marginal return from the segregation. Based on a user-specified $\overline{x}$ and s determined from a test strip, and an initial cutoff value of 3s below the mean, the calculation utilizes the following algorithm:

1. Generate the NORMSDIST function available in MS-Excel to compute the fraction below the cutoff value
2. Compute the fraction above this cutoff by subtracting the fraction below from unity.
3. Compute the mean protein of both bins using Eq. [1].
4. Using grain prices stored in a lookup table, compute the U.S. dollar value of the large-bin and small-bin fractions by multiplying their relative mass by mean GPC and the marginal grain price.
5. Combine the prices for large- and small-bin grain and compare the results with the price of grain at the overall mean. This difference is the marginal return.
6. Repeat Steps 1 to 5 to compute the marginal return in steps of z-score increments of 0.02 up to 3s above the mean. A cutoff value is selected that maximizes the marginal return.

Use of the calculator assumes that data follow a normal distribution. Histograms of GPC in each field were examined to assess for normality of data. Deviation from a normal distribution may cause difficulty in estimating $\overline{x}$ and s precisely and not having the calculated cutoff value reflect the optimum cutoff value resulting in lost revenue. Using the calculator, actual returns based on how the segregator would successfully, or unsuccessfully, apply the cutoff value in a non-normal field were determined. The maximum attainable return was also calculated using a cutoff value determined by the real distribution of GPC though this distribution cannot be known in advance of harvest. A sensitivity analysis was conducted to show the effect of farm size and grain yield on profitability.

RESULTS AND DISCUSSION

Grain Yields and Grain Protein Concentration Levels

Mean grain yields varied among the 21 fields and ranged from 0.83 to 4.56 Mg ha^{-1} whereas mean GPC ranged from 108.7 to 176.0 g kg^{-1} (Table 2). A negative, albeit modest, correlation ($r < -0.4$) exists between the mean values of yield and protein across the 21 fields. In water-limiting environments, grain yield and GPC are often inversely related resulting from dilution (or concentration) of N by an increasing (or decreasing) amount of biomass (Campbell et al., 1977; Terman, 1979). Field 11 had no potential for profitable segregation because its mean protein value coincided with a price step where it is impossible to increase marginal return. In addition, three of the fields (13, 16, and 19) had no profit potential because mean GPC was above the highest price step (>160 g kg^{-1}) where premiums no longer increased. These four fields were not considered in the economic analysis since a decision whether to segregate is based on mean protein as determined from the results of a test strip before segregation. Nevertheless, they would be subject to annual fixed costs.

Increased Costs

Increased costs of grain segregation were mostly associated with annual fixed costs for equipment (Table 4). The grain protein sensor, grain segregator, and on-board PC were estimated to be \$2.63, \$1.88, and \$0.03 ha^{-1}. Grain segregation requires use of an additional truck to transport the higher valued grain from the field. Accordingly, expenses for purchasing, insuring, registering, servicing, and repairing this truck added to \$2.23 ha^{-1}. Opportunity cost on these items was \$2.08 ha^{-1}, bringing total fixed costs to \$8.86 ha^{-1}. The only variable costs considered in this analysis were test strip harvest time

Table 4. Costs of materials and services used for grain segregation at each site.

Variable costs	Cost	Unit
Added unloading stops	$1.83	Minute
Added time at each unloading	$1.83	Minute
Added time cutting test strip	$1.83	Minute
Fixed costs		
Grain protein sensor	$14,000	Each
Combine segregator system	$10,000	Each
Personal computer	$120	Each
Additional truck	$5,000	Each
Insurance	$300	Year
Registration	$30	Year
Service	$350	Year
Repair and maintenance	$1,000	Year
Opportunity cost		
Interest on fixed costs	7.14%	Per dollar

that increased with field size and added combine unloading time that increased with total yield and a field's distribution of grain. The latter cost is important as there is a large difference in how quickly the combine fills when the relative volume of grain segregated is 3% compared to 30%. Variable costs ranged from \$0.04 ha^{-1} to \$0.22 ha^{-1} across all fields except field 2. High variable cost (\$6.56 ha^{-1}) in field 2 was due to high yield and 37% of the grain being segregated, which lead to numerous unloadings of the small bin.

Increased Value per Megagram of Grain

There were 12 fields (1, 2, 3, 4, 5, 10, 12, 14, 15, 17, 18, and 20) in which grain segregation could have removed a small volume of low protein grain boosting the GPC of the remaining bulk (Table 5). For example, in field 12, low quality grain (5.1% lowest GPC) was segregated boosting the GPC of the bulk from 129.2 to 130.0 g kg^{-1} thereby reducing the price

Table 5. Mean grain protein concentration (GPC), relative grain volume, gross value, gross value weighted by relative volume of grain in small (S) vs. large (L) bin, and marginal return from segregated harvesting for 17 Montana dark northern spring wheat fields.

Site no.	Harvesting method	Bin	Mean GPC	Relative volume	Gross value†	Combined value†	Marginal return
			g kg^{-1}		$ Mg^{-1}		
1	Conventional	–	142.1	1.000	0.00	0.00	3.47
	Segregated	S	101.1	0.067	–38.37	3.47	
		L	145.1	0.993	6.46		
2	Conventional	–	108.7	1.000	–38.37	–38.37	5.43
	Segregated	S	99.8	0.323	–21.55	–32.94	
		L	127.6	0.667	–38.37		
3	Conventional	–	153.3	1.000	16.16	16.16	0.51
	Segregated	S	120.2	0.051	–34.48	16.67	
		L	155.1	0.949	19.39		
4	Conventional	–	136.6	1.000	–8.62	–8.62	2.66
	Segregated	S	119.6	0.048	–38.37	–5.96	
		L	137.5	0.952	–4.32		
5	Conventional	–	154.7	1.000	16.16	16.16	2.79
	Segregated	S	137.6	0.019	–4.31	18.95	
		L	155.0	0.981	19.40		
6	Conventional	–	152.6	1.000	16.16	16.16	0.02
	Segregated	L	152.5	0.981	16.16	16.18	
		S	179.3	0.019	25.86		
7	Conventional	–	135.1	1.000	–8.62	–8.62	0.17
	Segregated	L	135.0	0.994	–8.62	–8.45	
		S	157.6	0.006	22.63		
8	Conventional	–	146.0	1.000	6.47	6.47	1.02
	Segregated	L	145.0	0.947	6.47	7.49	
		S	163.1	0.053	25.86		
9	Conventional	–	135.3	1.000	–8.62	–8.62	0.43
	Segregated	L	135.0	0.987	–8.62	–8.19	
		S	160.2	0.013	25.86		
10	Conventional	–	138.9	1.000	–4.31	–4.31	2.35
	Segregated	S	120.3	0.057	–34.48	–1.96	
		L	140.0	0.943	0.00		

(continued)

discounts significantly for 94.9% of the grain. In another five fields (6, 7, 8, 9, and 21), segregation could have removed a small volume of high protein grain to sell at a premium price without reducing the GPC of the remaining bulk below the price step. For example, in field 8, high quality grain (5.3% highest GPC) was segregated, but 94.7% of the grain remained at 145.0 g kg^{-1} without being penalized by discounts. Consequently, grain segregation produced positive returns for each Mg of wheat based on 21-yr average Portland market prices. Marginal returns ranged from \$0.02 Mg^{-1} in field 6 to as much as \$5.43 Mg^{-1} in field 2 over returns from conventional bulk harvesting.

These data indicated that the total amount of segregated grain could be contained on one truck. At some point, this truck would need to be driven to on-farm storage, but harvesting could continue provided another truck was positioned for unloading the combine. Conceptually, hauling grain from the field could be accomplished by one driver shuttling the two trucks between the combine and the granary provided a round trip does not require more time than filling the combine. In Montana, the harvested grain is often stored on the farm in multiple grain storage units before it is sold. These units could be used for storing grain segregated by GPC.

Expected Change in Net Return from Grain Segregation

Partial budget results for grain segregation for 21 yr (1994–2014), and 2004 and 2010 average September prices for DNS wheat are shown in Table 6. The price differential between 140 and 150 g kg^{-1} GPC was \$20.58 Mg^{-1} (\$0.56 bu^{-1}) in 2004 and \$43.37 Mg^{-1} (\$1.18 bu^{-1}) in 2010 vs. the 21-yr average of \$12.86 Mg^{-1} (\$0.35 bu^{-1}), and thus these 2 yr were chosen to show their impact on net returns. Compared with conventional harvesting, the cost of grain segregation was substantial and was mostly a result of additional required equipment (e.g., grain protein sensor, grain segregator, and truck). The added costs were the sensor (30%), additional truck (25%), interest (24%), and segregation equipment (21%). Except in field 2, variable costs for additional time unloading the combine and cutting the test strip were <5% of fixed costs. Based on average 21-yr prices, there is no profitability in grain segregation because added costs were greater than added income from grain segregation. Field 2 is an exception because it was the only field with mean GPC < 120 g kg^{-1} where the bulk would be valued at the floor of the price function. In this unique case, the portion of grain segregated with GPC ≥120 g kg^{-1} would gain value while the grain below this inflection point would not lose value. Net returns from segregation were positive for fields 2, 5, and 10 using September 2004 prices and also for fields 1, 2, 5, 10, 12, 14, 15, 18, and 20 using September 2010 prices because more value was given to grain for each 2.5 g kg^{-1} increase in GPC than 21-yr average prices.

These findings largely contradict Miao and Hennessy (2015) who reported large positive net returns from segregating grain by protein during harvesting. By assuming that average GPC by area across the Pacific Northwest and northern Great Plains could be used as a proxy for site-specific protein data, the range in protein distribution that they used was wider than we found for single fields. Plus, their limit of three price steps did not

Table 5. (Continued).

Site no.	Operation	Bin	Mean GPC	Relative volume	Bin value	Combined value†	Difference
			g kg^{-1}			\$ Mg^{-1}	
12	Bulked	–	129.2	1.000	−21.55	−21.55	3.24
	Segregated	S	114.2	0.051	−38.37	−18.31	
		L	130.0	0.949	−17.24		
14	Bulked	–	159.8	1.000	22.63	17.38	2.89
	Segregated	S	125.3	0.007	−25.86	25.52	
		L	160.0	0.993	25.86		
15	Bulked	–	141.5	1.000	0.00	0.00	1.74
	Segregated	S	112.9	0.036	−38.37	1.74	
		L	142.5	0.964	3.23		
17	Bulked	–	158.8	1.000	22.63	22.63	1.43
	Segregated	S	133.7	0.046	−12.93	24.06	
		L	160.0	0.954	25.86		
18	Bulked	–	141.4	1.000	0.00	0.00	2.42
	Segregated	S	104.6	0.090	−38.37	2.42	
		L	145.1	0.910	6.46		
20	Bulked	–	144.3	1.000	3.23	3.23	2.26
	Segregated	S	112.4	0.022	−38.37	5.49	
		L	145.0	0.978	6.46		
21	Bulked	–	152.6	1.000	16.16	16.16	0.05
	Segregated	L	152.5	0.995	16.16	16.21	
		S	185.6	0.005	25.86		

† Gross value is based on 21-yr (1994–2014) average prices and normally distributed GPC values.

Table 6. Partial budget results for estimated change in cost, added income, and net return from grain segregation for 21-yr (1994–2014) average, and September 2004 and September 2010 average prices for 17 Montana dark northern spring wheat fields.

Site no.	Cost	Added income	Net return	Added income	Net return	Added income	Net return
		21-yr average		Sept. 2004		Sept. 2010	
	$ ha^{-1}						
1	8.95	8.35	−0.60	13.91	4.96	31.00	22.05
2	15.42	20.15	4.73	30.50	15.08	58.52	43.10
3	8.90	0.47	−8.43	0.93	−7.97	2.41	−6.49
4	8.99	2.77	−6.22	4.06	−4.93	7.77	−1.22
5	9.08	7.75	−1.33	12.35	3.27	26.07	16.99
6	9.07	0.05	−9.02	0.08	−8.99	0.16	−8.91
7	9.27	0.77	−8.50	1.23	−8.04	2.55	−6.72
8	8.97	2.30	−6.67	3.67	−5.30	7.70	−1.27
9	9.04	0.90	−8.14	1.43	−7.61	2.92	−6.12
10	8.99	6.71	−2.28	9.88	0.89	19.03	10.04
12	8.96	5.75	−3.21	8.42	−0.54	16.18	7.22
14	9.07	6.82	−2.25	10.92	1.85	23.10	14.03
15	9.02	4.43	−4.59	7.39	−1.63	16.56	7.54
17	8.90	1.18	−7.72	1.94	−6.96	4.22	−4.68
18	8.90	4.95	−3.95	8.55	−0.35	19.98	11.08
20	9.14	8.39	−0.75	13.65	4.51	29.61	20.47
21	9.11	0.13	−8.98	0.22	−8.89	0.43	−8.68

allow for the mean GPC in the lowest bin possibly being reduced to an even lower market price than the three bin model allowed.

Sensitivity Analysis

Several factors were considered in the costs and revenue increases due to segregation of GPC in the partial budget analysis. Costs that may either vary in time or from user to user or with land in production, sensor cost, segregator cost, truck cost, and interest rate. Some of these may be variable and others cannot be controlled, or at least not easily. Factors affecting income increases are the average GPC and its variance, the total yield, and the prices offered. Table 6 showed the dramatic effect that increasing grain price can have on added income and net return from segregation. Greatest profitability is associated with September 2010 when price differences between incremental changes in protein were largest compared to 21-yr average. September 2004 prices are also used to show the effect of a moderately high price step. However, land managers who are interested in grain segregation will generally consider these revenue affecting parameters as being uncontrollable.

Table 6 also shows one field that stands out from the others. Field 2 had very low protein because of abnormally high rainfall. Consequently, its GPC distribution straddled the floor price and a convex inflection point, which was ideal for profitable grain segregation. The variable costs for harvesting this field would have been much higher because the smaller front bin would have filled rapidly and required substantially more unloadings.

To demonstrate the effect of various combinations of total land in production and sensor cost on net return, a sensitivity analysis was conducted to show net return sensitivity using average 21-yr prices and an average marginal return of $1.83 Mg^{-1} from the 17 fields in which DNS wheat could be segregated. Positive returns are generated when sensor cost is ≤$10 000 and land in production is ≥1215 ha, or sensor cost is ≤$15 000 and land in production is ≥1620 ha (Table 7). Grain segregation would be more profitable if costs could be spread over more land though there is a practical limit to how large an area could be cut by a single segregator-equipped combine due to time considerations of harvest. Spreading cost over more land would be possible by increasing cropping intensity and using the sensor for more than one purpose. An example of the latter is using information from crop quality sensors and crop yield monitors for resolving spatial patterns in soil N fertility across fields and calculating fertility requirements in precision N management (Long et al., 2000).

Table 7. Net return sensitivity corresponding to increases and decreases in sensor cost, and area of land in production or total grain production based on average 21-yr (1994–2014) Portland prices for dark northern spring wheat and an average marginal return of $1.83 Mg^{-1} from segregation of grain in 17 fields in northern Montana.

Sensor cost	Area of land in production (ha)†				Total grain production (Mg)‡			
	608	810	1215	1620	500	1500	2500	3500
	$ ha^{-1}							
$5,000	−2.52	−0.87	0.79	1.61	−5.25	−2.24	0.77	3.78
$10,000	−3.82	−1.84	0.14	1.12	−6.55	−3.54	−0.53	2.48
$15,000	−5.12	−2.82	−0.51	0.64	−7.85	−4.84	−1.83	1.18
$30,000	−9.02	−5.74	−2.46	−0.82	−11.75	−8.74	−5.73	−2.72

† Average grain yield: 2.31 Mg ha^{-1}.

‡ Total land in production: 608 ha.

When examining the effect of total grain production vs. sensor cost, segregation is profitable when sensor cost is ≤$5000 and total production is ≥2500 Mg, or if sensor cost is ≤$15 000 and total production is ≥3500 Mg (Table 7). Such an observation suggests that segregation might be more profitable should sensor costs decrease in the future or grain yields increase. The inverse relationship between GPC and yield complicates the effect of yield on returns. However, marginal returns from segregation are more dependent on the distance from a price step rather than the absolute GPC value. In addition, mean grain yield was 2.31 Mg ha^{-1} across the 17 fields. Yields of 2 Mg ha^{-1} or more are shown to generate positive net returns for land in production of 1215 ha or more and yields of 3 Mg ha^{-1} for land in production of 810 ha or more (Table 8). Therefore, grain yield per hectare has a large effect on profitability since the segregation benefit is paid by grain mass and fixed costs are spread over the land in production.

As always in economics, available capital will influence profitability. On a farm in which an extra truck used for other purposes is available, or that loans were not needed, grain segregation might be more profitable by reducing those costs. For instance, fixed costs could be brought to $3.88 ha^{-1} with a $5000 sensor, an existing available truck, and a 5% interest loan spread over 810 ha of land in production. A profit of $1.61 ha^{-1} would be generated if grain yield averaged 3 Mg ha^{-1}. The revenue increases not only depend on the weather and productivity of the field, but also on the mean and variance of GPC in terms of magnitude and proximity to a price step.

Complications of Grain Segregation

A limitation of on-combine grain segregation is the need to know $\overline{x}$ and s of GPC in a field prior to harvest. In this study, the number of GPC measurements obtained by hand sampling within a test strip would have likely been too small to adequately represent a field and thus the question remains whether a much larger volume of GPC measurements derived from optical sensing would work well for this purpose. Accuracy of the ProSpectra sensor is limited to a GPC of ± 5.0 g kg^{-1} in DNS wheat, which becomes problematic in precisely measuring these values and accurately computing the correct cutoff value.

Accuracy of the sensor also becomes a problem with price schedules that are incremented in intervals of 2.5 g of protein kg^{-1}. However, since spectra are averaged over 3 s, additional precision is gained by averaging. In a 40.5 ha field, this is 13,333 spectra. If 2% of the grain is going into the segregation bin, this would be 267 measurements, which would reduce the error of the mean to 0.31 g kg^{-1} (5 g kg^{-1} ÷ $\sqrt{267}$ = 0.31). The precision of the grain in the bulk tank would be even better. More significant than the precision of the on-combine sensor is the precision of the instrument used to establish dollar value of grain at the point of delivery. While this will be a more precise benchtop instrument, the luxury of repeated measurements will not be provided. A reproducibility of 0.25 g kg^{-1} could make grain segregation infeasible even if a grower has more precisely known protein values.

Another complication is that the calculator assumes a normal distribution of GPC for user specified $\overline{x}$ and s. Consequently, the cutoff value that is calculated for segregating grain into two lots assumes that the GPC values in a field also will have a normal distribution. Illustrated in Fig. 2A is the normal distribution of GPC (solid black line) based on the user specified $\overline{x}$ and s in field 15 vs. the post-harvest distribution of GPC (gray filled area), which has a longer tail in the low protein range and a steeper

Table 8. Net return sensitivity corresponding to increases and decreases in land in production and grain yield based on $5000 grain protein sensor cost, average 21-yr (1994–2014) Portland prices for dark northern spring wheat, and an average marginal return of $1.83 Mg^{-1} from segregation of grain in 17 fields in northern Montana.

Land in production	Grain yield, Mg ha^{-1}				
	1	2	3	4	5
ha	$ ha^{-1}				
405	–8.24	–6.41	–4.58	–2.75	–0.92
608	–4.93	–3.10	–1.27	0.56	2.39
810	–3.28	–1.45	0.38	2.21	4.04
1215	–1.62	0.21	2.04	3.87	5.70
1620	–0.80	1.03	2.86	4.69	6.52

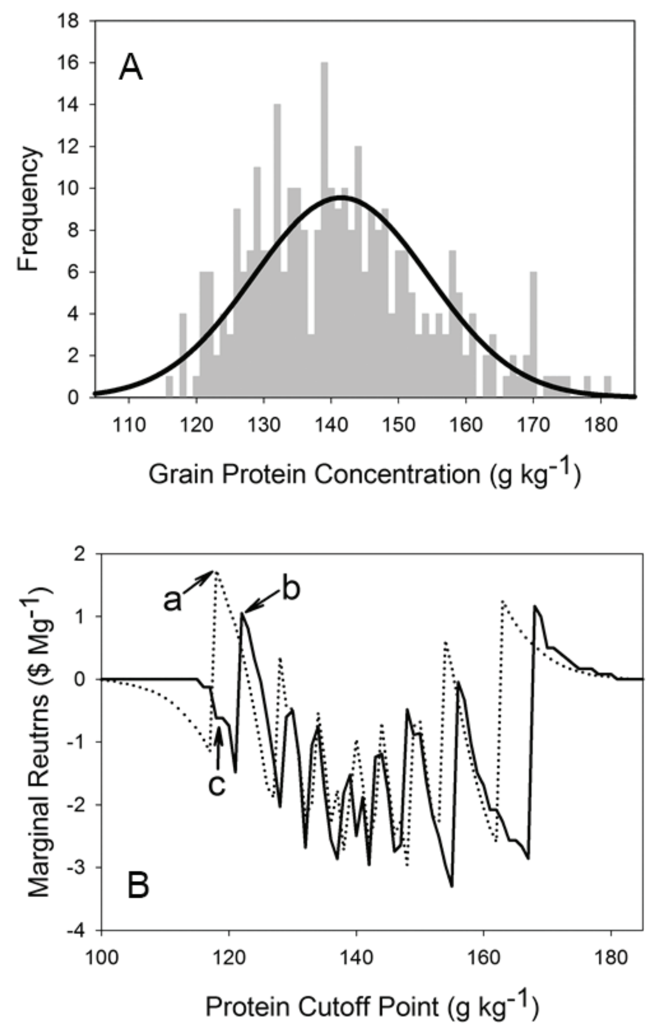

Fig. 2. (A) Frequency distribution of grain protein concentration in field 15 in comparison with normal distribution used by grain protein segregation calculator, and (B) plots of marginal return vs. cutoff value showing the effect of non-normality of grain protein distribution on the calculation of the cutoff value for grain segregation. Point “a” is the optimum cutoff predicted by the segregation calculator, point “b” is the cutoff value derived from the distribution of real data, and point “c” is the marginal value returned if point “a” was used for segregation.

Table 9. Return from grain segregation predicted from normally distributed protein data vs. actual return when the cutoff value predicted from normally distributed data is applied to real non-normal data and maximum attainable return if cutoff value were optimized from the real distribution.

Site no.	Return		
	Predicted	Maximum attainable	Actual
	$ Mg^{-1}		
1	3.47	3.74	2.38
2	5.43	5.71	4.67
3	0.51	0.59	0.09
4	2.66	2.25	–1.03
5	2.79	2.75	2.19
6	0.02	0.00	–3.03
7	0.17	0.17	0.08
8	1.02	0.94	0.64
9	0.43	0.40	0.40
10	2.35	2.23	–1.39
11	0.00	0.00	0.00
12	3.25	3.10	3.10
13	0.00	0.00	0.00
14	2.89	2.85	2.71
15	1.74	1.16	–0.62
16	0.00	0.00	0.00
17	1.43	0.96	0.96
18	2.43	2.03	0.52
19	0.00	0.00	0.00
20	2.26	1.83	1.70
21	0.05	0.06	0.01
Average	1.57	1.47	0.64

cutoff in the high range. If one were to use the optimum cutoff value predicted by the segregation calculator (Point a on dotted line in Fig. 2B), it would not precisely line up with the optimum value produced by the distribution of the real data (Point b on solid line) and produce a loss (Point c on solid line).

Table 9 shows the profit predicted by the segregation calculator using the mean and standard deviation of the field and how that revenue gain would have been negatively affected by the actual distribution using a cutoff value to the nearest 1 g kg^{-1} (0.1%). In the nine fields where the predicted gain in revenue was >$2 Mg^{-1} (mean = $3.06 Mg^{-1}), the actual gain in revenue averaged ≤$1.65 Mg^{-1} with two of these fields showing a loss. Sometimes potential gain is lost due to slight misalignment of the estimated cutoff value with the actual distribution. In fields with a positive skew, this misalignment can turn a potential profit to a loss as shown with fields 6, 10, and 15 (see Fig. 2). Clearly, non-normal distributions will play havoc with attempts to segregate grain by protein concentration. On the other hand, the marginal return would have still been positive had the actual GPC cutoff value been increased by a small amount. The one exception was field 4, which had an abnormal number of samples between 123 and 124 g kg^{-1}, this required a block of 2.6% of the total grain to be segregated to one or the other bin. A possible solution to having to assume the GPC distribution in advance of harvest may be tracking the GPC and yield of each bin during harvest and adjusting the cutoff value as the mean protein value in each bin is known more and more precisely as the harvest progresses.

SUMMARY AND CONCLUSIONS

This study quantified the net returns per hectare from DNS fields in a 50:50 wheat–fallow rotation in northern Montana when the conventional harvesting system is replaced with one that allows for segregation by GPC on the combine. Despite a shift in the northern Plains to grain carts and semi-trailer trucks to move the harvest from field to storage, a rigid, single axle truck was the basis for hauling the segregated grain. The concepts with regard to variance in GPC and profitability still apply to both. Four of 21 fields showed no potential for revenue gain and would never be profitable. Segregation increased the dollar value of each Mg of grain in the 17 remaining fields. However, partial budget analysis based on average 21-yr grain prices indicated that the increased income would not offset the increased costs of equipment such that net returns per hectare were smaller than that received from conventional harvesting. The increase in grain value from segregation could sometimes offset the costs, particularly in 2004 and 2010 when the price differential for DNS wheat was greater than in other years of the 21-yr period. Sensitivity analyses showed grain segregation to be profitable in years of large differences between price steps and above average grain yields, and if costs could be spread over more land in production. Grain segregation is a technique that might be further refined for benefit to the producer, but requires large investment in sensing equipment and the ability to regulate the GPC of a bin within a fraction of a percent, unless the mean GPC straddles a floor price. Prices of DNS wheat have been more volatile over the past 5 yr with four of the five highest price steps occurring since 2009. We do not know if this is a trend that would make grain segregation more profitable in future years.

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