Baling Straw for Ethanol Production: The Long-Term Implications on Soil Quality and Productivity

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INTRODUCTION

When one considers agricultural production on a global basis, greater than 50% of the production is crop residues (Smil 1999). For many, this is viewed as low cost and readily available materials that can easily be diverted to the production of fuels, chemicals and materials (Lynd et al. 1999). With recent advances in enzyme and bio-processing technology, more attention is being focused on the use of crop residues as the preferred feedstock for ethanol production (Carolan et al. 2007; Lynd et al. 2005). Energy life cycle analyses comparing grain-based ethanol to cellulose-based ethanol favors cellulose over grain (Sheehan et al. 2004; Main et al. 2007). However, crop residues should not be viewed as simply a waste or benign product because of its critical role in sustaining soil organic matter (Paustian et al. 1997) and the importance of soil organic matter for the global carbon cycle (Flach et al. 1997). The importance of soil organic matter on soil physical, chemical and biological properties is very well documented (Stevenson 1972).

Plant residues are the major sources of carbon input into terrestrial ecosystems with animal manures representing a secondary source although indirectly derived from plant materials. The rate of carbon input is the most important factor in determining how much carbon can be maintained or increased in the soil (Paustian et al. 1997). On the Canadian prairies, the carbon input into agricultural soils is directly related to the amount of crop residues produced and returned to the soil. Crop residue production is a function of the intensity of cropping (frequency of fallow vs continuous cropping), rates of inorganic fertilizers used (mainly nitrogen and phosphorus), organic amendments, conservation tillage (promotes water conservation and more crop growth), use of forages and grain legumes in the rotation, soil texture, inherent fertility of the soil and climatic conditions (Lafond et al. 1996; Campbell et al. 1997; Campbell and Zentner, 1997; Janzen et al. 1997; Juma et al 1997).

Sustaining industries based on crop residues as their basic feedstock has large implications on the long-term productivity of prairie soils. In the past, crop residues were removed intermittently for use as fodder or bedding in livestock operations or burned during years of high production to ease problems with primary tillage operations and/or seeding.

Results from long-term studies where crop residues were removed through burning or baling, provide important clues as to the impact on soil quality and crop production. Research at Indian Head, SK in the thin-black soil zone showed no effects of straw removal with baling on spring wheat grain yields and on soil organic carbon and nitrogen after 30 years (Campbell et al. 1991) and after 40 years (Campbell et al. 2001). Research on a Dark Gray soil in Northern Alberta also showed no effect of yearly straw removal on soil organic carbon and microbial biomass (Soon 1998) or nutrient uptake and grain yields after 10 years (Soon 1999). In an 11-yr study with continuous barley conducted on a Gray Luvisol and a Black Chernozem in north central Alberta, Nyborg et al. (1995) found no significant effect of straw removal on soil organic C for the Gray soil, but significantly lower soil C (0- to 15-cm depth) in the Black. In an 8-yr study on a Gray Luvisol in northeastern Saskatchewan, Malhi and Lemke (2007) found no significant difference in soil organic carbon or nitrogen levels for treatments with crop residues removed or retained. However, in the final years of the study crop yields and light fraction C levels (0-15 cm soil depth) were lower on treatments where residues had been removed, indicating a negative impact on the long-term sustainability of those treatments. Other shorter term research under irrigation showed no impact of straw removal on grain yield and nitrogen uptake after six years but caution was expressed as to the long-term impact on soil nitrogen reserves (Carefoot and Janzen 1997).

A twenty five year study at Melfort, SK in the Black soil zone comparing spring burning with various fall tillage operations showed no adverse effects of burning on spring wheat grain yields and grain protein or soil organic carbon (Nuttall et al. 1986). The percent soil carbon and nitrogen was 5.8 and 0.55, respectively at the start of the study suggesting very fertile soils possibly explaining the lack of an effect on grain yields, even after twenty five years. Also, given that the study was in continuous wheat production, the burn treatments may also have had a sanitizing effect for stubble born diseases favoring subsequent grain yields. Other studies in Western Canada have also confirmed the lack of a straw burning effect on grain yields but reductions in bacterial populations and soil respiration were noted reflecting changes in soil biological activity (Biederbeck et al. 1980). Studies in Oregon have confirmed that long-term continued removal of crop residues through straw burning (~50 years) will lead to reductions in soil organic carbon and nitrogen and overall biological activity (Rasmussen and Parton 1994). It would appear that straw removal through baling is less destructive on the soil than burning and industrial opportunities may be possible with crop residues, but not without great caution.

In order to explain the near non-existent changes in soil organic carbon and nitrogen with the continual removal of crop residues through baling, the current hypothesis is that roots are contributing more carbon to the soil and the soil organic matter pool than above-ground crop residues (Campbell 1991). It has been estimated that carbon input into the soil from corn roots and from rhizodeposition was 1.7 – 1.8 times the carbon input from above-ground residues (Wilts et al. 2004). We postulate that the amount of crop residues removed through the actual baling operation is much less than 66% as suggested by Campbell et al. (1991) and when combined with the previous hypothesis provides further explanations as to why straw removal through baling is having very little long-term effects on soil organic carbon and nitrogen and grain yields (Campbell et al. 1991).

The objectives of this study are to firstly, quantify the amounts of crop residues removed through baling using three different spring wheat grain harvesting systems and secondly, to measure the impact of straw removal through baling after 50 years on spring wheat grain yields, grain protein, soil organic carbon and nitrogen using the Indian Head Long-Term Crop Rotations of which the last 18 years have been under no-till.

MATERIALS AND METHODS

Experiment # 1: Quantifying crop residue removal with baling.

Site description: This study involved quantifying the amount of above ground biomass other than grain that is removed through the baling operation when using different harvest management systems over four growing seasons (2002-2005). The site was located at the Agriculture and Agri-Food Canada Research Farm at Indian Head, Saskatchewan, Canada (Lat. 50º 32' N, Long. 103º 39' W). The soil type was an Indian Head heavy clay, a Rego Black Chernozem (Udic Haploboroll) situated in the thin Black soil zone.

Study Description: The study consisted of comparing three different harvest management systems. The first system consisted of swathing (4.27m width), then harvesting with straw dropped on the ground and then baling. The second system consisted of straight harvesting with 4.57 m straight table with straw dropped on the ground followed by baling. The third system involved harvesting with a 2.44 m Shelbourne-Reynolds^{tm} stripper header (Anonymous 2008a), followed by swathing and then baling. A New Holland^{tm} square baler was used for all three approaches. The baled straw was weighed separately for each plot and a sub-sample kept from each plot to determine moisture content of the straw. The samples were weighed and then placed at 60^{o}C for 48 hours and then weighed again. The actual weights of baled straw were then corrected to 0% moisture. All harvest management systems utilized a 1964 Massey 300^{tm} combine equipped with a conventional threshing cylinder and a Redekop^{tm} chaff collector (Anonymous 2008b). The grain yields were corrected to 14% moisture content. The chaff collector collected all the material from the top sieve of the combine and transferred the material via a blower to a partially covered wagon equipped with a load cell for measurement of chaff yield. A sub-sample of chaff from the wagon was taken to determine the proportion of chaff, straw and grain in the chaff sample. The weights of grain, straw and chaff are reported as kg ha^{-1}. The entire plots were harvested and baled for each treatment and replicate for all variables collected for the field samples. A randomized complete block design with four replicates was used in all years.

Prior to the application of the harvest management treatments, six – one meter row samples of total above-ground biomass were randomly collected from each plot and bulked. The samples were dried at 60^{o}C for 48 hours and weighed for determination of total above ground biomass. The bulked hand samples from each plot were then processed individually using a Wintersteiger^{tm} plot combine and the weight of grain, straw and chaff were then individually determined for each combination of treatment and replicate and reported as kg ha^{-1}.

The actual amount of crop residues removed from each plot through the baling operation relative to total above ground biomass other than grain was calculated using two methods:

Method 1: The first method involved determining the ratio of the weight of crop residues removed through baling to the weight of straw determined from collected hand samples where grain, straw and chaff weights were determined i.e. (FS straw weight / HS straw + HS chaff weights) *100 where FS refers field baled samples and HS to hand samples.

Method 2: The second method involved two steps. The first step determined the ratio of the weights of straw and chaff to grain from the hand samples and multiplying that ratio with plot grain yields to obtain an estimate of above ground matter other than grain for each plot i.e. [(HS straw +HS chaff weights)/HS grain weights] * 100 *FS plot grain yields. The second step involved taking the ratio of the weights of baled straw to the value obtained in part 1. The value obtained from the second step provided another estimate of the proportion of straw removed with baling relative to the total above ground biomass other than grain. Method 2 allowed us to reduce the effects of sampling error with the hand samples.

Details of the other pertinent agronomic information for each year are provided in Table 1. Management of weeds was done using recommended products and rates and the choice of products was dependent on the weeds present.

Experiment #2: Assessment of the long-term impact of residue removal through baling on crop production and soil organic carbon and nitrogen.

Site Description: The assessment of the impact of straw removal on spring wheat grain yields was done using the Indian Head Long-Term Crop Rotations initiated in 1958 on a Rego Black Chernozem (Udic Haploboroll) located at Indian Head, SK (Lat. 50º 32' N, Long. 103º 39' W). Details about the nine spring wheat based crop rotations have been provided elsewhere (Zentner et al. 1987; Campbell et al. 1991). For the purpose of this paper, we are interested in only three of the nine crop rotations and for the years 1988-2007. The impact of straw removal on soil organic carbon and nitrogen and grain yields for the period 1958-1987 was previously reported by Campbell et al. 1991. We are interested in exploring what changes may have occurred since 1987 given that the plots were converted to no-till management in 1991.

Study Description: The three rotations of interest were all fallow-spring wheat-spring wheat (F-W-W) but with some important differences between the three. The first one (a) was not fertilized with straw retained. The second one (b) was fertilized with straw retained and the third one (c) was also fertilized but the straw was baled every year except during the fallow year. All phases of the rotation were present every year. The plot design was a randomized complete block with four replicates. Up till 1990, the rotations were managed by a conventional tillage system involving one fall and one spring pre-seeding tillage operation. More tillage operations were used during the fallow period. The plots were seeded with a double disc press drill on 15 cm spacing and the phosphorus fertilizer placed with the seed. From 1991 onwards, the plots have been managed using a no-till system and the fallow phase managed as a chemical fallow involving only herbicides to control weeds. The plots were seeded with a high clearance hoe press-drill on 20 cm spacing with the phosphorus fertilizer placed with the seed and the fertilizer nitrogen mid-row banded between every second row from 1991-1994. From 1995 onwards, the plots were seeded with an air drill on 30.48 cm spacing and all fertilizer nitrogen and phosphorus placed 25 mm to the side and 50 mm below the seed. The average seeding date for the reported period was May 11th (range April 23rd – May 30th). Fertilizer N and P rates for the period 1988-1991 were determined using regional recommendations for spring wheat. From 1992 to present, the target N and P rate used was based on residual levels of soil nitrate in the 0-60 cm soil layer and residual PO4-P for the 0-15 cm soil layer using average growing season precipitation for the area and soil texture. The average annual rates of N and P and the range of rates used are provided in Table 2. The nitrogen and phosphorus fertilizer forms used were urea and mono-ammonium phosphate, respectively except for the years 1988-1990 where nitrogen fertilizer used was ammonium nitrate fertilizer applied in the spring prior to seeding as a broadcast application. Recommended products, applications and rates were used to control weeds and insects as they occurred.

Spring wheat grain yields as well as grain nitrogen and phosphorus removed from the plots were reported yearly but the grain nitrogen and phosphorus contents have only been determined since 2003.

Soil Organic Carbon and Nitrogen Determinations:

Three samples approximately equidistant running length wise were taken in the middle of each plot and the samples were bulked by depth for each plot for the three previously described crop rotations. The depth increments used were 0-7.62 cm and 7.62-15.24 cm. The diameter of the core used was 6.53 cm giving an area of 33.49 cm^2.The volume of each core for each depth increment was 255.2 cm^3. At each of the three sampling points, the surface crop residues and standing stubble were carefully removed over a 0.093 m^2 area and all soil removed from attached roots and the other residues. The crop residue samples were then bulked for the three samples. The soil and crop residue samples were taken on May 30th and 31st, 2005, July 6th, 2006 and June 20th, 2007. Determinations for three consecutive years allowed for all plots of the rotation to be sampled and quantified during the fallow year.

Upon collection, the soil and residue samples were dried at 80^{o}C for a minimum of 48 hours. The soil samples were weighed to determine soil bulk density and then ground using a 2mm screen. The bulk densities were used to report soil organic carbon and nitrogen on a mass basis (kg ha^{-1}). The dry weights of the surface crop residues present on the soil surface were weighed and their carbon and nitrogen contents reported as kg ha^{-1}. The soil samples in 2005 were ground before being weighed resulting in some soil losses resulting in inaccurate soil bulk densities. As a result, the soil bulk density value used for reporting soil organic carbon and nitrogen on a mass basis was based on the average of the 2006 and 2007 samplings for each depth increments and the same values used for all three years. The bulk densities used for the 0-7.62 and 7.62-15.24 cm depth increments were 1.31 and 1.30 g cm^{-3}, respectively. Campbell et al. (1991) used bulk densities of 0.95 and 1.22 g cm^{-3}, respectively for the same two depths of sampling and 1.05 and 1.40 g cm^{-3} for the 1997 samplings (Campbell et al. 2001).

Total carbon and nitrogen for the soil and crop residues were determined using a NA1500 NCS Analyzer, supplied by Carlo Erba Instruments, using the manufacturers suggested operational parameters and protocols. Organic Carbon is determined on the same equipment, using a new method for the automatic and selective determination of total organic carbon in sediments, soils, compost, particles in air, etc. by Marco Baccanti and Bruno Colombo (Carlo

Erba Instruments, Rodano (Milano), Italy). This method involves a pre-treatment of the sample with HCl in a silver capsule. The inorganic carbon present as carbonates is released as CO_2 while the soluble organic compounds remain in the liquid phase in the capsule. The container is then dried and total carbon and nitrogen determined using the elemental analyser.

Statistical Analysis:
Study #1: Data were analyzed with the PROC MIXED procedure of SAS (Littel et al. 1996). The effect of replicate and year were considered random in study #1 and #2, and the effects of harvest management treatments were considered fixed. Contrasts were used to make specific treatment comparisons. Treatment effects were declared significant at $P < 0.05$.

Study #2 Grain Yield and Grain Protein Content: Data were analyzed with the PROC MIXED procedure of SAS (Littel et al. 1996). The effect of replicate and year were considered random, and the effects of crop rotation and rotation phase (fallow vs stubble) were considered fixed. In addition to year as a random effect, the effect of year also was considered to be a time-related continuous variable completely cross-classified with the applied treatments for data from the long-term rotations (Loughin 2006)**.** This model configuration allowed for an assessment of random variation of treatment effects across years and linear deviations for treatment effects over time.

Measurements were repeated on the same experimental unit (plot) across years for the data analysis in study #2 involving grain yields and grain protein content from the Indian Head Long-term Rotations. Therefore different covariance structures were employed with the repeated statement of PROC MIXED (Littel et al. 1996) to determine if model fit could be improved. A compound symmetry (split-plot across time analysis) and first-order autoregressive (correlation between year's decreases as the number of years between measurements increases) were among the covariance structures tested. However, the corrected Akaike's information model fit criterion (AICC) indicated that there was no advantage to modeling repeated measurements.

A combination of variance estimates and *p-values* were used to determine the importance of the year and year by treatment random effects. Contrasts were used to make specific treatment comparisons at the same time periods that treatment means were estimated. Treatment effects were declared significant at $P < 0.05$ for all analyses.

Study #2 Soil organic carbon and nitrogen, residue cover and residue carbon and nitrogen: The effect of replicate was considered random and the effect of crop rotation was considered fixed. Contrasts were used to make specific comparisons among the three rotations and rotation effects were declared significant at $p < 0.05$ for all analyses.

RESULTS AND DISCUSSION

Experiment # 1: Quantifying crop residue removal with baling.

The analysis of variance for each variable measured is provided in Table 3. A treatment effect was only observed for chaff and straw weights collected from the field samples. One would not expect treatment differences for the hand samples since the harvest management systems treatment had not been imposed when the hand samples were taken. The hand samples were taken to estimate as precisely as possible how much straw was actually produced other than grain and chaff in order to calculate straw removal through the baling operation as a function of harvesting system and to also uncover any unexpected spatial variability among treatments not accounted for by replication. A year effect was observed for all the variables measured which is expected due to differences in grain yield as a function of year to year variability in climatic conditions. A year by treatment interaction was observed for chaff weights in the hand sample and the percentage of grain in the chaff samples collected from the field samples. There is no plausible explanation for this observed interaction other than possibly sampling error.

A summary of the means and results of the contrasts comparing treatments is provided in Table 4. The overall estimate of grain yield from the hand samples was 2823 kg ha^{-1} vs 2496 kg ha^{-1} for the field samples collected with the combine. The hand samples predicted overall actual grain yields to within +11.5%. The hand samples therefore provided a good estimate of the actual productivity of the plots and of actual straw and chaff production over the four years of the study. When the amount of straw removed through baling was determined relative to total above ground biomass other than grain, overall values of 29% (range 22-35%) were obtained for method #1 and 32% (range 26-47) for method #2 (Table 4). Straw removal with baling was greater with swathing (first system) and straight cutting (second system) than with the stripper header (third system). The lower recovery values with the stripper values may be partially an artifact of the recovery methodology used. The actual stripper header width was 2.44 m and the combined width of the tires on the combine was 0.86 m. This means that 35% of the area harvested was trampled. The plots were swath shortly after harvesting and the straw in the wheel tracks remained flat on the ground and uncut and therefore not picked up by the baler. We did adjust the area accordingly to take into consideration this effect. The weight of chaff from the field samples was greater for the stripper header than the other two harvesting systems. Stubble height was similar among all treatments.

Boyden et al. (2001), in a similar designed study using a harvest system of swath, harvest and bale approach reported values of 35-46% as the proportion of straw baled relative to total mass of above ground residues other than grain. They also showed that the amount of straw removed was not linear with stubble height. With 20 cm stubble heights, only 60% of the total straw was available for baling and only 47% with stubble heights of 30 cm. In our studies, the stubble height averaged 10 cm. In addition, Boyden et al (2001) showed that straw recovery was even less for a combine with a rotary threshing cylinder than for a combine with a conventional threshing cylinder, and that the moisture content of the straw at time of harvest influences the straw removal with baling. Under dry conditions, the removal of straw with baling will be less than under conditions of higher straw moisture content. Under Ontario growing conditions, Opaku and Vyn (1997) estimated straw removal with baling at between 50 and 57% from studies conducted over two growing season.

In this study, the proportion of total above ground residues other than grain was 55 % for chaff and 45% for straw. Collins et al (1970) reported values of 30% for chaff and 70% for straw while McClelland et al (1970) reported values of 33% and 67% respectively. In our study, the proportion of grain, straw and chaff determined in the hand samples was done mechanically with a plot combine while in the two previous cited studies the samples were separated by hand. This means that more straw would have ended up with the chaff in our study. This is supported by the high proportion of straw in the chaff taken from the field samples (Table 4). The weight of the straw in the chaff samples ranged from 25-29% of the total weight of chaff collected behind the combine. This is a further indication of the effects of mechanical harvesters on crop residues and how they influence the actual amount of straw that can be recovered with baling.

The study quantified the amount of above ground plant material other than grain that can be removed through the baling operation following different harvesting systems. The first method of calculation showed a range of 22-35% and the second method 26-40% which is much less than the 66% postulated by Campbell et al. (1991) but more than the 22% later postulated (Campbell et al. 2001). If industries are to be established around baled cereal crop residues as the primary feedstock, the area required to supply a plant will have to take into consideration the percentages estimated in this study. In the drier areas of the prairies, the positive benefits of tall stubble (30-35 cm) on crop production have been well established (Cutforth and McConkey 1997; Cutforth et al. 2002; Cutforth et al. 2006). Boyden et al (2001) estimated that with 30 cm stubble heights, only 47% of the above-ground residues other that grain remained and given the calculated percentages from this study, the amount of residues removed with baling would be very low. If producers in the drier areas were to adopt the concept of tall stubble to capture the benefits of increased water conservation and water use efficiency, the land area required would have to be very large in order to meet the on-going needs of the plant for baled crop residues, not to mention the added transportation costs. Competition from the livestock industry for crop residues, especially in the drier areas, would also have to be factored in.

Experiment #2: Assessment of the long-term impact of crop residue removal through baling on soil organic carbon and nitrogen and spring wheat production.

A summary of the effects of straw removal on soil organic carbon and nitrogen and surface crop residue amounts, surface crop residue carbon and nitrogen at the soil surface is provided in Table 5. A rotation effect was observed for soil organic carbon and nitrogen in the 0-7.6 cm soil layer but not the 7.6-15.2 cm layer. The rotation where no fertilizer nitrogen or phosphorus has ever been added since 1958 (Rotation 5) showed lower soil organic carbon and nitrogen levels than the fertilized rotations (Rotations 6&7). There was no difference between the two fertilized rotations (Rotations 6 & 7) at either depth even though Rotation 7 had the straw baled every year during the fallow and stubble phase of spring wheat production for the last 50 years. Campbell et al (1991) observed no differences in soil organic carbon and nitrogen after 30 years using the same study and also after 40 years (Campbell et al. 2001).

The mass of crop residues present at the soil surface when the soil samples were collected for soil organic carbon and nitrogen determinations were highest for Rotation 6 (fertilized rotation with straw retained) and similar between Rotation 5 and 7 even though the residues were baled every cropping year in Rotation 7 (Table 5). The same observations were noted for the mass of carbon and nitrogen in the residues.

The analysis of variance for the effects of 50 years of straw removal on grain yield and grain protein content is provided in Table 6. No main effects or interactions were observed for grain protein but pre-planned contrasts for rotation showed some important differences under fallow and stubble cropping (Table 7). With grain yield, a year, rotation and phase effect as well as a rotation by phase, a time by phase and a year by rotation by phase interaction were noted (Table 6). The rotation effect is due to a fertilizer nitrogen and phosphorus effect. Rotation 5 is not fertilized while Rotations 6 and 7 are fertilized. The phase effect is due to expected yield differences between growing spring wheat on fallow versus on stubble. The rotation by phase interaction is due to differences in the magnitude of the yield difference between fertilized and unfertilized fallow versus stubble. A year effect is expected due to differences in climatic conditions and the year by rotation by phase interaction is due to climatic differences interacting with fertilizer use and differences in yield between fallow and stubble across years.

Grain yield and grain protein content were higher for the fertilized than the unfertilized rotations regardless of whether spring wheat was grown on fallow or stubble (Rotation 5 vs Rotation 6&7) (Table 7). Of interest is the lack of grain yield or grain protein difference between the two fertilized rotations (Rotation 6 & 7) under fallow or stubble cropping conditions even though Rotation 7 had the straw removed with a baler for the last 50 years.

Campbell et al. (1991) reported no yield differences after 30 years using the same study. No other studies were found where 50 years of straw removal through baling were measured for their effects on soil organic carbon and nitrogen and grain production. Shorter length studies often did not reveal any differences of straw removal on grain yields (Carefoot and Janzen 1997; Soon 1999), although yield differences were observed by Malhi and Lemke (2007) in the final years of their 8 year study. Their comparison was made on a four-year crop rotation with more residue removed annually than in our current study. Saffih-Hdadi and Mary (2008) estimated through modeling, assuming 60% of total above ground plant matter other than grain is removed one year out of two, that a reduction of between 2.5 – 10.9% of the initial soil organic carbon would be lost after 50 years. The effects were dependent on soil, climate and overall productivity and the size of the initial carbon pool. In this study, straw was removed two years out of three and there was no difference in soil organic carbon and nitrogen after 50 years but the amount of straw removed is postulated as being much less than 60%, based on the results from the first study.

The nitrogen and phosphorus removed with the grain for the period 2003-2007 is provided in Table 8 and the amount of fertilizer nitrogen and phosphorus added for that same period is provided in Table 9. During this period, the amount of fertilizer N added, when both the fallow and stubble phase are considered was much higher than the amount of nitrogen removed through the grain. The amount of phosphorus added as fertilizer was very similar to the amount of phosphorus removed in the grain (Table 8 & 9). It should be noted that the amount of nitrogen and phosphorus exported in the straw in Rotation 7 with the baling operation was not quantified and reflected in the reported values in Table 8. Campbell et al. (2007) stresses the importance of a positive nitrogen balance in order to increase soil organic carbon and nitrogen.

The lower than expected amount of straw removed through baling combined with the observation that roots may be contributing more to the soil organic carbon pool (Wilts et al 2004) helps shed light on the results of this study. Given the adoption of more diverse crop rotations as a result of increased crop diversity on the Canadian Prairies (Anonymous 2007), it is hypothesized that cereal crop residues, if used for industrial purposes, would be removed two years out of four, assuming a cereal – oilseed – cereal – pulse crop rotation. When combined with proper fertilizer management and no-till to avoid soil organic carbon losses from erosion, it may be feasible to harvest crop residues without adversely affecting long-term soil productivity.

CONCLUSION

The studies attempted to shed light on two questions. How much crop residue is removed with the baling operation and what is the long-term impact of straw removal on soil quality and productivity. The first study showed that depending on the harvesting system, only 26 – 40% of total above ground crop residues other than grain are removed with baling. The other study showed that 50 years of straw removal did not influence spring wheat grain yield and grain protein concentration and there was no measurable impact on soil organic carbon and nitrogen. The potential therefore exists to harvest cereal residues for industrial purposes from medium to heavy-textured soils on the Prairies without adversely affecting soil quality and productivity providing that proper soil and crop management practices are employed.

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Table 1. Pertinent agronomic information for the harvest management systems study with spring wheat from 2002-2005

Variable	2002	2003	2004	2005
Seeding Date	May 14	May 13	May 18	April 26
Cultivar	Prodigy	Prodigy	Prodigy	Prodigy
Seeding Rate (kg/ha)	134	134	134	134
Fertilizer N rate (kg/ha) & Form	85 Liquid UAN	112 Liquid UAN	89 Urea	75 Urea
Fertilizer P_2O_5 rate (kg/ha) using mono-ammonium phosphate	28	33	28	25
Pre-Seeding Herbicide-Product, Rate and Date	No pre-seeding burn-off	Glyphosate 440 g ai /ha May 13th	Glyphosate 440 g ai /ha May 8	Glyphosate 440 g ai /ha May 8
In-Crop Herbicides - Product, Rate and Date	Fenoxy-prop ethyl 92 g ai/ha Bromoxynil 280 g ai/ha MCPA 280 g ai/ha June 14	Tralkoxydim 200 g ai/ha Bromoxynil 280 g ai/ha MCPA 280 g ai/ha June 13	Fenoxy-prop ethyl 92 g ai/ha Bromoxynil 280 g ai/ha MCPA 280 g ai/ha June 9	Tralkoxydim 200 g ai/ha Bromoxynil 280 g ai/ha MCPA 280 g ai/ha June 13
Dry Matter Samples (6 x 1m row per plot)	August 29	August 21	September 2	August 8
Swathing	August 29	August 21	September 29	August 8
Harvest - Swathing Treatments	September 16	August 26	November 5	September 8
Harvest - Straight and Stripper Header Treatments	September 17	August 26	November 5	September 8
Baling straw	September 18	September 11	November 5	September 23
Weighing Bales	September 19	September 25	November 10	September 23
Plot Size m (width x length)	23 x 88	23 x 57	12 x 61	14 x 27

Table 2. Average annual rates and range of rates (kg ha^{-1}) used for nitrogen and phosphorus fertilizer for the period 1988-2007 under fallow and stubble cropping conditions for the long-term studies at Indian Head. Values in parenthesis represent the range of rates used during that period of time.

Rotation	**Fertilized**	**Straw Baled**	**Fallow**		**Stubble**	
			Nitrogen-N	**Phosphorus-P**	**Nitrogen-N**	**Phosphorus-P**
F-W-W	**No**	**No**	-	-	-	-
F-W-W	**Yes**	**No**	57 (0-112)	9 (0-13)	87 (50-122)	10 (0-13)
F-W-W	**Yes**	**Yes**	59 (0-112)	9 (0-13)	85 (50-112)	10 (0-13)

Table 3. Analysis of variance for the effects of harvest management systems on grain yield, straw and chaff removal for field and hand samples for the period 2002-2005.

Effects	**Hand Samples**			**Field Samples**			**Stubble Height**	**Percentage of each in Chaff Samples**			**Straw Removed with baling**	
	Grain	**Chaff**	**Straw**	**Grain**	**Chaff**	**Straw**		**Grain**	**Chaff**	**Straw**	**Method 1**	**Method 2**
	p-values											
Treatment	0.913	0.571	0.684	0.111	**0.054**	**0.047**	0.202	0.726	0.060	0.082	**0.020**	**0.017**
	***Variance estimate* †**											
Year	669385 **	2690652 **	1779468 **	603147 **	315215 **	1334053 **	36.3**	0**	64**	58**	13**	39.5**
Year*Trt	16295	0 **	54091	2493	15893	177972	4.9	0**	2	2	19.1	18.6
	***% total variance estimate*‡**											
Year*Trt	2	0	3	0	5	12	12	0	3	3	59	32

†The statistical significance of variance component are indicated as follows: '*' = 0.05 ≥ P value ≥ 0.01; and '**' = P value < 0.01.
‡The variance for a given effect, divided by the sum of the variance estimate for the effects associated with year, and multiplied by 100.

Table 4. Mean values for the various variables collected from the hand and field samples of the harvest management study. Each value represents the mean of sixteen observations i.e. four replicates over four years.

Harvest Management (#)	Hand Samples (kg ha^{-1})			Field Samples (kg ha^{-1})			Stubble Height cm	Percentage of each in Chaff Samples†			Straw Removed‡ with baling %	
	Grain	**Chaff**	**Straw**	**Grain**	**Chaff**	**Straw**		**Grain**	**Chaff**	**Straw**	**Method 1**	**Method 2**
Swathing (1)	2834	3465	2907	2460	1515	2373	9	4.2	70.9	24.9	35	40
Straight (2)	2792	3653	2944	2593	1562	1972	12	3.3	71.8	24.9	29	31
Stripper (3)	2843	3570	2743	2435	1802	1376	9	3.6	67.0	29.4	22	26
Mean	**2823**	**3563**	**2865**	**2496**	**1626**	**1907**	**10**	**3.7**	**69.9**	**26.4**	**29**	**32**
s.e.	**419**	**842**	**688**	**391**	**290**	**618**	**3**	**0.9**	**4.2**	**4.0**	**3.0**	**4.0**
Contrasts	***p-values***											
1 vs 3	ns**§**	ns	ns	ns	**0.021**	**0.024**	ns	ns	ns	ns	**0.013**	**0.018**
1 vs 2&3	ns	ns	ns	ns	**0.026**	**0.018**	ns	ns	ns	ns	**0.007**	**0.006**

†The proportion of grain, chaff and straw in the chaff samples collected from the chaff wagon during the harvesting of the plots with the commercial combine..

‡The percentage of straw removed through baling is the amount of straw baled as a proportion of total above ground dry matter other than grain calculated using two different methods.

§ ns refers to non-significant because p-values are >0.05.

Table 5. The effects of fertilizer and straw removal on soil organic carbon and nitrogen, surface crop residues, carbon and nitrogen content of the surface crop residues for a Fallow-Wheat-Wheat rotation from the Indian Head Long-Term Crop Rotations after 50 years.

Rotation (#)	Fertilizer	Straw Baled	Soil Organic Carbon kg ha^{-1}		
			0-7.6 cm	**7.6-15.2 cm**	**0-15.2 cm**
F-W-W (5)	**No**	**No**	20580	17583	38163
F-W-W (6)	**Yes**	**No**	23192	18244	41436
F-W-W (7)	**Yes**	**Yes**	22443	19498	41942
s.e.			**934**	**1710**	**2514**
Effects/Contrasts			***p*-values**		
Rotation			**0.030**	ns^{z}	**0.033**
Rotation 5 vs Rotation 6&7			**0.011**	ns	**0.010**
Rotation 6 vs Rotation 7			ns	ns	ns
Rotation (#)	**Fertilizer**	**Straw Baled**	**Soil Organic Nitrogen kg ha^{-1}**		
			0-7.6 cm	**7.62-15.2 cm**	**0-15.2cm**
F-W-W (5)	**No**	**No**	1988	1816	3804
F-W-W (6)	**Yes**	**No**	2229	1849	4078
F-W-W (7)	**Yes**	**Yes**	2154	1932	4086
s.e.			**79**	**152**	**223**
Effects/Contrasts			***p*-values**		
Rotation			**0.008**	ns	**0.040**
Rotation 5 vs Rotation 6&7			**0.003**	ns	**0.012**
Rotation 6 vs Rotation 7			ns	ns	ns
Rotation (#)	**Fertilizer**	**Straw Baled**	**kg ha^{-1}**		
			Surface Residues	**Residue Carbon Content**	**Residue Nitrogen Content**
F-W-W (5)	**No**	**No**	3052	859	23
F-W-W (6)	**Yes**	**No**	6611	1693	52
F-W-W (7)	**Yes**	**Yes**	2977	747	21
s.e.			**646**	**148**	**3**
Effects/Contrasts			***p*-values**		
Rotation			**0.001**	**<0.001**	**<0.001**
Rotation 5 vs Rotation 6&7			**0.054**	**0.065**	**0.003**
Rotation 6 vs Rotation 7			**0.001**	**<0.001**	**<0.001**

^{z} values followed by ns means that the p-values were >0.05 and therefore considered non significant.

Table 6. Analysis of variance for spring wheat grain yield (kg ha^{-1}) and grain protein (%) collected from the Indian Head Long-Term Crop Rotations. The analysis for grain yield is for the period 1988-2007 and the period 2003-2007 for grain protein.

Effect	**Grain Yield**	**Grain Protein**
	p-values	
Rotation	< 0.001	0.864
Phase (Fallow vs Stubble)	< 0.001	0.151
Rotation*Phase	0.014	0.968
Time	0.124	0.189
Time*Rotation	0.443	0.665
Time*Phase	0.045	0.171
Time*Rotation*Phase	0.428	0.977
	Variance Estimate†	
Year	257350**	1.12
Year*Rotation*Phase	89625**	0.24*
	Total Variance Estimate‡	
Year*Rotation*Phase	26	17

†The statistical significance of variance component are indicated as follows: '*' = 0.05 ≥ P value ≥ 0.01; and '**' = P value < 0.01.
‡The variance for a given effect, divided by the sum of the variance estimate for the effects associated with year, and multiplied by 100

Table 7. The effects of nitrogen fertilizer and straw removal on spring wheat grain yield (kg ha^{-1}) and grain protein (%) collected from the Indian Head Long-Term Crop Rotations. The grain yields reported are for the period 1988-2007 and grain protein for the period 2003-2007.

Rotation	**Fertilized**	**Straw Baled**	**Grain Yield (kg ha^{-1})**		**Grain Protein (%)**	
			Fallow	**Stubble**	**Fallow**	**Stubble**
F-W-W (5)	**No**	**No**	1437	701	13.8	13.4
F-W-W (6)	**Yes**	**No**	2533	2162	14.7	14.6
F-W-W (7)	**Yes**	**Yes**	2586	2259	15.0	14.8
s.e.			**149**		**0.5**	
Contrasts			***p*-values**			
Rot 5 vs Rot 6&7			<0.001		<0.001	
Rot 6 vs Rot 7			ns†		ns	
Fallow Phase: Rot 5 vs Rot 6&7			<0.001		0.004	
Fallow Phase: Rot 6 vs Rot 7			ns		ns	
Stubble Phase: Rot 5 vs Rot 6&7			<0.001		0.001	
Stubble Phase: Rot 6 vs Rot 7			ns		ns	

†values followed by ns means that the p-values were >0.05 and therefore considered not significant.

Table 8. The effects of nitrogen fertilizer and straw removal on the average yearly removal of nitrogen and phosphorus for the period 2003-2007 from the F-W-W spring wheat rotations of the Indian Head Long-Term Crop Rotations. The numbers in brackets are the standard errors of the means.

Rotation	**Fertilized**	**Straw Baled**	**N removed in Grain (kg ha^{-1})**		**P removed in Grain (kg ha^{-1})**	
			Fallow	**Stubble**	**Fallow**	**Stubble**
F-W-W (5)	**No**	**No**	37 (2.1)	16 (1.0)	6.4 (0.4)	3.2 (0.3)
F-W-W (6)	**Yes**	**No**	62 (2.9)	51 (1.9)	9.8 (0.5)	8.6 (0.4)
F-W-W (7)	**Yes**	**Yes**	65 (3.5)	55 (1.9)	10.1 (0.6)	9 (0.4)

Table 9. The average yearly amount of nitrogen and phosphorus fertilizer added to the fallow and stubble cropping phase of the F-W-W spring wheat rotation for the period 2003-2007 in the Indian Head Long-Term Crop Rotations. The numbers in brackets are the standard errors of the means.

Rotation	**Fertilized**	**Straw Baled**	**N Fertilizer Added (kg ha^{-1})**		**P Fertilizer Added (kg ha^{-1})**	
			Fallow	**Stubble**	**Fallow**	**Stubble**
F-W-W (5)	**No**	**No**	0	0	0	0
F-W-W (6)	**Yes**	**No**	62 (2.9)	86 (5.5)	9.2 (1.1)	9.2 (1.1)
F-W-W (7)	**Yes**	**Yes**	60 (4.8)	82 (4.3)	9.2 (1.1)	9.2 (1.1)