Sustainability **2015**, *7*, 8621-8634; doi:10.3390/su7078621

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Corn Stover Nutrient Removal Estimates for Central Iowa, USA

Douglas L. Karlen [1,*], John L. Kovar [1,†] and Stuart J. Birrell [2,†]

[1] National Laboratory for Agriculture and the Environment (NLAE), USDA-Agricultural Research Service, 2110 University Boulevard, Ames, IA 50011-3120, USA; E-Mail: John.Kovar@ars.usda.gov

[2] Department of Agricultural and Biosystems Engineering, Iowa State University, 2323 Elings Hall, Ames, IA 50011, USA; E-Mail: sbirrell@iastate.edu

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: Doug.Karlen@ars.usda.gov; Tel.: +1-515-294-3336; Fax: +1-515-294-8125.

Academic Editors: Susan Krumdieck and Deepak Pant

Received: 29 May 2015 / Accepted: 29 June 2015 / Published: 2 July 2015

Abstract: One of the most frequent producer-asked questions to those persons striving to secure sustainable corn (*Zea mays* L.) stover feedstock supplies for Iowa's new bioenergy conversion or other bio-product facilities is "what quantity of nutrients will be removed if I harvest my stover?" Our objective is to summarize six years of field research from central Iowa, U.S.A. where more than 600, 1.5 m^2 samples were collected by hand and divided into four plant fractions: vegetative material from the ear shank upward (top), vegetative material from approximately 10 cm above the soil surface to just below the ear (bottom), cobs, and grain. Another 400 stover samples, representing the vegetative material collected directly from a single-pass combine harvesting system or from stover bales were also collected and analyzed. All samples were dried, ground, and analyzed to determine C, N, P, K, Ca, Mg, S, Al, B, Cu, Fe, Mn, and Zn concentrations. Mean concentration and dry matter estimates for each sample were used to calculate nutrient removal and estimate fertilizer replacement costs which averaged \$25.06, \$20.04, \$16.62, \$19.40, and \$27.41 Mg^{-1} for top, bottom, cob, stover, and grain fractions, respectively. We then used the plant fraction estimates to compare various stover harvest scenarios and provide an answer to the producer question posed above.

Keywords: plant nutrients; source carbon; fertilizer replacement costs; feedstock quality; EZ™ bales

1. Introduction

Corn stover is the above-ground, non-grain plant material that remains following grain harvest. To support emerging cellulosic bioenergy operations in the U.S.A., such as the POET-DSM Project Liberty near Emmetsburg, Iowa, and DuPont Cellulosic Ethanol near Nevada, Iowa, stover was identified as the primary initial feedstock [1] because of the vast area upon which the crop is grown. For example, from 2004 through 2013, corn was planted on an average of 13.5 million acres in Iowa and produced an average of 2.2 billion bushels of grain each year [2]. However, before assumptions are made that corn stover is abundantly available and simply waiting to be harvested, it is important to recognize that it already provides many important ecosystem services that include: (i) protecting surface soil from raindrop impact and wind erosion; (ii) reducing runoff and soil erosion; (iii) providing a renewable source of carbon for maintaining soil organic matter (SOM); (iv) recycling essential plant nutrients; and (v) reducing evaporative loss of soil water [3], which can be crucial for subsequent crop production as annual weather patterns become more variable. Fortunately, during the past 25 years, corn grain yields and the resultant quantity of stover have increased significantly [4] and in some high-yielding areas, stover management has become a concern because of increased cost [5] and its potential negative effects on subsequent crops. Therefore, to ensure corn stover and other crop residues, such as wheat (*Triticum aestivum*) or rice (*Oryza sativa*), are being managed in a sustainable manner, it is important to balance both economic drivers put forth by biorefineries and environmental constraints [6] within every field or potential sub-field harvest area.

Farmers have harvested corn stover for many years as animal feed and bedding, but elemental composition was rarely measured since most nutrients were cycled back to the fields through manure. Interest in quantifying stover nutrient removal began following the 1970’s oil crisis when cellulosic feedstocks were first evaluated for bioenergy production [7], because those operations were destined to increase export of plant nutrients from individual fields. Furthermore, though nutrient composition for corn silage was well known, stover studies showed significant differences in nutrient concentrations because of a later harvest and separation of grain and vegetative plant fractions [8]. Estimating stover nutrient removal is also complicated by potential translocation or leaching of soluble elements such as K from upper plant parts during the period between physiological maturity and combine harvest. Those challenges, plus the wide variation associated with stover harvest operations remain, so even though some stover nutrient composition data are available [4,9–12], estimates are often quite variable and may not be useful for making operational decisions regarding whether or not to harvest and market a portion of this resource from specific fields.

Several authors [1,13–15] have suggested that harvesting stover can be a “win-win” management practice, often stating that stover is an underutilized resource that could be used as a feedstock and simultaneously reduce residue management costs that currently range from \$49–74 ha^{-1} [5]. However, the decision to harvest corn stover for bioenergy or any other use is not that simple, because stover (plant residue) also supports many ecosystem services [6,16,17] and its harvest will increase annual nutrient removal [18,19] when compared to harvesting only the grain.

To support emerging U.S. cellulosic bioenergy industries, several field research studies were conducted by the USDA Agricultural Research Service (ARS) Resilient Economic Agricultural Practices (REAP) team [formerly known as the Renewable Energy Assessment Project (REAP) team] and their university partners as part of the Department of Energy (DOE) Bioenergy Technologies Office's Regional Feedstock Partnership Corn Stover Team and USDA-National Institute for Food and Agriculture (NIFA) Sun Grant Initiative. Studies at 36 sites in seven states produced 239 site-years of data [8] that were summarized to provide an overview of crop yield and nutrient removal impacts of stover harvest. Our objective for this article is to provide more detailed nutrient removal information, using 605 site-years of data for various hand-sampled plant fractions and 400 site-years of machine-harvested stover samples collected in central Iowa, U.S.A. between 2008 and 2013.

2. Methods and Materials

Whole-plant corn samples were collected between physiologic maturity and combine harvest from 1.5 m^2 areas within numerous field research plots in Boone and Palo Alto Counties of Iowa. The predominant soils at both locations are classified as being within the Clarion-Nicollet-Webster soil association. The Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls) consists of very deep, moderately well-drained soils on uplands. Clarion soils formed in glacial till and have slopes ranging from 1% to 9%. The Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) consists of very deep, somewhat poorly drained soils that formed in calcareous loamy glacial till on till plains and moraines. Slopes range from 0% to 5%. The Webster series (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) consists of very deep, poorly drained, moderately permeable soils formed in glacial till or local alluvium derived from till on uplands. Slopes range from 0% to 3%. Mean annual air temperature for all three series ranges from 8 to 9 °C (47 to 48 °F), and mean annual precipitation ranges from 660 to 760 mm (28 to 30 inches). Plant samples were separated into four components: (1) vegetative material from the ear shank upward (top); (2) vegetative material from approximately 10 cm above the soil surface to just below the ear (bottom); (3) cobs; and (4) grain. Weights for the non-grain components were summed to estimate the above-ground biomass associated with each plant fraction. Oven dry (0 $g \cdot kg^{-1}$ water content) grain weights were divided by the sum of grain plus dry non-grain plant fractions to estimate the harvest index (HI). Stover samples were generally collected with a John Deere 9750 STS (Mention of a specific product or proprietary name is for reference only and does not constitute preference or endorsement by Iowa State University or the USDA-Agricultural Research Service (ARS) combine [4], although a few samples were collected using an AgCo combine with attached baler, or by collecting multiple cores from stover bales made after shredding, raking, and baling stover material remaining after grain harvest [11]. All plant samples were dried at 70 °C to a constant weight to determine total above-ground biomass production. Plant samples were subsequently ground to pass a 0.5 mm screen. One sub-sample was analyzed by dry combustion to determine total C and N concentrations, while another was digested with sulfuric acid and hydrogen peroxide in a commercial laboratory before analyzing the material to determine P, K, Ca, Mg, Na, S, Al, B, Cu, Fe, Mn, and Zn concentrations using an inductively-coupled plasma spectrophotometer (ICP).

Mean nutrient concentration values for the stover, three vegetative plant fractions, and grain were determined using Proc Means within SAS Version 9.3 software. Fertilizer replacement values were calculated for the various plant fractions based on May 2015 price data [20].

3. Results and Discussion

3.1. Yields, Nutrient Concentrations and Potential Removal

Corn grain yield at a water content of 155 g·kg^{-1} averaged 10,370 kg·ha^{-1} for the 607 sampling sites. This was identical to the 2008–2013 average grain yield for Iowa (165 bu·ac^{-1}) in the National Agricultural Statistics Service (NASS) database [2], confirming that our sampling was representative of the crop in this production area. The grain yield was also similar to the 6-year average reported by Avila-Segura [12], which means the two data sets are suitable for comparison. The harvest index (HI) averaged 0.50 ± 0.06 which is within the typical range (0.48 to 0.53) for corn [21]. Cobs accounted for 17.4% of the average above-ground, non-grain biomass which is also consistent with values reported in literature [12,22]. The amount of dry (0 g·kg^{-1} water content) vegetative plant material from the ear shank upward (tops), averaged 3390 kg·ha^{-1} (±887 kg·ha^{-1}), while the dry matter content from a stubble height of ~10 cm to just below the ear averaged 4176 kg·ha^{-1} (±1076 kg·ha^{-1}).

Mean concentration and standard deviation values for C, N, P, K, Ca, Mg, S, Na, Al, B, Cu, Fe, Mn, and Zn concentrations and estimated removal per hectare for top, bottom, cob, and grain samples are presented in Table 1. For those interested in computing carbon balances and the potential for sustaining or increasing SOM by returning the corn residue rather than harvesting it, the hand-collected top, bottom, and cob fractions had C concentrations of 431, 438, and 454 g·kg^{-1}, respectively, and therefore would have returned an average of 1454, 1828, or 725 kg·ha^{-1} of source carbon to the soil for subsequent mineralization and partial conversion to SOM. The machine-collected stover samples, which integrated plant material from a much larger area, had an average C concentration of 445 g·kg^{-1}. This suggests the stover samples contained more cob material than other plant parts, but we did not attempt to identify anatomical sources of the vegetative material contained within the stover samples. Harvesting all of the machine-collected stover would have removed an average of 1921 kg·ha^{-1} or 48% of the source carbon associated with non-grain biomass. Similar calculations for the grain fraction show that it removed an average of 3884 kg·ha^{-1} of C (Table 2) or 49% of the total above-ground C.

Table 1. Nutrient concentration † and calculated removal per hectare for three hand-sampled plant fractions from 607 sampling sites and machine-collected corn stover from 400 sites in central Iowa, U.S.A. from 2008 through 2013.

	Ear Shank and Above (Top)				Below Ear Shank (Bottom)			
Nutrient	**Mean**	**Standard Deviation**	**Removal**	**Percent of Total ‡**	**Mean**	**Standard Deviation**	**Removal**	**Percent of Total ‡**
		$g \cdot kg^{-1}$	$kg \cdot ha^{-1}$			$g \cdot kg^{-1}$	$kg \cdot ha^{-1}$	
Carbon	431	7.5	1454	18	438	10.2	1828	23
Nitrogen	7.96	1.38	28	16	6.82	1.37	29	17
Phosphorus	0.88	0.46	3	10	0.65	0.41	3	10
Potassium	9.34	2.68	32	28	9.41	3.41	40	35
Calcium	3.74	1.05	13	38	3.54	0.86	15	44
Magnesium	2.42	1.21	8	31	2.22	0.76	9	35
Sulfur	0.72	0.19	2	16	0.49	0.12	2	16
Sodium	0.10	0.02	0.3	17	0.10	0.01	0.4	22
		$\mu g \cdot g^{-1}$	$g \cdot ha^{-1}$			$\mu g \cdot g^{-1}$	$g \cdot ha^{-1}$	
Aluminum	49	70	150	19	120	96	524	68
Boron	8.7	2.1	26	28	6.5	2.0	27	29
Copper	7.0	2.4	21	34	4.1	1.5	17	27
Iron	107	147	337	23	205	253	852	57
Manganese	39	16	117	43	30	13	124	45
Zinc	14	8	50	20	9	11	38	15

Table 1. *Cont.*

	Cobs				Machine Harvested Stover			
Nutrient	**Mean**	**Standard Deviation**	**Removal**	**Percent of Total**	**Mean**	**Standard Deviation**	**Removal**	**Percent of Total**
		$g \cdot kg^{-1}$	$kg \cdot ha^{-1}$			$g \cdot kg^{-1}$	$kg \cdot ha^{-1}$	
Carbon	454	10.3	725	9	445	13.9	1921	24
Nitrogen	6.65	1.80	10	6	5.95	1.16	25	14
Phosphorus	0.36	0.16	0.6	2	0.56	0.25	2.5	8
Potassium	6.74	1.56	10	9	7.91	2.14	35	31
Calcium	0.60	0.34	0.9	3	2.20	0.89	9.5	28
Magnesium	0.32	0.22	0.5	2	1.42	0.69	6.2	24
Sulfur	0.29	0.12	0.4	3	0.47	0.17	2.1	17
Sodium	0.10	0.02	0.2	11	0.15	0.21	0.7	39
		$\mu g \cdot g^{-1}$	$g \cdot ha^{-1}$			$\mu g \cdot g^{-1}$	$g \cdot ha^{-1}$	
Aluminum	13	28	20	3	66	212	770	100
Boron	3.4	1.4	5	5	5.7	1.9	25	27
Copper	3.2	1.5	5	8	4.7	1.8	20	32
Iron	41	62	62	4	122	312	415	28
Manganese	4	4	7	3	22	13	97	35
Zinc	12	8	18	7	14	37	54	22

† Measurements and calculations on a dry basis; ‡ Percent of total above-ground accumulation (grain plus vegetative plant parts).

Table 2. Nutrient concentration † and calculated removal per hectare by corn grain at a water content of 155 g·kg^{-1}.

Nutrient	Mean	Standard Deviation	Removal	Percent of Total ‡
		g·kg^{-1}	kg·ha^{-1}	
Carbon	435	7	3884	49
Nitrogen	12.6	1.4	106	61
Phosphorus	2.6	0.4	23	78
Potassium	3.4	0.5	31	27
Calcium	0.6	0.6	5	15
Magnesium	0.9	0.2	8	31
Sulfur	0.8	0.1	8	65
Sodium	0.1	0.02	0.9	50
		μg·g^{-1}	g·ha^{-1}	
Aluminum	9	12	78	10
Boron	4	2	34	37
Copper	2	2	19	31
Iron	26	123	245	16
Manganese	3	2	26	9
Zinc	16	6	141	57

† Measurements and calculations on a dry basis; ‡ Percent of total above-ground accumulation (grain plus vegetative plant parts).

The average grain N concentration in our data 12.6 g·kg^{-1} (1.26%) was slightly lower than in the Wisconsin study [12], but consistent with previous studies in Iowa [10,11]. Average values for vegetative material above and below the ear shank and for the cob fraction (Table 1), however, were higher in the Iowa samples than those from Wisconsin. In fact, cob N levels were more than twice as high. Concentrations of other essential plant nutrients measured in both studies were generally quite similar, suggesting that results from these two studies can be used to project stover nutrient removal in northern and western portions of the U.S. Corn Belt.

Potential macronutrient (N, P, K) removal per hectare from above (top) and below (bottom) the ear shank (Table 1) were very similar averaging 28, 3, and 36 kg·ha^{-1}, respectively, and much greater than that in the cob fraction (10, 3, and 10 kg·ha^{-1}, respectively). That difference in potential macronutrient removal is one reason that bioenergy conversion facilities initially targeted corn cobs as their preferred feedstock [10,13,22]. However, logistics studies quickly showed that harvesting only the cob fraction could not provide sufficient biomass to support the emerging conversion facilities [4]. Secondary (Ca, Mg, and S) and trace element (Al, B, Cu, Fe, Mn, and Zn) concentrations and calculated removals per hectare are also presented in Table 1. This information is rather unique, since with the exception of Avila-Segura *et al.* [12], who also reported on Ca, Mg, and S concentrations and removal, most stover and other feedstock studies focus only on macronutrient removal. Two major reasons for not including secondary and micronutrients are the increased cost of analysis and relatively low levels of removal, that are generally not compensated for through subsequent fertilizer applications.

Calcium, Mg, and S concentrations in the cobs were much lower than in other vegetative plant parts. As a percentage of total above-ground nutrient accumulation, cobs contained only 3, 2 and 3% of those nutrients, respectively. Although not considered an essential plant nutrient, Na concentrations in all samples were very low, generally approaching the commercial laboratory's reported instrument detection limits. The low variability in Na concentrations was why there was essentially no detectable standard deviation within the data for each of the plant fractions. Trace element concentrations in the stover and various plant fractions showed extremely high variation, especially for Al, Fe, and Zn, presumably due to soil contamination either on the plant material itself or in samples from the stover bales. This was not a surprise, since no attempt was made to wash the plant material before drying and grinding it for chemical analysis. Overall, the values for these nutrients were consistent with previously reported removal amounts [8].

Nutrient concentrations and estimated removal through the grain are presented in Table 2. Nitrogen removal with the grain (106 $kg \cdot ha^{-1}$) plus that contained in the other plant fractions (Table 1) averaged 173 $kg \cdot ha^{-1}$ for the samples collected for this evaluation. In contrast to the Wisconsin study [12], which indicated 74% of the total above-ground N was contained in the grain, our data indicated that only 61% of the N was in the grain. However, allowing for some N cycling through the soil organic C and N pools, our nutrient removal results are in agreement with Iowa State University Extension guidelines for N application to corn in Iowa, U.S.A. [20]. Phosphorus removal by corn grain was ~350% greater than in the vegetative plant fractions, but for K, grain removal accounted for only 27% of total aerial accumulation. This relatively low level of K removal is one reason producers have often concentrated on fertilizing to meet plant N and P requirements, while inadvertently allowing soil K levels to be gradually depleted as shown in a recent assessment of long-term soil fertility trends for both continuous corn and a 2-year, corn—soybean [*Glycine max* (L.) Merr.] rotation [23].

Overall, corn grain samples (Table 2) had secondary (Ca, Mg, and S) nutrient concentrations that were similar to those in the cob fraction (Table 1), but substantially lower than in fractions collected from above or below the ear. On a percentage basis, grain removal accounted for 14%, 31%, and 64% of the Ca, Mg, and S removal, respectively. Trace element removal by the grain (Table 2) was very low, but consistent with previously published levels [8].

3.2. Stover Value and Harvest Method Effects

Nutrient replacement cost per Mg of corn grain for the various plant fractions based on 2015 fertilizer costs are presented in Table 3. Due to the lower nutrient content, harvesting only the cob fraction would have the lowest nutrient replacement cost, but as previously stated there simply is not enough of that material to sustain a cellulosic conversion facility. Estimated nutrient replacement costs for the machine-harvested stover fraction (\$19.40 Mg^{-1}) were consistent with previous reports [4,9]. Furthermore, a comparison of nutrient replacement values for grain-only harvest *versus* collecting a portion of the vegetative material as bioenergy or bio-product feedstock emphasizes the importance of monitoring soil-test and plant-available K, especially if the feedstock will be transported from the production area and not returned via manure, biochar, or spent mushroom compost (http://www.mushroomcompost.org/).

Table 3. Nutrient replacement value in U.S. dollars per Mg based on May 2015 fertilizer cost and the average quantity removed in corn grain and various stover fractions.

Nutrient	**Fertilizer Cost** †	**Top Fraction**		**Bottom Fraction**		**Cobs**	
		Quantity	Value	Quantity	Value	Quantity	Value
	$\$\cdot kg^{-1}$	$kg\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$	$kg\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$	$kg\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$
Nitrogen	1.0244	7.96	8.15	5.95	6.10	6.65	6.81
Phosphorus	3.3197	0.88	2.92	0.56	1.86	0.36	1.20
Potassium	1.0999	9.34	10.27	7.91	8.70	6.74	7.41
Calcium	0.0747	3.74	0.28	2.20	0.16	0.60	0.04
Magnesium	0.2266	2.42	0.55	1.42	0.32	0.32	0.07
Sulfur	1.7671	0.72	1.27	0.47	0.83	0.29	0.51
Sodium		0.10		0.15		0.10	
	$\$\cdot g^{-1}$	$g\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$	$g\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$	$g\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$
Aluminum		49		120		13	
Boron	0.0143	8.7	0.12	6.5	0.09	3.4	0.05
Copper	0.0226	7.0	0.16	4.1	0.09	3.2	0.07
Iron	0.0072	107	0.77	205	1.48	41	0.30
Manganese	0.0110	39	0.43	30	0.33	4	0.04
Zinc	0.0089	14	0.12	9	0.08	12	0.11
Total Fertilizer Value in $\$\cdot Mg^{-1}$			**25.06**		**20.04**		**16.62**
		Stover		Grain			
		Quantity	Value	Quantity	Value		
	$\$\cdot kg^{-1}$	$kg\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$	$kg\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$		
Nitrogen	1.0244	5.95	6.10	12.6	12.91		
Phosphorus	3.3197	0.56	1.86	2.6	8.63		
Potassium	1.0999	7.91	8.70	3.4	3.74		
Calcium	0.0747	2.20	0.16	0.6	0.04		
Magnesium	0.2266	1.42	0.32	0.9	0.20		
Sulfur	1.7671	0.47	0.83	0.8	1.41		
Sodium		0.15		0.1			
	$\$\cdot g^{-1}$	$g\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$	$g\cdot Mg^{-1}$	$\$\cdot Mg^{-1}$		
Aluminum		66		9			
Boron	0.0143	5.7	0.08	4	0.06		
Copper	0.0226	4.7	0.11	2	0.05		
Iron	0.0072	122	0.88	26	0.19		
Manganese	0.0110	22	0.24	3	0.03		
Zinc	0.0089	14	0.12	16	0.14		
Total Fertilizer Value in $\$\cdot Mg^{-1}$			**19.40**		**27.41**		

† Fertilizer cost estimates were made using the most economical sources available [24]. Values for Al and Na are not provided as these materials are not routinely applied to corn in fertilizer mixtures.

The large number of samples analyzed and contributing to the mean values presented in this article, coupled with the consistency of this data with previous results [4,8–12], provides confidence that the values can be used to estimate potential nutrient removal for various stover harvest scenarios. For example, POET-DSM's Project Liberty currently promotes the harvest of only a small portion of the crop residue (~1 $Mg\cdot ha^{-1}$) from appropriate areas (slopes ≤ 3%) using "2nd Pass Cob Bales" which are also referred to as the "EZ Bale™". The stover samples in this data set (Table 1) did not include any "EZ bale" data, but to assist producers who are considering this harvest strategy, we are confident our results can be used to help producers compute estimated nutrient replacement costs associated with harvesting a portion of their corn stover.

Based on Project Liberty marketing data [25]. EZ bales consist of 33% cob, 43% leaf/husk, 16% stalk material and 8% ash. The bales are made by turning off the residue chopper/spreader on the grain combine and dropping the crop residue passing through the machine in a windrow. After drying for a few days, the windrowed material is baled in a second-pass operation. Since the remaining corn stalks are not shredded or disturbed in any way, POET-DSM agronomists assume the baled material will consist primarily of cobs and plant material from above the ear (Table 1). In contrast, standard stover bales are generally made by allowing the stover to dry for a few days after harvesting the grain. The remaining stalks and other plant material are then chopped and a portion is raked into a windrow before baling. Using the same Project Liberty marketing data, standard stover bales are reported to consist of 9% cobs, 42% leaf/husk, 35% stalk material and 14% ash. For our calculations, we assume that because of mixing associated with chopping and raking operations, 40% of the leaf/husk and stalk biomass collected in standard stover bales can be attributed to plant material from below the ear shank. This assumption is supported by the higher ash content which generally reflects an increased amount of soil contamination, especially on lower plant parts, as documented by high standard deviation values for the Al, Fe, and Mn concentrations. Projected nutrient removals (Table 4) for both the standard stover and EZ bales™ were calculated as follows:

Nutrient removal = (Cob fraction × Cob nutrient content) + (Upper plant fraction × Upper plant nutrient content) + (Lower plant fraction × Lower plant nutrient content).

Based on our dataset, both the EZ™ bale and standard, two-pass rake and bale operation would increase N, P, and K removal by approximately 6.5, 0.6, and 7.6 $kg \cdot Mg^{-1}$, respectively, compared to harvesting only the grain. In general, the increase in N and P removal associated with harvesting only 1 $Mg \cdot ha^{-1}$ of stover can be considered negligible with regard to developing long-term nutrient management plans. Fertilizer management at the field scale is simply not that precise and as previously documented [11] spatial variability in soil properties and nutrient levels is much greater than the small increase in N and P removal. For K, the increase in removal could have significant consequences if initial soil-test levels are low [10] or if the stover was harvested before senescence and possible leaching or translocation of plant K to lower plant parts. Producers contemplating stover harvest after years of harvesting only corn grain may need to be reminded that K removal with vegetative plant parts was more than twice the amount per megagram when compared to the grain, and therefore, the potential for soil K depletion will be greater than if only the grain is being harvested.

Table 4. Nitrogen, phosphorus and potassium content and removal by EZ™ bales, standard stover bales, and corn grain.

		Nitrogen		**Phosphorus**		**Potassium**	
Plant Part	**Fraction of Bale**	**Content**	**Removal**	**Content**	**Removal**	**Content**	**Removal**
				kg·Mg^{-1}			
			EZ™ Bales				
Upper plant	0.59	7.96	4.70	0.88	0.52	9.34	5.51
Cobs	0.33	6.65	2.19	0.36	0.12	6.74	2.22
Total			6.89		0.64		7.73
			Standard Stover Bales				
Upper plant	0.462	7.96	3.68	0.88	0.41	9.34	4.32
Lower plant	0.308	5.95	1.83	0.56	0.17	7.91	2.44
Cobs	0.09	6.65	0.60	0.36	0.03	6.74	0.61
Total			6.11		0.61		7.37
			Corn Grain				
Grain	1.00	12.6	12.6	2.6	2.6	3.4	3.4

4. Summary and Conclusions

This article summarizes primary, secondary, and micronutrient concentrations measured in more than 600 hand-harvested, vegetative corn plant samples from above (tops) and below (bottom) the ear, as well as in cob and grain fractions collected in central Iowa, U.S.A. between 2008 and 2013 as part of a bioenergy feedstock assessment project. Similar data from more than 400 machine-harvested, single-pass and baled stover samples are also summarized. Nutrient removal for the various plant fractions was calculated and used to compute fertilizer replacement costs associated with harvest of this material as a cellulosic feedstock for bioenergy or bio-products. Average nutrient replacement costs were \$25.06, \$20.04, \$16.62, \$19.40, and \$27.41 Mg^{-1} for top, bottom, cob, stover, and grain fractions, respectively. Carbon content in each of the samples was also measured and used to calculate potential amounts of source carbon that could be returned to the soil for subsequent mineralization and partial conversion to SOM. Those analyses indicated that if non-grain plant biomass was not removed from the field, the hand-collected top, bottom, and cob fractions would have returned an average of 1454, 1828, or 725 $kg \cdot ha^{-1}$ of source carbon. Similar calculations indicated that harvesting all of the machine-collected stover would have removed an average of 1921 $kg \cdot ha^{-1}$ or 48% of the source carbon associated with non-grain biomass. The data were also used to quantify nutrient removal for the POET-DSM EZ™ bale and standard, two-pass rake and bale operations. Both stover harvest methods increased N, P, and K removal by an average of 6.5, 0.6, and 7.6 $kg \cdot Mg^{-1}$, respectively, compared to harvesting only the corn grain. Overall, we anticipate this information will be useful for producers contemplating stover harvest, and to those striving to develop markets for biomass feedstock or assessing carbon and nutrient cycling within agricultural ecosystems.

Acknowledgments

The authors recognize that this project could not have been accomplished without the full support and dedication of research support personnel associated with the USDA-ARS National Laboratory for Agriculture and Environment (NLAE) and Iowa State University (ISU) Agronomy and Agricultural Biosystems Engineering Research Center (AABERC).

This research was funded by the USDA-ARS Resilient Economic Agricultural Practices (REAP) project with additional funds from the Department of Energy (DOE) Bioenergy Technologies Office's Regional Feedstock Partnership Corn Stover Team, administered by the North Central Regional Sun Grant Center at South Dakota State University under DOE award number DE-FC36-05GO85041.

The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, *etc.*) should contact USDA's TARGET Center at (202) 720–2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C.

20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

Author Contributions

All three authors participated equally in planning, conducting, and interpreting the data associated with this contribution.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Perlack, R.D.; Wright, L.L.; Turhollow, A.F.; Graham, R.L.; Stokes, B.J.; Erbach, D.C. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. Available online: http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf (accessed on 6 May 2015).
2. USDA-National Agricultural Statistics Service (NASS). Data and Statistics [Online]. Available online: http://nass.usda.gov (accessed on 30 June 2015).
3. Baumhardt, R.L.; Schwartz, R.; Howell, T.; Evett, S.R.; Colaizzi, P. Residue management effect on water use and yield of deficit irrigated corn. *Agron. J.* **2013**, *105*, 1035–1044.
4. Karlen, D.L.; Birrell, S.J.; Hess, J.R. A five-year assessment of corn stover harvest in Central Iowa, USA. *Soil Tillage Res*. **2011**, *115–116*, 47–55.
5. Plastina, A. Estimated Costs of Crop Production in Iowa—2015. Available online: https://store.extension.iastate.edu/ItemDetail.aspx?ProductID=1793 (accessed on 26 June 2015).
6. Wilhelm, W.W.; Hess, J.R.; Karlen, D.L.; Johnson, J.M.F.; Muth, D.J.; Baker, J.M.; Gollany, H.T.; Novak, J.M.; Stott, D.E.; Varvel, G.E. Review: Balancing limiting factors and economic drivers for sustainable Midwestern US agricultural residue feedstock supplies. *Ind. Biotechnol*. **2010**, *6*, 271–287.
7. Karlen, D.L.; Hunt, P.G.; Campbell, R.B. Crop residue removal effects on corn yield and fertility of Norfolk sandy loam. *Soil Sci. Soc. Am. J*. **1984**, *48*, 868–872.
8. Sawyer, J.E.; Mallarino, A.P. *Nutrient Considerations with Corn Stover Harvest. PM3052C*; Iowa State University (ISU) Extension and Outreach, ISU: Ames, IA, USA, 2014.
9. Karlen, D.L.; Birrell, S.J.; Johnson, J.M.F.; Osborne, S.L.; Schumacher, T.E.; Varvel, G.E.; Ferguson, R.B.; Novak, J.M.; Fredrick, J.R.; Baker, J.M.; *et al*. Multilocation corn stover harvest effects on crop yields and nutrient removal. *BioEnergy Res*. **2014**, *7*, 528–539.
10. Hoskinson, R.L.; Karlen, D.L.; Birrell, S.J.; Radtke, C.W.; Wilhelm, W.W. Engineering, nutrient removal and feedstock conversion evaluations of four corn stover harvest scenarios. *Biomass Bioenergy* **2007**, *31*, 126–136.
11. Birrell, S.J.; Karlen, D.L.; Wirt, A. Development of sustainable corn stover harvest strategies for cellulosic ethanol production. *BioEnergy Res*. **2014**, *7*, 509–516.

12. Avila-Segura, M.; Barak, P.; Hedtcke, J.L.; Posner, J.L. Nutrient and alkalinitiy removal by corn grain, stover and cob harvest in Upper Midwest USA. *Biomass Bioenergy* **2011**, *35*, 1190–1195.
13. Biomass Research and Development Board (BRDB). Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications and the Role of Research. Available online: http://www.ascension-publishing.com/BIZ/HD4-Brdi.pdf (accessed on 6 May 2015).
14. Nelson, R.G. Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States—Rainfall and wind-induced soil erosion methodology. *Biomass Bioenergy* **2002**, *22*, 349–363.
15. Adler, P.R.; Rau, B.M.; Roth, G.W. Sustainability of corn stover harvest strategies in Pennsylvania. *BioEnergy Res.* **2015**, doi:10.1007/s12155-015-9593-2.
16. Johnson, J.M.F.; Papiernik, S.K.; Mikha, M.M.; Spokas, K.A.; Tomer, M.D.; Weyers, S.L. Soil processes and residue harvest management. In *Carbon Management, Fuels, and Soil Quality*; Lal, R., Stewart, B.A., Eds.; Taylor and Francis, LLC: New York, NY, USA, 2010; pp. 1–44.
17. Wilhelm, W.W.; Johnson, J.M.F.; Karlen, D.L.; Lightle, D.T. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agron. J.* **2007**, *99*, 1665–1667.
18. Karlen, D.L.; Varvel, G.E.; Johnson, J.M.F.; Baker, J.M.; Osborne, S.L.; Novak, J.M.; Adler, P.R.; Roth, G.W.; Birrell, S.J. Monitoring soil quality to assess the sustainability of harvesting corn stover. *Agron. J.* **2011**, *103*, 288–295.
19. Karlen, D.L.; Birrell, S.J.; Wirt, A.R. Corn stover harvest strategy effects on grain yield and soil quality indicators. In *Striving for Sustainable High Productivity through Improved Soil and Crop Management*, Proceedings of the 19th Triennial ISTRO Conference, Montevideo, Uruguay, 18–24 September 2012.
20. Blackmer, A.M.; Voss, R.D. *Nitrogen Fertilizer Recommendations for Corn in Iowa*; Iowa State University Extension: Ames, IA, USA, 1997; p. 4.
21. Prihar, S.S.; Stewart, B.A. Using upper-bound slope through origin to estimate genetic harvest index. *Agron. J.* **1990**, *82*, 1160–1165.
22. Halvorson, A.D.; Johnson, J.M. Cob Characteristics in Irrigated Central Great Plains Studies. *Agron. J.* **2009**, *101*, 390–399.
23. Karlen, D.L.; Kovar, J.L.; Cambardella, C.A.; Colvin, T.S. Thirty-year tillage effects on crop yield and soil fertility indicators. *Soil Tillage Res.* **2013**, *130*, 24–41.
24. Smith, J.J. Brandt Consolidated LLC, 2935 South Koke Mill Road, Springfield, IL, USA. Fertilizer prices. Personal communication, May 2015.
25. POET-DSM. Project Liberty grand-opening highlights. 2014. Available online: www.projectliberty.com (accessed on 30 June 2015).