Impacts of corn-based biofuel production on soil fertility and ecosystem sustainability

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Introduction

Increasing demand for renewable energy and the great potential for using corn stover for biofuel production in the United States raises concerns about agricultural sustainability. Excessive harvest of corn stover could have long-term impacts on soil quality, soil carbon and nutrient balances, and lead to enhanced soil erosion. It is critical to find the minimum residue level required to maintain soil fertility in various agricultural regions and the maximum stover feedstock available for future biofuel production. This study aims to:

1. Estimate both current and future corn stover production (from 2010 to 2050)
2. Evaluate potential harvestable corn stover for biofuel production by defining the minimum corn stover necessary to be left in the field to maintain soil fertility

Materials and Methods

Essential Data:

1. Historical county-based corn yield statistics and 2009 cropland maps for 41 States of the USA, derived from USDA National Agricultural Statistics Service (http://www.nass.usda.gov/) and used for setting up the baseline and predicting future trend.
2. Fractions of stover components and their nutrient contents, synthesized from literature reviews.
3. Minimum residue requirement (MRR) for different tillage and crop rotation systems, synthesized from literature reviews.
4. Average grain yields from 2005 to 2009 for each county within a state, generated as the baseline for predicting yields from 2010 to 2050.
5. Acreage data of tillage and residue management, obtained from the Conservation Technology Information Center (CTIC).

Methods:

1. Prediction of corn yield from 2010 to 2050

Corn yield has linearly increased over time with varying rates from state-to-state. We tried to find the best function to describe the yield change trend over time for each state, which was also used to predict future county yields, using a relatively conservative approach (logarithm function, see Fig. 1). As illustrated in the embedded graph, corn yield can be predicted by extending historical trends. The spatial distribution of the county average yield from 2005 to 2009 is presented in Fig. 2 where the potential of feedstock for biofuels can be seen. Higher yields are usually associated with irrigation in the western US.

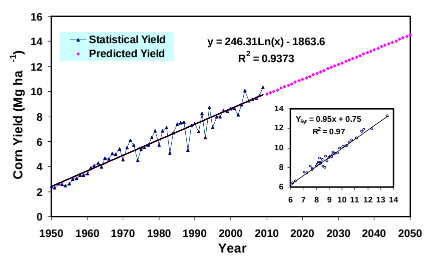

Fig. 1. US historical corn yield trend from 1950 to 2009 and its extended prediction from 2000 to 2050.

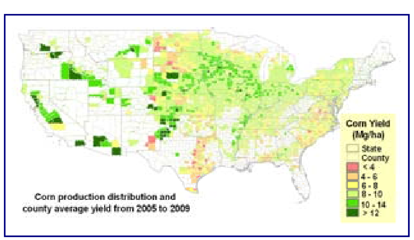

Fig. 2. County corn yield averaged for years from 2005 to 2009.

2. Fractions of stover components and their nutrient contents

The fractions of stover components and contents (dry matter) of elements at harvest were synthesized from existing observations in literature and used to compute biomass yields of interest stover components and their nutrient contents.

3. Minimum residue required to maintain soil fertility

The conceptual model (Fig. 3) was designed to develop approaches to define MRR and harvestable residue amount (HRA) for biofuels. Existing observations suggest that grain yield (Y_{grn}), tillage, and crop rotation are most critical to MRR:

$$MRR = f(Y_{grn}, \text{Tillage}, \text{Rotation}) \quad (1)$$

Our analysis of existing data resulted in a linear correlation of dry stover biomass (Y_{stv}, kg ha^{-1}) to the corn grain yield (Y_{grn}, in dry matter assuming 15.5% moisture content) as:

$$Y_{stv} = 0.61\,Y_{grn} + 2400 \quad (2)$$

Then $HRA = Y_{stv} - MRR$ (3)

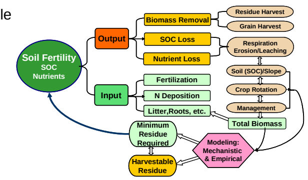

Fig. 3. Conceptual model of biofuel production-soil fertility balance

No-till (NT), reduced-tillage (RT), and conventional tillage (CT) were included in this study and their average proportions in total corn harvested hectares in the last 5 years at county levels were derived from CTIC database and used for estimating HRA. Nation-wide, the proportions are 0.20, 0.45, and 0.35 for NT, RT, and CT, respectively. The estimation of HRA assumes that continuous corn accounted for 70% of all harvested area and corn-related rotation systems were 30%.

4. Calculation of required nutrients (N, P, and K)

According to Dobermann et al. (2006), the yield target (Y_t) can be simulated as a function of nutrient uptake and yield potential (b)

$$Y_t = \text{if}(x<=c,\ b(3/2)*(x/c) - (1/2)*(x)^3),\ b) \quad (4)$$

where Y_t is the yield target (Mg ha^{-1}), x is nutrient uptake for a given yield target (kg ha^{-1}), b is yield potential (=20 Mg ha^{-1}), and c is uptake at yield approaching the maximum yield (kg ha^{-1}).
And $c = (a + d(Y_t))$ (5)

Y_t ranges from 6.0–20 mg ha^{-1}. Constants a and d can be defined for N, P, and K, respectively, from literature review.

Results

1. Predicted yield in the future

The annual change rate after 2009 is not always linearly proportional to the average NASS yield in the last 5 years for all states as shown in Fig. 4. The state average yield will increase 39% by 2050, ranging from 17% (Colorado) to 71% (Alabama). Higher yields are usually associated with irrigation beyond the Corn Belt region.

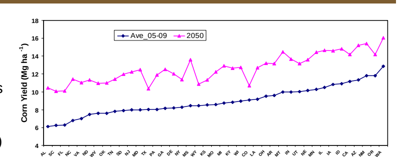

Fig. 4. State average corn yield in 2050 vs. the average yield from 2005 to 2009

2. Stover feedstock and its harvestable fraction for biofuels

The data in Table 1 show that, nation-wide, annual HRA was about 59.1 Tg (or 2.00±0.64 Mg ha^{-1}) in the last five years, and could be 118.9 Tg (or 3.82 ±1.22 Mg ha^{-1}) in 2050 if the corn harvest area is the same as the average of the last 5 years; this implies that HRA will double by 2050. In the past 5 years, there were 438 counties where the current annual HRA was greater than 2.00 (±0.49) Mg ha^{-1}, and there could be 1457 counties that could have annual HRA of 4.00(±0.59) Mg ha^{-1} by 2050.

Table 1. Current and potential of stover for biofuels

State		Harvest Area	Average 05-09			2050		
			Stover	Harvestable		Stover	Harvestable	
		Mha	Tg	Tg	Mg ha^{-1}	Tg	Tg	Mg ha^{-1}
Iowa		5.26	42.02	13.11	2.49	52.29	23.37	4.44
Illinois		4.85	37.83	10.10	2.08	48.24	20.49	4.23
Nebraska		3.45	26.33	8.10	2.35	32.43	14.19	4.11
Minnesota		2.90	22.31	5.93	2.04	28.53	12.11	4.17
Indiana		2.30	17.34	4.26	1.86	21.71	8.63	3.76
South Dakota		1.68	10.87	2.15	1.28	14.37	5.55	3.31
Ohio		1.30	9.53	2.17	1.67	11.99	4.62	3.55
Kansas		1.41	9.58	2.16	1.53	11.61	4.07	2.89
Wisconsin		1.20	8.41	1.77	1.48	10.74	4.05	3.38
Missori		1.17	7.99	1.46	1.25	10.16	3.58	3.06
Michigan		0.85	5.85	1.06	1.26	7.66	2.85	3.37
Texas		0.75	4.88	1.01	1.35	5.78	1.69	2.26
Others		3.62	24.14	5.16	1.34	31.0	11.73	3.16
Sum	Tg		231.5	59.1		292.4	118.9	
	Mha	31.4	31.4	29.6		31.4	31.2	
Mean	Mg ha^{-1}				2.00(0.64)			3.82(1.22)

3. Nutrient requirements and balance with stover harvest scenarios

The data in Table 2 indicate that a large portion of required nutrients is attributed to the grain harvest, especially P, and only a small fraction comes with any residue removals Obviously, besides fertilization, a significant portion of required nutrients is derived from the previous below-ground biomass that accounts for more than 60% of all above-ground biomass.

Table 2. Required nutrients for yield target and their concentrations in different biomass components

Element	Unit	Total Required	Content or Removed by Harvest (kg ha^{-1})					
			Grain	Stover	Cob	Cob+Abv	Normal Cut	HRA
	Average of for Years from 2005 to 2009							
N	kg ha^{-1}	161	110.4	49.9	5.6	12.0	25.9	13.6
P		23	24.6	5.2	0.5	1.7	2.7	1.4
K		156	32.5	61.9	7.5	15.6	32.2	16.9
N	% of Required		69	31	3.5	11.0	16.1	8.5
P			100	23	2.0	9.3	11.9	6.2
K			21	40	4.8	14.8	20.7	10.8
	By 2050							
N	kg ha^{-1}	235	153.4	63.0	7.0	15.2	32.7	25.9
P		33	34.2	6.6	0.6	2.1	3.4	2.7
K		227	45.1	78.1	9.5	19.7	40.6	32.1
N	% of Required		65	27	3.0	9.5	14.0	11.0
P			100	20	1.8	8.0	10.3	8.1
K			20	34	4.2	12.8	17.9	14.1

Discussion

Our estimates of MRR for 2005 to 2009 are much smaller than previous ones (89.8 Tg by Gallagher et al. (2003); 108.9 Tg by Walsh et al. (2000)) due to their very small MRR (e.g., Gallagher et al. using 1.6 Mg ha^{-1} under mulch tillage). In our study, the average harvested area proportions of 0.20, 0.45, and 0.35 were used for NT, RT, and CT, respectively, coupled with 30% corn-based crop rotations.

For a one-pass harvest system (currently very common), the theoretical HRA may not make sense for field collection operations. The collection of cob only, cob plus the above ear, or the top stover above a certain height (typically 40 cm from the ground) is usually applied. At this point, our current estimates are about 34.7Tg for cob, 88.0 Tg for cob plus above ear, and 133.0 for the top stover over 40cm-stubble, and our estimates by 2050 are 43.9 Tg, 111.1 Tg, and 184.9 Tg, respectively.

It is well-known that crop residue plays a critical role in preventing soil erosion, and therefore mitigates SOC loss. At the same time, residue is also recognized for its role in replenishing SOC and other nutrients that was removed by harvesting grain and/or residue. However, Wilts et al. (2004) found that only 5.3% of the total residue C input is retained as SOC under a moldboard plow. While the belowground biomass (roots and rhizodeposition) contributes much more. Similarly, results from long-term experiments by Hooker et al. (2005) suggest that the annual residue return may not necessarily increase SOC storage in the long-term once soils have reached a steady-state SOC level. Increasing source C input leads to a net increase in SOC until a new dynamic equilibrium level is reached, after which little additional net increase in SOC occurs (Jenkinson, 1981; Lal et al., 1998). In other words, the decomposition of unnecessary residue contributes to greenhouse effects at a cost of extra soil N for microbes to decompose it.

As addressed by other studies (Tan et al., 2007, 2008; West et al., 2010), soils with high SOC contents tend to lose SOC once cultivated regardless of tillage practices. This may explain why the MRR values reported so far appear to have little correlation to SOC levels when soils have greater than 2% organic carbon contents. Most previous observations from the Corn Belt region where average SOC content is much higher than other US regions show a greater MRR than those from other regions where SOC contents are usually lower. This suggests that SOC losses under tillage and rotation systems are not necessarily or simply attributed to the magnitude of residue left on fields.

Conclusion

For the sake of soil fertility sustainability, US corn stover feedstock harvestable for biofuels could double by 2050 in comparison with 59 Tg averaged from 2005 to 2009 assuming an increase in yield at the historical change trend. Collecting cobs (even plus the above-ear fraction) has little effect on SOC and nutrient balances under different tillage practices and corn-related rotations. A greater potential of corn stover feedstock supply for biofuels in the future that may come from an increase in the biomass yield, an area harvest index, and an expansion of irrigated area in semiarid regions. This information will help farmers to balance soil nutrients by adjusting fertilizer rates and to sustain soil fertility by predicting C removal for different harvest scenarios.

Acknowledgments

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