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Estimating sustainable crop residue removal rates and costs based on soil organic matter dynamics and rotational complexity

Hilla Kludze [a], Bill Deen [a,*], Alfons Weersink [b], Rene van Acker [a], Ken Janovicek [a], Aaron De Laporte [b], Ian McDonald [c]

[a] Department of Plant Agriculture, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G 2W1
[b] Department of Food, Agricultural and Resource Economics, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G 2W1
[c] Ontario Ministry of Agriculture, Food and Rural Affairs, 1 Stone Road West, Guelph, Ontario, Canada N1G 4Y2

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ABSTRACT

The government of Ontario, Canada, has committed to stopping the use of coal for electrical generation by 2014 and agricultural biomass is being considered as replacement. However, there is limited information on whether the annual 2 million Mg of biomass required to replace coal could be sustainably supplied by agriculture and at what costs. This study assesses the sustainable availability and the farm-gate break-even cost of residue biomass from three crops (corn, soybean and winter wheat) grown under two common rotation scenarios in Ontario. Sustainably removable residue (SRR) rates are determined using a five-step approach that accounts for maintenance soil organic matter (MSOM) in the presence of yield and rotation variations across counties. Under typical SOM formation and decomposition conditions and assuming typical corn-soybean and corn-soybean-winter wheat rotation scenarios, about 1.1 million Mg of residue could be sustainably removed each year, primarily from the major agricultural counties in the province. While rotational complexity enhances SRR, the inclusion of soybean decreases available residue compared to corn and winter wheat. The break-even price for crop residues, representing the minimum price necessary to cover all variable and fixed costs for the farmer, is between \$57 Mg^{-1} and \$87 Mg^{-1}. However, the actual amount supplied for each biomass price depends critically on the opportunity costs associated with not growing typical crops in the conventional manner.

1. Introduction

Agricultural biomass continues to gain attention as a source of alternative energy given its potential ability to offset fossil fuels and reduce CO_2 emissions while simultaneously providing an added source of income to farmers. Interest in agricultural biomass has been spurred in Ontario, Canada, by the need to look for a replacement for coal in the generation of electricity. Given the concentrated crop production regions in the province, crop residues from corn (*Zea mays* L.), wheat

Abbreviations: OMAFRA, Ontario Ministry of Agriculture, Food and Rural Affairs; CS, corn-soybean rotation; CSW, corn-soybean-winter wheat rotation; SRR, sustainably removable crop residue; MSOM, maintenance soil organic matter.

* Corresponding author. Tel.: +1 519 8244120x53397; fax: +01 519 7638993.
E-mail address: bdeen@uoguelph.ca (B. Deen).

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(*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.) are considered to be particularly promising sources of biomass feedstock to replace coal. However, the removal of these crop residues is not straightforward. Crop residues are important in the maintenance and protection of soil quality, which limits the amount that can be removed. Crops are also grown in common rotations in Ontario, so residue availability must account for the temporal dimension. Other limitations to crop residue procurement and competing uses for these residues will affect the sustainable availability of crop residue biomass along with the cost of its supply.

While the production of bio-energy from crop residues is a valuable initiative, indiscriminate removal of crop residues can adversely impact soil properties, soil organic matter (SOM) dynamics, water and wind erosion and crop production. For example, stover removal at rates as low as 25% reduced the stability of aggregates in nearly level silt loam and clayey soils [1]. The extent of impact depends on soil-specific characteristics (e.g., texture and drainage), topography, crop grown, management practices adopted and their duration, and climate zones [2]. Earlier studies indicated that changes in soil organic carbon (SOC) concentration due to crop residue removal can be slower in nearly level clayey soils compared to sloping and erosion-prone soils [1,3].

Crop yields are reduced as a result of removing essential plant nutrients associated with residue removal [4–6]. For example, stover removal in a sloping soil at 50% reduced grain yield by 1.8 Mg ha^{-1} yr^{-1} and at 100% by 3.3 Mg ha^{-1} yr^{-1}, in three out of 4 years post removal [1]. Crop residues are rich in essential plant nutrients; therefore, their removal would directly reduce nutrient pools and alter chemical properties such as soil pH, electrical conductivity, and cation exchange capacity. Ontario soils are characterized by reduced carbon inputs and high SOM decomposition rates, which would impact the amount of residue available for removal [7,8]. In cultivated soils in Ontario C storage decreases due to reduced C inputs and enhanced rates of plant litter decay [7].

Agricultural practices determine the level of SOC by influencing the amount of residue returned to, and retained by, the soil [9]. For example, the amount of crop residue that can be harvested would be influenced by crop rotation type, depending on the quantity of root and above-ground residue produced in the rotation. In Canadian prairie soils, annually cropped rotations sequestered substantially more carbon than rotations including years of bare fallow [10]. Furthermore, enhancing rotation complexity results in significant accumulation of SOC [11]. Research on the long-term effects of residue removal on Canadian soils are very limited [7] and addressing this potentially serious shortcoming becomes even more important as the use of agricultural biomass for the emerging bio-energy industry is being promoted. It is imperative to have some level of knowledge about the impact of residue removal on soil quality attributes and crop yield before attempts are made to remove residue on a commercial scale.

The purpose of this paper is to assess the sustainable availability and procurement cost of biomass from crop residues in common Ontario crop rotation scenarios, on a county scale. The specific objectives are: 1) to estimate the quantity of crop residue that could be sustainably removed from an average farmer's field after grain harvest, at the county level, taking into account county-specific yields and sustainability constraints; and 2) to estimate the farm-gate cost of collecting the residue. Crop residue requirements to maintain SOC and nutrient pools are higher than those required to control soil erosion [12]; thus, the amount of residue that needs to remain on the field to maintain current SOM levels was the major consideration and focus of our study. The quantitative assessment of residue availability was based on previous studies [13–17] and several literature reports on changes in SOC with various levels of crop residue removed to estimate quantities of source carbon needed to maintain SOC. Although the above approach relies on well-documented values of 'minimum annual source carbon inputs (MSC)' from several studies in the literature, it is limited in use because the MSC values referenced may not be applicable to all Ontario conditions and, most importantly, no MSC values are available for rotation diversity and complexities that involve more than two crops (e.g. corn-soybean-wheat systems). However, the intent of this study is not to provide removal estimates to specific farm locations, but to create an aggregate, county-level estimate of potentially available residues in Ontario.

2. Materials and methods

2.1. Study area

The area encompassed by this study is limited to the agricultural counties of Ontario. Ontario, located in the east-central part of Canada, is the largest province by population and second largest in total area. While there is some agricultural production in Northern Ontario, this area has been excluded from this study due to its comparatively poor growing season and data constraints. The Ontario counties under consideration in this study are shown in Fig. 1.

2.2. County level estimates of average crop residue availability in Ontario

The sustainable harvest of crop residues for each of the Ontario counties identified in Fig. 1 is estimated using a five-step approach that focuses explicitly on SOM resulting from residue retention. This method aggregates representative farms in a given county to estimate potential biomass availability. Therefore, it is not site-specific in nature, but uses measures of statistical dispersion to incorporate differences from average actual county yield data provided by OMAFRA. The yields incorporate local climatic, soil and topographical differences, which cannot be attributed to specific farms, but are certainly valid at the county level. The five steps include estimating the:

1) minimum amount of residue required to be left in the field to maintain current soil organic matter levels;
2) above-ground residue produced from grain yield under a rotation system (i.e., above-ground post-harvest residue less the grains);
3) below-ground root residue (including rhizodeposits), produced under a rotation system;