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Potential impacts of agricultural land use on soil cover in response to bioenergy production in Canada

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ABSTRACT

The introduction of a market for agricultural biomass to feed large-scale second generation bioenergy (cellulosic ethanol) or other bio-products has positive implications for food producers and bio-product industries but may impact soil quality. In order to assess the potential impact on Canada's agricultural lands, we integrated land use and soil capability maps and land management information to introduce several scenarios of crop residue harvest rates and land use conversions. The implications for soil quality, as represented by soil cover, were assessed for each scenario. The results showed that average soil cover at the national scale would decrease by more than 1 day if 40% of annual crop residues (by mass) were harvested, but the negative impacts could be resolved by increased adoption of conservation tillage methods. Additional biomass could be produced by converting low quality agricultural land to perennial biomass crops, but this would result in increased intensity of food production on high quality land. The total area of high and low quality land within the agricultural region of Canada is roughly equal, and the amount of high quality land currently used for perennial crops is about the same as the amount of low quality land used for annual crops, and 'balancing' production with capability would result in a net increase in both food and biofuel feedstock, with little impact to soil quality. About 6.73 M ha of high quality land is covered by forest, shrub and grass, and conversion of this land to agricultural production would have a negative impact on soil quality. The study indicates considerable potential for production of both food and biofuel feedstock on Canada's agricultural lands through careful land use planning. Our analysis using soil cover as an indicator of environmental sustainability also indicates that land use planning should be cautious to prevent soil degradation. Particularly, regional variability of land use and soil capability distribution requires region specific land use policy for sustainable biofuel feedstock production.

1. Introduction

The consumption of fossil fuels has contributed to an increase in atmospheric CO_2, which is directly related with global warming. The use of biomass for biofuel production could mitigate global warming by reducing the dependence on fossil fuels and decreasing CO_2 emissions (Naik et al., 2010). Current global bioenergy production is about 10% of that produced by fossil fuels (IPCC, 2012), and a greater potential can be anticipated from the world's vegetated lands outside denser forests, croplands, urban areas and wilderness (Haberl et al., 2013; Guo et al., 2015). Hence, many countries have developed biofuel policies to boost an economic sector and a market for bio-products (HLPE, 2013). Both federal and provincial governments in Canada are promoting biofuel industry to exploit the huge stock of biomass resources (Le Roy and Klein, 2012). From census data it has been estimated that average yearly potential bioenergy production from crop residue in Canada could be about 81.8 million barrels of ethanol (Li et al., 2012). However, questions remain on how an expanding bioenergy sector will interact with other issues such as food production, biodiversity, soil degradation, environmental sustainability and carbon sequestration (Berndes et al., 2003).

First generation biofuels, consisting of bioethanol from grain and sugar and biodiesel from oilseeds, are considered to compete with food supply and thus increase food prices (Mueller et al., 2011; Mitchell, 2008). The development of second generation biofuels such as cellulosic ethanol may mitigate the impact of biofuel production on food supply. Crop residue and perennial woody/herbaceous bioenergy crops from agricultural landscapes are two important bioenergy supply chains (Smith et al., 2015; Mabee and Saddler, 2010). Growing perennial energy crops on surplus and/or poor quality agricultural land can be a

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major contributor to bioenergy production (Hoogwijk et al., 2003; Chemento et al., 2016; Feng et al., 2017).

Agricultural land use and management practices can impact soil quality and greenhouse gas emissions (King et al., 2004; Smith et al., 2010). Potential impacts on greenhouse gas emissions by converting marginal land to perennial energy crops has been assessed by Liu et al. (2017). Crop residues on the soil surface protect soil from the erosive forces of wind and rain, and provide the building blocks for soil organic matter (Johnson et al., 2010). Therefore, removing crop residue can cause both direct and indirect adverse impacts, over short and long terms (Allmaras et al., 2004; Wilts et al., 2004; Mann et al., 2002; Lindstrom, 1986). Determination of a sustainable residue removal amount requires an integrated approach (Muth et al., 2013; Muth and Bryden, 2013). Contrary to annual row crops that can contribute to soil carbon losses, the establishment of perennial crops for biofuel has the potential to increase soil carbon stocks and generate other ecosystem services such as wildlife habitat and runoff prevention (Awasthi et al., 2017; Kantola et al., 2017). In addition, incorporating perennial bioenergy crops into agricultural landscapes can make use of land that is marginal for annual crops, and hence alleviate competition with food crops (Awasthi et al., 2017; Feng et al., 2017).

To support the development of sustainable bioenergy production from agricultural land, the availability of land resources and the impact on the environment need to be assessed. A review shows that estimated production capacity varies greatly among different studies because land availability and yield levels of energy crops are uncertain (Berndes et al., 2003). In the context of intensification of agricultural production and environmental conservation, agri-environmental indicators have been developed to evaluate and report on the status and trends of environmental quality impacted by agricultural production activities (e.g., Clearwater et al., 2016). Soil cover provides environment protection through diminished wind and water erosion, limited leaching and run-off, increased weed control and improved soil fertility (as references cited in Büchi et al., 2016). The Soil Cover Indicator was developed to evaluate the status of soil cover provided by vegetation, crop residues and snow at a regional scale in Canada (Huffman et al., 2012, 2015). It was further developed for field and farm level applications in Switzerland by integrating crop model simulations (Büchi et al., 2016). In this paper, a study was conducted mainly to understand the resource potentials for bioenergy production in Canada using several land use change scenarios and crop residue harvest levels, and to evaluate the impact on soil quality. Agricultural census data, a national land use map and a soil capability rating system were used as a base to estimate land resources, land use conditions and land management practices across Canada's croplands. The impact of agricultural cellulosic biofuel on soil quality was assessed using the Soil Cover Indicator.

2. Material and methods

2.1. The Soil Cover Indicator

Soil Cover is included in the OECD list of farm management indicators (OECD, 2001). It is defined as "the equivalent number of days in a year that soil of agricultural land is covered with vegetation". The concept was adopted in Canada and a model was developed to estimate the total equivalent number of days in a year that the land is covered by crop canopy, crop residue and snow (Huffman et al., 2012, 2015). It has been used as a tool for agri-environmental health assessment and reporting at national and regional scales, providing direct information on the impact of different crops and field activities on the risk of soil erosion. By integrating information on crop type, soil, climate and associated field activities, plant growth and residue decomposition are simulated using a crop calendar at a daily time step to quantify the fraction of soil under cover. Thus, the indicator can quantify not only the daily fraction cover but also the annual equivalent number of days the soil is covered for a given crop in a given region, which is referred to as Soil Cover Days (SCD). To report at different spatial scales, the SCD is calculated according to the proportions of different crops and management practices. For perennial crops this include the frequency and timing of harvest or grazing, and for annual crops it includes different tillage types such as conservation/conventional/no-tillage, crop growth and residue decomposition. Detailed information on the indicator can be found in Huffman and Liu (2016) and Huffman et al. (2015).

2.2. Soil and land use inventory

In our scenarios we assumed that high quality soils would be used for annual food crop production, while poor quality soils would be exploited for perennial crop production. This trend is supported in a study on cropland change in Alberta, Canada (Zhang et al., 2014). In reality, economic benefit generally determines land use, but in the case of food versus fuel, we assume that legislation, incentives or competitive advantage would relegate biofuel crops to land less suited to annual cultivation due to low fertility, poor climate or physical limitations. In order to investigate the potential for land use changes involving food and biofuel crops on different land types, a national land use map at 30 m resolution was intersected with the Canada Land Inventory (CLI) Soil Capability for Agriculture maps at 1:250,000 scale.

A circa 2000 digital land cover map for the agricultural regions of Canada developed by Agriculture and Agri-Food Canada (AAFC, 2009) was acquired and is referred to as Circa-2000 LC. The map consists of 13 general land cover types (Table 1), 5 of which were of interest in this study; Annual Cropland, Perennial Cropland, Forest, Shrubland, and Grassland.

CLI is a comprehensive multi-disciplinary land inventory of rural Canada that categorizes agricultural land into Soil Capability classes based on characteristics of the soil as determined from detailed soil surveys (AAFC, 2013a). Table 2 provides definitions of the classes. Generally (and for this study) soils rated as Classes 1–3 are considered prime (or good) agricultural land, whereas Classes 4–6 are considered marginal (or poor) for agriculture. Class 7 has no capacity for arable agriculture or permanent pasture. A similar approach has been adopted to identify marginal land in USA (Gelfand et al., 2013; Feng et al., 2017). Digital versions of the appropriate CLI map sheets were downloaded from the AAFC website and georeferenced to Circa-2000 LC. All data manipulations were performed using ArcMap.

The intersection of the land use map and the CLI maps was conducted in order to provide an inventory of the areas of different combinations of land-use and land-capability classes at regional, provincial and national levels. In particular, the area of annual crops, perennial crops and forest/shrub/grass on CLI soil classes 1–6 were of interest. Fig. 1 illustrates the national extent of the study at a generalized level.

2.3. Census data

The Census of Agriculture is conducted every 5 years in Canada, and collects a wide variety of land use, land management and economic information for every farm in the country (Statistics Canada, 2008). Census data interpolated to Soil Landscapes of Canada polygons (AAFC,

Table 1
Circa-2000 land cover types; "*" denotes land use types considered in land use management scenarios in this study.

Water
Exposed Land
Built-up
Shrubland*
Wetland
Grassland*
Annual Cropland*
Perennial Cropland and Pasture*
Forest/ Trees*