BIOMASS AND BIOENERGY 64 (2014) 321–328

Available online at www.sciencedirect.com

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Cob biomass supply for combined heat and power and biofuel in the north central USA☆,☆☆

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ARTICLE INFO

Article history:
Received 31 May 2013
Received in revised form
28 February 2014
Accepted 25 March 2014
Available online 17 April 2014

Keywords:
Corn cobs
Biofuel
Biorefinery
Combined heat and power
Ethanol
Life cycle assessment

ABSTRACT

Corn (*Zea mays* L.) cobs are being evaluated as a potential bioenergy feedstock for combined heat and power generation (CHP) and conversion into a biofuel. The objective of this study was to determine corn cob availability in north central United States (Minnesota, North Dakota, and South Dakota) using existing corn grain ethanol plants as a proxy for possible future co-located cellulosic ethanol plants. Cob production estimates averaged 6.04 Tg and 8.87 Tg using a 40 km radius area and 80 km radius area, respectively, from existing corn grain ethanol plants. The use of CHP from cobs reduces overall GHG emissions by 60%–65% from existing dry mill ethanol plants. An integrated biorefinery further reduces corn grain ethanol GHG emissions with estimated ranges from 13.9 g CO_2 equiv MJ^{-1} to 17.4 g CO_2 equiv MJ^{-1}. Significant radius area overlap (53% overlap for 40 km radius and 86% overlap for 80 km radius) exists for cob availability between current corn grain ethanol plants in this region suggesting possible cob supply constraints for a mature biofuel industry. A multi-feedstock approach will likely be required to meet multiple end user renewable energy requirements for the north central United States. Economic and feedstock logistics models need to account for possible supply constraints under a mature biofuel industry.

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1. Introduction

Agricultural residues and dedicated energy crops are expected to provide substantial biomass supplies for conversion into biofuels [1]. Agricultural residues like corn stover are projected to have lower economic feedstock costs than dedicated energy crops, a major factor for an emerging cellulosic biofuel industry where biorefinery capital costs are expected to be four to five times higher than dry mill corn grain ethanol plants [2,3].

Abbreviations: CHP, combined heat and power; CDI, cropland data inventory; DDGS, dried distiller's grain and soluble; GHG, greenhouse gas; iLUC, indirect land use change; LCA, life cycle assessment; SOC, soil organic carbon; GIS, geographic information systems.

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http://dx.doi.org/10.1016/j.biombioe.2014.03.051
0961-9534/Published by Elsevier Ltd.

Corn stover harvest estimates exceed 54 million Mg year^{-1} for the U.S. with most amounts available in southern Minnesota and northern Iowa [4].

Excessive corn stover removal can lead to increased soil erosion and decreased soil organic carbon (SOC) levels [5,6]. Corn stover required to maintain SOC is greater than stover residue required to limit water and wind erosion [7]. Corn cob only harvest is expected to be more sustainable in maintaining SOC since more corn residue is retained, has negligible short-term impacts on nutrient replacement [8], and glucan recovery and ethanol production is higher for cobs than corn stalks under similar pretreatment and hydrolysis methods [9]. One-pass harvest methods have been developed to collect both corn grain and corn cob biomass that reduces harvesting constraints [10]. In addition, corn cobs have a greater bulk density than corn stover that improves transportation logistics. Potential applications for cobs are fossil fuel displacement at a traditional corn grain ethanol facility to lower corn grain ethanol plant GHG emissions or conversion to cellulosic biofuel. Retrofitting existing dry mill ethanol plants from fossil fuel based power generation with biomass-based power generation has been estimated to reduce corn grain ethanol GHG emissions [11,12].

Most biomass transportation models, optimal plant size models, and life cycle assessment (LCA) models have assumed minimal biomass availability constraints for a given collection area or have assumed that biomass resources would be used for a singular purpose. A limitation of some bioenergy and logistics models is that spatial constraints are also ignored that is critical in biofuel feedstock analysis [13]. Estimates from these analyses may overestimate the availability of biomass since transportation distance is a major economic cost in biomass related enterprises. This study addresses spatial variability in corn cob supply using a multi-criteria geographic information systems (GIS) approach and evaluates the potential supply availability in using corn cobs for bioenergy in the north central USA. The north central U.S. region represents a spatially diverse area with highly concentrated corn production areas with corresponding high corn grain ethanol plant densities to areas with modest corn production and yields. Study objectives were to estimate corn cob availability in the north central U.S. region (Minnesota, North Dakota, and South Dakota) based on current and projected corn grain yields and develop a GIS enabled evaluation to identify corn cob supplies and possible supply constraints under variable utilization scenarios.

2. Material and methods

Corn cob availability was determined for Minnesota, South Dakota, and North Dakota based on average corn production data (2005–2009 where available) and cropland data inventory (CDI) values (2010) [14]. Corn production from 2005 to 2009 takes into account both weather variability and recent yield gains for this region while 2010 CDI values account for the recent increase in corn plantings for this region. Crop production and harvestable area were determined for northern Iowa, northeastern Nebraska, and western Wisconsin to eliminate edge effects during analysis. Corn yields were interpolated across the north central region using ordinary kriging in ArcGIS (Geostatistical Analyst ESRI Corp. Redland, CA) based on county corn yield averages (2005–2009). The CDI was converted from a raster (30 m $\times$ 30 m) to a vector layer using ArcGIS. Corn fields were selected in the attribute table and converted to a vector dataset. Converting the CDI raster to a vector layer resulted in small vector polygons identified as corn fields that were primarily less than 0.4 ha. Vector polygons identified as corn fields less than 20 ha were omitted from this analysis. Corn vector fields were overlain onto interpolated corn yields, and average yield was assigned to each corn field. Cob biomass was estimated to be 20% of dry matter (DM) corn grain biomass [15,16]. An assumption was made that corn stover (leaf, stalk, husks) collected in addition to cob biomass at the harvest phase was equivalent to cob biomass loss during the storage phase. All biomass values are reported on a dry matter basis.

We assume cellulosic bioenergy facilities will be co-located with existing corn grain ethanol plants and cobs will either be used in a combined heat and power (CHP) system for fossil fuel displacement or used to produce cellulosic ethanol with process power requirements derived from the non-fermentable cell wall portions (primarily lignin) of cobs [11,12,17]. Cob supply of 509 Mg d^{-1} was estimated to meet 100% heat and power demand at a dry mill corn grain ethanol plant with 189 million L production capacity [18]. For a co-located integrated ethanol refinery (378 million L capacity), cob biomass capacity was 2073 Mg d^{-1} to produce 189 million L of cellulosic ethanol and provide heat and power demand for both cellulosic and corn grain conversion (189 million L capacity). Ethanol plant operations are assumed to run 24 h a day for 350 days per year. Electrical power requirements for both scenarios were considered to be met from biomass (lignin) generation with no electrical export. Dried distiller's grain and soluble (DDGS) was the only co-product produced from either scenario.

Locations of operational corn grain ethanol facilities were obtained from the Renewable Fuels Association (http://www.ethanolrfa.org/industry/locations/) and locations were approximated based on town geographic coordinates (Fig. 1) [19]. Nearest neighbor analysis was conducted on existing ethanol plants to determine whether ethanol plants were clustered or dispersed using the Euclidean distance method. A 40 km and 80 km radius circle was overlaid at individual ethanol plant locations to determine cob availability from existing corn grain plants. Buffers were split into multiple selectable polygons using the Union command in ArcGIS (ESRI Corp, Redlands, CA). Areas of overlap were identified and exported as a shapefile for the 40 km and 80 km collection radius from each current ethanol plant. Crop production regions were created by overlaying ordinary kriged corn county data over the CDI vector layer within the buffer layer to estimate total cob availability. Cob availability was estimated at current corn grain yields and for expected corn grain yields by 2022. For the 2022 year scenario, corn grain yields and cob yield are estimated to increase by 1%, 2% and 3% year^{-1} from 2005 to 2009 corn yield averages. The amount of harvestable corn area that is available for cob removal is referred to as the utilization rate. Utilization rates were simulated from 25% to 90%. Corn grain production area was