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Research paper

# GIS-based assessment of sustainable crop residues for optimal siting of biogas plants

Kamalakanta Sahoo[a], Sudhagar Mani[a,*], Lalitendu Das[b], Pete Bettinger[c]

[a] School of Chemical, Material and Biomedical Engineering, University of Georgia, Athens, GA 30602, USA
[b] Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, KY 40546, USA
[c] Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

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ABSTRACT

The assessment of biomass at high spatial resolution is critical to manage supply risks and to identify optimal plant sites for producing sustainable biofuels and co-products. The spatial variabilities in soil type, topography, climate, and crop management practices further require vast computational time and resources to estimate the availability of sustainable biomass for a large study area. In this study, we developed a GIS-based integrated predictive modeling platform to assess the availability of sustainable crop residues at high spatial (30 m) and temporal (2010–2022) scales. A GIS-based multi-criteria inclusion-exclusion analysis and facility location-allocation models were used to identify suitable sites, and optimal siting of biogas plants respectively with biomass delivered cost. The Artificial Neural Network (ANN) based predictive models were well suited to predict sustainability indicators (soil erosion SE- $R^2$ = 0.96, soil conditioning index, SCI– $R^2$ = 0.98 and organic matter factor, OMF- $R^2$ = 0.83) for assessing sustainable removal rates of crop residues (corn stover and wheat straw). The GIS-based integrated model was applied to the State of Ohio and found that about 4–13 dry Tg of crop residues can be sustainably available to build 1–25 regional biogas plants. A typical optimal biogas plant with a feedstock capacity of up to 500 dry Gg could be drawn from a transport radius of about 19–35 km with a delivered cost of 40–46 $ dry $Mg^{-1}$. The temporal and spatial variations in assessing the availability of biomass largely affected the supply chain decisions and its delivered costs.

## 1. Introduction

Lignocellulosic biomass is one of the most promising renewable sources to produce biofuels, biochemicals, and industrial bioproducts as an alternative to fossil-derived products while mitigating climate change [1,2]. In the U.S., the Energy Independence and Security Act (EISA) mandated the replacement of 30% of fossil-based liquid transportation fuel with biofuel by 2030 using more than one dry Pg of available cellulosic biomass. Crop residues alone contribute to a significant fraction (20%-30%) of total available biomass [3]. Crop residues need to be harvested and utilized in a sustainable manner, i.e., removal of crop residues and its delivery to biorefineries should be economically viable without compromising the long-term productivity of soil health and water quality [2,4]. Therefore, crop residues removal from agricultural lands must not adversely affect soil erosion while maintaining organic matter levels, and preserving or improving long-term soil productivity [4]. Hence, soil scientists, conservation specialists, and agronomists recommend leaving certain percent of crop residues before removing residues for bioenergy applications. The removal rate of crop residues from any cropland dependent on the number of parameters that later served the basis for developing sustainability indicators for croplands. The important sustainability indicators identified were soil erosion, soil organic carbon, plant nutrient balance, soil compaction, bulk density, stream water sediment and nutrient concentrations [4,5]. The complex interactions among soil, climate, and land management practices could affect these sustainability indicators [6]. The most critical and widely used indicators to guide sustainable removal rate of crop residues are the soil erosion (SE) rate and the soil conditioning index (SCI) [3,6,7].

There have been numerous studies on the assessment of sustainable crop residue to assist in developing plans for sustainable biorefineries across the US. For example, a county-level crop residues assessment considering SE only for few soil types was investigated using Revised Universal Soil Loss Equation (RUSLE) [8,9]. In addition to SE, a recent study by Graham et al. [10] included soil moisture, and nutrient replacement cost constraints to estimate crop residues from irrigated croplands. However, the use of SE limit (T-value) did not provide sufficient protection against soil quality and productivity loss [4].

* Corresponding author.
*E-mail address:* smani@engr.uga.edu (S. Mani).

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Therefore, Soil Organic Matter (SOM), one of the most critical soil quality indicators, was introduced that influences the physical, chemical and biological properties of soils [11]. Field management practices, especially tillage type and equipment used during crop cultivation directly affect the retention of organic matter in the soil [12].

The Soil Conditioning Index (SCI) was developed as one of the key sustainability indicators for predicting accumulation or reduction of soil organic carbon due to field management practices, climate, yield, and soil erosion. The SCI for any cropland can be estimated by the weighted sum of the organic matter factor (40%), the SE factor (20%) and the field operations factor (40%). SCI values can be positive, negative or zero indicating accumulation, degradation, and no change in soil organic matter respectively [11,13]. In addition to SE value, Wilhelm et al. [14] adopted the SCI value estimated from RUSLE2 (Revised Universal Soil Loss Equation (2)) and WEPS (Wind Erosion Prediction System) for corn stover to predict a sustainable removal rate of corn stover at certain locations and to illustrate the amount of residues required to prevent soil erosion and maintain positive SCI values. Recently, a large-scale assessment of crop residues availability in the U.S. was demonstrated by Muth et al. [6,15]. Muth et al. [6] developed an automated tool by integrating RUSLE2 and WEPS to predict SE and SCI for cropland across the entire U.S. and to estimate the availability of sustainable crop residues at the soil polygon level using representative input values of topography, climate, crop yield, and crop management practices.

Sustainable crop residues removal rates from agricultural land are extremely site-specific and vary based on the local crop yield, climate, and management practices [4,14]. RUSLE2 is one of the robust and widely-used tool available for estimating sustainability indicators (e.g. SE due to rainfall and SCI index for soil types) at the field level. The critical inputs for RUSLE2 include the location (county), soil type, slope, slope length, field management practices (i.e., schedule and type of operations, crop rotation, etc.) and the crop yield. However, certain inputs, such as topography (i.e., slope and slope length) and crop yield may vary within a field and can have a significant impact on estimated sustainability indicators values and finally on the crop residue assessment results. Muth et al. [16] illustrated a significant difference in the availability of sustainable crop residue using field and sub-field level inputs. For the assessment of sustainable biomass in a large-scale study area, the least spatial resolution of required input data used in an integrated crop residue assessment model developed by Muth et al. [6] were soil polygons. However, soil polygons may be spread across the large geographic region (area varies from few to thousands of hectares) with significant variations in topography. Therefore, crop residues assessment using typical input data values at a soil polygon level may produce unreliable results without accommodating the inherent spatial and temporal variations in the models. Hence, the sustainability indicators should be assessed at the sub-field level or grid-level (i.e., 30 m) to better represent actual field conditions, which is critical for assessing sustainable crop residues availability [7].

The integration of grid-level sustainability indicator data in GIS platform for assessing biomass in large study area requires vast computational resources and time [6,15]. On the other hand, predictive models such as Linear Regression Model (LRM) and Artificial Neural Network (ANN) could be developed with grid-level data to significantly reduce computational time and data accuracy for assessing sustainable availability of biomass [17–21]. A similar approach was previously adapted to predict SE and sediment loss in the water stream using the Soil and Water Assessment Tool (SWAT) and Water Erosion Prediction Project (WEPP) software platforms [17,22,23]. ANN-based predictive models are better suited to accommodate highly non-linear and complex relationships between the dependent and independent variables [24–26]. The quality or goodness of fit of prediction models are often be judged based on the high correlation coefficient ($R^2$) and low Sum of Square of Errors (SSE) values.

In addition to biomass assessment, a selection of optimal plant locations is important for investors and policymakers for the development of sustainable bioenergy industries. A GIS based multi-criteria analysis tool can be fast and efficient to identify possible appropriate plant sites [27,28]. However, limited selection of constraints could be used for identifying biogas plant locations. The complexity of constraints increased further by including spatial and temporal variations of sustainable biomass availability, which ultimately affects the economics of bioenergy supply chain and its optimal network structure. Biomass is dispersed over a large geographic area aggregated to the county level. However, aggregation of biomass at county level could underestimate or overestimate the actual road network distances from a farm gate to the plant [29]. Hence, an integrated and efficient GIS-based approach is necessary to estimate the availability of sustainable crop residues at the high spatial resolution and identify optimal siting of biogas plants for a large study area.

The objectives of this study were to (i) estimate annual availability of sustainable crop residues at a high spatial resolution using an integrated predictive modeling approach in a GIS platform; (ii) identify possible sites to locate plants and determine the optimal siting of a certain number or capacity of biogas plants; and (iii) illustrate the spatial and periodic temporal variations of crop residues availability on optimal configuration of biomass supply chain and estimate the delivered cost of multiple crop residues.

## 2. Methods and approaches

The proposed approach include (i) the development of efficient and robust predictive models to estimate availability of multiple crop residues at high spatial resolution (30 m) for a large study area, (ii) the identification of potentially suitable sites for establishing bioenergy production plants, e.g., biogas and (iii) the selection of optimal plant locations and their biomass delivered cost (Fig. 1). The RUSLE2 software tool [30] was used to simulate sustainability indicators [SE, SCI, and OMF (organic matter factor)] at representative locations across the study area using location-specific information. The simulated data were used to develop the best models such as multiple linear regression and Artificial Neural Networks (ANNs) for predicting sustainable removal rate of residues from each grid [31]. All geospatial analyses (sustainable crop residues quantification, identifying potential plant locations and optimal siting of the plants) were performed using a module builder in ArcGIS version 10.2 and its extensions such as Spatial Analyst and Network Analyst [32]. The cost model developed by Sahoo and Mani [33] was used to estimate logistics cost of crop residues delivered to optimal plant sites.

### 2.1. Study region and data use

In this study, we selected the State of Ohio, USA as a primary study region. Corn, soybeans, and wheat are the three major crops cultivated in Ohio, but only corn stover and wheat straw were considered for biogas production [3]. The availability of sustainable biomass, i.e., corn stover and wheat straw, was estimated on an annual basis (2010–2014) and projected to the year 2022 at a spatial resolution of 30 m. We assumed that biogas plants could be regionally located with small-to-medium plant capacities (50–1000 dry Mg day$^{-1}$) unlike a typical cellulosic biorefinery (2000 dry Mg day$^{-1}$). The annual Cropland Data Layer (CDL) raster dataset representing unit land (30 × 30 m) from 2010 to 2014 and GIS tools were used to identify the agricultural lands that supported major crops grown and crop rotations in Ohio [34]. Only land areas cultivated with one of the major crops at least once in last five years were included in the study. Among all crop rotations identified in the study area, corn-soybean and corn-soybean-wheat were used in this study period. The gSSURGO database was used to incorporate soil related information. In the study, data related to soil type, soil texture, slope, slope length, and organic matter content were used to develop the predictive model as well as estimating the sustainable crop residues availability [35].