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Sustainable agricultural residue removal for bioenergy: A spatially comprehensive US national assessment

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HIGHLIGHTS

- We perform an assessment of US agricultural residue availability for bioenergy.
- The assessment considers multiple sustainability factors using an integrated model.
- The study is spatially comprehensive for the US at an analysis scale of 10–100 m.
- More than 150 million metric tons of residue were sustainably available in 2011.
- More than 207 million metric tons of available residue are projected in 2030.

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ABSTRACT

This study provides a spatially comprehensive assessment of sustainable agricultural residue removal potential across the United States for bioenergy production. Earlier assessments determining the quantity of agricultural residue that could be sustainably removed for bioenergy production at the regional and national scale faced a number of computational limitations. These limitations included the number of environmental factors, the number of land management scenarios, and the spatial fidelity and spatial extent of the assessment. This study utilizes integrated multi-factor environmental process modeling and high fidelity land use datasets to perform the sustainable agricultural residue removal assessment. Soil type represents the base spatial unit for this study and is modeled using a national soil survey database at the 10–100 m scale. Current crop rotation practices are identified by processing land cover data available from the USDA National Agricultural Statistics Service Cropland Data Layer database. Land management and residue removal scenarios are identified for each unique crop rotation and crop management zone. Estimates of county averages and state totals of sustainably available agricultural residues are provided. The results of the assessment show that in 2011 over 150 million metric tons of agricultural residues could have been sustainably removed across the United States. Projecting crop yields and land management practices to 2030, the assessment determines that over 207 million metric tons of agricultural residues will be able to be sustainably removed for bioenergy production at that time. This biomass resource has the potential for producing over 68 billion liters of cellulosic biofuels.

1. Introduction

Biomass is being investigated and developed around the world as a potential low carbon, renewable energy source. National and continental renewable energy strategies are being investigated to utilize the range of biomass resources available [1–5], establish the energy conversion technologies that are most appropriate for the available biomass resources [6–8], and understand how global bioenergy markets may impact local food, feed, and fiber production [9]. As a part of this worldwide effort the US federal government has established goals for biofuel production through the Energy Independence and Security Act of 2007 [10]. The law specifically calls for US biofuel production of liquid transportation fuels to increase to more than 136 billion liters annually by 2022, with approximately 56 billion liters coming from non-cornstarch feedstocks. Assuming a conversion rate of 330 l of biofuel per metric ton for cellulosic feedstock [11,12], meeting this target will require at least 240 million metric tons of biomass resources. A number of research efforts have examined cellulosic bioenergy feedstocks such as switchgrass, miscanthus, energycane, energy sorghum,

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willow, hybrid poplar, forest residues, and agricultural residues, and the conversion technologies that can utilize these feedstocks [13–17]. Of these feedstocks, the resource with the greatest near term potential (1–5 years) for achieving national targets is agricultural residues [18].

Identifying a sustainable and reliable agricultural residue resource base has been a significant challenge for the emerging cellulosic biofuels industry [19]. Agricultural residue removal must be managed carefully to be sustainable, and spatial and temporal variability (soil, climate, and management practices) impact the reliability of the supply. Residues play a number of critical roles within an agronomic system including direct and indirect impacts on physical, chemical, and biological processes within the soil [19–22]. Excessive residue removal can degrade the long term productive capacity of soil resources [23,24]. The large capital investments required for cellulosic biorefineries (>$100 M) require knowledge of the agricultural residue resource base that is locally available to support a facility. This includes not only regional and national scale perspectives, but also local, subfield scale spatial and temporal impacts on potential residue removal. Furthermore, the analyses must lead to residue removal rates that will be certified as sustainable by the Natural Resource Conservation Service (NRCS) of the US Department of Agriculture (USDA) conservation management planning process.

To address this need for a robust national assessment of sustainably available agricultural residues built upon local soil, climate, and land management data, this study utilizes an integrated modeling strategy to perform a multi-factor assessment of sustainably available agricultural residues across the United States. This integrated assessment utilizes the models and data currently used by the NRCS to administer agricultural land management policy. This novel approach integrates the environmental process models and associated databases required to determine the impact of residue removal. Specifically, this study is performed at the Soil Survey Geographic (SSURGO) Database [25] soil type scale and is then aggregated to county-level projections using USDA Cropland Data Layer data [26]. This integration of models and data results in three new contributions to the discussion of large spatial scale sustainable agricultural residue removal for the United States. These are a complete national scale assessment that (1) considers soil organic matter impacts of residue removal, (2) incorporates remotely sensed crop rotation data, and (3) connects NRCS conservation management planning methods with national scale residue availability projections. The data produced through this study is consistent with the guidance of sustainable agricultural land management practices as administered by the farm bill and the NRCS. Based on this, the results of this integrated assessment are data and analyses that can support cellulosic biorefinery decisions utilizing agricultural residues as the primary sources.

The paper is structured to first review the earlier regional and national scale sustainable agricultural residue removal studies. This review focuses on the limiting environmental factors considered, the spatial and temporal scale assumptions, and the modeling methodologies. The integrated modeling methodology used for this study is then presented, focusing on the key data sources, scenarios, and assumptions used for the assessment. Lastly, the results of the study are provided showing the projected sustainably available residue at the county, state, and national scales. Key conclusions from the results are discussed.

1.1. Background

One of the key challenges associated with identifying the availability of agricultural residues is accounting for the many important roles that residues play in the agronomic system. Wilhelm et al. [19] performed an extensive review of sustainability indicators for agricultural residue removal. The result of this review was the identification of six environmental factors that potentially limit agricultural residue removal—soil erosion from wind and water; soil organic carbon; plant nutrient balances; soil, water, and temperature dynamics; soil compaction; and off-site environmental impacts. From their review Wilhelm et al. also determined that no model or methods were available that could comprehensively consider the range of factors that potentially limit agricultural residue removal.

Several previous efforts have considered a subset of Wilhelm et al.'s six limiting factors (Table 1) in projecting regional or national sustainable residue availability. The first large spatial scale study of agricultural residue availability was published by Larson [27]. He estimated that approximately 49 million metric tons of crop residues could be sustainably harvested at that time in the Corn Belt, Great Plains, and Southeast regions of the United States. The focus of this study was on limiting erosion below tolerable soil loss limits, and the calculations were performed utilizing the Universal Soil Loss Equation (USLE) [28]. The study investigated the effect of tillage practices on the potential of residue removal and considered the impacts of nutrient removal. At that time using the USLE required significant spatial aggregation of soil characteristics, land management practices, and crop yields to reduce the number of calculations. Because of this requirement, this study provided regional scale projections of residue availability, but could not provide local sustainable removal projections. In addition, Larson's study did not consider the relationship between residue removal and soil organic carbon.

As a result of low oil prices and generally decreased interest in bioenergy development in the United States, the next large-scale assessment of agricultural residue availability was presented more than two decades later by Nelson [29]. This was the first of a series of assessments focused on residue removal within the context of residue retention requirements. The approach for these assessments was to assemble a limited set of representative crops, rotations, and field management scenarios; apply them to selected soils; and then utilize the Revised Universal Soil Loss Equation (RUSLE) [30] and the Wind Erosion Equation (WEQ) [31] to generate residue retention requirements to limit rainfall and wind erosion below tolerable loss limits. The yield needed at the time of harvest was then correlated to an average county-level yield to determine the possible quantity of available residues at the county scale. This methodology was applied to 37 states from the Great Plains to the East Coast for the period of 1995–1997. This study determined that over 50 million metric tons of corn stover and wheat straw were potentially available annually for removal over this time span. Soil organic carbon was not considered in this study. The ability to determine residue availability at the county scale provided a significant step forward in generating data that could support bioenergy industry decisions. However, this study was computationally limited in the number of scenarios that could be investigated, and consequently, it was not able to consider the variability in soil characteristics and management practices that are typically found within a single county. These local (10–100 m) considerations are important for certifying sustainable removal practices within NRCS conservation management planning guidelines, thus ensuring reliable biomass supplies for biorefiners.

Sheehan et al. [23] applied the methodology developed by Nelson [29] to a life cycle assessment of corn stover to produce ethanol. This study focused on providing a stover-to-ethanol system level analysis including collection, transport, and conversion for the state of Iowa. Nelson's methodology [29] was extended by including the CENTURY agro-ecosystem model [32,33] to quantitatively assess the impact on soil carbon from residue removal. The scale of the calculations was at the county level, consistent with