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An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systems☆

D.J. Muth Jr. [a,*], K.M. Bryden [b]

[a] Biofuels & Renewable Energy Technologies Division, Idaho National Laboratory, P.O. Box 1625, MS 2025, Idaho Falls, ID 83415-2025, USA
[b] Department of Mechanical Engineering, Iowa State University, 2274 Howe Hall, Ames, IA 50011, USA

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ABSTRACT

Agricultural residues have been identified as a significant potential resource for bioenergy production, but serious questions remain about the sustainability of harvesting residues. Agricultural residues play an important role in limiting soil erosion from wind and water and in maintaining soil organic carbon. Because of this, multiple factors must be considered when assessing sustainable residue harvest limits. Validated and accepted modeling tools for assessing these impacts include the Revised Universal Soil Loss Equation Version 2 (RUSLE2), the Wind Erosion Prediction System (WEPS), and the Soil Conditioning Index. Currently, these models do not work together as a single integrated model. Rather, use of these models requires manual interaction and data transfer. As a result, it is currently not feasible to use these computational tools to perform detailed sustainable agricultural residue availability assessments across large spatial domains or to consider a broad range of land management practices. This paper presents an integrated modeling strategy that couples existing datasets with the RUSLE2 water erosion, WEPS wind erosion, and Soil Conditioning Index soil carbon modeling tools to create a single integrated residue removal modeling system. This enables the exploration of the detailed sustainable residue harvest scenarios needed to establish sustainable residue availability. Using this computational tool, an assessment study of residue availability for the state of Iowa was performed. This study included all soil types in the state of Iowa, four representative crop rotation schemes, variable crop yields, three tillage management methods, and five residue removal methods. The key conclusions of this study are that under current management practices and crop yields nearly 26.5 million Mg of agricultural residue are sustainably accessible in the state of Iowa, and that through the adoption of no till practices residue removal could sustainably approach 40 million Mg. However, when considering the economics and logistics of residue harvest, yields below 2.25 Mg ha^{-1} are generally considered to not be viable for a commercial bioenergy system. Applying this constraint, the total agricultural residue resource available in Iowa under current management practices is 19 million Mg. Previously published results have shown residue availability from 22 million Mg to over 50 million Mg in Iowa.

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Software availability

The VE-Suite software is freely available under the GNU LGPL license. Documentation and software are available at www.VE-Suite.org.

The models and databases used are listed in Table 1.

1. Introduction

Global initiatives to develop renewable, low carbon energy sources have identified biomass feedstocks as a resource with significant potential (Bauen and Kaltschmitt, 2001). Biomass feedstocks provide a renewable pathway to support liquid transportation fuels and are also being investigated as a low net carbon feedstock for electricity generation. As in many countries, the United States has set national targets for bioenergy production through biofuel and biopower generation (Energy Independence and Security Act, 2007). Meeting these goals requires development and utilization of biomass resources well beyond current production levels.

In 2005 a US Department of Energy (DOE) study identified that more than one billion tons of biomass may be available annually for energy production in the US (Perlack et al., 2005). Three-hundred million tons of this biomass will come from agricultural residues (i.e., materials other than grain including stems, leaves, and chaff

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* Corresponding author. Tel.: +1 208 526 0963; fax: +1 208 526 2639.
E-mail address: David.Muth@inl.gov (D.J. Muth).

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[Perlack et al., 2005]). However, sustainable use of agricultural residues for bioenergy production must take into consideration the critical role of agricultural residue in maintaining soil health and long-term productivity (Johnson et al., 2009, 2006; Wilhelm et al., 2007; and Karlen et al., 2003). A recent review study identified six environmental factors that can limit sustainable agricultural residue removal—soil organic carbon, wind and water erosion, plant nutrient balances, soil water and temperature dynamics, soil compaction, and off-site environmental impacts (Wilhelm et al., 2010). These factors result from complex interactions between local soil characteristics, climate, and land management practices. Because of the breadth of soils, climate, and land management practices, it is not possible to determine the agricultural residue removal limits from experimental measurement or current practice at the level of detail and accuracy needed for policy decisions. Currently, there are no tools or models that perform this type of analysis (Wilhelm et al., 2010). Delivering this tool requires integrating the set of models that describe wind erosion, water erosion, and soil carbon together with an extensive set of databases that describe soil, climate, and land management practices.

Agricultural residue availability analysis is further complicated by the need for aggregate assessments across entire states, regions, and the nation. Historically, due to the constraints imposed by manual input and interaction with models, large geographic assessments of sustainable agricultural residue removal potential have relied on a reduced-scenario modeling approach that utilizes a limited number of representative agricultural production scenarios (Graham et al., 2007; Nelson, 2002; and Nelson et al., 2004). Using representative scenarios has several weaknesses. To accurately represent the wide variety of soil types, climates, and management practices, a large number of scenarios are needed, which requires significant computational time. Because of this, the reduced-scenario modeling approach cannot effectively represent the decision space. This approach significantly limits the ability of the decision maker to explore and understand unique or hypothetical management scenarios and provides little capability for performing robust sensitivity analysis. In addition, the manual process of developing a set of representative scenarios is not readily extensible. For example, adding a new model or a new database requires rebuilding the entire set of representative scenarios, which is time-consuming and costly.

This paper presents an integrated modeling strategy capable of characterizing the multiple limiting factors impacting sustainable agricultural residue removal within a single, extensible, interactive residue removal analysis system. To do this the integration framework must address three requirements:

1. *Seamless integration of existing models.* Models and databases that address individual aspects of this overall system exist today. These models are fully developed, validated, and peer-reviewed. The integration framework must be able to incorporate these models without change to their source code or validity.
2. *Plug-and-play interaction.* The core set of models has been developed independently from this framework and from each other. As a result, these models will continue to be updated and revised independently from the integration framework. In addition, different scenarios will require different models and databases, and researchers may wish to compare the results of one set of models or databases with the results of another. Because of this, a "hard coded" approach is not appropriate and the integration framework must support interactive update and revision of the models and databases within the systems model.
3. *Intuitive, real-time interaction.* The integrated computational model will be used by a number of different groups and individuals, each with different skills and different analysis needs. The framework needs to be able to interactively support the disparate needs of each of these groups for varying models, assumptions, scenarios, and user interfaces.

The development of this integrated residue removal modeling system is described in this paper. The case study presented demonstrates the initial implementation of this modeling tool following the description of the development of the modeling system.

2. Background

2.1. Sustainable residue removal studies

In the past, the majority of efforts regarding the sustainability of agricultural crop residue removal were focused on limiting water and wind erosion to the tolerable soil loss limits established by the Natural Resources Conservation Service (NRCS) of the US Department of Agriculture (USDA). Little effort was focused on the impact of agricultural crop residue removal on broader soil tilth or productivity concerns. In 1979, Larson conducted one of the first large-scale studies focused on crop residue removal and its effect on soil erosion using the Universal Soil Loss Equation (Larson, 1979). This study included the Corn Belt, the Great Plains, and the Southeast. The effect of tillage practices (i.e., conventional, conservation, and no-till) and residue management were investigated with respect to rainfall and wind erosion, runoff, and potential nutrient removal. This study found that for the management practices and crop yields at the time, nearly 49 million metric ton of residue was available annually throughout the Corn Belt. Soil carbon, tilth, and productivity maintenance were not considered.

As a result of limited interest in agricultural residues for energy production during the 1980s and 1990s, no additional large spatial scale assessments of residue availability were performed until more than two decades after Larson's study. Nelson (2002) used the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1996) and Wind Erosion eQuation (WEQ) (NRCS, 2011a) to expand on Larson's analysis to develop a methodology to estimate the sustainable removal rates of corn stover and wheat straw at the soil-type level. This methodology considered rainfall and wind-induced soil erosion as a function of reduced and no-till field management practices. In 2004, Nelson et al. used the same approach to assess five other major one- and two-year cropping rotations (e.g., corn–soybean). Neither of these studies addressed soil organic matter as a function of removal. Researchers have also used the Revised Universal Soil Loss Equation, Version 2 (RUSLE2 [NRCS, 2011b]) and/or Wind Erosion Prediction System (WEPS [NRCS, 2011c]) to address a number of erosion-based questions on crop residue removal (Karlen et al., 2003; Nelson, 2002).

Agricultural residue removal studies have also been performed using the DAYCENT (Adler et al., 2007), Environmental Policy Integrated Climate (EPIC) (Gregg and Izaurralde, 2010), and Agricultural Policy/Environmental eXtender (APEX) (Powers et al., 2008) models. These studies have focused on specific case study analyses without focusing on larger scale residue availability projections. Also, these analyses were focused on specific sustainability questions, such as greenhouse gas (GHG) impacts of residue removal, carbon sequestration impacts, and potential water quality impacts. Each of these models is reviewed below.

RUSLE2 simulates daily changes in field conditions based on soil aggregation, surface wetness, field management practices, and residue status, and is driven by daily weather parameters. Currently, these parameters are manually entered into RUSLE2 from various disparate databases. RUSLE2 is mainly used as a guide for conservation planning and accurately represents trends