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DEVELOPING AN INTEGRATED MODEL FRAMEWORK FOR THE ASSESSMENT OF SUSTAINABLE AGRICULTURAL RESIDUE REMOVAL LIMITS FOR BIOENERGY SYSTEMS

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ABSTRACT

Biomass provides a renewable pathway to support current and future energy needs for liquid transportation fuels, and is also being investigated as a low net carbon feedstock for electricity generation. To leverage this renewable source of energy requires the development and utilization of biomass resources beyond the current production levels. One source of renewable biomass energy feedstock is agricultural residues. However, a recent study[1] identified six factors that limit sustainable agricultural residue removal, and it stated that a comprehensive assessment of sustainable residue removal limits must consider each of the six factors. These factors are: (1) soil organic carbon, (2) wind and water erosion, (3) plant nutrient balances, (4) soil water and temperature dynamics, (5) soil compaction, and (6) off-site environmental impacts. Each of these factors is described by a set of disparate and heterogeneous models that are not currently integrated together. In addition each of the models has been validated, developed, and is currently maintained by a subject area expert separate from the other models. Recoding the complete set of models into a single monolithic software structure is impractical due to the time needed to develop and validate the completed set of models. Instead an extensible software framework is needed that can integrate the model set together enabling analysis and optimization of agricultural residue harvest for energy usage. This paper presents an integrated modeling strategy that incorporates these model sets together with the needed GIS information within a single integrated computational engineering framework. This integrated computational engineering framework has been implemented to facilitate high fidelity spatial assessments of biomass resource management. A case study demonstrating initial implementations of the resulting interactive analysis and optimization framework is presented. The case study demonstrates how multiple constraints can be simultaneously considered as a part of assessing sustainable agricultural residue removal potential.

INTRODUCTION

Global initiatives to develop renewable, low carbon energy sources have identified biomass feedstocks as a resource with significant potential [2]. Biomass feedstocks provide a renewable pathway to support liquid transportation fuels [3], 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 [3,4]. Meeting these goals requires development and utilization of biom—ass resources well beyond current production levels. Previous studies have identified a potential availability of more than one billion tons of biomass annually in the United States [5]. Three-hundred million tons of this identified biomass will come from agricultural residues, i.e., materials other than grain including stems, leaves, and chaff [5]. However, sustainable use of agricultural residues for bioenergy production must take into consideration the critical roles of agricultural residue in maintaining soil health and environmental sustainability [6,7,8,9]. A recent review study [8] specifically identified six factors that limit sustainable agricultural residue removal, and stated that a comprehensive assessment of sustainable residue removal limits must consider each of the six factors. These factors are (1) soil organic carbon, (2) wind and water erosion, (3) plant nutrient balances, (4) soil water and temperature dynamics, (5) soil compaction, and (6) off-site environmental impacts. Additionally, it was noted by Wilhelm et al. [1] that no tools or models currently exist that are capable of addressing all factors simultaneously.

Residue availability analysis is further complicated by the need for aggregate assessments across entire states, regions, and the nation. Historically, due to constraints imposed by the manual input and interaction with models, large geographic assessments of sustainable agricultural residue removal potential have relied on selecting a limited number of representative agricultural production scenarios [10,11,12]. This approach has several weaknesses. When changing soil types, climates, and management practices are considered the assessments quickly require large numbers of model iterations to fully explore the decision space. The reduced scenario modeling approach cannot fully explore this space, 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. More importantly, historical analyses with manual model interactions become infeasible as additional models are included to address the full suite of limiting factors.

This paper presents an integrated modeling strategy capable of characterizing multiple limiting factors within a single analysis framework. This framework has been implemented to facilitate high fidelity spatial assessments across large geographic regions. Three fundamental requirements needed to addressed as a part of the design and development of this integration framework.

1. Seamless integration of existing models—Each environmental process modeling tool to be included in the framework must be able to be integrated without changes to the existing source code. There exist today well-developed, peer-reviewed models that address individual aspects of this overall system. The computational framework must be able to preserve the significant investment that has been made developing these models and preserve historic peer review and validation.
2. Plug and play interaction—This requirement enables models to be moved into and out of the analysis depending upon the needs of a particular scenario, as well as allowing dynamic version control when model updates are released
3. Intuitive, real-time interaction—The ability to assemble analysis scenarios and visualize results is critical. The integrated computational engineering will be used by a number of different groups and individual, each with different skills and different analysis needs. The framework needs to be able to each of their visualization and interaction needs.

A case study will demonstrate the initial implementation of the modeling framework and its ability to deliver scenario results to the user. The case study demonstrates how multiple constraints can be simultaneously considered as a part of assessing sustainable agricultural residue removal potential.

BACKGROUND

There are two connected challenges being addressed through this work. The first is establishing a modeling pathway to more comprehensively addressing the multiple factors that determine sustainable limits of residue removal. The second is developing a computational framework that can facilitate the assembly and use of the disparate models required to answer the questions at hand. Each of these challenges has research history to build from in this development effort.

Previous Work on Sustainable Residue Assessments

In the past the majority of efforts regarding sustainability concerning agricultural crop residue removal have focused primarily on limiting water and wind erosion to the NRCS-mandated tolerable soil loss and much less on maintaining soil tilth or productivity. This was primarily due to the availability of erosion-based models such as USLE, RUSLE, and RUSLE2 that were simple to apply in detail (e.g., soil-type level) across large areas. Computational efforts to investigate crop residue removal effects on soil tilth and productivity Required much more complex models that were more difficult to apply to large areas [13]. However, in recent years, efforts have been stepped up to incorporate soil productivity concerns as part of a total removal analysis especially with the incorporation of USDA's Soil Conditioning Index which is directed at assessing the effect of stover removal rates on soil carbon and has been incorporated into the latest RUSLE2 [14] and WEPS (Wind Erosion Prediction System) models [15].

Larson et al. [16] conducted a study to investigate crop residue removal and its effect on soil erosion in large-scale resolution areas (MLRA's) of the United States including the Corn Belt, the Great Plains, and the Southeast. The effect of tillage practices (conventional, conservation, and no-till) and residue management were investigated with respect to rainfall and wind erosion, runoff, and potential nutrient removal. They concluded that limitations exist with respect to crop residue removal. Soil carbon, tilth, and productivity maintenance was not considered.

Nelson [11] expanded on Larson's analysis and developed a methodology to estimate the permissible removal rates of corn stover and spring and winter wheat straw from continuous corn and wheat rotations on an annual basis at the soil type level subject to consideration of rainfall and wind-induced soil erosion as a function of reduced and no-till field management practices. Nelson et al. [12] took the same soil-type-based approach and assessed five other major one and two-year cropping rotations such as corn-soybean, but neither of these studies included aspects related to soil organic matter as a function of removal. The following discussion provides information of the key models that have been used historically for these type of analyses, and are integrated into a more robust analysis tool through this work.

Revised Universal Soil Loss Equation 2 (RUSLE2)

RUSLE2 is intended to describe main effects of agricultural cropping practices on soil erosion by rainfall and/or overland flow and is mainly intended to be used as a guide for conservation planning and to represent trends demonstrated in field data[17,18]. RUSLE2 can be, and has been, applied to applications involving cropland, pastureland, rangeland, and disturbed forest land[19,20,21,22]. The equation for RUSLE2, presented in equation (1) provides a daily calculation of certain time-varying factors that define soil erosion due to rainfall.

$$a = r\ k\ l\ s\ c\ p \qquad (1)$$

where:

r - Rainfall/Runoff	s - Slope steepness
k - Soil erodibility	c - Cover-management
l - Slope length	p - Supporting practices

RUSLE2 computes both temporal and spatially variable effects such as the effect of soil and management varying along a hillslope. RUSLE2 uses a set of databases concerned with soils, field management (e.g., tillage), climate, vegetation and crop growth that are used at various times during the simulation period to make daily and/or annual soil loss calculations. Essentially the prediction of an average annual soil loss is a function of both erodibility and erosivity with erodibility related to the susceptibility (inverse of resistance) of the soil to erosion and affected by management and erosivity (a function of climate and management) a measure of the forces actually applied to the soil by the erosive agents of raindrop impact, waterdrops falling from plant canopy, and surface runoff. RUSLE2 was used in this project to provide average annual estimates of soil erosion on individual soils types for a variety of cropping rotations both with and without residue removal.

Several previous efforts have utilized RUSLE2 to simulate water erosion processes within broader analysis efforts ranging from watershed scale soil quality assessments [23], to assessing risks at abandoned mining sites[24], and even socio-economic impacts of biophysical processes[25]. These studies implemented RUSLE2 within a manual data flow process where direct human interaction with the RUSLE2 user interface was required for each model run. Modeling systems requiring this level of interaction are limited in the number and character of simulations that can be included in an analysis. Several efforts have worked to overcome these limitations by building conceptual models representations of RUSLE2 [26], or custom recoding of the RUSLE2 equation set [27]. These approaches to utilizing the model technology allow for more flexibility in application, but don't allow the custom tools to leverage the significant multi-institution investment already put into validating the version controlled RUSLE2 core model.

Wind Erosion Prediction System (WEPS)

WEPS is similar to RUSLE2 in that it is process based daily time step model that supplies soil erosion estimates due to wind forces by direction and magnitude[28,29]. WEPS, just like RUSLE2, simulates daily changes in field conditions based on soil aggregation, surface wetness, field management practices, and residue status (quantity present on the field and standing or flat) and is driven by daily weather parameters. The factors that comprise WEPS are very similar to those used in RUSLE2 with parameters for climate, soils, field scale, cropping rotations and growth, and field management. WEPS builds upon the previous wind erosion methodology (WEQ, Wind Erosion eQuation circa 1965) that was designed to provide gross estimates of wind erosion[30]. WEPS provides detailed data/information in annual and period erosion events as well as saltation/creep, suspension, PM-10 emissions, wind energy, and boundary loss which can further help estimate off-site impacts. WEPS also employs many different databases similar to those used in RUSLE2 to make daily and annual wind erosion calculations.

WEPS has significantly less history than RUSLE2 of use within integrated modeling environments. Previous efforts have utilized WEPS with GIS tools to perform wind erosion soil loss assessments across different spatial extents[32,33,34]. The relationship between the GIS tools and the WEPS model in these studies does not represent dynamic coupling as required for this analysis.

Model Integration Frameworks

The definitions of "framework" are varied and can refer to software libraries, software applications, structural components of a building, and everything in between. A general definition is "a basic structure underlying a system, concept, or text" [35]. In this discussion *framework* will refer to a software application that is the basic structure utilized to integrate, simulate, and understand complex systems. Currently available software frameworks that address one or more aspects of this task include a host of open-source and commercial packages. Examples of open-source frameworks include:

- SCIRun is used for scientific visualization and computational steering [36].
- Dataflow visualization-oriented packages such as OpenDX [37] are used for integration of visualization.
- The Common Component Architecture (CCA)-capable CCaffeine [38] is used for the numerical integration of large distributed simulation (e.g., nuclear simulation, munitions simulation)

Examples of closed-source packages include:

- Matlab's Simulink [39] is used to integrate third-party software such as LMS Virtual.Lab [40] with the Matlab

- Fiper [41], used for distributed collaboration of design teams. This package has been customized primarily for GE.
- Aspen Plus [42] is utilized for chemical process plant simulation
- ModelCenter [43] is used to integrate a wide range of third-party solvers (e.g., Excel™, user subroutines) with optimization and design space exploration
- Protrax [44] is used to model large plants at a system level

These packages tend to be targeted to specific applications (e.g., Aspen Plus to chemical process modeling and CCaffeine to terascale-level high-performance computing) and do not address the need for generalized framework that can be used to create integrated computational environments for engineering of generic complex systems and processes. SCIRun has computational steering capability and visualization support but does not provide an extensible method for integrating generic simulation and modeling tools. ModelCenter, Fiper, Protrax, and Matlab's Simulink all have support for the integration of specific sets of tools or for high-level systems modeling capability. Each of these packages fills a specific commercial need and provides a desired set of tools for a specific clientele but does not include the capability for the inclusion of a generic set of models.

Padula et al. [45] noted that the main issues facing the development of software frameworks are:

1. the verification and validation of federated simulation environments,
2. knowledge capture stemming from these large federated simulation environments, and
3. easy access to construct large simulations through graphical displays

One of Padula's key ideas is that many frameworks center around creating data repositories that tie information to the components they represent. These repositories then enable the users of the frameworks to seamlessly query information on a per-component basis. This work highlights the difficulty in creating a software framework to begin to address the other issues outlined by Padula.

In this research the goal of model integration framework is to enable integration of the modeling tools discussed in the previous section to create a comprehensive, accessible, and interactive decision space for engineering of complex systems. This framework needs to be able to provide the information needed to make informed decisions about sustainable agricultural residue removal. That is the framework needs to create an integrated simulation that is greater than the sum of the individual component models.

The integrated model framework presented in this paper primarily captures four of the limiting factors discussed previously: erosion, soil carbon, nutrient management, and soil water and temperature dynamics. The tools as presented here comprehensively address the erosion concerns with the accepted best methodologies available. The soil carbon analysis is qualitative in nature, with the approach implemented directly matching that used by NRCS to administer federally mandated conservation management planning. Nutrient dynamics are captured through the monitoring of plant nutrients removed through the specific harvest practices, and through the fertilizer applications rates. Nutrient issues for the purposes of this analysis are considered largely economic. As the framework expands to consider off-site impacts of nutrient run-off and atmospheric losses the detailed process modeling will be implemented. Soil water and temperature dynamics play a key role in the interaction between climate and the process models currently integrated in the framework.

THE INTEGRATED ENVIRONMENT PROCESS MODELING FRAMEWORK

As discussed earlier the agricultural residue removal tool described here must include the models must cover the dynamic processes related to soil carbon cycles, climate, wind and water erosion, and land management. The successful integration and use of these models also requires a series of data management modules which acquire, assemble, process, and format the scenario data for an integrated modeling assessment. There are three such modules that have been developed for this framework: a soils data module, climate data module, and management data module. The development of these modules has targeted an ability to move from raw, or original, datasets into the model specific formats required for each analysis scenario. This capability is important within the framework allowing the use of any number of potential spatial and temporal data sources that may be most appropriate for a given assessment. The initial development of these modules has focused on utilizing standard datasets which are well reviewed and accepted to perform the analyses.

Several basic rules for integration and interaction with unique environmental process models have been identified and adopted to guide the development of this framework. The most important of which is that each model has to be implemented within the framework in its executable form. That is, no code changes to any individual model are allowed by the framework development team. Each of the models entering the framework has extensive investment in validation, and using the models without internal changes preserves that validation. Another basic construct guiding integration is the framework will be run as a daily time step application. The extensive empirical data available from research on the environmental processes of interest clearly identify the relationship between daily climatic events, daily land management events and the critical processes. In this implementation of the framework only daily time step models are targeted.

The computational framework was developed using multiple programming languages and data management tools. The base functionality of the toolkit was built using C++. Database systems including Microsoft AccessTM, SQLite, and MySQL server are all accessible and utilized through the framework. The POCO C++ libraries were implemented to manage database interactions for the framework. Models integrated into the toolkit are wrapped using a custom C++ wrapper. The data management modules are built in C++ and compiled into shared libraries with an exposed two way data transfer interface to the core framework. Additional data processing libraries were implemented when available for each of the models integrated into the system. An available java library was implemented to organize and construct soils data inputs in one case. Another example was the use of a C++ library exposed through a model API to directly create climate scenarios within a model's database structure. The organization and data flow through the integration framework is presented in Figure 1.

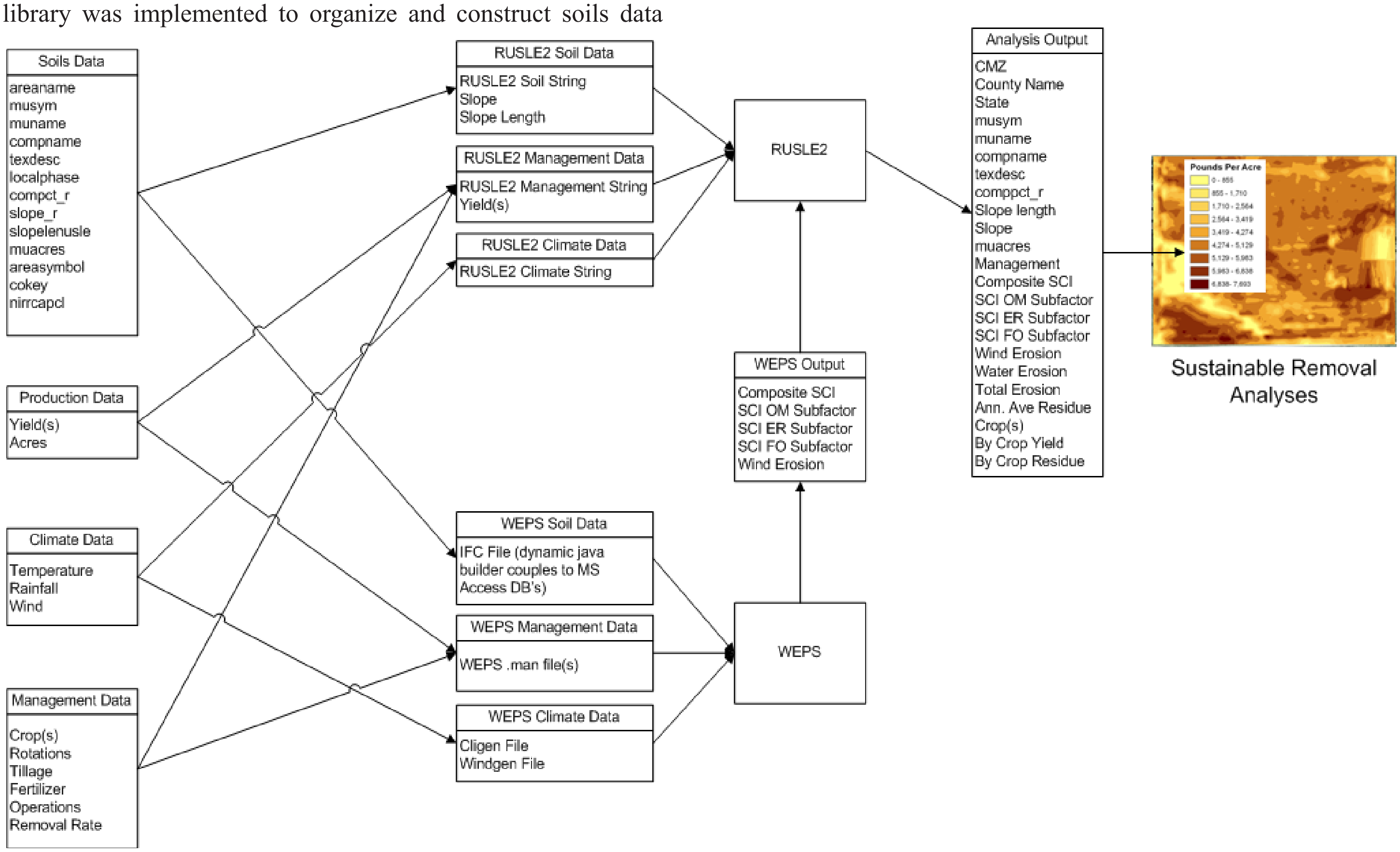

Figure 1. Supporting the following discussion, this figure represents the key components and data flow through this integrated modeling framework.

Soils Data Module

The base level spatial discretization for the environmental process models of interest for this work is soil identification. Soil Survey Geographic (SSURGO) database [46] is the most detailed level of soil mapping done by the Natural Resources Conservation Service (NRCS) and provides coverage for nearly all regions in the contiguous states. SSURGO will serve as the primary resource of soil data for this analysis framework facilitating unique investigations into predicted scenarios involving weather/climate change, cropping rotations, and alternative management practices.

The soils data module provides a mechanism for parsing SSURGO to the environmental process models within the framework. The importance of using simulation models in their native configuration means that each individual process model has a different format in which it receives soil data, e.g., ASCII/binary files and command line arguments. To facilitate a plug & play interaction, the soils data module is constructed in a way that allows each of the environmental process models to connect and receive soils data in a useable form contingent on the spatial scenario under investigation. Another consideration being accounted for is the effect of computer network and hardware limitations that may be imposed on users of the framework. To counteract these limitations, the soils data module is capable of using alternate data stores such as SQLite.

Having all soils information in an easily accessible database greatly enhances the speed at which data for a dynamic spatial assessment can be gathered in new simulations. Direct access to the National Soil information System (NASIS), which houses the SSURGO data, is currently unavailable to the general public. Various NRCS sponsored websites serve as a central delivery point for official soil survey (SSURGO) data, but data can only be downloaded one state at a time as tabular text files per county per table. In order to use this data, the NRCS provides a Microsoft (MS) Access "SSURGO template database" into which downloaded soil tabular data can be imported. This template provides a number of convenience routines for automatically generating soil data reports, but this requires manual interaction to extract the data. In addition, MS Access has a data capacity limit of around two gigabytes which is much too small to contain the entire SSURGO database.

As a solution to the problems mentioned above, downloaded SSURGO data was combined into a local MS SQL Server database with pertinent table relationships as shown in Figure 2. The table “LEGEND” contains all soil survey areas that have been completed in the SSURGO database. The tables “MAPUNIT”, “COMPONENT”, and “CHORIZON” contain most of the relevant data for each soil survey area. A map unit is a collection of defined areas that can be uniquely identified for each survey area. A map unit may be composed of one or more components which represent a particular soil type or unique area. Additionally, each component is divided into horizons or layers based on depth of the soil. Soil attributes can be obtained for each map unit by aggregating data for each horizon in a component and then for each component in the map unit. Since a particular map unit may not necessarily be confined within spatial boundaries of interest, the tables “LAOVERLAP” and “MUAOVERLAP” identify acreage overlap for certain geographic regions such as state and county borders. Using this derived database schema, an assortment of dynamic SQL queries were created giving the soils data module the ability to quickly extract the necessary information based on user input.

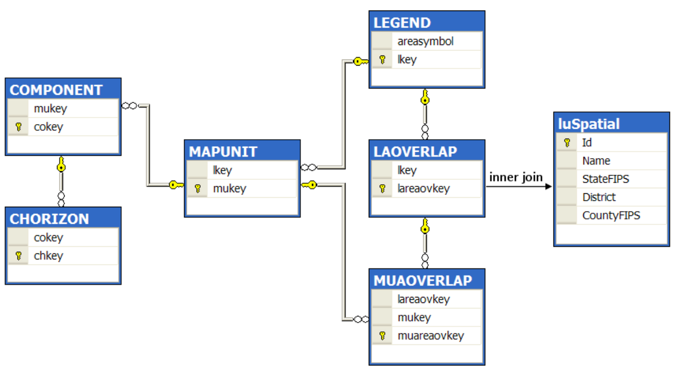

Figure 2. Local replicated SSURGO server database structure built within the Soils Data Module to efficiently manage hundreds of thousands of data records for the framework.

Climate Data Module

The environmental process models operating in the integrated environment are mechanistic daily time step models. They simulate the impact of daily climatic events on the specific environmental process(es) targeted by the model relative to soils and land management characteristics of the simulation scenarios. Generally similar daily climatic events such as high temperature, low, temperature, rainfall, sustained winds, wind gusts, etc., are used to drive each of the models. The format and extent of the data tends to be unique for each modeling tools though. The unique data characteristics can include pulling from different weather databases, using specialized input file formats, tracking different climate events, and even historical extent of climate event data required for the simulation.

To support the integrated modeling approach required in this work a generic climate data management module has been built. The fundamental charge of the climate module is providing a flexible toolset for interacting with multiple weather event databases and data structures, then assembling the data in the required format for the suite of models being utilized within the framework. The basic structure of climate module (Figure 3) is designed to pull data directly from databases where public web-service interaction is allowed, or from intermediate data structures such as portable database systems like Microsoft Access and SQLite, or even user-defined data files.

Climate data for RUSLE2 is assembled into the model’s native database format via the automated programming interface (API) discussed in greater detail in later discussion. To support the use of WEPS, the climate data module utilizes the climate generator models Cligen [47] and WINDGEN as an input data sources to generate weather files. Cligen and WINDGEN are stochastic weather generators that create daily weather events over specified temporal extents. Cligen generates daily values for precipitation, minimum and maximum temperature, solar radiation, dewpoint, and wind speed and direction for a single geographical location based on historical measurements [48] while WINDGEN wind generator provides accurate hourly wind speed and direction that enables capturing hourly erosion events.

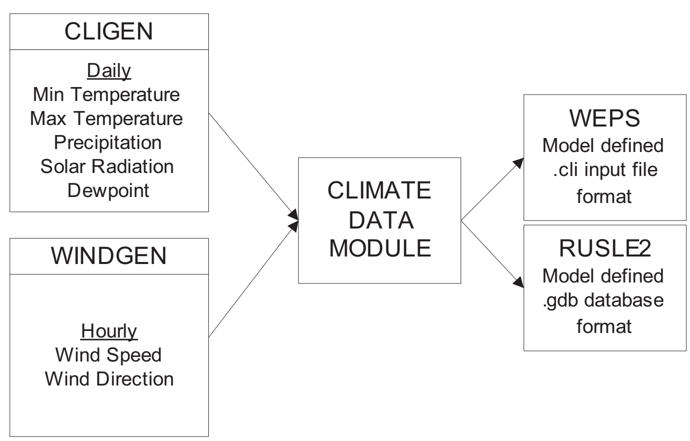

Figure 3. The basic functionality of the climate module is managing raw data, CLIGEN and WINDGEN generated data in this case, and distributing that data to the required format for the environmental process models.

Management Module

Mechanistically simulating the environmental processes of interest in this analysis requires a detailed representation of how the land is managed. The key criteria are vegetation and cropping rotation choices, soil tillage methods, fertilizer use and application methods, and harvesting practices. These criteria, and the details required about each criteria are duplicative across the models in the integrated environment. Similarly to the soils and climate event data discussed previously, the models utilized in this work have specialized formats for interaction with management data. To facilitate plug and play interaction a management module has been built. The structure and organization of the module heavily leverages the USDA NRCS data schema for management scenarios. Leveraging this schema is advantageous for several reasons, 1) multiple NRCS models are utilized in the framework, 2) the schema is comprehensive and regularly updated, and 3) leveraging the NRCS methodology employs the work of many additional practitioners.

The management module currently does not provide a dedicated user interface for assembling scenarios. The extensive NRCS database of operations and management processes is accessed through the RUSLE2 API, and unique or individualized scenarios can be constructed through the RUSLE2 or WEPS interfaces. The NRCS management template format is the management data interchange format utilized in the framework. Through the template format management scenarios can imported and assembled into the native formats for each of the models in the framework.

Water Erosion Model Integration

The RUSLE2 model integration approach implemented for this analysis has followed the previously stated requirements of 1) not changing version controlled source code, maintaining validation, and 2) facilitating plug and play interaction, which requires the dynamic exchange of data between the simulation environment and the RUSLE2 model. The framework has utilized the Rome DLL Automation API version of the RUSLE2 model. The framework is interacting with the API through a C++ interface. The framework interface is generic, taking the formatted scenario definition datasets from the Soils, Climate, and Management modules then dynamically exchanging the data with RUSLE2. Upon exchange of data, the framework interface delivers the required command structure telling the model to run, waits for completion, and receives model outputs making them available for other tools within the framework. Figure 4 demonstrates sample interface commands that communicate several of the key data parameters required for model execution, as well as the interface commands which acquire desired model outputs. Within the integrated framework, RUSLE2 iterations including assembling and distributing data, running the model, and getting back output take less than one second on average.

```
FileSetAttrValue(pProfile, "CLIMATE_PTR", static_cast < RT_CSTR > ( climatePtr.c_str() ), 0);
FileSetAttrValue(pProfile, "SOIL_PTR", static_cast < RT_CSTR > ( soilPtr.c_str() ), 0);
FileSetAttrValue(pProfile, "SLOPE_HORIZ", static_cast < RT_CSTR > ( slopeLenPtr.c_str() ), 0);
FileSetAttrValue(pProfile, "SLOPE_STEEP", static_cast < RT_CSTR > ( slopePtr.c_str() ), 0);
FileSetAttrValue(pProfile, "MAN_BASE_PTR", static_cast < RT_CSTR > ( managePtr.c_str() ), 0);

romeResults.push_back( ::RomeFileGetAttrValue(pProfile, "SLOPE_T_VALUE", 0) );
romeResults.push_back( ::RomeFileGetAttrValue(pProfile, "SLOPE_DEGRAD", 0) );
romeResults.push_back( ::RomeFileGetAttrValue(pProfile, "SLOPE_DETACH", 0) );
romeResults.push_back( ::RomeFileGetAttrValue(pProfile, "#RD:SOIL_COND_INDEX_PTR:SOIL_COND_INDEX_OM_SUBFACTOR", 0) );
romeResults.push_back( ::RomeFileGetAttrValue(pProfile, "#RD:SOIL_COND_INDEX_PTR:SOIL_COND_INDEX_RESULT", 0) );
romeResults.push_back( ::RomeFileGetAttrValue(pProfile, "ANNUAL_TOTAL_BIOMASS_REMOVAL", 0) )
```

Figure 4. Basic use of the RUSLE2 API is demonstrated.

As demonstrated in Figure 1, RUSLE2 runs completed the analysis flow. The RUSLE2 API is robust and facilitates the use of the model in this function. The critical inputs from the other models, discussed in greater detail in the following sections, are able to move through the RUSLE2 API with the appropriate mathematical impacts.

Wind Erosion Model Integration

The WEPS model consists of multiple executable components, including a java based user interface that manages the assembly of the analysis scenario and multiple FORTRAN executables that perform core model calculations. The FORTRAN executables use a set of input and output files to communicate with the java interface. The WEPS model interface built for this integration framework essentially replaces the primary functions of the java interface in creating and managing the input and output files that drive the core model executables. The framework utilizes the formatted scenario definition datasets from the Soils, Climate, and Management modules to assemble the WEPS input files dynamically. The comprehensive WEPS model wrapper distributes functionality between the data management modules discussed previously and the core integration wrapper here. In the case of soils data inputs, the WEPS model wrapper exposes a java library that builds and organizes the necessary soils data inputs. With completion of the data inputs as performed jointly between the data modules and WEPS wrapper, the basic model run parameters are set for the given analysis scenario of interest through the model wrapper. This includes building the custom WEPS run file, and establishing the correct command line arguments for the core WEPS Fortran executables. The wrapper then facilitates the parsing and distribution of results data for the continued analysis through the framework. Figure 5 demonstrates the basic process flow for the functions performed by the framework interface for the WEPS model. Within the framework, WEPS model iterations, including the exchange of data, construction of input files, running of the model, and acquisition of model results takes between five and ninety seconds depending on whether the model is being calibrated for a specific yield scenario.

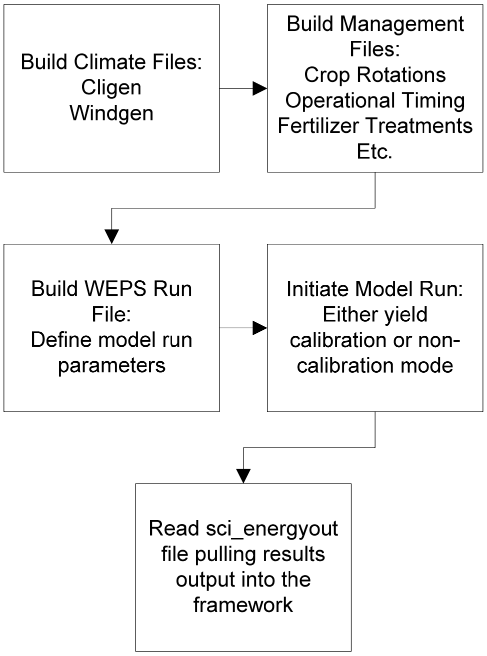

Figure 5. The WEPS model wrapper within the toolkit walk utilzes the data provided through the previously described models to perform all necessary functions setting up the WEPS model run scenario.

Soil Conditioning Index Modeling: Qualitative Soil Organic Carbon Metric

The Soil Conditioning Index (SCI) provides qualitative predictions of the impact of cropping and tillage practices on soil organic carbon. The SCI is comprised of three sub-factors, the organic matter sub-factor (SCI OM), the field operation sub-factor (SCI FO), and the erosion sub-factor (SCI ER). The SCI OM sub-factor models the amount of organic material returned and removed from the soil. The SCI FO sub-factor takes into consideration the effects of field operations on organic matter decomposition. The SCI ER sub-factor reflects the impacts of erosion on organic matter cycles. The three sub-factors are used to calculate the SCI as follows:

$$(\text{SCI OM} * 0.4) + (\text{SCI FO} * 0.4) + (\text{SCI ER} * 0.2) = \text{SCI}$$

Effective utilization of the SCI to assess the soil organic carbon impacts of agricultural residue removal scenarios requires coupled analysis with both the WEPS and RUSLE2 models. RUSLE2 models the SCI OM and SCI FO sub-factors, as well as accounting for the water erosion component of SCI ER sub-factor. The wind erosion component of the SCI ER sub-factor calculated by WEPS and a comprehensive composite SCI value must supply RUSLE2 with the required WEPS output. The model integration interfaces built for the RUSLE2 and WEPS models for this analysis facilitate the distribution of data between models required to accurately calculate the SCI.

RESULTS AND DISCUSSION

The following example demonstrates the application of the integrated modeling toolkit to perform a high spatial fidelity assessment of sustainable residue availability within a single management unit in Cerro Gordo County, Iowa. The farm being investigated is approximately 140 acres, and is managed utilizing typical agronomic practices for the region. The farm has been in a continuous corn for grain cropping rotation for the last six years, with a corn-soybean rotation having been implemented for at least the two prior decades. Reduced tillage practices using a chisel plow in the fall are used on this management unit. A fall manure application with slight surface residue processing and soil disruption has been utilized over the last six years of continuous corn rotation. Spring field cultivation is performed directly prior to planting. Fertilizer applications have varied based on annual weather constraints. Modeled fertilization for this analysis has been spring side dress application of N at varying rates based on the composition of the manure being applied. Yields on this management unit are slightly less than local production averages as non-genetically modified (GMO) varieties have been grown over the last several years. The management unit being investigated for this case study in comprised of seven SSURGO soils (Figure 6). These soils are typical of north central Iowa, having generally low slopes and moderate to high baseline organic matter.

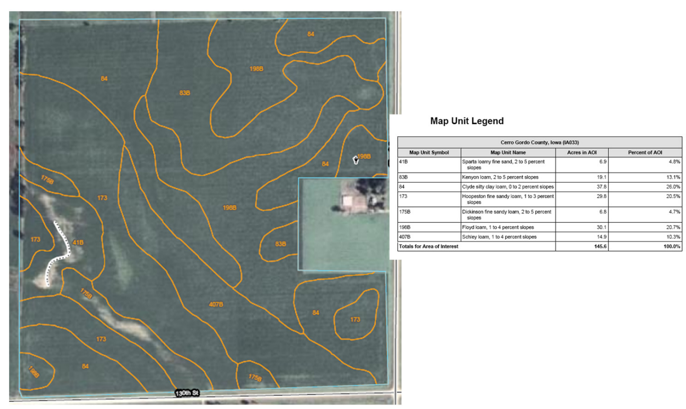

Figure 6. The SSURGO soil type layout for the management unit investigated in this case study.

Figure 7 represents actual yield maps collected by the yield monitor on the harvester in the fall of 2008 and 2009. Crop year 2009 had greater yield variation across the field due to two main factors: 1) flooding in the spring, and 2) lower than average heat units throughout the year. Both 2008 and 2009 had lower than normal average yields with 162 bu/acre and 154 bu/acre respectively. Significant across field variation was seen in both years also, with yields ranging from less than 120 bu/acre to over 250 bu/acre. In both years the vast majority of acres fall within the 140-200 bu/acre range. The map for 2008 represents 24,807 data collection points collected by the harvester across the field. The 2009 map is comprised of 31,363 data collection points. At each data point the GPS coordinates, elevation, grain moisture, wet mass of grain, wet volume of grain, dry mass of grain, dry volume of grain, and several operational performance criteria. The key data points of interest for this analysis were dry yield volume, reported in bu/acre, and the GPS coordinates overlaid with the SSURGO soil survey data in Figure 6 allowing identification of the soil type associated with each data collection point.

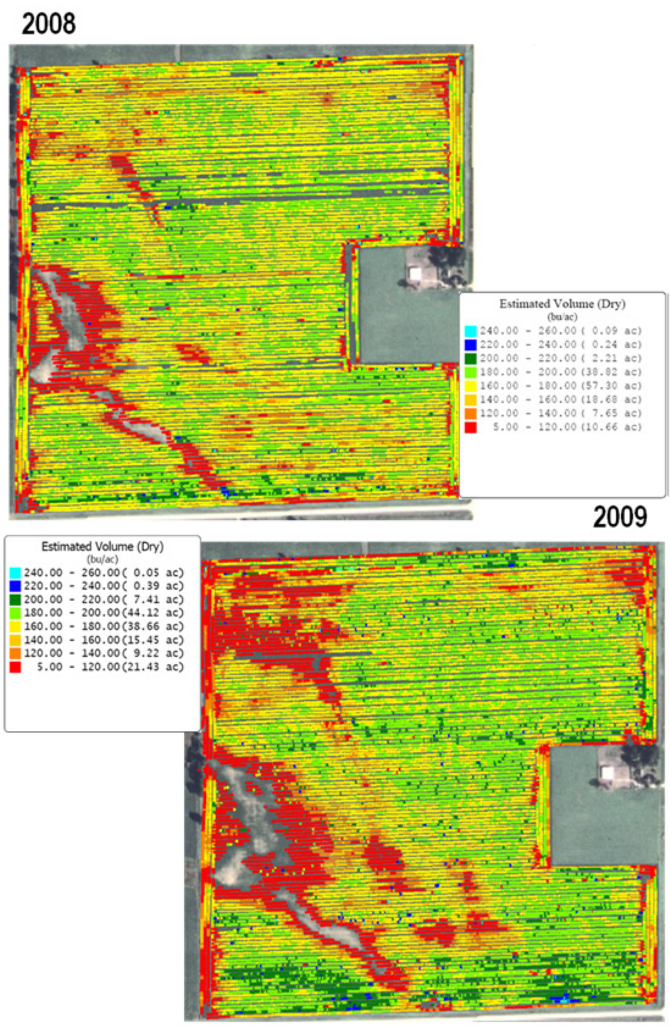

Figure 7. High spatial fidelity yield maps generated on the combine harvester utilized on the field being investigated in crop years 2008 and 2009.

The toolset was used to calculate the sustainable removal limit for a representative range of grain yields, 80 bu/acre – 250 bu/acre, as seen in the yield maps in Figure 7. Residue harvest was modeled as a direct baling operation where the combine is pulling and powering a large 3'x4'x8' square baler which takes material coming directly off the harvest to make the bales. The key enabling technology assumption made with the modeled residue harvest technology is the ability to control the residue moving through the machine and into the baler from 25% - 85% of the total residue. The modeled machine is a computational representation of a hypothetical variable rate harvester that this analysis is assessing the need.

Table 1. For each soil type removal rates from 25%-85% of the total corn stover were run through the toolkit with yields ranging from 80 bu/acre - 250bu/acre.

		80-250 bu/acre: 10 bu increments
41B	Sparta loamy fine sand, 2 to 5 percent slopes	25%-85% removal rate: 10% increments
83B	Kenyon loam, 2 to 5 percent slopes	25%-85% removal rate: 10% increments
84	Clyde silty clay loam, 0 to 2 percent slopes	25%-85% removal rate: 10% increments
173	Hoopeston fine sandy loam, 1 to 3 percent slopes	25%-85% removal rate: 10% increments
175B	Dickinson fine sandy loam, 2 to 5 percent slopes	25%-85% removal rate: 10% increments
198B	Floyd loam, 1 to 4 percent slopes	25%-85% removal rate: 10% increments
407B	Schley loam, 1 to 4 percent slopes	25%-85% removal rate: 10% increments

The sustainable removal analysis matrix supporting this case study is represented in Table 1. The integrated model set was iterated for 7 soils, 7 removal rates, and 18 yields for a total of 882 iterations. Upon completion of the model runs, for each soil and yield scenario the highest removal rate which met sustainability requirements was selected. Sustainability requirements for this analysis were set as 1) not exceeding combined tolerable soil erosion losses (wind and water) as set by NRCS for each soil type, and 2) a combined Soil Conditioning Index (SCI) Organic Matter sub-factor (SCI-OM) greater than zero, which demonstrates that the scenario at a minimum maintains current soil organic matter levels. Table 3 represents the maximum sustainable removal rate for each soil and yield scenario.

Table 2. The toolkit was then used to down select the maximum sustainable removal rate for each scenario.

SCI-OM		80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
41B	Sparta loamy fine sand, 2 to 5 percent slopes	-	-	-	-	-	-	2,010	2,144	3,166	3,353	3,539	4,755	4,993	5,231	5,469	6,926	7,215	7,503
83B	Kenyon loam, 2 to 5 percent slopes	-	-	-	-	1,741	2,607	2,793	2,980	4,042	4,280	4,517	5,771	6,059	6,348	6,637	8,127	8,465	8,804
84	Clyde silty clay loam, 0 to 2 percent slopes	-	1,339	2,047	2,234	3,090	3,328	4,327	4,616	4,904	5,193	6,432	6,771	7,110	7,449	7,788	9,310	9,698	10,086
173	Hoopeston fine sandy loam, 1 to 3 percent slopes	-	-	-	-	1,741	2,607	2,793	2,980	4,042	4,280	4,517	5,771	6,059	6,348	6,637	8,127	8,465	8,804
175B	Dickinson fine sandy loam, 2 to 5 percent slopes	-	-	-	-	1,741	2,607	2,793	2,980	4,042	4,280	4,517	5,771	6,059	6,348	6,637	8,127	8,465	8,804
198B	Floyd loam, 1 to 4 percent slopes	-	-	-	-	1,741	2,607	2,793	2,980	4,042	4,280	4,517	5,771	6,059	6,348	6,637	8,127	8,465	8,804
407B	Schley loam, 1 to 4 percent slopes	-	-	-	-	1,741	2,607	2,793	2,980	4,042	4,280	4,517	5,771	6,059	6,348	6,637	8,127	8,465	8,804

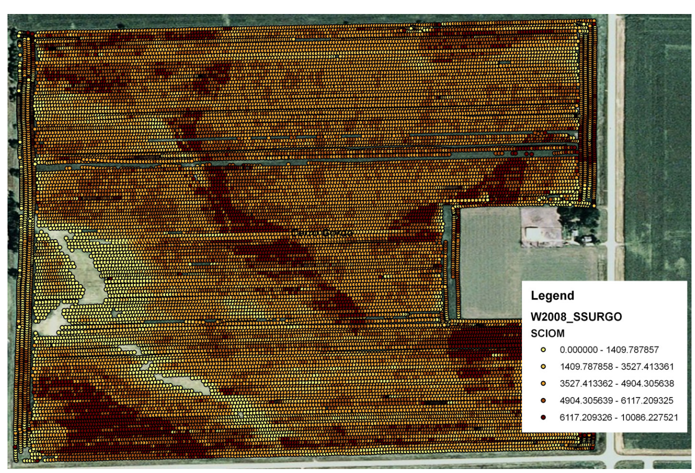

Figure 8. The maximum sustainable removal rate results were then applied to each point on the yield map.

The final step in the case study analysis was assigning the maximum sustainable removal rates (Table 2) for each scenario to each of the yield data points in Figure 7. A linear interpolation was used for yields in between the 10 bu/acre increments for which the full sustainability analysis was run. Using GIS tools, each yield data point was identified with its corresponding soil type and the yield was rounded to the nearest integer value and a sustainable residue removal rate was then assigned. Figure 4 maps the modeled sustainable removal rate to each of the yield data points for the 2008 yield map. The variability in available corn stover residue is vast, ranging from 0 lbs/acre to over 8,000 lbs/acre. The mapping in Figure 8 also demonstrates the impact of soil characteristics in conjunction with grain yield. Figure 9 shows this data with a sustainable residue yield contour plane across the management unit. Figure 6 shows the 2009 modeled sustainable residue removal rates in the point map (top) and contour plane (bottom).

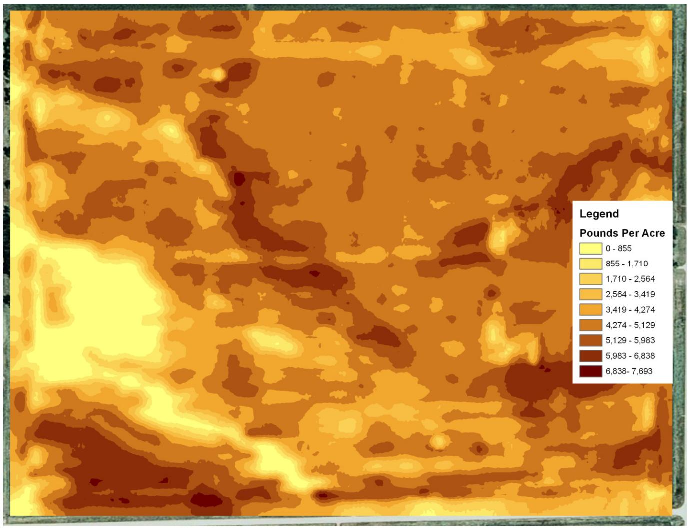

Figure 9. A kriging technique was used to create a contour plane which can be used as a guiding decision tool for residue removal.

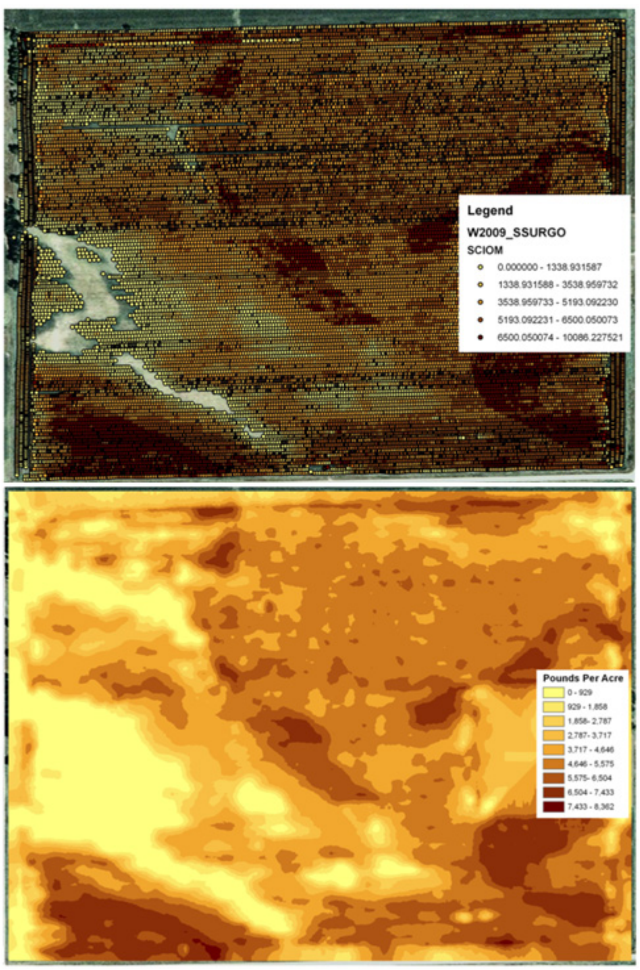

Figure 10. Map visualizations were representing the 2009 yield dataset.

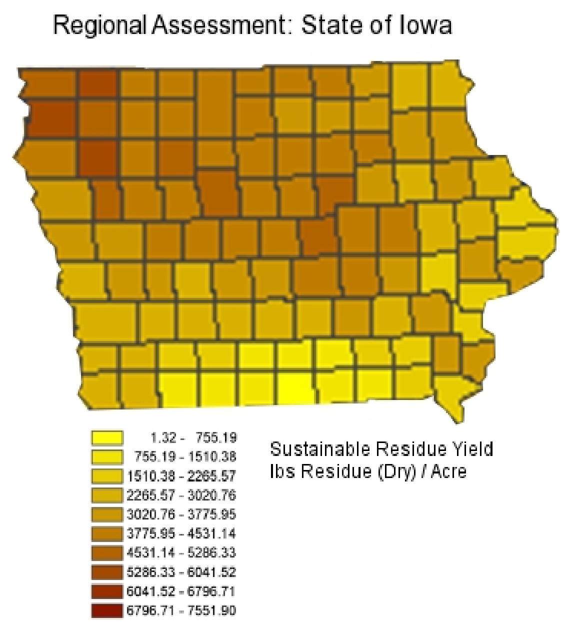

Figure 11. The integrated modeling framework is built to be efficient and flexible supporting large iterative assessments over large spatial extents.

Another important function as part of the analysis supported by this integration framework is developing assessments of sustainably accessible agricultural residues across large spatial extents. Figure 11 represents the results of an analysis for the state of Iowa. In this assessment the high fidelity yield and management practice data is clearly not available for all land units. Instead, statistics assembled by USDA have been used to get county averages for yield, cropping rotations and management practices. For all of the SSURGO soils across a county each possible rotation and management scenario is run. Then averaging across a counties soils and production statistics is used to assign a county level average residue removal rate. As demonstrated in Figure 11, even a highly productive state like Iowa has significant variation is sustainably available agricultural residues.

CONCLUSIONS

The modeling framework described here has successfully integrated disparate environmental process models to support multi-factor assessments of sustainable agricultural residue availability. These assessments are challenging because several unique environmental processes can limit residue access. Validated and peer-reviewed models exist to support analysis of the important environmental processes, but they have been developed as stand-alone tools with little or no concern about their ability to be deployed in integrated analysis architecture. The framework developed for these models has overcome a series of software and data management challenges accomplishing the goal of integrated model assessments. The framework is robust, flexible, and computationally efficient supporting analyses at multiple scales and fidelities. The framework is currently being employed to support decisions at the management unit level for several projects demonstrating feasibility of agricultural residue removal. It is also being used to support sustainable residue potential analyses for multiple regional and national resource assessment projects.

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REFERENCES

[1] WW Wilhelm et al. (2010) “Balancing limiting factors and economic drivers for sustainable Midwest agricultural residue feedstock supplies” Industrial Biotechnology. October 2010, Vol. 6, No. 5: 271-287

[2] Bauen and Kaltschmitt, 2001, “Current use and potential of solid biomass in developing countries and their implications for CO2 emissions.” In: *Proceedings of 1st World Biomass Conference*, James & James, London.

[3] Department of Energy, Office of Biomass Programs. (2010) “Multi-Year Program Plan”. http://www1.eere.energy.gov/biomass/pdfs/mypp.pdf. March 2010.

[4] Energy Independence and Security Act, 2007, *Independence and Security Act of 2007: A Summary of Major Provisions*, Retrieved March 6, 2011 from http://energy.senate.gov/public/_files/RL342941.pdf.

[5] Department of Energy, Office of Biomass Programs. (2005). “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply”. Retrieved March 6, 2011, from http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf.

[6] Johnson JMF, Papiernik SK, Mikha MM, Spokas K, Tomer MD, Weyers SL, 2009, *Soil processes and residue harvest management. Advances in Soil Science: Soil quality and biofuel production*, Lal R. and Steward B. (eds.) CRC Press, Taylor and Francis Group, Boca Raton, FL., pp. 1–44.

[7] Johnson JMF, Reicosky D, Allmaras R, Archer D, Wilhelm WW, 2006, “A matter of balance: Conservation and renewable energy,” *J. Soil Water Cons*, **61**, pp. 120A–125A.

[8] Wilhelm WW, Johnson JMF, Karlen DL, Lightle DT, 2007, “Corn stover to sustain soil organic carbon further constrains biomass supply,” *Agron. J.*, **99**, pp. 1665–1667.

[9] Karlen DL, Andrews SS, Wienhold BJ, Doran JW, 2003, “Soil quality: Humankind’s foundation for survival,” *J. Soil Water Cons*., **58**(4), 171–179.

[10] Graham, R.L., R. Nelson, J. Sheehan, R.D. Perlack, and L.L. Wright, 2007, “Current and Potential U.S. Corn Stover Supplies,” *Agron. J.*, **99**, pp. 1-11.

[11] Nelson, R.G., 2002, "Resource Assessment and Removal Analysis for Corn Stover and Wheat Straw in the Eastern and Midwestern United States – Rainfall and Wind Erosion Methodology," *Biomass & Bioenergy*, **22**, pp. 349-363.

[12] Nelson, R.G., Marie E. Walsh, John J. Sheehan, and Robin L. Graham, 2004, “Methodology to Estimate Removable Quantities of Agricultural Residues for Bioenergy and Bioproduct Use,” *Applied Biochemistry and Biotechnology*, **113**, pp. 0013-0026.

[13] Predicting Soil Erosion by Water. A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). United States Department of Agriculture, Agricultural Research Service, Agricultural Handbook Number 703, 1997.

[14] RUSLE2, 2010, *Revised Universal Soil Loss Equation, Version 2 (RUSLE2), Official NRCS RUSLE2 Program, Official NRCS Database*. Retrieved March 6, 2011, from http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm.

[15] NRCS-WEPS, 2011, *Official NRCS-WEPS Site, Wind Erosion Prediction System*. Retrieved March 6, 2011, from http://www.weru.ksu.edu/nrcs/wepsnrcs.html.

[16] Larson et al. Effects of tillage and crop residue removal on erosion, runoff, and plant nutrients. In: Journal of Soil and Water Conservation, Special Publication No. 25, Soil Conservation Society of America, Ankeny, IA., 1979.

[17] D.K. McCool, G.R. Foster and D.C. Yoder, 2004, “The Revised Universal Soil Loss Equation,” Version 2 ISCO 2004 – 13th International Soil Conservation Organisation Conference – Brisbane, July 2004.

[18] G.R. Foster, D.C. Yoder, G.A. Weesies, T.J. Toy,2003, “The Design Philosophy Behind RUSLE2: Evolution of an Empirical Model,” Pp. 95-98 in Soil Erosion Research for

the 21st Century, Proc. Int. Symp. (3-5 January 2001, Honolulu, HI, USA), ASAE. 701P0007.

[19] Ismail, J, 2008, "RUSLE2 model application for soil erosion assessment using remote sensing and GIS," *Water Resources Management*, **22**(1), pp. 83.

[20] Dabney, S.M., Yoder, D.C., Foster, G.R., Nearing, M.A., 2006, "Application of RUSLE2 to Pasturelands," Proceedings of the 14th International Soil Conservation Organization Conference, May 14-19, 2006, Marrakesh, Morocco.

[21] Foster, G., Romkens, M.J., Dabney, S.M., 2006, "Soil erosion predictions from upland areas - a discussion of selected RUSLE2 advances and needs," Beijing, China, Nov. 25-26, 2006. Proceedings of the Sino-American Workshop on Advanced Computational Modeling in Hydroscience and Engineering.

[22] Schmitt, L. K., 2009, "Developing and applying a soil erosion model in a data-poor context to an island in the rural Philippines," *Environment, Development and Sustainability*, **11**(1), pp. 19.

[23] Douglas L. Karlen, Mark D. Tomer, Jerry Neppel, Cynthia A. Cambardella, 2008,"A preliminary watershed scale soil quality assessment in north central Iowa, USA," *Soil and Tillage Research*, **99**(2), pp. 291-299.

[24] Vaszita, Emese; Siki, Zoltán; Gruiz, Katalin, 2009, "GIS-based quantitative hazard and risk assessment of an abandoned mining site," *Land Contamination & Reclamation*, **17**(3-4), pp. 513-529.

[25] Halim, R., Clemente, R. S., Routray, J. K. and Shrestha, R. P.,2007, "Integration of biophysical and socio-economic factors to assess soil erosion hazard in the Upper Kaligarang Watershed, Indonesia," *Land Degradation & Development*, **18**, pp. 453–469.

[26] XU Hai-yan,ZHAO Wen-wu,XIE Chun-ying,JIN Ting, 2010, "Multiscale Soil Loss Evaluation Model Based on Component Object Model GIS Technology," *Research of Soil and Water Conservation*.

[27] Tom L. Richard, Ed Van Ouwerkerk, and Rob Anex, 2007, "I-FARM – A decision tool for biomass production," 29th Symposium on Biotechnology for Fuels and Chemicals. Denver, CO. 2007

[28] L.E. Wagner and J. Tatarko. Pp. 372-375 in Soil Erosion Research for the 21st Century, Proc. Int. Symp. (3-5 January 2001, Honolulu, HI, USA). Eds. J.C. Ascough II and D.C. Flanagan. St. Joseph, MI: ASAE. 701P0007.

[29] Flanagan, D.C., Ascough II, J.C., Wagner, L.E., 2008, "Development of a common water and wind erosion model for soil conservation planning," In: Proceedings of the AgroEnviron 2008 (Sixth International Symposium AgroEnviron), April 28-May 1, 2008, Antalya, Turkey. p. 12.

[30] Skidmore, E.L., 2007, "Predicting Wind Erosion: WEQ/WEPS," Proceedings of the American Society of Agricultural and Biological Engineers International (ASABE) 2007 Annual International Meeting, 17-20 June 2007, Minneapolis, Minnesota. 2007 CDROM.

[31] Skidmore EL. Wind erosion. In: Soil erosion research methods. Anakeny, IA: Soil and Water Conservation Society, 1988.

[32] Guanglong, F., Sharratt, B.S., 2007, "Scaling from Field to Region for Wind Erosion Prediction Using WEPS and GIS," *Journal of Soil and Water Conservation*, 62:312-328.

[33] Hagen, L. J., 2010, *Erosion by Wind: Modeling Encyclopedia of Soil Science: Second Edition.* 1-4, < http://www.informaworld.com/10.1081/E-ESS-120044016 >, accessed 18 September 2010.

[34] Shao, Y, 2009, "Physics and Modeling of Wind Erosion," *Atmospheric and Oceanographic Sciences Library*, Volume 37, 1-11, DOI: 10.1007/978-1-4020-8895-7_1, http://soils.usda.gov/sqi/concepts/soil_organic_matter/som_sci.html.

[35] Soanes, C. & Stevenson, A. (2005). *Concise Oxford English Dictionary.* New York: Oxford University Press, USA, p. 368.

[36] SCI Institute, 2011, SCIRun, *Scientific Computing and Imaging Institute.* Retrieved March 6, 2011, from http://www.sci.utah.edu/cibc/software/106-scirun.html.

[37] OpenDX, 2011, OpenDX: The Open Source Software Project Based on IBM's Visualization Data Explorer, *OpenDX.* Retrieved March 6, 2011 from http://www.opendx.org.

[38] Allan, B., Armostrong, R., Lefantzi, S., Ray, J., Walsh, E., & Wolfe, P. (2005)., Ccaffeine - a CCA component framework for parallel computing, *The Common Component Architecture Forum*. Retrieved March 6, 2011, from http://www.cca-forum.org/ccafe.

[39] The MathWorks, Inc., 2011, Simulink, *The MathWorks: Accelerating the pace of engineering and science*. Retrieved March 6, 2011 from http://www.mathworks.com/products/simulink.

[40] LMS International, 2011, Solutions overview, 3D virtual prototype simulation, LMS Virtual Lab, *LMS Engineering Innovation.* Retrieved March 6, 2011, from http://www.lmsintl.com/simulation/virtuallab.

[41] Engineous Software, 2011, Fiper, *Engineous Software*. Retrieved March 6, 2011, from http://www.simulia.com/products/see.html.

[42] AspenTech, 2011, AspenOne, *AspenTech*. Retrieved March 6, 2011 from http://www.aspentech.com.

[43] Phoenix Integration, Inc., 2011, Products, *Phoenix Integration.* Retrieved March 6, 2011, from http://www.phoenix-int.com/software/phx_modelcenter.php.

[44] Pro-Trax, 2011, ProTRAX Suite, *Simulation Software.* Retrieved March 6, 2011 from http://www.traxintl.com/simulator-systems/simulation-software.

[45] Padula, S. L., & Gillian, R. E., 2006, "Multidisciplinary environments: A history of engineering framework development," AIAA 2006-7083, Portsmouth, VA, AIAA.

[46] SURGO, 2011, http://soils.usda.gov/survey/geography/ssurgo/

[47] USDA Cligen (2011). Cligen, *Cligen Overview*. Retrieved

March 6, 2011, from http://www.ars.usda.gov/Research/docs.htm?docid=1809
[48] Windgen, 2011, http://www.ars.usda.gov/Research/docs.htm?docid=18094