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Agricultural Biomass Removal Rate Estimation for Real-time Optimization of Single Pass Crop Grain and Biomass Harvesting System

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Abstract. As the demand for biomass feedstocks grows, agricultural residue may be removed in a way that compromises soil sustainability due to increased soil erosion, depletion of organic matter and deterioration of soil physical characteristics. Since soil erosion from agricultural fields depends on several factors including soil type, field terrain and cropping practice, the amount of biomass that can be removed while maintaining soil tilth varies substantially over space and time. The RUSLE soil erosion model, which takes into account these spatio-temporal variations, was used to estimate sustainable agricultural biomass removal rates for single pass crop grain and biomass harvesting system. Soil type, field topography, climate data, management practices and conservation practices were stored in individual databases on a state and/or county basis. Geographic position of the field was used as a spatial key to access the databases to select site specific information such as soil, topography and management related parameters. These parameters along with the actual grain yield

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were provided as the inputs to the RUSLE model to calculate the yearly soil loss per unit area of the field. An iterative technique was then used to determine the site-specific biomass removal rate that keeps the soil loss below the soil loss threshold (T) of the field. The sustainable removal rate varied substantially with field terrain, crop management practices and soil type. At a location in a field in Winnebago county, Iowa with ~1% slope steepness and conventional tillage practice, up to 98% of 11 Mg/ha total corn stover was available for collection with negligible soil loss. The study, however, has considered only the soil erosion tolerance level and has neglected the potential effects in organic matter content and other biophysical properties of the soil due to excessive biomass removal. There was no biomass available to remove with conventional tillage practice in steep slopes such as a location in Crawford County, Iowa field with a 12.6% slope. If no-till crop practices were adopted, up to 70% of available biomass could be collected at the same location with 12.6% slope. In case of soybean-corn rotation with no-till practices, about 98% biomass was available for removal at the locations in Winnebago field with low slope steepness, whereas 77% biomass was available at a location in the Crawford field with 7.5% slope steepness. Sustainable removal rates varied substantial over an agricultural field, which showed the importance of site specific removal rate estimation. These sustainable removal rates will be provided as recommended rates for the producers to use during a single pass crop grain and biomass harvesting operation. This type of site-specific biomass removal rate estimation is necessary to achieve field level sustainability in agricultural biomass production and collection systems.

Keywords. corn stover, biomass feedstocks, biomass harvesting, variable rate removal, sustainable agricultural production, rainfall erosion, soil loss

1 Introduction

2 One of the most critical challenges the world is facing today is the increasing demand for
3 energy. To minimize the adverse effects on environment and the dependence on non-
4 renewable fossil fuels, renewable energy sources must be explored and expanded in every
5 possible dimension (Glassner et al., 1999). Because the use of grain to produce ethanol will
6 likely increase the food prices, there is a rapidly increasing interest in using biomass for bio-
7 fuel generation. Studies have shown the potential and importance of using cellulosic biomass
8 for bio-fuel and other bioenergy generation. University researchers and private companies are
9 developing and improving technologies and infrastructure for the fuel production from cellulosic
10 biomass (Hettenhaus et al. 2000). The US Department of Energy (USDOE, 2007) has set a
11 30*30 goal which aims to replace 30% of fossil fuel with bio-fuel by the year 2030. One billion
12 dry ton of biomass feedstock is necessary to meet this goal, which will not be possible without
13 extensive use of various types of cellulosic biomass (Perlac et al., 2005). In recent years, the
14 use of energy crops, forest biomass and agricultural residue have been widely studied as viable
15 sources of cellulosic biomass (Wilhelm et al., 2004; Andrews, 2006). Among these sources,
16 agricultural residues, particularly corn stover, has been the primary focus because of its instant
17 availability in huge quantities and relatively low cost (DePardo, 2000; Allmaras et al., 2000;
18 Wilhelm, 2004; Blanco-Canqui, 2010). Consequently, agricultural biomass such as corn stover
19 has been and will be collected at a steadily increasing rate to meet the increasing demand of
20 biomass feedstocks in short to medium term.

21 Although agricultural biomass is a renewable energy source with great potential, it also
22 presents sustainability challenges due to its interdependence with the soil and environment.
23 Various studies have shown that excessive removal of agricultural biomass from the fields will
24 have adverse effects on soil quality and environment. Soil structure, soil organic matter (SOM)
25 content, soil organic carbon (SOC) sequestration, nutrient cycling, soil biodiversity and crop
26 production can be affected if crop biomass is removed without considering the sustainability
27 issues (Karlen et al., 1994; Andrews, 2006; Blanco-Canqui, 2010). Lindstrom (1986) found that
28 increased corn stover removal at both reduced tillage and no tillage planting system will
29 increase the water runoff and soil erosion, which may cause the nutrient removal to exceed the
30 nutrients available from the standard fertilization practices. Studies such as Wilhelm et al.
31 (2007) and Blanco-Conqui et al. (2009) have shown that SOM will decrease with increased corn
32 stover removal. Karlen et al. (1994) found that a continuous removal of crop residue over a
33 decade will cause reduced soil carbon, microbial and fungal activities and earthworm
34 populations, which will lead to poor agricultural soil function. According to Hargrove (1991),
35 surface biomass residue provides positive impacts on soil quality, which will lead to increased
36 yields. However, other studies showed an improved crop yield when residue was removed
37 (Swan et al., 1987). These conflicting results suggest that the effect of biomass removal on yield
38 may not be substantial in short term. However, the yield is very likely to decrease in the long run
39 with continuous biomass removal due to increased erosion, reduced SOM and nutrients and
40 lowered biodiversity (Andrews, 2006). Therefore, it is necessary to be careful in removing
41 agricultural residue so that degradation of soil and environment is prevented and agricultural
42 production can be sustained.

43 To ensure the sustainability of agricultural production systems, only a certain proportion
44 of biomass can be removed from agricultural fields. The actual removable amount depends on
45 various parameters related to the agricultural field, cropping systems and environment. The
46 effect of residue removal from agricultural fields will be more adverse in conventional tillage
47 systems, which suggest a strong interaction between the tillage and the amount of biomass that
48 can be removed safely (Benoit and Lindstorm, 1987; Linden et al., 2000; Wilson et al., 2004).

49 Sustainable biomass removal rate also depends on soil type and condition (Benoit and
50 Lindstorm, 1987) and crop type and crop rotation (Reicosky, 1995; Dick, 1998). Climate is
51 another factor influencing the available biomass for sustainable removal (Wilhelm, 2004). Potter
52 et al. (1998) compared the effects on soil quality due to biomass removal in various climatic
53 conditions and found that climatic conditions interact strongly with the biomass removal rate.
54 Field topography will be another important factor as the level of soil erosion depends heavily on
55 the slope and slope length. Andrews (2006) recommended the use of tools such as revised
56 universal soil loss equation (RUSLE), wind erosion equation (WEQ), or the soil conditioning
57 index to estimate sustainable crop residue removal rate, which take into account the factors
58 such as soil type, terrain, management practices and yield in determining the sustainable
59 removal rate.

60 Some researchers have estimated the sustainable agricultural biomass removal rates for
61 different types of crops in various US states. Nelson (2002) used tolerable soil loss due to
62 water/rain and wind erosion to calculate the recommended corn stover and wheat straw removal
63 rates for 37 US states. Nelson et al. (2004) performed similar studies for corn and wheat straw
64 in 10 largest corn producing states in mid-western USA. RUSLE was used as the water erosion
65 model. In these studies, county level average removal rates were determined and a 20%
66 general biomass removal rate was recommended. McAloon et al., (2000) suggested an average
67 corn stover removal rate of 30% and Hettenhaus et al. (2000) suggested an average rate of
68 50% - 60% for the sustainable agricultural production in the corn-belt. Sheehan et al. (2004)
69 applied the methodology of Nelson (2002) in 99 counties of the state of Iowa and suggested that
70 about 40% of the residue can be collected from Iowa corn fields under reduced/mulch tillage
71 while keeping the soil erosion at or below tolerable level. The sustainable removal rate
72 increased to 70% for no-till condition. However, the study was making an assumption that all
73 farmers will implement continuous corn rotation, which is not common in Iowa. Johnson et al.
74 (2006) estimated that 50-60% of biomass can be removed from corn fields assuming that
75 reduced tillage is used.

76 These studies suggest that there exists a substantial proportion of agricultural biomass
77 such as corn stover and wheat straw that can be removed while keeping soil erosion and soil
78 organic matter loss within tolerable limits. General guidelines for agricultural biomass removal
79 practices can be formulated based on these studies. However, none of these studies
80 incorporated the in-field variability into recommended biomass removal rates. The removable
81 amount varies from 0% to 100% over the space and time within a field depending on various
82 parameters such as soil type, crop management practices, topography, climate and yield
83 (Nelson et al., 2004; Newman, 2010) and county level average removal rates estimated by this
84 literature may not be useful for within field optimization of biomass collection rates. It is
85 necessary to develop site-specific harvest guidelines that can adapt to the changing parameters
86 within a field during harvesting operation so that a sustainable use of agricultural biomass can
87 be ensured (Wilhelm, 2004; Andrews, 2006). The objective of this study was to develop a
88 decision method to vary the percentage of stover material collected in a field by a single pass
89 harvesting system based on site-specific parameters such as management practice, field
90 topography, soil type, conservation practice, crop yield and climate.

91 **Methods**

92 Water/rain- and wind-induced soil erosion can deteriorate the soil tilth and hamper
93 sustainable agricultural production. The extent of both types of soil erosion depends on various
94 factors including soil type and condition, field operations, crop management practices, field
95 topography, climate and extent of field cover by agricultural residue (Nelson, 2002). For a given
96 location with all other variables being fixed, the extent of soil loss can be guided primarily by the

97 amount of agricultural biomass left on the field. Based on the rate and role of top soil formation,
98 USDA-NRCS has recommended a tolerable soil loss threshold (T) across the United States.
99 This threshold can be viewed as the tolerable soil loss for the sustainable agricultural production
100 (Nelson, 2002). If a field experiences soil erosion above this threshold, overall soil quality will
101 decline over the years and agricultural production will not be sustainable. A methodology
102 developed to estimate the site specific sustainable biomass removal rate will be described in
103 this section. This methodology considered only the soil erosion and not the other factors such as
104 SOM and soil bio-physical characteristics in assessing sustainable biomass removal rate. Soil
105 erosion due to wind was also neglected in this study. The RUSLE erosion model was used to
106 estimate the biomass removal rate so that the soil erosion from agricultural fields does not
107 exceed the soil loss threshold. Biomass removal rates estimated based on the water/rain
108 erosion tolerance will be reasonable in the fields of Iowa where wind erosion is not substantial.
109 However, the removal rates have to be treated carefully in relatively flat fields where SOM loss
110 due to biomass removal may be a concern even though the soil loss is negligible.

111 ***RUSLE 2 Water/Rain-induced Soil Erosion Model***

112 Water/rain-induced erosion moves the soil particles along the down slope of the field and
113 deposits the mass on another portion of the field, deposits it entirely on another field or transfers
114 it to waterways like streams and rivers. RUSLE (Revised Universal Soil Loss Equation) is a
115 semi-empirical water/rain-induced soil loss prediction model developed based on universal soil
116 loss equation (USLE). RUSLE is a widely used soil loss model in conservation practices. USDA
117 Natural Resource Conservation Service (NRCS) uses RUSLE to review conservation
118 compliance of various agricultural and conservation programs (USDA-NRCS, 2010). NRCS also
119 suggests the use of RUSLE to estimate the sustainable biomass removal rate from agricultural
120 fields.

121 The basic RUSLE and USLE model is represented by

$$122 \quad A = r * k * l * S * c * p \quad (1)$$

123 where, A = average annual soil loss, r = erosivity factor, k = soil erodibility factor, l = soil
124 slope length factor, S = slope steepness factor, c = cover-management factor, and p =
125 supporting practices factor.

126 RUSLE differs from USLE in the way different model parameters (factors) are calculated.
127 Based on the RUSLE model, the USDA-Agricultural Research Service (ARS), in collaboration
128 with the University of Tennessee, has developed and maintained a water/rain-induced soil
129 erosion prediction software called RUSLE 2. The RUSLE2 software, which was an improved
130 version of RUSLE software, provides a friendly graphical user interface for providing inputs and
131 getting outputs from the model (Table 1). To simplify the usage of the model, the software takes
132 parameters such as soil type and climatic zone and performs calculations internally to get model
133 parameters such as erosivity and cover-management factors. The model software requires
134 surface cover data every 15 days to calculate cover-management factor. RUSLE 2 team has
135 also developed and distributed a collection of dynamically linked RUSLE2 libraries called
136 RomeDLL. RomeDLL was incorporated into an application in this study to estimate the site-
137 specific sustainable biomass removal rates.

138 ***Parameter Estimation***

139 Input parameters required to run the erosion model were acquired using public domain
140 data. Management practices were based on common practices of Iowa farmers and
141 implemented with RUSLE2 using operations defined in the crop management database.
142 Conventional and no-till crop management practices were used (Table 2). Field operations for
143 these management practices were defined based on the recommendations of Nelson (2002),

144 Nelson et al. (2004), Newman et al. (2010), and RUSLE2 crop management templates
 145 (RUSLE2, 2005). Two types of crop rotations were used, single year corn and two year
 146 soybean-corn rotations. Because the majority of farmers in the US corn-belt use soybean-corn
 147 rotation and apply conventional aggressive tillage (Brenner et al., 2002; Sheehan et al., 2002,
 148 Sheehan et al., 2004), it was important to study the combination of these tillage and rotation
 149 practices. It was also important to analyze continuous corn rotation with no-till as that is a likely
 150 future practice to meet the demand of cellulosic biomass.

151 Table 1. Important inputs and outputs of the RUSLE2 software.

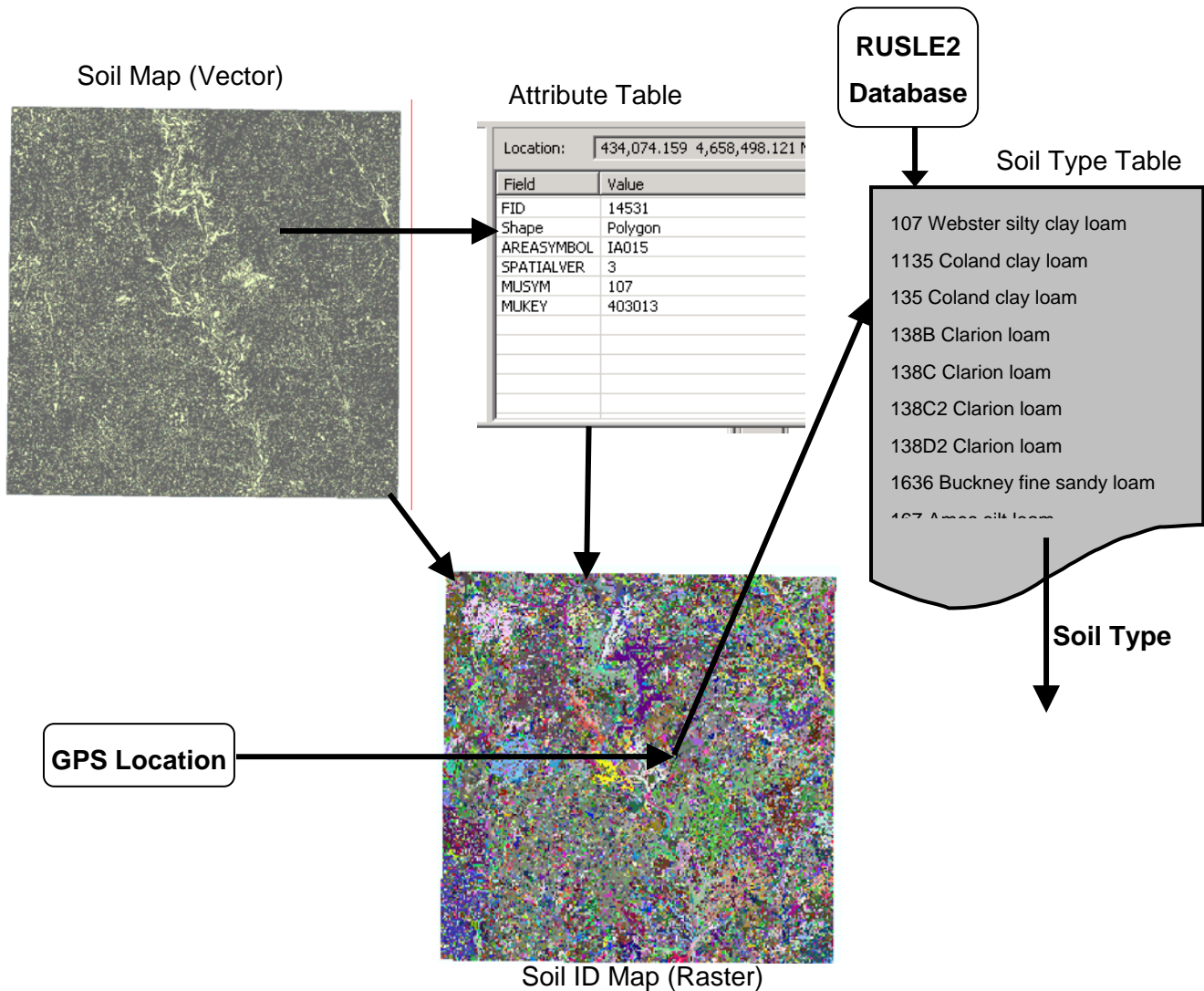
Inputs	Outputs
Management Practices	Soil Loss
Soil Data	Soil Loss Threshold
Slope Steepness and Slope Length	Surface Residue Cover
Climate Data	Sediment Delivery
Crop Grain Yield	
Supporting Practices	

152 Table 2: Field operations for conventional- and no-till management practices. These operations
 153 were used in RomeDLL to estimate the soil loss for various combinations of crop rotations and
 154 field operations at two different fields in Iowa.

	Corn		Soybean	
	Date (mm/dd)	Operation	Date (mm/dd)	Operation
Conventional Till	04/25	Plow, moldboard	05/11	Plow, moldboard
	05/10	Cultivator, field 6-12 in sweeps	05/26	Disk, tandem secondary operation
	05/15	Disk, tandem secondary operation	05/31	Disk, tandem light finishing
	05/17	Disk, tandem secondary operation	06/03	Cultivator, field 6-12 in sweeps
	05/20	Planter, double disk opener w/ fluted coulter	06/05	Planter, double disk opener w/ fluted coulter
	10/25	Harvest	10/30	Harvest
No Till	05/20	Planter, double disk opener w/ fluted coulter	06/05	Drill or air seeder single disk openers 7-10 in spacing
	10/25	Harvest	10/30	Harvest

155 County level soil databases were distributed with the RUSLE2. RomeDLL used the soil
 156 type name to access the database for the required soil type and its attributes. Spatial soil type
 157 maps were downloaded in ArcView shapefile format (ESRI Inc, Redlands, CA) from the United
 158 States Geological Survey (USGS) and were used to determine the soil type at particular
 159 locations (Fig. 1). The vector soil maps were converted into 10 m resolution raster maps to
 160 represent soil type identifiers (Soil ID) in gridded form. The soil type ID corresponding to a
 161 location of interest was then accessed in the raster map. This soil type ID was used to search
 162 the corresponding soil type name in the RUSLE2 database. The soil type name was then used

163 as an input to the model. Slope steepness and slope length at a location were calculated using
 164 a 10 m resolution digital elevation model (DEM) of the field. DEMs for whole United States were
 165 acquired through USGS. Slope steepness was calculated as the resultant of the slope in east-
 166 west direction and the slope in north-south direction. A program implemented by GRASS GIS
 167 software, which was publicly available for download, was modified and used in this study to
 168 calculate the slope length parameter.



169
 170 Fig. 1: Determining soil type name at a location using vector soil map, attribute table and
 171 soil type name list available in RUSLE2 soil database.

172 Climatic data specific to a county was also retrieved from the databases distributed with
 173 the RUSLE2 software and RomeDLL. Crop yield data was also available in the crop
 174 management templates available in the RUSLE2 database. To be more realistic, however,
 175 county level average yield provided by USDA National Agricultural Statistics Services (USDA-
 176 NASS, 2010) was used in this study. The yield value will eventually be acquired using yield
 177 monitor when the system is used in single pass grain and biomass harvesting operation. It was
 178 assumed the crop rows were parallel to the contour lines in the field. It was also assumed that

179 there were no supporting practices such as strips, barriers, diversion, terrace, sediment basin
180 and subsurface drainage implemented in the field.

181 **Calculating Sustainable Biomass Removal Rate**

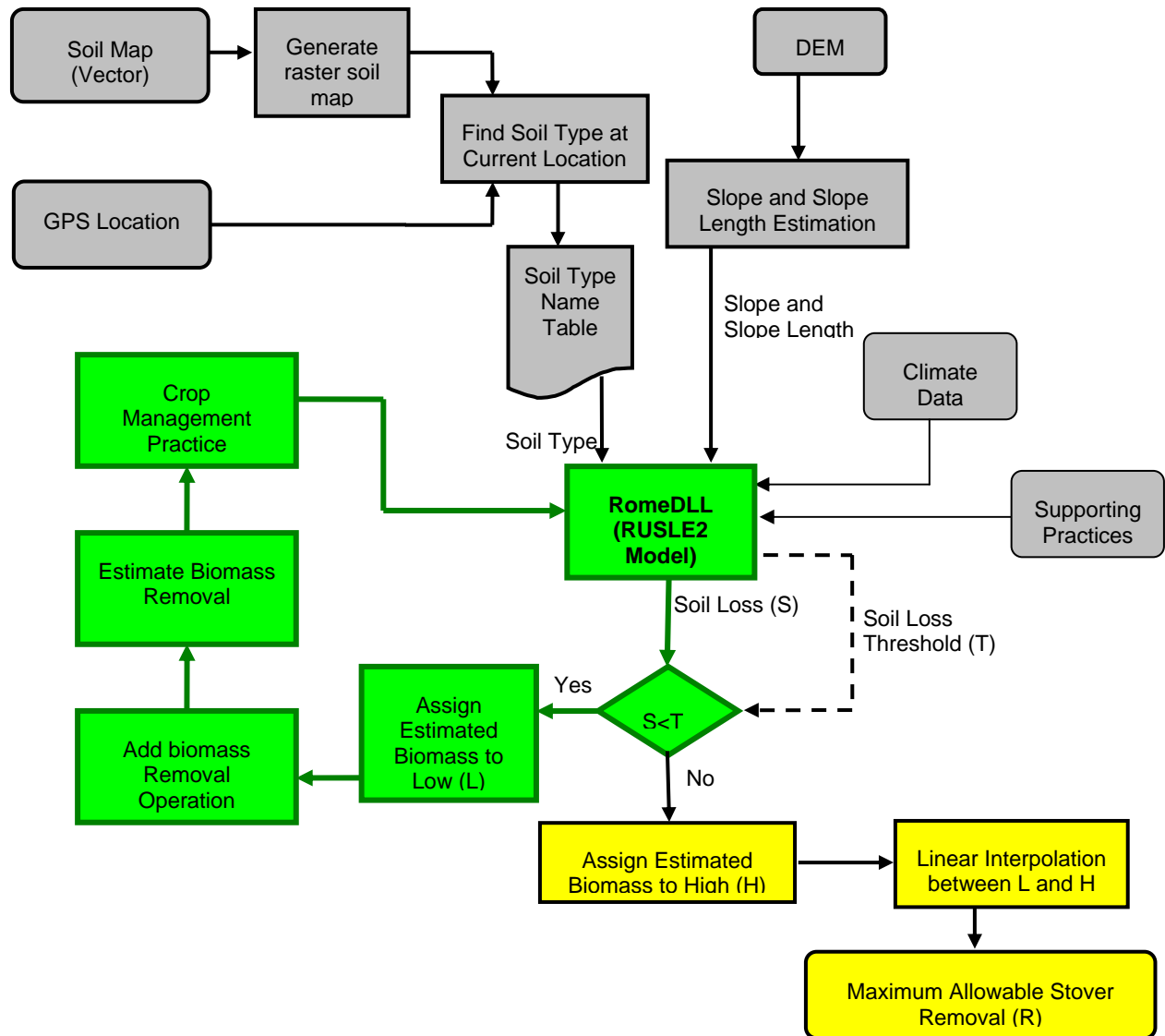
182 The RUSLE 2 model was used to calculate soil losses in a field with site-specific inputs and
183 specific amount of agricultural residue left in the field (Fig. 2). Because the RUSLE2 database
184 did not include single pass grain and biomass harvesting operations, a combination of harvest
185 types, shredding operations and baling operations were used to vary the amount of biomass
186 removed from the field, thus varying the level of surface cover due to residue. The RUSLE
187 model calculated the soil loss iteratively with different amounts of surface cover in each
188 iteration. The total amount of biomass available in the field was also calculated by RUSLE
189 based on the crop yield data, and the difference between two biomass amounts was calculated
190 as the removal rate. When two removal rates were found, which caused soil losses above and
191 below the soil loss threshold (T), linear interpolation was applied to estimate the biomass
192 removal rate that caused a soil loss equal to the soil loss threshold. Because the removal rate
193 and soil erosion are not related linearly, the linear interpolation may cause some error in
194 estimating biomass removal rates (Nelson, 2002). The iterations were repeated with small
195 increments in biomass removal so that the two bounding points were close to each other, which
196 helped to reduce the error due to the nonlinear relationship. A RomeDLL-based application was
197 developed in Visual C++ (Microsoft Corporation, Redmond, WA) to perform this iterative
198 process of estimating sustainable biomass removal rates.

199 This method of estimating sustainable biomass removal rate was applied to two
200 agricultural fields in the state of Iowa (one in each of Winnebago and Crawford Counties) (Table
201 3, Fig. 3). Two locations were selected in the Winnebago field and four locations were selected
202 in Crawford field with varying slope and soil type. Slope steepness values were 0.1% and 1.1%
203 at the two locations of the Winnebago field and that at the four locations in the Crawford field
204 ranged from 2% to 13%. At each location, combinations of two field operation practices
205 (conventional- and no-till) and two crop rotations (single crop corn and two crop corn-soybean)
206 were considered, which gave a total of 24 different scenarios for biomass removal rate
207 estimation. To estimate the biomass availability in the soybean-corn rotation, it was assumed
208 that no biomass as collected during the soybean harvesting season. The methodology was also
209 used to develop a regularly gridded removal rate map for the western part of the Crawford
210 county field.

211 Table 3: Field boundaries for the two agricultural fields (Winnebago and Crawford Counties, IA)
212 used in the study.

Field	County	Corner	Latitude	Longitude
1	Winnebago	South-West	43.260503 N	93.881886 W
		North-East	43.262456	93.872101 W
2	Crawford	South-West	41.957432 N	95.562966 W
		North -East	41.964771 N	95.547173 W

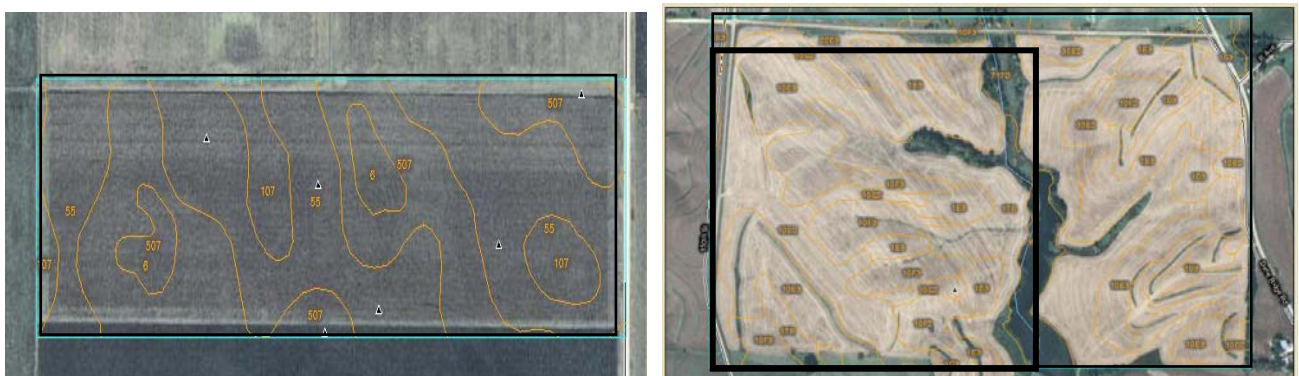
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215

Fig. 2: Process and data flow chart for optimal biomass removal rate calculation.



216

217

218

Fig. 3: Soil survey maps of Winnebago (left) and Crawford (right) agricultural fields downloaded from USDA Web Soil Survey portal (websoilsurvey.nrcs.usda.gov)

219 Results and Discussion

220 Sustainable agricultural biomass removal rates varied widely over the two agricultural
221 fields in Iowa depending on the crop management practices (tillage and rotation), field
222 topography and soil type (Table 4, Fig. 4). At the two locations in a relatively flat field in
223 Winnebago County, 98% of the 11 Mg/ha (9900 lb/ac) total biomass could be removed with
224 negligible soil loss for both continuous corn and soybean-corn rotations. No changes in biomass
225 removal rates were observed with the changes in tillage practice and soil types between the two
226 locations in this field because the soil loss in the field was always negligible and almost all
227 available biomass was removable. At these locations, the soil type were Nicollet Loam and
228 Canisteo Clay respectively, 2009 county level average corn yield was 11.3 Mg/ha and soybean
229 yield was 3.4 Mg/ha. In estimating this removal rate, however, only the soil erosion tolerance
230 level was considered as a constraint and potential effects in organic matter content and other
231 biophysical properties of the soil due to excessive biomass removal were neglected. These
232 results are in agreement with the results of Newman (2010) in similar field terrains, soil types
233 and management practices. Other studies (e.g. Nelson, 2002; Johnson et al., 2006) have
234 reported removal rates varying from 20% to 70%. However, these studies were based on the
235 county wise average slope steepness values which generally were higher than the slope
236 steepness of this field.

237 At four locations in the rugged Crawford field, the biomass availability decreased
238 substantially as the slope steepness increased from 2.6% to 7.5% and then to 12.6% with the
239 same soil type, tillage practice and crop rotation. At these locations, soil types were Monona Silt
240 Loam (first three locations) and Ida silt loam (last location), 2009 average corn yield was 12.4
241 Mg/ha and soybean yield was 3.6 Mg/ha. At a location with 2.6% slope, 98% biomass was
242 available for removal in both conventional- and no-till practices when farmers were practicing
243 continuous corn rotation. However, no biomass was available for removal at locations with 7.5%
244 and higher slopes when the farmers were using conventional tillage practice. If no-till practices
245 were adapted, the removal rate went as high as 88% for the continuous corn rotation and 77%
246 for the soybean-corn rotation at the location with 7.5% slope steepness. The interaction
247 between tillage practices and biomass removal rates became more apparent with increasing
248 slopes. As the intensity of tillage was reduced from conventional to no-till, the amount of
249 removable biomass increased, which is in agreement with the results from previous studies
250 including Nelson et al. (2004) and Wilson et al. (2004). At two locations with similar slope
251 steepness values, the biomass removal rate differed from one soil type to the other. For a no-till
252 continuous corn management practice, the removable rate was 70% at a location with Monona
253 silt loam and 12.6% slope steepness whereas the same was 74% at another location with Ida
254 silt loam and similar slope steepness.

255 A lower level of sustainable biomass availability for the conventional tillage practices was
256 expected as the soil erosion will be more prevalent in the tilled soil and additional surface cover
257 is required to keep the soil loss below the tolerance level. No-till cropping practices with
258 increased area of continuous corn production will be essential to increase the availability of
259 removable biomass. Lower levels of sustainable removal rates in steep slopes were also
260 expected. In sloped terrain, higher level of agricultural residue is required to minimize the soil
261 erosion, which will leave very little to remove from the field. Generally, the actual yield in the
262 sloped area will be lower than the county level average yield used in this study. This
263 discrepancy may lead to even less availability of removable biomass during actual field
264 operations. On the other hand, the single pass biomass removal operation was mimicked using
265 conventional multi-pass operations as the single-pass harvesting operation was not included in
266 the RUSLE2 database. This mimicking may cause underestimation of the biomass removal
267 rates as additional field operations considered in the soil loss calculation will not be there in the

268 actual single-pass harvesting operation. The discrepancy will favor the sustainability and soil
 269 tilth, though it may not be substantial. In this work, it was assumed that no supporting practices
 270 were used in the field. If the farmers built supporting structures such as barriers and diversions,
 271 the water/rain-induced soil erosion will decrease and the availability of removable biomass will
 272 likely increase.

273 Table 4: Sustainable biomass removal rates at six different locations in two agricultural fields
 274 (Winnebago and Crawford Counties) in the state of Iowa.

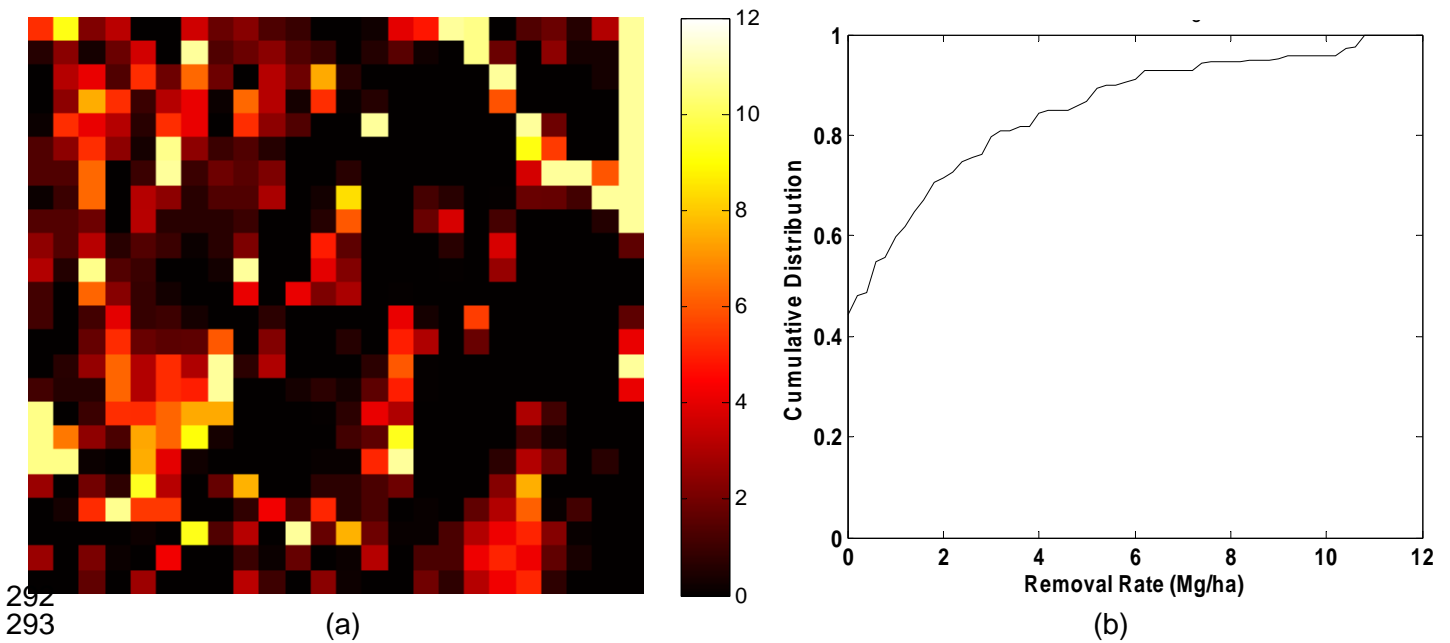
Field	County	Loc.	Lat/ Lon	Soil Type	Slope (%)	Crop Rotation	Yield* (Mg/ha)	Tillage	Biomass (Mg/ha)	
									Available	Removable (%) [#]
1	Winnebago	1	3.261706 / -93.873024	55 - Nicollet Loam	00.1	Corn	11.3	Conv.	11.1	10.9 (98%)
						No-till	11.1	10.9 (98%)		
			Soybean /Corn	3.4/ 11.3	Conv.	11.1	10.9 (98%)			
				No-till	11.1	10.9 (98%)				
2	43.262206/ -93.872509	507- Canisteo Clay	01.1	Corn	11.3	Conv.	11.1	10.9 (98%)		
				No-till	11.1	10.9 (98%)				
	Soybean /Corn	3.4/ 11.3	Conv.	11.1	10.9 (98%)					
		No-till	11.1	10.9 (98%)						
2	Crawford	1	41.961772/ -95.562108	10B2- Monona Silt Loam	02.6	Corn	12.4	Conv.	12.3	12.1(98%)
						No-till	12.3	12.1 (98%)		
			Soybean /Corn	3.6/ 12.4	Conv.	12.3	12.1 (98%)			
				No-till	12.3	12.1 (98%)				
		2	41.964085/ -5.560799	10C2- Monona Silt Loam	07.5	Corn	12.4	Conv.	12.3	0
						No-till	12.3	10.8(88%)		
			Soybean /Corn	3.6/ 12.4	Conv.	12.3	0			
				No-till	12.3	9.6 (77%)				
3	41.958852/ -95.560777	10E3 – Monona Silt Loam	12.6	Corn	12.4	Conv.	12.3	0		
				No-till	12.3	8.6 (70%)				
	Soybean /Corn	3.6/ 12.4	Conv.	12.3	0					
		No-till	12.3	7.0 (56%)						
4	41.960320/ -95.552065	1E3-Ida Silt Loam	12.8	Corn	12.4	Conv.	12.3	0		
				No-till	12.3	9.2 (74%)				
	Soybean /Corn	3.6/ 12.4	Conv.	12.3	0					
		No-till	12.3	8.4 (68%)						

275 *Yield data was acquired from the USDA online resource (USDA-NASS 2010).

276 [#] Only water/soil induced erosion was considered in the removable rate estimation

277

278 Site specific sustainable removal rates (Mg/ha) were also calculated in regular grids to
 279 create a removal rate map for part of the Crawford county field (Fig. 4a). The map was
 280 developed for the continuous corn conventional-till management practice with 35m spatial
 281 resolution. The sustainable removal rate varied from 0 to 12 Mg/ha over the field. This variation
 282 in the removable rates was caused by the changing field terrain in conjunction with the changing
 283 soil type. The field slope varied from 0 to approximately 25% and the average slope length used
 284 was 45 m. The removal rate was relatively higher in the north-west region where the field was
 285 relatively planer and the soil was less erodible. No or very small amount of biomass was
 286 available in the east-central and south-east areas of the field. This result was expected as the
 287 area was characterized by very high slope and highly erodible Monona/Ida Silt Loam soil type.
 288 The linear pattern of the pixels in the north-east area with higher removal rates was formed over
 289 the ridge line of the field terrain with very small slope steepness. The histogram showed that
 290 about 45% field area had no or negligible quantity of removable biomass and about 3% area
 291 had 11 Mg/ha to 12 Mg/ha biomass removal rate.



294 Fig. 4: a) Sustainable biomass removal rate map (Mg/ha) for the west part of the Crawford
 295 county field (Fig. 3) and b) cumulative histogram of the removal rate map. The map was
 296 developed for continuous corn conventional tillage management practice. The spatial resolution
 297 of the map was 35m.

298 These results indicated that there was a substantial variability in biomass removal rates
 299 within an agricultural field and a site-specific variable rate biomass collection system is essential
 300 to develop sustainable biomass feedstock supply system. In the variable rate single-pass crop
 301 grain and biomass harvesting system, these site-specific sustainable removal rates will be
 302 estimated during the field operations and provided as a recommended rate to the operators.
 303 Depending on the willingness of the farmers, capacity of the harvesting and collection
 304 equipments, and market and weather conditions, only a certain percentage of the recommended
 305 rate may be collected.

306 **Conclusions**

307 A methodology was developed for the site-specific estimation of the sustainable
308 agricultural biomass removal rates for single pass crop grain and biomass harvesting system.
309 The methodology was used to estimate biomass removal rates in two different agricultural fields
310 in the state of Iowa. It can be concluded from this study that the sustainable removal rates vary
311 substantially over different locations in a field depending on the field terrain, crop management
312 practices and soil types. At a location in a field in Winnepego county, Iowa with ~1% slope
313 steepness and conventional tillage practice, up to 98% of 11 Mg/ha total corn stover was
314 available for collection with negligible soil loss. The study, however, has considered only the soil
315 erosion tolerance level and has neglected the potential effects in organic matter content and
316 other biophysical properties of the soil due to excessive biomass removal. In contrast, there was
317 no stover available for collection at a location in Crawford County, Iowa field with a 12.6% slope
318 steepness and conventional tillage practice. If no-till crop practice was adapted, up to 70%
319 biomass could be collected from the same location. In case of soybean-corn rotation with no-till
320 practices, about 98% biomass was available for removal at the locations with small slope
321 steepness values in Winnebago field, whereas about 56% biomass was available at a location
322 in Crawford field with 12.6% slope steepness. The removal rate map developed in this study
323 also showed a substantial variation in sustainable biomass removal rates over an agricultural
324 field, which showed the importance of the site specific removal rate estimation. The sustainable
325 removal rates estimated in this work will be provided as a recommended value for the farmers to
326 set a biomass removal level during the single pass crop grain and biomass harvesting
327 operation. This type of site-specific biomass removal rate estimation is necessary to achieve
328 field level sustainability in agricultural biomass production and collection system.

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