EVAAL

Erosion Vulnerability Assessment for Agricultural Lands

Methods Documentation

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WISCONSIN
DEPT. OF NATURAL RESOURCES

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ACRONYMS

- BMP: Best Management Practice
- CDL: Cropland Data Layer
- CSA: Critical Source Area
- DEM: Digital Elevation Model
- EVAAL: Erosion Vulnerability Assessment for Agricultural Lands
- GIS: Geographic Information System
- gSSURGO: gridded Soil Survey Geographic Database
- LiDAR: Light Detection And Ranging
- NASS: National Agriculture Statistics Service
- NOAA–NWS: National Oceanic and Atmospheric Administration – National Weather Service
- NRCS: Natural Resource Conservation Service
- RUSLE2: Revised Universal Soil Loss Equation version 2
- SCS: Soil Conservation Service
- SPI: Stream Power Index
- TMDL: Total Maximum Daily Load
- USDA: United States Department of Agriculture
- USLE: Universal Soil Loss Equation
- WDNR: Wisconsin Department of Natural Resources
- WTM: Wisconsin Transverse Mercator

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EXECUTIVE SUMMARY

The Wisconsin Department of Natural Resources (WDNR) Bureau of Water Quality has developed the Erosion Vulnerability Assessment for Agricultural Lands (EVAAL) toolset to assist watershed managers in prioritizing areas within a watershed which may be vulnerable to water erosion (and associated nutrient export) and which may contribute to downstream surface water quality problems. It evaluates locations of relative vulnerability to sheet, rill, and gully erosion using information about topography, soils, rainfall, and land cover. This toolset is intended for relatively small watersheds (less than ~75 km^2) that have already been identified as watersheds that contribute higher nonpoint source pollutant loads, such as subbasins identified in a Total Maximum Daily Load (TMDL) study as relatively high-loading. This tool enables watershed managers to prioritize and focus field-scale data collection efforts, thus saving time and money while increasing the probability of locating fields with high sediment and nutrient export for implementation of best management practices (BMPs). The toolset has been incorporated into an ArcGIS Toolbox, for which a tutorial has been developed. The toolbox and tutorial are available on the WDNR website for download by watershed managers throughout the state.

1.0 INTRODUCTION

Excessive nutrients and sediment from agricultural fields, streambanks, and other sources can make their way to surface waters, negatively impacting aquatic habitat and even leading to public health concerns as in the case of blue-green algae blooms. In many of Wisconsin's watersheds the nutrients and sediment originate largely from rural nonpoint sources. Targeting nonpoint source contributions and prioritizing implementation of best management practices (BMPs) remains a difficult task for water resource managers.

One way to begin to address these issues is though a Total Maximum Daily Load (TMDL). TMDLs are being, or have been developed, in several large watersheds throughout Wisconsin. TMDLs allocate reductions for point and nonpoint sources of nutrients and sediment on a subwatershed basis. TMDLs are typically developed using water quality models which identify subwatersheds with high nutrient and sediment export. To move from developing the TMDL to implementing the TMDL's necessary reductions, efforts must be focused on those specific areas within the high-loading subwatersheds. The TMDL subwatershed scale is typically still too large to decide where to focus efforts for implementation, so it is necessary to focus on a more manageable scale (i.e. farm or field scale) since it is at that scale that best management practices are implemented.

When moving to the field scale, the data required to understand sediment and nutrient exports increase dramatically. In some cases watershed managers have gone to great lengths to collect field-level land management information for entire subbasins. This process takes considerable time and effort and often cannot procure detailed information for all fields due to differences in the willingness of producers to share their information.

The limitations of time, money, and information led to the WDNR's development of a qualitative, easy-to-use software tool for prioritizing implementation efforts within a watershed. The methodology is based on readily available spatial data (e.g., land cover, soil, digital elevation models) that allows a watershed manager to determine areas that are vulnerable to sediment and nutrient loss with minimal effort. Using a simple, cost-effective, prioritization approach should reduce the need to conduct watershed-wide agricultural inventories. The EVAAL tool gives an erosion index based on the relative vulnerability to erosion, rather than precisely estimating the pollutant load associated with all agricultural fields. This simpler, alternative method identifies potential areas of concern for which precise load reduction estimates can then be calculated (Figure 1). These methods allow more efficient and effective use of local watershed management staff time while also having a greater potential impact on water quality by prioritizing the most vulnerable sites.

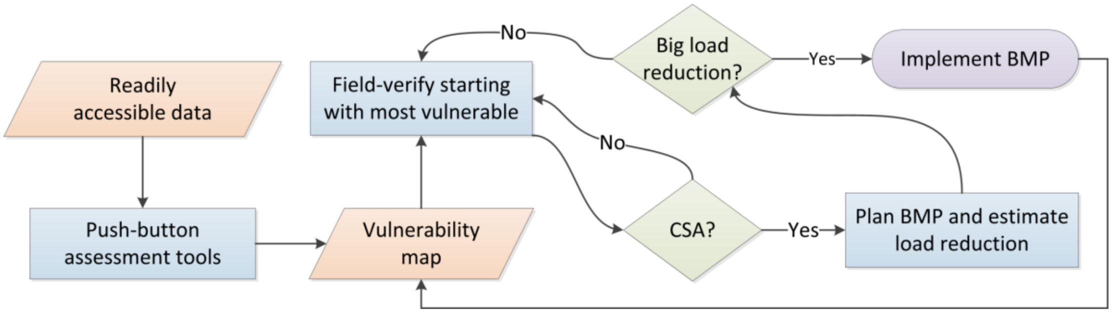

Figure 1. Decision framework for identifying potentially critical source areas (CSA) of nonpoint source pollution and prioritizing best management practices (BMP) on agricultural lands.

EVAAL was designed to quickly identify areas vulnerable to erosion, and thus more likely to export nutrients like phosphorus, using readily available data and a user-friendly interface. This tool estimates vulnerability by separately assessing the risk for sheet and rill erosion (using the Universal Soil Loss Equation, USLE), and gully erosion (using the Stream Power index, SPI), while deprioritizing those areas that are not hydrologically connected to surface waters (also known as internally drained, or non-contributing areas). These three pieces are combined to produce the following outputs:

- erosion vulnerability index for the area of interest;
- areas vulnerable to sheet and rill erosion;
- areas of potential gully erosion;
- areas hydrologically disconnected from surface waters.

It is important to note that erosion “vulnerability” refers to an area’s susceptibility to sediment and nutrient runoff given certain management practices. Further, the erosion vulnerability index output is a *relative* index, which means that output from separate model runs should not be compared directly. Direct comparison is only advisable for areas that have been included in the same model run. The erosion vulnerability output is a non-dimensional index, meaning it is only intended to *prioritize or rank*, not estimate the real value of sediment or nutrient runoff.

It is also important to note that EVAAL is designed to prioritize lands vulnerable to erosion, however an assumption can be made that loss of soil may also lead to nutrient loss. Phosphorus binds readily to soil particles, especially the smaller size fractions (silt and clay) that are easily eroded. In water quality samples, runoff events where high concentrations of sediment are measured are often associated with high concentrations of total phosphorus (Robinson et. al., 1992). Therefore, EVAAL can be used to identify areas vulnerable to nutrient loss in areas where phosphorus loss is known to be associated with erosion, for example, areas where soil phosphorus measurements are unusually high.

EVAAL is an ArcGIS Toolbox divided into several different tools, to facilitate greater control over inputs. The workflow can be divided into several stages: creation of a hydrologically conditioned DEM, identification and removal from analysis those areas on the landscape that do not drain to surface waters, estimation of potential gully erosion, estimation of soil loss from sheet and rill erosion, and the calculation of an erosion vulnerability index.

The following report provides information on the model inputs, methodology, outputs, applications, and limitations; it also presents a comparison to another soil loss model for validation purposes. Section 2 of this report describes the framework upon which EVAAL is built. Section 3 specifies the standard and user-defined inputs to EVAAL. Section 4 explains the methodologies behind the internally draining area, USLE, SPI, and erosion vulnerability index calculations. Section 5 describes the outputs generated by EVAAL as well as some example applications. The model limitations are outlined in Section 6. Section 7 illustrates a comparison of the soil loss estimate of EVAAL to soil loss from SnapPlus, a widely-used software program for calculating soil and phosphorus loss in Wisconsin. The appendices contain additional tabular information used in the model processes. A companion report, the EVAAL Tutorial, outlines in detail, the necessary steps to install and run EVAAL with the accompanying tutorial or user-specified data inputs.

2.0 EVAAL FRAMEWORK

EVAAL is distributed as an Esri ArcGIS Toolbox that can be easily loaded into an ArcMap document. The underlying programming uses the Python scripting language. It is currently designed to work in the Wisconsin Transverse Mercator geographic projection (EPSG: 3071).

The EVAAL Toolbox was developed within the ArcGIS 10.x Desktop framework and requires the Spatial Analyst extension. Additional system requirements are presented in the accompanying tutorial document. EVAAL and the associated tutorial datasets can be downloaded from WDNRs webpage (http://dnr.wi.gov/topic/Nonpoint/EVAAL.html). The ArcToolbox menus allow the user to run the analysis using data specific to their area of interest; additionally, tutorial example datasets are provided. Detailed descriptions of the tool inputs and required datasets are included in the tutorial.

3.0 EVAAL DATA SOURCES

EVAAL requires specific spatial datasets to accomplish the erosion vulnerability analysis. Some datasets must be acquired by the user prior to running the toolset, while others are downloaded directly from the Internet by the tool. All input datasets must be in the Wisconsin Transverse Mercator geographic projection (EPSG: 3071) or the tool will not run.

The user must provide the following datasets to run EVAAL:

> LiDAR-based Digital Elevation Model (DEM): The high resolution of a LiDAR-based DEM allows for detailed analysis of surface water flow paths as well as the

location of internally draining areas (areas that do not generally contribute to surface water runoff).

Area of Interest Boundary: This is recommended to be a watershed boundary, but the tool allows any polygon feature to be used. The area of interest limits the spatial extent of the analysis. It is strongly recommended that the area of interest be less than 75 km^2. The tool may or may not run to completion on areas larger than recommended.

Soils: Soil erodibility (or K Factor) and hydrologic soil group are extracted from the gridded version of the USDA-NRCS Soil Survey Geographic (SSURGO) Database, or gSSURGO. The K factor indicates the susceptibility of a soil to erosion and is applied in the calculation of sheet and rill erosion vulnerability, while the hydrologic soil group is used in calculating the Curve Number for estimating runoff as part of the non-contributing area analysis.

Culvert Lines: A LiDAR DEM is a representation of the landscape surface, and thus does not represent the locations of underground surface water conveyances (i.e., culverts and bridges). In order to model surface water flow across the landscape using a DEM, the surface water flow paths must be accurately represented, necessitating the explicit spatial locations of culverts and bridges. This dataset often needs to be created manually (see Tutorial Document for guidance on creating this layer).

The datasets below are directly downloaded by the tool, but alternatively may be provided by the user:

Frequency-Duration Precipitation Data: The amount of precipitation given an event of a certain frequency and duration (e.g., 10-year, 24-hour) is used to identify internally draining areas. The toolset downloads this data from the National Weather Service.

Land Cover: Several years of the USDA-NASS National Cropland Data Layer (CDL) are used to determine generalized crop rotations within the area of interest. The CDL is a raster, geo-referenced, crop-specific land cover data layer created annually for the continental United States using moderate-resolution satellite imagery and extensive validation.

These datasets are optional, but may be provided by the user:

Zone Boundaries: This polygon layer delineates specific zones within the area of interest and is used to aggregate the erosion vulnerability index. For example, these boundaries could be for tracts, agricultural fields, or tax parcels.

BMP Locations: This raster layer can be used to show where BMPs that control sediment loss already exist on the landscape. These areas are then deprioritized within the erosion vulnerability analysis. Examples include grassed waterways, strip cropping, cover crops, and riparian buffers.

4.0 EVAAL METHODOLOGY

The EVAAL Toolbox uses the inputs described in Section 3 to calculate an erosion vulnerability index that is based on three variables. The first variable in the index de-prioritizes areas if they flow into an internally draining area, and therefore do not directly contribute to surface water quality. The second variable is the Stream Power Index (SPI), which can indicate the potential for gully erosion. The third variable is a grid-based estimate of soil loss potential by sheet and rill erosion using the Universal Soil Loss Equation (USLE). Prior to calculating any of the variables, the tool uses the LiDAR DEM and culvert lines to create a hydrologically conditioned DEM for use in the following analysis.

4.1 DEM Conditioning

Due to the high resolution of LiDAR DEMs, a conditioning process must be completed before the DEM can be used in any hydrologic analysis. The conditioning process applies the user-provided culvert lines to “cut” the LiDAR DEM in order to eliminate the “digital dams” caused by road berms and other natural and manmade features, while preserving those features that truly do inhibit downstream flow. This creates a DEM that can be used to correctly model surface flow paths across the landscape.

The DEM conditioning process uses several steps that run within the Condition DEM tool in the EVAAL toolset:

1) Clips the DEM to the user-input watershed boundary buffered by 300 feet.
2) Projects the DEM to the Wisconsin Transverse Mercator (WTM) projection and resamples it to 3-meter by 3-meter.
3) Runs the Topo To Raster function to create a hydrologically correct surface with digital dams cut.
4) Saves the conditioned DEM.
5) Runs the Optimized Pit Removal tool developed by the University of Texas at Austin, Center for Research in Water Resources. This tool provides an alternate method to purely “filling” sinks, which can lead to non-representative flat areas, by balancing filling and cutting. (http://tools.crwr.utexas.edu/OptimizedPitRemoval/CRWR%20Tools%20Optimized%20Pit%20Removal.html).
6) Saves the conditioned DEM and the optimized filled conditioned DEM.

The results of this process are two conditioned DEMs both with culverts/bridges represented; the optimized filled DEM also has the sinks filled/cut in order to best represent the hydrologic flow across the landscape.

4.2 Internally Draining Areas

Many watersheds include areas that do not directly contribute to surface water, and therefore do not greatly impact downstream surface water quality within a watershed. These areas are identified using the LiDAR DEM and a curve number-based estimation of runoff (USDA SCS, 1986) for a given frequency and duration precipitation event. The larger the storm (the less frequent and the longer duration) selected, the fewer the areas that will be considered as disconnected to surface waters and not contributing to runoff.

The process to identify internally draining areas has three steps. First a precipitation raster is created for a user-defined frequency and duration storm; next, the tool creates a curve number raster to be used in a runoff volume calculation; and finally, those layers are used in the determination of internally drained areas.

The first step creates a precipitation layer from either a user-supplied precipitation dataset or a user-defined precipitation event (frequency and duration), from which the associated precipitation amount for the area of interest is downloaded directly from the Internet by the tool. The source of the data is the NOAA NWS Hydrometeorological Design Studies Center's Precipitation Frequency Data Server and is the same information that is contained in NOAA ATLAS 14. The precipitation data is clipped to the area of interest, resampled to the LiDAR resolution and projected into WTM.

The next step is to create a curve number raster layer to be used in the runoff calculation. The curve number is based on land cover, cover condition, and hydrologic soil group. Land cover is downloaded directly by the tool from the USDA NASS server or supplied by the user. Since the cover condition is difficult to assess without direct field observation, the tool outputs both a high estimate of runoff potential (high curve number) and a low estimate (low curve number) representing both worst-case and best-case scenarios. The user can then decide which condition is more indicative of their area of interest. The tool combines the land cover with the hydrologic soil group value from the gSSURGO dataset to look up the associated curve number (APPENDIX A). The tool then outputs high and low curve number layers.

The final process in determining the internally draining areas uses the precipitation and curve number layers to determine the volume of runoff for the given precipitation event. That runoff volume is compared to the volume of the remaining sinks in the conditioned DEM. If the sink volume is greater than the runoff volume, then it is considered an internally draining area and would be excluded from the erosion analysis. If the sink volume is less than the runoff volume, then it would contribute to downstream surface water quality and remains in the erosion vulnerability analysis (Figure 2). The tool creates a raster layer of the internally draining areas (Figure 3). The default of the 10-year frequency, 24-hour duration storm was chosen because of the relatively low probability (10%) of that size storm each year. If an area is determined to be internally draining given the runoff volume from this large of event, there is little chance the area will be a big contributor to surface water quality impairments. The default values can be changed if the user so desires.

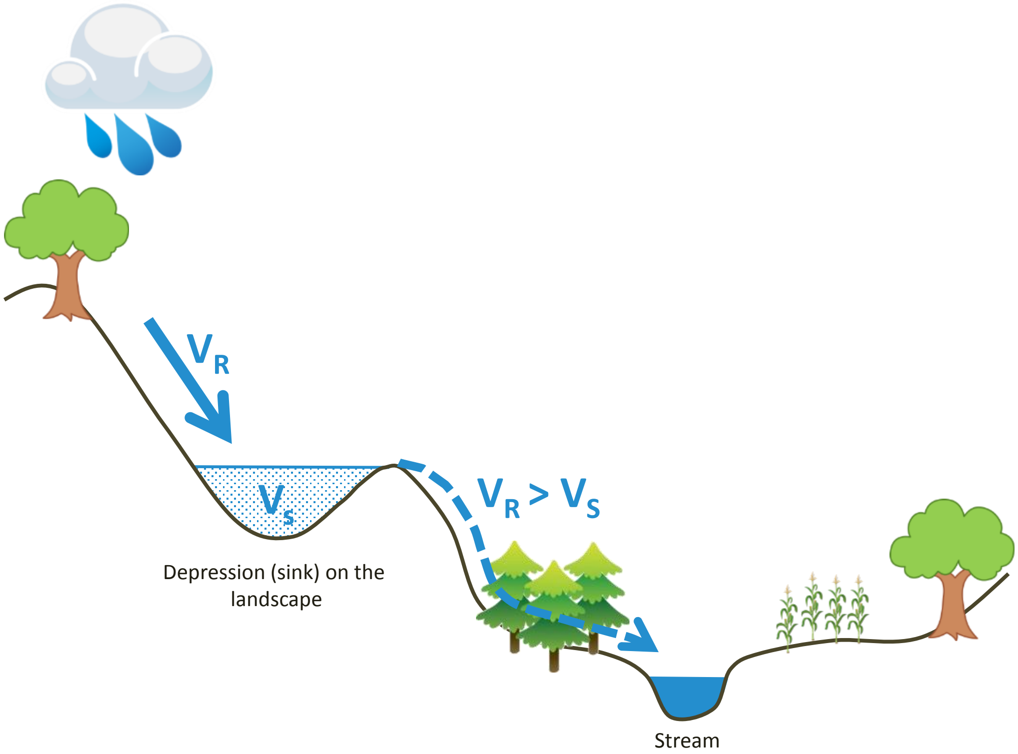

Figure 2. Schematic diagram of identification of internally draining areas. Runoff volume (V_R) is calculated by partitioning precipitation into runoff and infiltration using the curve number method. The runoff volume (V_R) is compared to the sink volume (V_S) downstream, and if the runoff exceeds the sink volume, the sink is not considered internally draining and vice versa ($V_R > V_S \neq$ internally drained; $V_R < V_S =$ internally drained).

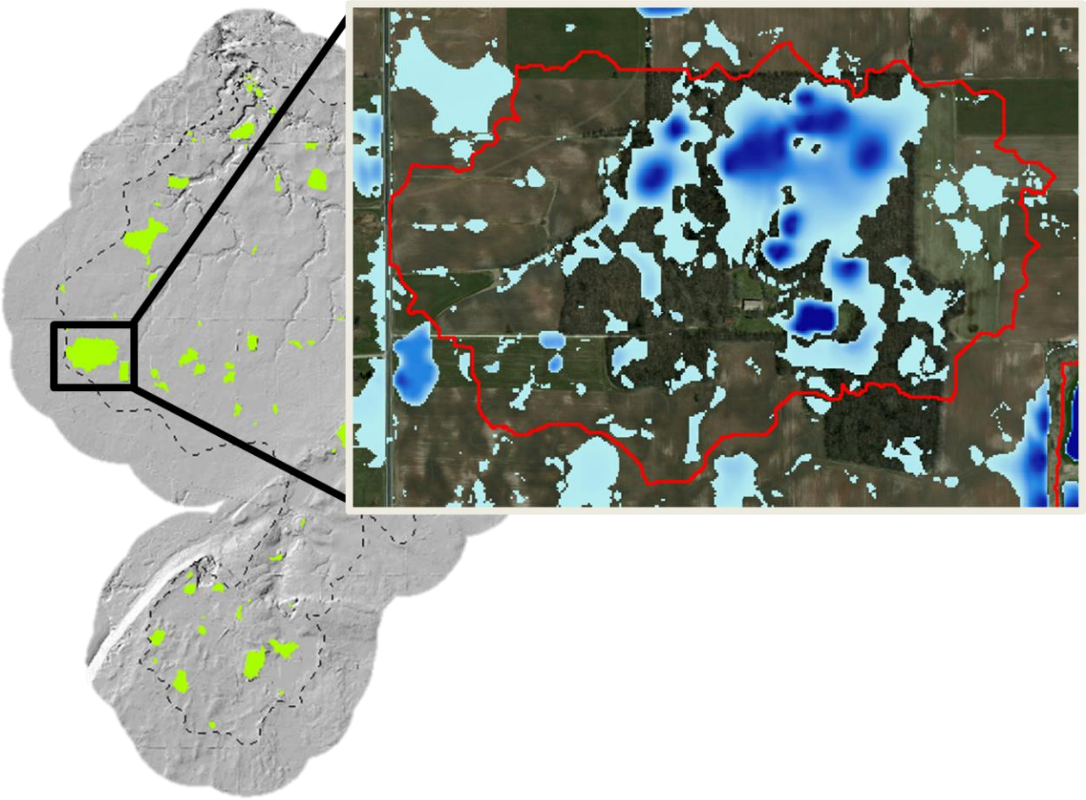

Figure 3. Example of an internally draining watershed. Sink depths are shown in blue and the watershed of the contributing area of the internally draining areas is shown in red.

4.3 Gully Location Estimation using the Stream Power Index (SPI)

The Stream Power Index (SPI) is a measure of the erosive power of flowing water. Its calculation is based on slope and contributing area and approximates locations where gullies might be more likely to form on the landscape. Gullies are a more severe form of erosion — that is, they occur when sheet and rill erosion accumulate downslope. Generally, gullies are wide and deep enough that they cannot be tilled over. Therefore, the presence of gullies can be an indication of extensive soil and nutrient loss.

The SPI is calculated using the following equation:

$$SPI_i = ln(DA_i \times tan(G_i))$$

where SPI is the stream power index at gridcell i, DA is the upstream drainage area (flow accumulation at gridcell i multiplied by gridcell area), and G is the slope at a gridcell i in radians (Galzki, et. al., 2011).

The slope and flow accumulation are determined from the conditioned DEM. The flow accumulation threshold (default of 50,000 for a 3-meter by 3-meter resolution DEM) is used to determine which cells are likely to be perennial streams and which are likely to contain overland flow. The SPI is not calculated for those cells considered to be perennial streams. Overlaying the SPI on an aerial photo can be useful for determining the threshold value for which gullies may be likely (Figure 4).

Figure 4. Yellow indicates areas of high stream power and thus potential for gully erosion. The yellow areas coincide with areas on the aerial photo that appear to be eroding.

4.4 Soil Loss Potential using the Universal Soil Loss Equation (USLE)

Soil loss potential due to sheet and rill erosion can be estimated on a grid basis within a GIS using the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The datasets required for this analysis are LiDAR elevation data to determine the slope/slope-length factor and the Cropland Data Layer to determine generalized crop rotations (e.g., dairy or cash grain). The generalized crop rotations are used in a novel methodology (WDNR, 2014) for estimating rotational averages of the USLE cover factor (or C Factor).

Soil loss potential is calculated using the following equation:

$$E_i = R_i \times K_i \times LS_i \times C_i \times P_i$$

where at each gridcell i, E is soil loss in $tons \cdot (ha \cdot year)^{-1}$, R is rainfall erosivity in $(megajoule \cdot millimeter) \cdot (ha \cdot hour \cdot year)^{-1}$, K is soil erodibility in $(tons \cdot ha \cdot hour) \cdot (ha \cdot megajoule \cdot mm)^{-1}$, LS is slope/slope-length (dimensionless), C is a land cover factor (unitless), and P is a practice factor (unitless).

Rainfall erosivity (or R factor) is the cumulative force of rainfall on soil. In Wisconsin where topographic impacts to rainfall amount and intensity are minimal, erosivity varies at very coarse spatial scales. Because this tool is intended for small watersheds, erosivity can safely be assumed to be constant across the area of interest, and thus is an optional input to the erosion calculation. If desired, an appropriate constant value of erosivity can be found in EPA Fact Sheet 3.1 page 5 (http://www.epa.gov/npdes/pubs/fact3-1.pdf) which gives a map of erosivity in U.S. customary units. Multiply this value by 17.02 to convert to international (SI, or metric) units.

The value for erodibility (K factor), is derived from the USDA gSSURGO database. The gSSURGO dataset is organized by three, nested levels: horizon, component, and map unit. The soil map unit is a 2-dimensional polygon representation of soil patterns. Each map unit is composed of one or more components, which represent a particular soil type, usually a soil series. Within components are horizons which comprise the vertical, stratigraphic units of the soil profile. The K factor value used in the tool is the area-weighted average of all the components in the top horizon.

The slope/slope-length, or LS factor is determined by GIS analysis of the LiDAR DEM. The equation used to calculate the LS factor for any grid point **r** = (x,y) is:

$$LS(\boldsymbol{r}) = (m+1)[A(\boldsymbol{r})/a_0]^m[\sin b(\boldsymbol{r})/b_0]^n$$

where A is the upslope contributing area per unit contour width (meters), b is the slope (degrees), m and n are parameters (0.6 and 1.3 are typical and the values used in the tool), and a_0 = 22.1 meters is the length and b_0 = 0.09 = 9% = 5.16 degrees is the slope of the standard USLE plot (Mitasova et. al., 1996, Mitasova et. al., 1999).

The cover factor (C factor) is a unitless metric that adjusts the amount of soil loss based on land cover type and management. To create the C factor raster layer, the tool uses several years of the CDL, similar to the curve number calculation. From the series of annual land cover classification maps, a generalized crop rotation (e.g., dairy, cash-grain, or potato rotation) is derived based on typical management in Wisconsin (Figure 5, APPENDIX B). The generalized crop rotations were calibrated using 5 years of CDL data in the Wisconsin River Basin, so at least 5 years of data with similar agriculture types to the Wisconsin River Basin (corn/soy, continuous corn, dairy, or potato/vegetable) is recommended to obtain the intended result. Once the rotation is defined, each rotation is given two annual average C factors, a high and a low estimate. Details about the management strategies (e.g., tillage, cover crops) are difficult to collect for every farm in a watershed. Rather than requiring this data, this tool produces a high C factor estimate, where management practices that increase runoff are assumed to be in use, and a low C factor estimate, where conservation management practices are in use.

Annual average C factors were estimated using the SnapPlus tool for nutrient management in Wisconsin (http://snapplus.wisc.edu/). A sensitivity analysis was conducted to identify the parameters that most impacted the C factor in SnapPlus, which runs the Revised Universal Soil Loss Equation version 2 (RUSLE2); the two primary factors were cropping and tillage. The inputs to the SnapPlus tool represented typical farm management in Wisconsin with respect to cropping, tillage, and soil type (WDNR, 2014, and Table C2). Because C factors calculated in SnapPlus are only sensitive to cropping and tillage, the C factors used in EVAAL were calculated by averaging all SnapPlus runs within cropping and tillage groups. These C factors can be adjusted in the table, “cFactorLookup.csv”, where each class in the column either represents a generalized rotation or other natural land cover value from the CDL (see APPENDIX C).

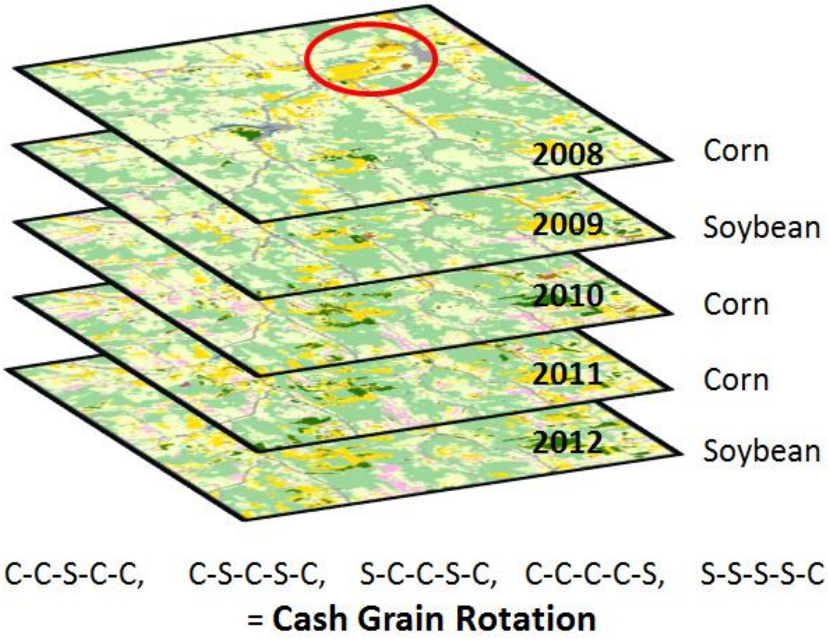

Figure 5. Illustration of rotation analysis using several years of the Cropland Data Layer.

The practice factor, P Factor, is a unitless metric describing the capacity of a land-management practice to prevent erosion compared to straight row cropping up and down the slope. Practices such as contour farming would be represented by the P factor. Since this information is field-specific and not widely or readily available, the P factor is assumed to be 1 in this analysis.

The R, K, LS, C, and P factors are multiplied together to arrive at the soil loss potential. The values of soil loss potential calculated by the tool can be used to compare the relative potential for sheet and rill erosion throughout the area of interest. Using the resulting values as estimates of actual soil loss (e.g., tons/acre/yr) is not recommended as the results have not been validated as such. Rather, it is only appropriate to interpret relative difference between locations within a watershed.

4.5 Erosion Vulnerability Index

The erosion vulnerability index combines the soil loss potential, the stream power index, and internally drained areas to derive an index of erosion vulnerability. Areas with high soil loss and stream power index will have high erosion vulnerability, whereas areas that are internally draining will be excluded from the vulnerability analysis.

For the index calculation, the soil loss and SPI values are normalized and added together. The index can be output as a raster grid layer and/or summarized in tabular form by zones (such as fields) using the zone boundaries layer.

5.0 EVAAL OUTPUTS

The intention of EVAAL is to locate *where* BMP assessment should be prioritized. Therefore, the results are provided as a series of maps. The primary results of EVAAL are the erosion vulnerability index and then the components of this index, the SPI, USLE soil loss, and the internally drained areas. Some of the intermediate maps produced by the toolset are useful in and of themselves. EVAAL makes it easy to create different application scenarios by varying the input parameters. In this way, it is possible to create different scenarios and deeper insight into potential erosion issues.

5.1 Primary Outputs

Maps are provided for the erosion vulnerability index and each of the model components (i.e., SPI, and soil loss). Any of these results can be interpreted at their base resolution (3-meter) or aggregated to the level of an agricultural field, or other, (Figure 6) if a zone boundary layer is available. The diversity of output allows for analysis to be conducted on several levels. For example, if the erosion index is averaged by farm or parcel, the holding with the highest average vulnerability to erosion is easily identified. To find those areas of the farm that have the highest susceptibility to erosion, one need only study the continuous, grid-based output of the erosion vulnerability index. Further, to assess contribution of gully erosion to the index, as opposed to rill and sheet erosion, the maps of SPI and the USLE soil loss can be reviewed individually.

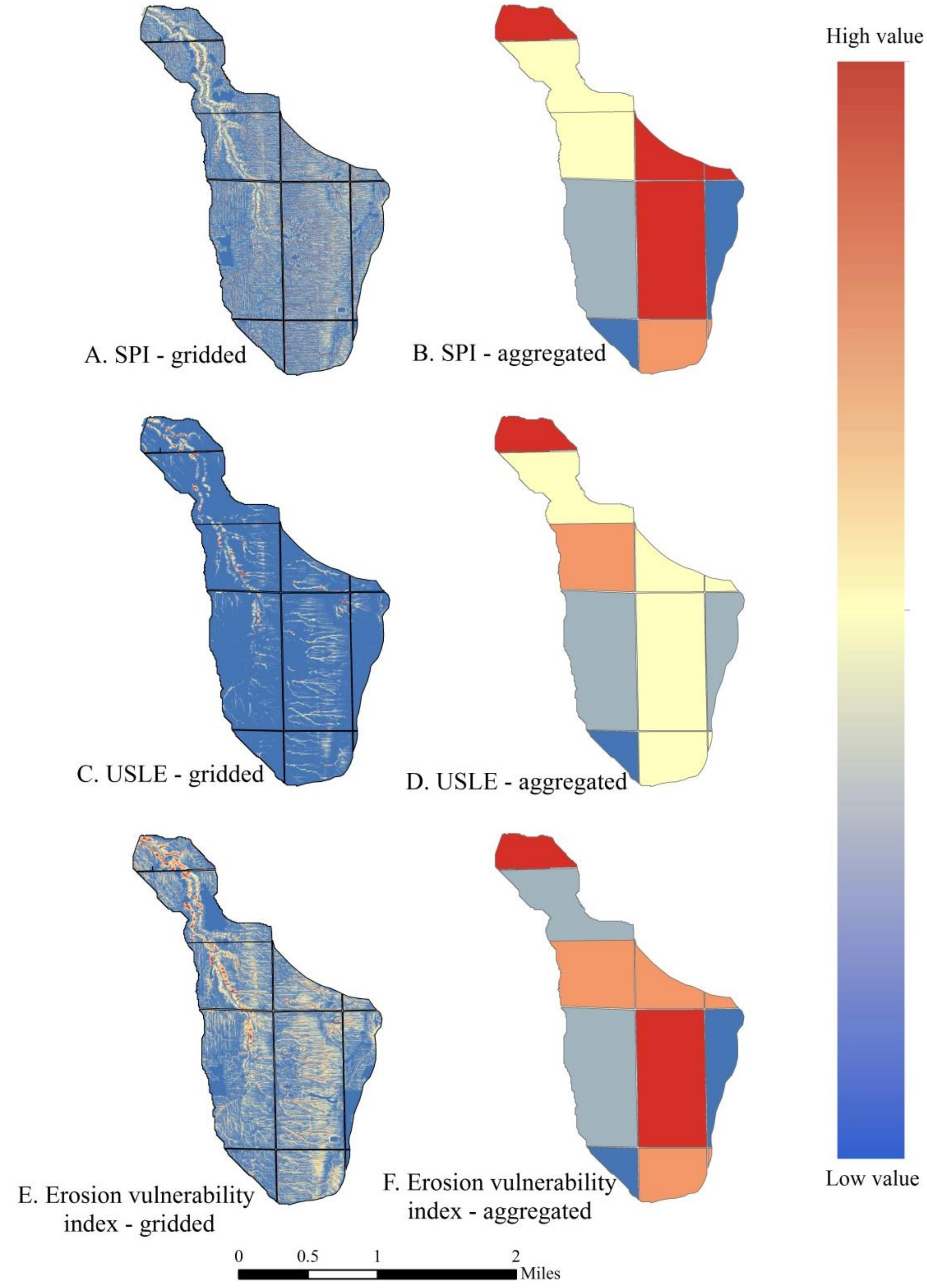

Figure 6. Primary outputs of EVAAL, showing the raster grid version and aggregated to parcel scale, with red indicating high values, blue low values, and beige showing intermediate values.

5.2 Intermediate Outputs

In addition to the erosion vulnerability index and its components, several intermediate results are provided including, for example, internally draining areas, cover factors, and crop rotations. These individual products can be used to assess specific watershed impacts. For example, locations under a dairy rotation could potentially have more manure applications, and thus more potential for high soil phosphorus values which if congruent with high erosion potential could be areas of high phosphorus export. Several examples of intermediate layers are shown in Figure 7.

5.3 Application Examples

To illustrate the flexibility and different options available in the EVAAL toolset, different examples are described.

Example 1 High C Factor vs Low C Factor
The C factor in the USLE reflects the land cover, approximated with the crop rotations layer, and management, including the amount of canopy, surface cover, surface roughness, and prior land use. As stated previously, management details can be difficult to inventory, and so two C factors are estimated, one assuming that management is increasing erosion (high C factor), and one assuming that management is preventing or minimizing erosion (low C factor). Each of these can be used in turn to create its own soil loss map and erosion vulnerability index.

It assumed here that if the tool were to be run only once, the most useful scenario would be the "worst-case" scenario, where the high C factor is used. This would create a soil loss map and soil erosion vulnerability index under the assumptions that the management practices occurring in the area of interest are increasing or contributing to erosion. The erosion vulnerability index can be used to identify the most vulnerable areas, and then check to see whether those areas are indeed without conservation measures.

The tool can also be run twice, using both the high and low C factors, to produce USLE soil loss and erosion vulnerability maps under both "worst-case" and "best-case" scenarios, respectively. By subtracting the worst-case erosion vulnerability index map from the best-case, a map showing the areas with greatest potential for improvement is created. This can be extremely useful for land managers who are interested in achieving the greatest load reductions with least amount of resources.

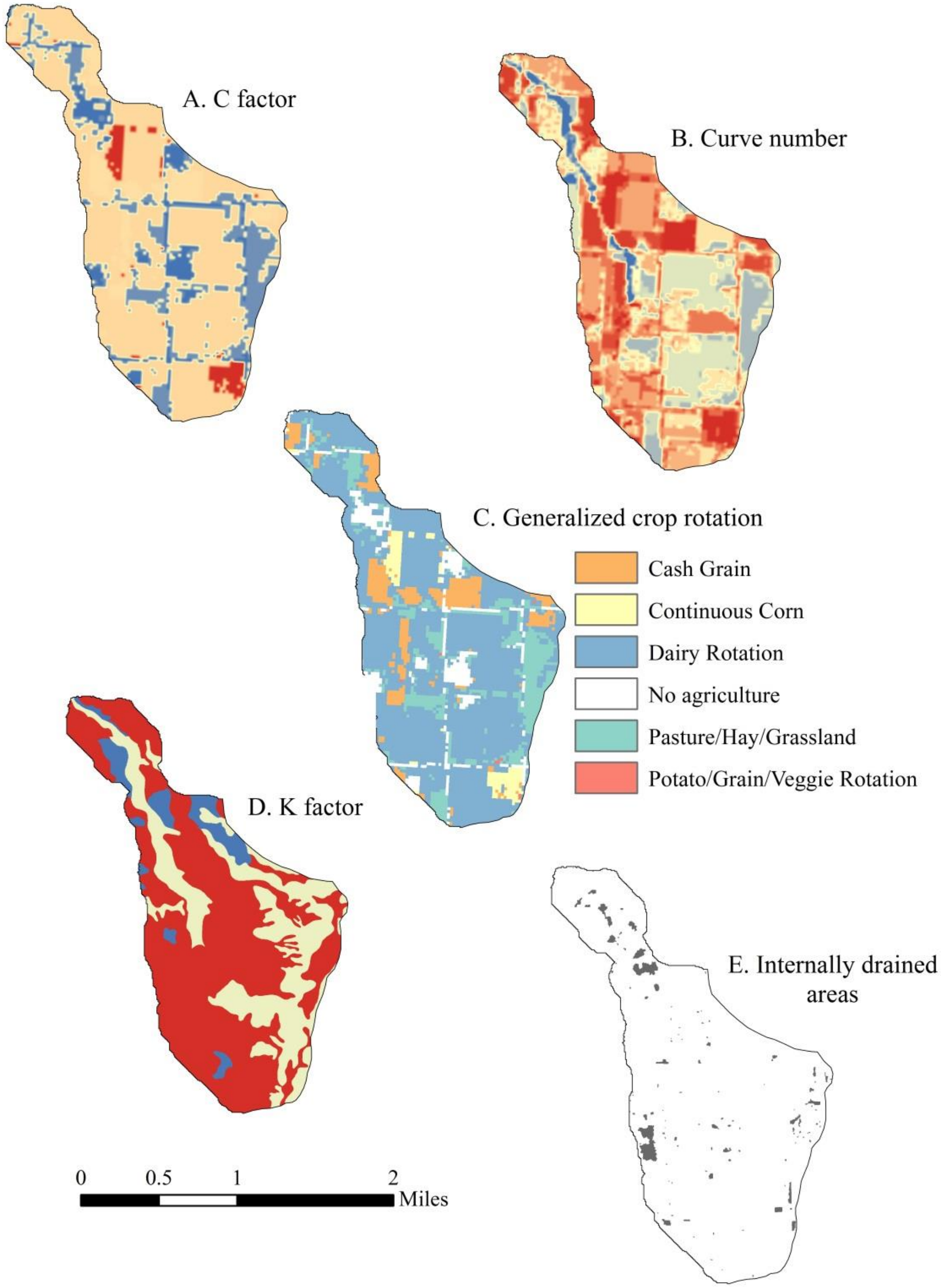

Figure 7. The intermediate outputs of EVAAL, for A, B, and D, red indicate high values, blue low values and beige intermediate values, for C, the legend is shown, and E, internally drained areas are shown in grey. Note: to find key and symbology for crop rotation layer, see Appendix C in the EVAAL tutorial document.

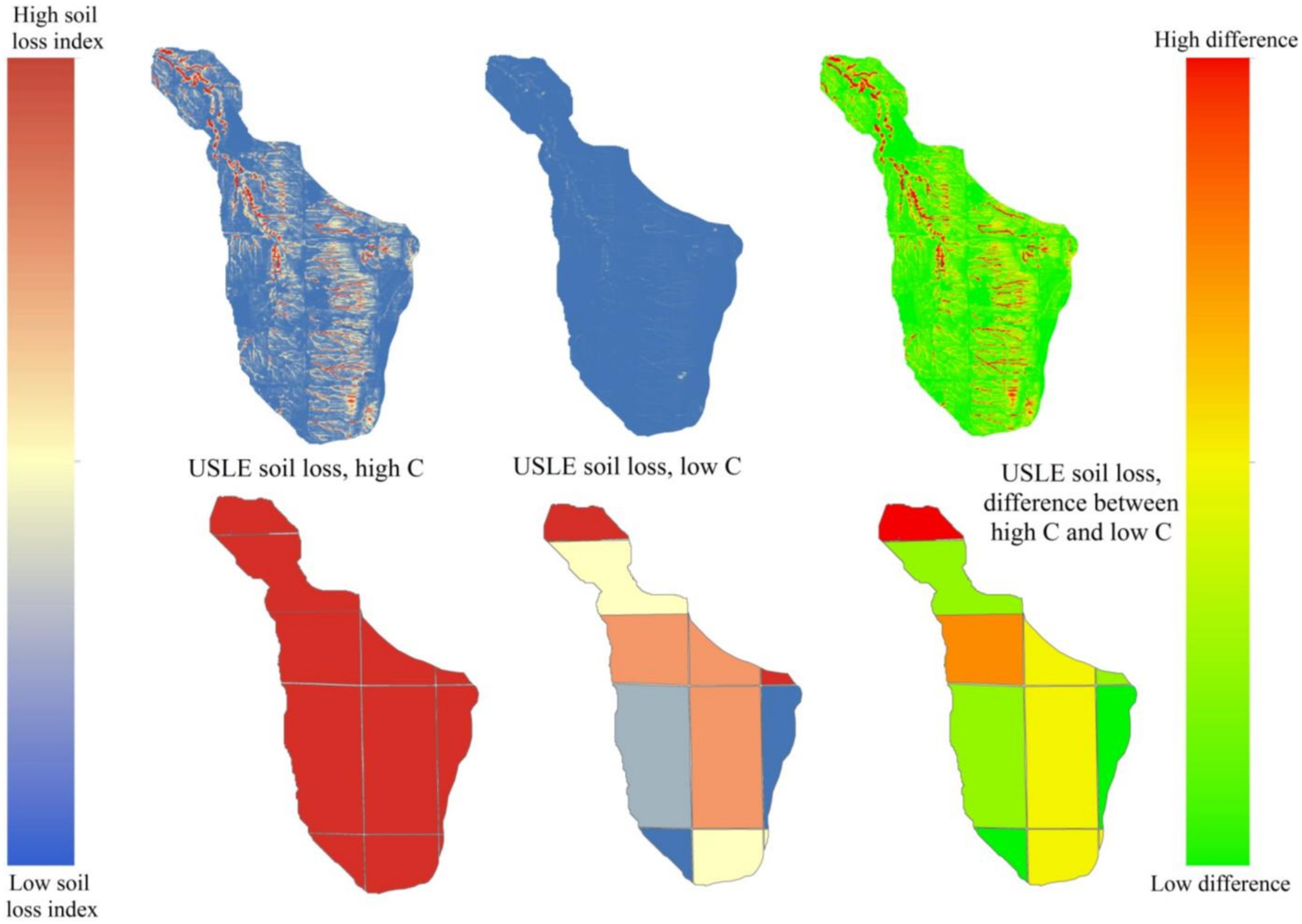

Figure 8. Results from subtracting the best-case scenario (middle) soil loss from the worst-case scenario soil loss (left). The resulting map (right) illustrates areas where a larger relative improvement will result from installation of best management practices if they do not already exist. In the above case, it can be seen clearly that the parcel in the north has the largest difference and could have the highest potential for erosion mitigation.

Example 2 Changing Parameters for Internally Drained Areas

As stated previously the internally drained areas are based on how much water is likely to overflow local barriers and reach surface waters for a given management and storm intensity. Changing either the storm intensity or the management will affect the amount of area considered to drain internally. The shorter the frequency-duration, the less intense the storm runoff will be, and the less likely that areas will drain to surface waters and thus the more area will be calculated as internally drained. Similarly, if local land management is assumed to contribute to runoff, the high curve number should be used. With the high curve number, more runoff is calculated and is more likely to overflow its local barriers, and the less internally drained area calculated.

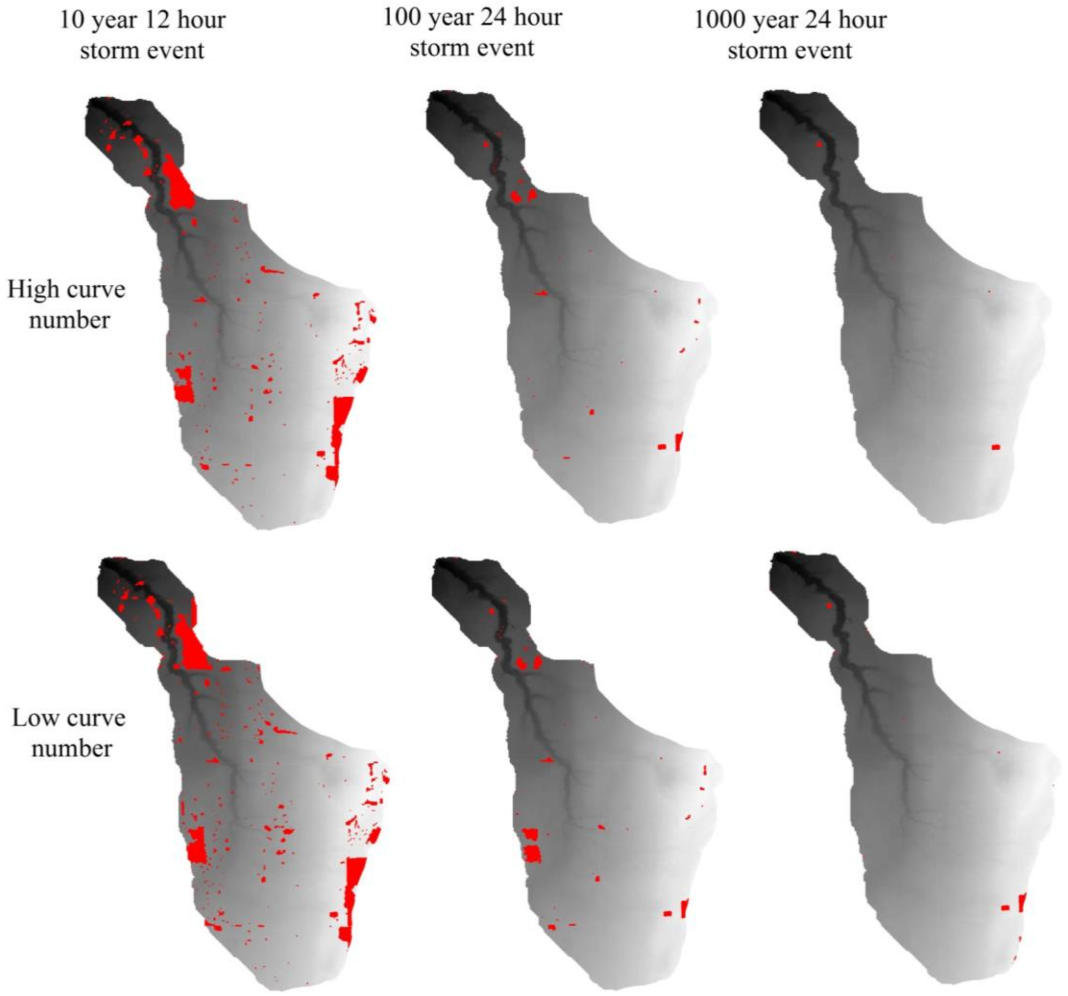

Figure 9. Maps illustrating how the extent of internally draining areas (shown in red) can be affected by changing the frequency-duration of the precipitation event and the curve number.

6.0 EVAAL LIMITATIONS

The EVAAL Toolset was developed to aid watershed managers in prioritizing areas within a subbasin to focus detailed data collection efforts to ultimately determine areas where BMP implementation will result in notable downstream water quality improvements. As with any numerical watershed model, there are limitations to how EVAAL can be used and interpreted:

- Even when aggregated to the field-scale, the results of EVAAL do not determine which fields are contributing the most sediment and/or nutrients to downstream surface waters; the data required for that type of analysis are much more detailed than what is used in EVAAL. EVAAL highlights those areas that are potentially more susceptible to contributing sediment (and associated nutrients) to surface waters.
- EVAAL assumes that overland erosion is the driving factor in nutrient delivery to surface waters. If it is known that an area has extensive subsoil drainage structures (e.g., tile lines) then EVAAL may not be appropriate.
- The erosion vulnerability index is a relative index; the index value for each grid cell is calculated relative to all the other grid cells within the study area. Thus, it is not recommended to compare the erosion vulnerability index values for different watersheds.
- EVAAL does not account for delivery factors or areas of deposition.
- The EVAAL erosion index makes general assumptions about land use and management. If actual conditions in the watershed are outside of the range of that typically found in Wisconsin, then the model results may not accurately reflect those actual conditions.
- EVAAL is designed to qualitatively model overland water erosion. The tool is not meant to model total erosion, only those areas most potentially vulnerable to erosion. Nor is the model meant to assess soil erosion from wind erosion.
- The function for deriving a generalized rotation expects a minimum of five years of cropland data, in the form of the CDL, and with crop types and rotations that are similar to those identified within the 9,156 mi^2 Wisconsin River basin.

7.0 EVAAL VALIDATION

The development team was interested to see how the output from the soil loss calculation compared to output from the SnapPlus model, since that model is widely used at the field-scale for estimating soil and phosphorus loss from agricultural fields.

Since the EVAAL tool does not estimate phosphorus loss, the comparison between model outputs was made on the soil loss calculations; the phosphorus index was not used. The team obtained data from a UW-Madison project in the Pleasant Valley watershed in southwestern Dane County in Wisconsin. Detailed field inventories had been performed in that watershed, and the SnapPlus files were made available to the project team. In order to compare similar scenarios, the Pleasant Valley SnapPlus field files were modified to simulate a three year corn grain rotation, and the EVAAL tool was run with that same rotation on all fields. The field slope used in the SnapPlus files was obtained from the information associated with the soil map unit specified for each field; therefore it was not necessarily representative of the actual slope in the field. Since slope plays such a large role in the erosion calculation, the field slopes in the SnapPlus files were replaced with the average field slope derived from the LiDAR DEM in GIS. The results of the comparison are shown in Figure 10. The R^2 of the trend line was 0.6 and the correlation coefficient was 0.7 which the team considers to be a good validation that the soil loss routines in EVAAL compare well with the RUSLE2 routines in SnapPlus.

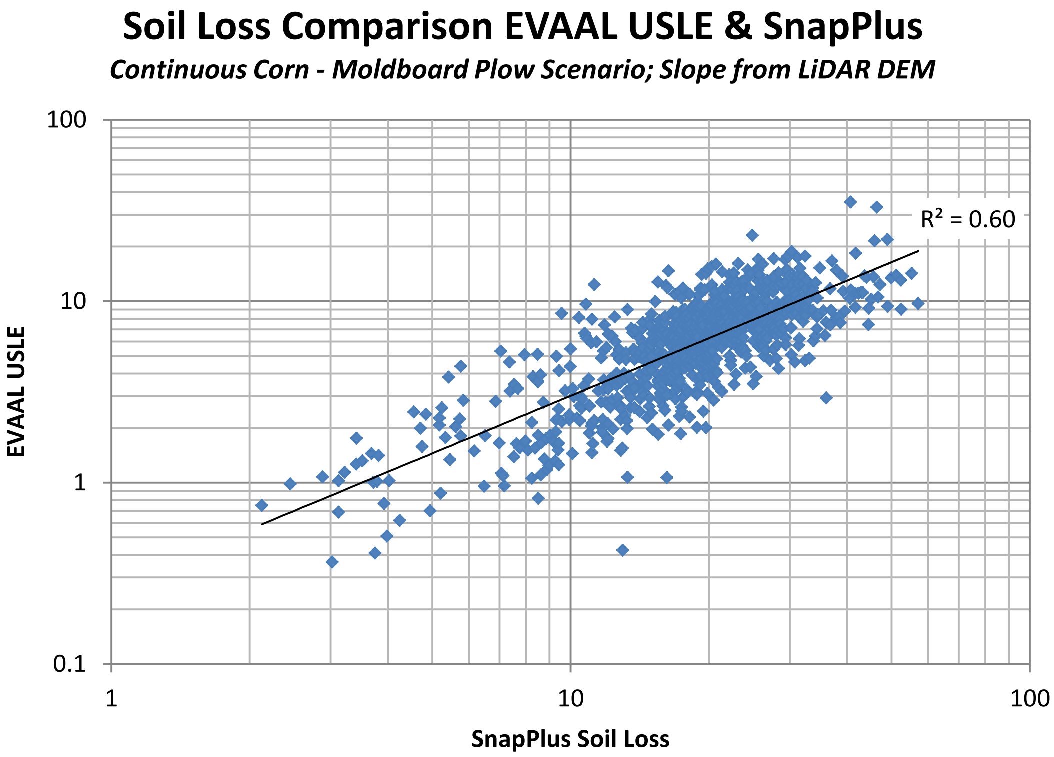

Figure 10. Scatterplot illustrating the correlation between soil loss estimates from SnapPlus and soil loss estimates from EVAAL. Each model run was parameterized equally, therefore the above correlation proves a relationship between the GIS-based estimate of soil loss in EVAAL and the RUSLE2-based estimate of soil loss in SnapPlus. The above results were modeled using parameters associated with a continuous corn rotation with a moldboard plow tillage.

8.0 CONCLUSIONS

The Wisconsin Department of Natural Resources (WDNR) Bureau of Water Quality has developed the Erosion Vulnerability Assessment of Agricultural Lands (EVAAL) Toolset to assist watershed managers in prioritizing areas within a watershed which may be vulnerable to erosion (and thus increased nutrient export) and which may contribute to downstream water quality problems. The output of the tool provides a way of prioritizing areas or farms within a watershed for BMP implementation and maximizing staff time and resources.

The tool is implemented as an ArcGIS Toolbox using easily and freely available data, decreasing time and costs associated with data acquisition and processing. The Toolbox and support documents are available to download from the WDNR's website [http://dnr.wi.gov/topic/Nonpoint/EVAAL.html].

The inputs of the tool include a high-resolution digital elevation model, a polygon boundary of the watershed of interest, polylines showing the locations of culverts in the area, and the gridded Soil Survey Geographic (gSSURGO) database.

The tool creates a hydrologically conditioned DEM from a LiDAR dataset and identifies portions of the area of interest that do not directly contribute to downstream surface water quality. Using the DEM, a stream power index is calculated which identifies areas vulnerable to gully erosion. The DEM along with several years of the Cropland Data Layer and soils information are used to calculate the relative potential for sheet and rill erosion using the USLE. These analyses are combined to create an erosion vulnerability index, with a value for each grid cell in the area of interest or aggregated to a boundary dataset, such as fields or farms.

EVAAL produces an erosion vulnerability index which shows which areas are potentially the most vulnerable to erosion. This index can be broken down into its component parts, which, like the index itself can be viewed for each grid-cell or aggregated by parcels or fields. It is possible to derive both best- and worst-case management scenarios, from which can be derived a map showing areas of greatest potential erosion mitigation.

As with any modeling application EVAAL has limitations both theoretical and practical, but every effort has been made to explain and document where and when they may be present.

The tool output for soil loss potential was compared to output from SnapPlus for similar conditions. This analysis showed good agreement between the estimates from both models.

EVAAL, including the documentation, tutorial, scripts and datasets are being made available to both internal and external WDNR customers and will be supported by the WDNR Modeling Technical Team.

9.0 REFERENCES

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10.0 APPENDICES

APPENDIX A

Table A1. Runoff curve numbers by land use type, treatment, condition, and hydrologic soil group (USDA SCS, 1986)

* BS = bare soil; CR = crop residue cover; SR = straight row; SRCR = straight row and crop residue cover; C = contoured; CCR = contoured and crop residue cover; CT = contoured and terraced; CTCR = contoured and terraced and crop residue cover)

COVER TYPE	TREAT-MENT*	HYDROLOGIC CONDITION	A	B	C	D
Open Space		Poor	68	79	86	89
Open Space		Fair	49	69	79	84
Open Space		Good	39	61	74	80
Paved parking lots			98	98	98	98
Streets and roads		curbs and storm sewers	98	98	98	98
Streets and roads		open ditches	83	89	92	93
Streets and roads		gravel	76	85	89	91
Streets and roads		dirt	72	82	87	89
Commercial and business			89	92	94	95
Industrial			81	88	91	93
Residential 1/8 acre or less			77	85	90	92
Residential 1/4 acre or less			61	75	83	87
Residential 1/3 acre or less			57	72	81	86
Residential 1/2 acre or less			54	70	80	85
Residential 1 acre or less			51	68	79	84
Residential 2 acre or less			46	65	77	82
Newly graded areas			77	86	91	94
Fallow	BS		77	86	91	94
Fallow	CR	Poor	76	85	90	93
Fallow	CR	Good	74	83	88	90
Row crops	SR	Poor	72	81	88	91
Row crops	SR	Good	67	78	85	89
Row crops	SRCR	Poor	71	80	87	90
Row crops	SRCR	Good	64	75	82	85
Row crops	C	Poor	70	79	84	88
Row crops	C	Good	65	75	82	86

Table A1. Runoff curve numbers by land use type, treatment, condition, and hydrologic soil group (USDA SCS, 1986)

* BS = bare soil; CR = crop residue cover; SR = straight row; SRCR = straight row and crop residue cover; C = contoured; CCR = contoured and crop residue cover; CT = contoured and terraced; CTCR = contoured and terraced and crop residue cover)

COVER TYPE	TREAT-MENT*	HYDROLOGIC CONDITION	A	B	C	D
Row crops	CCR	Poor	69	78	83	87
Row crops	CCR	Good	64	74	81	85
Row crops	CT	Poor	66	74	80	82
Row crops	CT	Good	62	71	78	81
Row crops	CTCR	Poor	65	73	79	81
Row crops	CTCR	Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
Small grain	SR	Good	63	75	83	87
Small grain	SRCR	Poor	64	75	83	86
Small grain	SRCR	Good	60	72	80	84
Small grain	C	Poor	63	74	82	85
Small grain	C	Good	61	73	81	84
Small grain	CCR	Poor	62	73	81	84
Small grain	CCR	Good	60	72	80	83
Small grain	CT	Poor	61	72	79	82
Small grain	CT	Good	59	70	78	81
Small grain	CTCR	Poor	60	71	78	81
Small grain	CTCR	Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
Close-seeded or broadcast legumes or rotation meadow	SR	Good	58	72	81	85
Close-seeded or broadcast legumes or rotation meadow	C	Poor	64	75	83	85
Close-seeded or broadcast legumes or rotation meadow	C	Good	55	69	78	83
Close-seeded or broadcast legumes or rotation meadow	CT	Poor	63	73	80	83
Close-seeded or broadcast legumes or rotation meadow	CT	Good	51	67	76	80
Pasture		Poor	68	79	86	89
Pasture		Fair	49	69	79	84
Pasture		Good	39	61	74	80
Meadow (protected from grazing but mowed for hay)			30	58	71	78
Brush		Poor	48	67	77	83

Table A1. Runoff curve numbers by land use type, treatment, condition, and hydrologic soil group (USDA SCS, 1986)

* BS = bare soil; CR = crop residue cover; SR = straight row; SRCR = straight row and crop residue cover; C = contoured; CCR = contoured and crop residue cover; CT = contoured and terraced; CTCR = contoured and terraced and crop residue cover)

COVER TYPE	TREAT-MENT*	HYDROLOGIC CONDITION	A	B	C	D
Brush		Fair	35	56	70	77
Brush		Good	30	48	65	73
Woods-grass combination (orchard or tree farm)			57	73	82	86
Woods-grass combination (orchard or tree farm)			43	65	76	82
Woods-grass combination (orchard or tree farm)			32	58	72	79
Woods		Poor	45	66	77	83
Woods		Fair	36	60	73	79
Woods		Good	30	55	70	77
Farmsteads			59	74	82	86
Open Water			100	100	100	100
Emergent wetlands			85	85	85	96
Wooded wetlands			85	85	85	96
Grassland			30	53	71	78
Barren			77	86	91	94

APPENDIX B

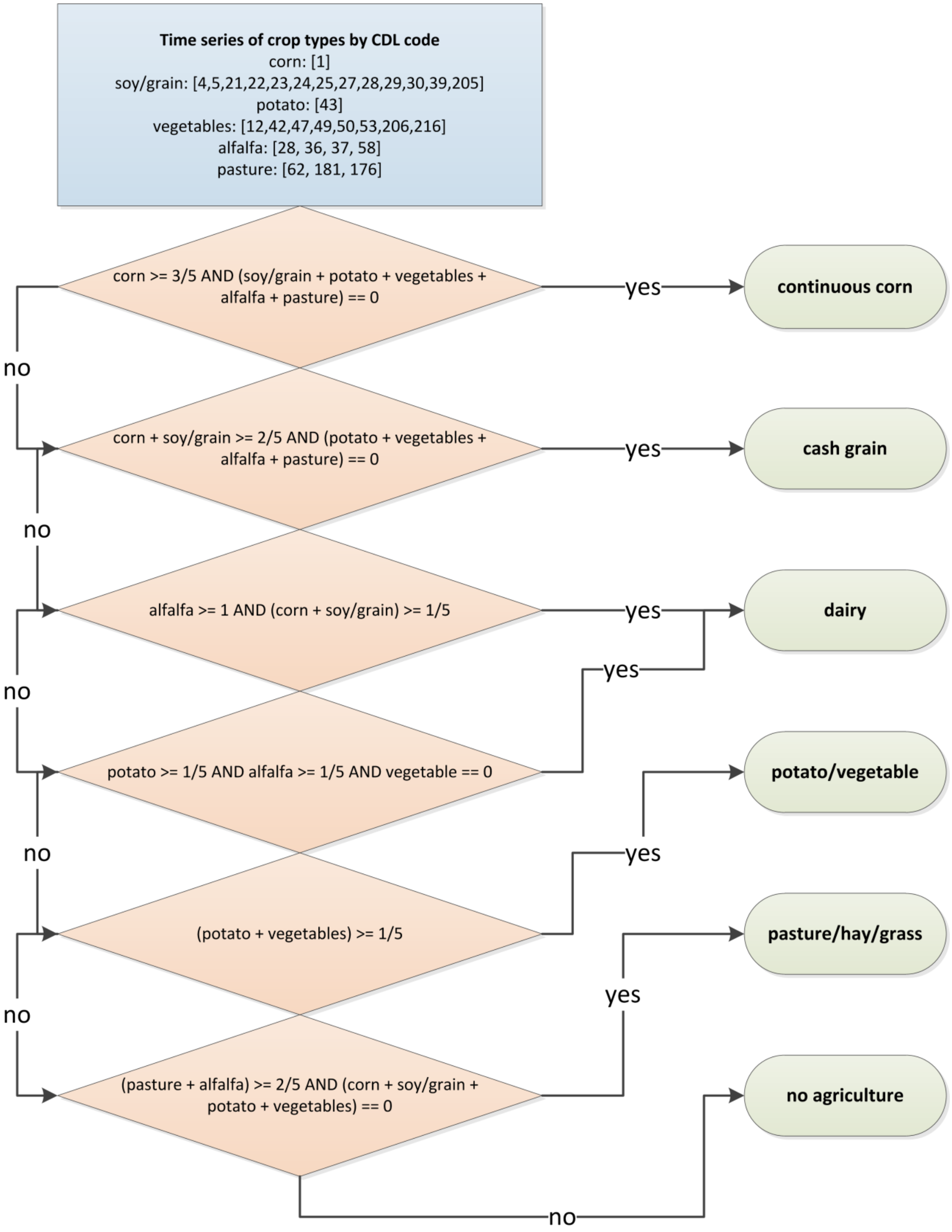

Figure B1. Decision rules for binning sequences of crops into generalized crop rotations. The input dataset are a series of raster maps called the Cropland Data Layer (CDL) that represents what crop is grown annually. Each crop was first aggregated into a crop type defined by the sets of codes in the input dataset (descriptions of CDL codes can be found in Table B2). Then, the numbers of each crop type are counted across the time series (5 years was used in the calibration dataset). Finally, the sequence of crops was binned into a generalized rotation by testing the numbers of crop types using the conditional statements above. For example, the first test, if the number of years of corn exceeded 3 out of 5 years, and there were no instances of soybeans, grain, potato, vegetable, alfalfa, or pasture, then the sequence would be binned into the "continuous corn" generalized rotation.

Table B1. Descriptions of codes used in the Cropland Data Layer (CDL).

CDL Code	Description
1	Corn
4	Sorghum
5	Soybeans
12	Sweet corn
21	Barley
22	Durum wheat
23	Spring wheat
24	Winter wheat
25	Other small grains
27	Rye
28	Oats
29	Millet
30	Speltz
36	Alfalfa
37	Other hay/non-alfalfa
38	Camelina
39	Buckwheat
42	Dry beans
43	Potatoes
47	Miscellaneous vegetables and fruit
49	Onions
50	Cucumbers
53	Peas
58	Clover/wildflowers
62	Pasture/grass
176	Grassland/pasture
181	Pasture/hay (deprecated in favor of class 176 for any CDL dataset downloaded after the year 2013)
205	Triticale
206	Carrots
216	Peppers

APPENDIX C

Table C1. Lookup table associating C-factors with generalized crop rotations. If a generalized crop rotation could not be identified, for instance in cases where land cover was defined as "non-agriculture," C-factors were defined as the annual average of land covers defined by the Cropland Data Layer (CDL) (Montana DEQ, 2012). C-factors can be highly variable; the user can modify the table with local values.

* Average of all developed classes
** Average of woody and herbaceous wetlands

ROTATION	COVER_LEVEL	C_FACTOR
Cash Grain	High	0.0098
Cash Grain	Low	0.1756
Continuous Corn	High	0.0050
Continuous Corn	Medium	0.1433
Continuous Corn	Low	0.3005
Dairy w/ Potato Year		0.0849
Dairy Rotation	High	0.0063
Dairy Rotation	Low	0.1803
Pasture/Hay/Grassland	High	0.0002
Pasture/Hay/Grassland	Low	0.0386
Potato/Grain/Veggie Rotation	High	0.1809
Potato/Grain/Veggie Rotation	Low	0.3055

LAND COVER	C_FACTOR
111 – Open Water	0
121 – Developed/Open Space	0.003
122 – Developed/Low Intensity	0.001
123 – Developed/Med Intensity	0.001
124 – Developed/High Intensity	0.001
131 – Barren	0.001
141 – Deciduous Forest	0.003
142 – Evergreen Forest	0.003
143 – Mixed Forest	0.003
152 – Shrubland	0.02
171 – Grassland/Herbaceous	0.02
176 – Grassland/Pasture	0.02
181 – Pasture/Hay	0.02
190 – Woody Wetlands	0.013
195 – Herbaceous Wetlands	0.003
63 – Forest	0.003
64 – Shrubland	0.02
65 – Barren	0.001
82 – Developed	0.0015*
83 – Water	0
87 - Wetlands	0.008**

Table C2. Generalized rotations used in SnapPlus to calculate annual average C factors. See SnapPlus help document for definitions of abbreviations. (http://snapplus.wisc.edu/Help/SnapPlusHelp.pdf).

Generalized rotation	Soil texture	Tillage rotation	Crop rotation
Cash grain - MBP	LOAMY_SAND	FP-FP-FP	Cg-Cg-Sg15
Cash grain - MBP	SILT_LOAM	FP-FP-FP	Cg-Cg-Sg15
Cash grain - MBP	SILT_LOAM	FP-FP-FP	Cg-Cg-Sg15
Cash grain - MBP	SILT_LOAM	FP-FP-FP	Cg-Cg-Sg15
Cash grain - NT	LOAMY_SAND	NT-NT-NT	Cg-Cg-Sg15
Cash grain - NT	SILT_LOAM	NT-NT-NT	Cg-Cg-Sg15
Cash grain - NT	SILT_LOAM	NT-NT-NT	Cg-Cg-Sg15
Cash grain - NT	SILT_LOAM	NT-NT-NT	Cg-Cg-Sg15
Continous corn grain MBP	SILT_LOAM	FP-FP-FP	Cg-Cg-Cg
Continous corn grain MBP	LOAMY_SAND	FP-FP-FP	Cg-Cg-Cg
Continous corn grain MBP	SILT_LOAM	FP-FP-FP	Cg-Cg-Cg
Continous corn grain MBP	SILT_LOAM	FP-FP-FP	Cg-Cg-Cg
Continous corn silage MBP	SILT_LOAM	FP-FP-FP	Csl-Csl-Csl
Continous corn silage MBP	LOAMY_SAND	FP-FP-FP	Csl-Csl-Csl
Continous corn silage MBP	SILT_LOAM	FP-FP-FP	Csl-Csl-Csl
Continous corn silage MBP	SILT_LOAM	FP-FP-FP	Csl-Csl-Csl
Continuous corn grain NT	SILT_LOAM	NT-NT-NT	Cg-Cg-Cg
Continuous corn grain NT	LOAMY_SAND	NT-NT-NT	Cg-Cg-Cg
Continuous corn grain NT	SILT_LOAM	NT-NT-NT	Cg-Cg-Cg
Continuous corn grain NT	SILT_LOAM	NT-NT-NT	Cg-Cg-Cg
Dairy rotation with Cg NT	LOAMY_SAND	NT-NT-NT-NT-None-None	Cg-Cg-Cg-AGs-AG-AG
Dairy rotation with Cg NT	SILT_LOAM	NT-SCD-NT-NT-None-None	Cg-Cg-Cg-AGs-AG-AG
Dairy rotation with Cg NT	SILT_LOAM	NT-NT-NT-NT-None-None	Cg-Cg-Cg-AGs-AG-AG
Dairy rotation with Cg NT	SILT_LOAM	NT-NT-NT-NT-None-None	Cg-Cg-Cg-AGs-AG-AG
Dairy Rotation with Cs MBP	LOAMY_SAND	FP-FP-FP-FP-None-None	Csl-Csl-Csl-As-A-A
Dairy Rotation with Cs MBP	SILT_LOAM	FP-FP-FP-FP-None-None	Csl-Csl-Csl-As-A-A
Dairy Rotation with Cs MBP	SILT_LOAM	FP-FP-FP-FP-None-None	Csl-Csl-Csl-As-A-A
Dairy Rotation with Cs MBP	SILT_LOAM	FP-FP-FP-FP-None-None	Csl-Csl-Csl-As-A-A
Dairy Rotation with potato FCP with disk	SILT_LOAM	FCD-FCD-FCD-FCD-None-None	Cg-Sg15-POl-As-A-A
Dairy Rotation with potato FCP with disk	LOAMY_SAND	FCD-FCD-FCD-FCD-None-None	Cg-Sg15-POl-As-A-A
Dairy Rotation with potato FCP with disk	SILT_LOAM	FCD-FCD-FCD-FCD-None-None	Cg-Sg15-POl-As-A-A
Dairy Rotation with potato FCP with disk	SILT_LOAM	FCD-FCD-FCD-FCD-None-None	Cg-Sg15-POl-As-A-A
Pasture Continuous High Density	LOAMY_SAND	None	Pu
Pasture Continuous High Density	SILT_LOAM	None	Pu

Table C2. Generalized rotations used in SnapPlus to calculate annual average C factors. See SnapPlus help document for definitions of abbreviations. (http://snapplus.wisc.edu/Help/SnapPlusHelp.pdf).

Generalized rotation	Soil texture	Tillage rotation	Crop rotation
Pasture Continuous High Density	SILT_LOAM	None	Pu
Pasture Continuous High Density	SILT_LOAM	None	Pu
Permanent grasslands	LOAMY_SAND	None	Gnh
Permanent grasslands	SILT_LOAM	None	Gnh
Permanent grasslands	SILT_LOAM	None	Gnh
Permanent grasslands	SILT_LOAM	None	Gnh
Potato veg rotation 1	LOAMY_SAND	SCND-CP/NTcvr-CP/NTcvr	SCm-[SB-SB]+cv-POl+cv
Potato veg rotation 1	SILT_LOAM	SCND-CP/NTcvr-CP/NTcvr	SCm-[SB-SB]+cv-POl+cv
Potato veg rotation 1	SILT_LOAM	SCND-CP/NTcvr-CP/NTcvr	SCm-[SB-SB]+cv-POl+cv
Potato veg rotation 1	SILT_LOAM	SCND-CP/NTcvr-CP/NTcvr	SCm-[SB-SB]+cv-POl+cv
Potato veg rotation 2	LOAMY_SAND	SP-SP-SP	SCm-[SB-SB]-POl
Potato veg rotation 2	SILT_LOAM	SP-SP-SP	SCm-[SB-SB]-POl
Potato veg rotation 2	SILT_LOAM	SP-SP-SP	SCm-[SB-SB]-POl
Potato veg rotation 2	SILT_LOAM	SP-SP-SP	SCm-[SB-SB]-POl