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Evaluating ephemeral gully erosion impact on *Zea mays* L. yield and economics using AnnAGNPS

Hao Li[a,c], Richard M. Cruse[b,*], Ronald L. Bingner[d], Karl R. Gesch[b], Xingyi Zhang[a,**]

[a] Key Laboratory of Mollisols Agroecology, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Harbin, 150081, China
[b] Department of Agronomy, Iowa State University, Ames, IA, 50011, USA
[c] University of Chinese Academy of Sciences, Beijing, 100049, China
[d] USDA-ARS National Sedimentation Laboratory, Oxford, MS, 38655, USA

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ABSTRACT

Ephemeral gully erosion causes serious water quality and economic problems in the Midwest United States. A critical barrier to soil conservation practice adoption is often the implementation cost, although it is recognized that erosion reduces farm income. Yet few, if any, understand the relationship between cost of conservation practice implementation and potential economic benefit gained from erosion control practices, especially as related to ephemeral gully erosion. The objectives of this research are to: (1) evaluate the soil loss and corresponding topsoil depth reduction due to annually ephemeral gully filling; and (2) estimate the economic loss associated with the crop production reduction attributed to topsoil thinning. Surface runoff and watershed sediment yield were flume measured at the approximately 1-ha drainage scale in Iowa. Sediment yield of the developing ephemeral gully was partitioned from measured total watershed sediment loss, by modeling ephemeral gully development with the Annualized Agricultural Non-Point Source Pollution model (AnnAGNPS), and subtracting this soil loss value from the flume measured watershed total. Topsoil thinning in the adjacent area used to fill the ephemeral gully was calculated based on the corresponding ephemeral gully sediment yield. The effect of A horizon thickness on corn yield obtained from published literature was used to calculate the corn (*Zea mays* L.) yield reduction due to topsoil thinning. Ephemeral gully erosion negatively impacts farm economics in the long term and implies that soil conservation measures should be carefully designed and well maintained. However, this evidence suggests that costs associated with establishment and use of structures such as grass waterways to minimize or eliminate ephemeral gully formation will not be recuperated in the short term through yield potential maintenance.

1. Introduction

Soil erosion by water is a major issue worldwide. Eroded cropland-soil deposited in water bodies exacerbates pollution because it not only is a physical pollutant itself but also usually contains adsorbed nutrients and pesticides. The loss of fertile soil degrades arable land and eventually renders it unproductive (Fenton et al., 2005; Pimentel et al., 1995). Half of the fertile topsoil of Iowa has been lost by erosion during the last 150 years of farming, and annual erosion costs for off-site and on-site damage in the United States are estimated at $17 billion and $27 billion, respectively (Pimentel et al., 1995).

The key consideration for soil conservation practice implementation is often economics (Lambert et al., 2007). Although the United States government provides technical and financial support for farm conservation efforts, insufficient soil conservation measures are adopted, at least partially because the farm operator believes that he or she will not directly or indirectly benefit economically from them. Indeed the net cost associated with adopting practices that keep soil in place may not be as high as it appears because soil erosion reduces farm income, especially through its negative impact on crop yields. Multiple studies have illustrated that soil changes caused by soil erosion have negative impacts on crop yield. Most notably, decrease in topsoil depth has consistently been associated with reduced crop yields (Fenton et al., 2005; Jagadamma and Lal, 2010). Hence, relating topsoil

Abbreviations: AnnAGNPS, Annualized Agricultural Non-Point Source Pollution model; no-till, no-tillage; RUSLE, Revised Universal Soil Loss Equation; CN, curve number; EGEM, Ephemeral Gully Erosion Model; HDC, headcut detachment coefficient; NSE, Nash-Sutcliffe efficiency coefficient; PBIAS, percent bias.

* Corresponding author.
** Corresponding author. Fax: +86 451 86603736.
E-mail addresses: rmc@iastate.edu (R.M. Cruse), zhangxy@iga.ac.cn (X. Zhang).

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depth change associated with soil erosion to crop yield change may be a critical step in evaluating in-field economic impacts of soil erosion and potential economic benefits of using conservation practices.

Ephemeral gully erosion is a critical component of cropland soil degradation (Poesen et al., 1996, 2003). The effects of soil thinning on crop productivity caused by ephemeral gully erosion are similar to those caused by sheet erosion; however, farmers play a role in accelerating soil loss in ephemeral gullies unlike that with sheet and rill erosion. By routinely filling ephemeral gullies with farm implements, topsoil depth over the adjoining area is systematically reduced. The topsoil loss by sheet and rill erosion can be estimated with empirically based models such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1996), and physically based models such as the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). However, ephemeral gully erosion estimation tools are limited even though concerns over this process have increased in recent decades (Poesen et al., 2003). Most ephemeral gully erosion research suggests empirical relationships exist between gully attributes and rates of soil loss derived from gullies (Campo-Bescós et al., 2013). Some physically based ephemeral gully erosion models have been tested by applying them in regions outside that where the model was developed (De Roo et al., 1996; Nachtergaele et al., 2001a).

The AnnAGNPS (Annualized Agricultural Non-Point Source) model (Bingner et al., 2015) can simulate continuous hydrologic, erosion, and water quality responses at the watershed scale. The erosion processes in the model include sheet erosion and ephemeral gully erosion as well as sediment delivery. AnnAGNPS is also effective in evaluating the impact of management decisions on soil erosion and water runoff. In the Cheney Lake Watershed, both streamflow and sediment were calibrated and validated with the measured data at the outlet, and then the most beneficial conservation practice within the watershed was identified (Theurer et al., 2010; Bingner et al., 2010; Theurer and Bingner, 2010). A simulation study of ephemeral gully development under various soil conservation measures suggests grass cover without construction of structures as the most profitable alternative for ephemeral gully control (Taguas et al., 2012). Based on measured soil properties, farming management, and climate input data, simulated erosion rates for gullies that were filled annually by tillage were 250% to 450% greater over a 10-year period than those occurring when gullies were left unfilled by tillage (Gordon et al., 2008). Although this simulation result was not compared with field data since no runoff and sediment measurements were available, it provides an opportunity to estimate ephemeral gully erosion and relate this to altered economic potential, e.g., crop production. The objectives of this research are to: (1) test AnnAGNPS estimation of ephemeral gully formation: (2) estimate the sediment yield from ephemeral gully erosion in instrumented watersheds; and (3) evaluate the economic impact of ephemeral gully erosion due to its impact on maize yields.

2. Materials and methods

2.1. Study area

AnnAGNPS was tested at the Neal Smith National Wildlife Refuge near Prairie City, Iowa (41°33′N, 93°16′W). The average annual precipitation registered over the last 30 years (1981–2010) was 910 mm, with the majority of the largest storms occurring between May and August (NCDC, 2011). Three watersheds identified as Interim 3 (0.8 ha), Orbweaver 3 (0.7 ha), and Basswood 6 (1.2 ha) were chosen for this ephemeral gully development study. The distance between these three watersheds was less than 5 km and they were managed by the same farmer. The land cover of these three watersheds was converted from native perennial vegetation to a no-tillage (no-till) corn (*Zea mays* L.) and soybean (*Glycine max*) rotation in 2006. The date and type of crop management were recorded each year, including the tillage scheme, crop type, plant density, and yield. The main soil type in Basswood 6 and Interim 3 was Ladoga (Mollic Hapludalfs), and that in Orbweaver 3 was Otley (Oxyaquic Argiudolls) (Helmers et al., 2012). In these three watersheds the mean topsoil depth was 30 cm and soil bulk density was 1.4 g/cm^3 (Zhou et al., 2009). In each watershed an ephemeral gully developed after 2006, and it was filled by disking and smoothed in the spring of 2012. Monitoring equipment used to supply supporting information for this study includes: a meteorological station (within the refuge) recording daily rainfall, air temperature, wind, and solar radiation; an instrumented flume placed at the outlet of each watershed for measurement of flow volumes; and a hydro-metrograph connected to an automatic runoff water sampler that was placed in each flume for the measurement of sediment concentration in the runoff water. Runoff flow volumes from each watershed were determined for each runoff event. A detailed description of the monitoring equipment is given by Helmers et al. (2012).

2.2. AnnAGNPS model description

AnnAGNPS is a continuous, distributed parameter model capable of simulating surface-runoff volume, peak flow rate, and sediment and pollutant transport from an agricultural watershed (Bingner et al., 2015). The surface runoff is determined by the SCS curve number (CN) technique (USDA, 1972), and the peak flow is calculated using the extended TR-55 method, which modifies the original NRCS TR-55 technology (McCuen, 1982). Sheet and rill erosion are calculated using RUSLE 1.05 technology, and the Hydro-geomorphic Universal Soil Loss Equation (HUSLE) is used for quantifying the sediment delivery ratio from the hillslope to the channel (Theurer and Clarke, 1991). The components of the Ephemeral Gully Erosion Model (EGEM), which was evaluated in the cropland of Spain and Portugal (Nachtergaele et al., 2001b), were revised and incorporated into AnnAGNPS to model ephemeral gully erosion (Gordon et al., 2007). The basic concepts, model components, and formulae are thoroughly described in the AnnAGNPS manual (Bingner et al., 2015).

2.3. Data preparation

The contiguous drainage area (cell) and the hydrographic network sedimentation into the channel (reach) of the research area were identified using TOPAZ (Topographic Parameterization) (Garbrecht and Martz, 1997) with the MAPwinGIS (Ames et al., 2007). The critical source area of 0.7 ha and the minimum source channel length of 50 m were chosen to obtain the flow geometry and surface flow network density that allowed a suitable representation of the drainage area and ephemeral gully in the field. The morphologic parameters (i.e. cell slope length and steepness) as well as the dominant land use and soil types were directly associated with each drainage area by means of the GIS interface. The National Soil Information System (NASIS) was used as the soil input data as suggested by the user manual (Schoeneberger, 2002). LIDAR data with 3-m resolution supplied the topography input. A no-till corn and soybean rotation existed in all watersheds. Management input parameters (crop types, rotation, and agricultural operations) were set following RUSLE guidelines and database. The initial CN values for these three watersheds were the same, 81, because the CN ID for the existing crop management and hydrologic soil group of the three watersheds were identical (Mishra and Singh, 2003).

Daily climate data (precipitation, maximum and minimum temperatures, solar radiation, and wind velocity) were obtained from the meteorological station within the refuge. The simulation began in 2008, as the first two years (2006 and 2007) were used to condition the model.

Ephemeral gully three-dimensional parameters were measured at the sampled cross-sections using tape before the rainy season in 2014, and they were compared with the simulated gully development. The interval distance of sampled cross-sections for each gully was set to 10 m, and gully width as well as depth in the thalweg of each gully cross-section was measured using a meter ruler. Additional measurements were obtained whenever the cross-section of the gully changed abruptly. With measured length, width, and depth, each ephemeral gully's volume was calculated.

2.4. Model evaluation

2.4.1. Sensitivity analysis

The Differential Sensitivity Analysis (DSA), which is a local sensitivity analysis method, was selected for its simplicity and low-need computational time compared to other statistical sensitivity analysis methods (Hamby, 1994). It is calculated at one or more points in the parameter space of an input keeping other inputs fixed. A value near zero indicates that the output is not sensitive to the parameter under study, whereas a value significantly different from zero shows high degree of sensitivity. Input parameters with the classification of high sensitivity (0.2–1) should be selected for calibration (Lenhart et al., 2002).

Previous studies have demonstrated that CN is much more sensitive than any other factors affecting runoff simulation in AnnAGNPS (Baginska et al., 2003; Licciardello et al., 2007; Shrestha et al., 2006; Yuan et al., 2001). Therefore, the sensitivity analysis was only performed for soil erosion simulation in this research. The main forms of soil erosion were sheet, rill, and ephemeral gully erosion in these three watersheds because there was no sign of classical gully erosion. Parameters that affect the RUSLE soil erodibility (K), crop management (C), and conservation practice (P) factors were selected for sensitivity analysis, including canopy cover, root mass, rain or water drop fall height, random roughness, sheet flow Manning's *n*, and concentrated flow Manning's *n*. The headcut detachment coefficient (HDC) using Wells #8 equation (Wells et al., 2013) was also selected because it was used to calculate the ephemeral gully headcut migration rate, which would promote ephemeral gully erosion (Bingner, personal communication). For the first six parameters the variation of the default value was set from −40% to 40%, changing with fixed percentage of 20%. For HDC, fixed input values between the maximum and minimum values were tested because their variation could not be represented as a percentage. The initial input values were either default values given by the model or obtained from the AnnAGNPS manual.

2.4.2. Calibration and validation processes

The runoff and sediment delivery to the watershed outlet were calibrated and validated in each watershed by comparison of observed and simulated values. Actual management practices, i.e. no-till with gully filled and smoothed in 2012, was simulated in the calibration and validation processes. All months were ranked from lowest to highest based on total precipitation depth. The ranked set was then divided into quarter groups and two thirds of the months in each group were randomly selected to go into the calibration set and the remaining months into the validation set. The final calibrated input parameters in Basswood 6 and Interim 3 were set as equal since the predominant soil types therein were the same (Ladoga). Orbweaver 3 with Otley soil had different calibration input parameters. In each watershed, measured runoff volume and sediment yield at the flume existed from 2008 to 2013 and 2008 to 2011, respectively, and in each year the monitoring period was from April to October. Model calibration was conducted in two steps. First, we calibrated the water flow, the driving force for sediment detachment and movement. Second, the erosion component of the model was calibrated. The procedure was performed by adjusting input parameters within the allowable range until the simulation results were reasonably close to the observed values on a monthly scale.

2.5. Model performance assessment

To assess AnnAGNPS performance, statistically and graphically based comparison methods were used in the calibration and validation phases. The Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) and percent bias (PBIAS) (Polyakov et al., 2007) were the statistical tools of choice. The former indicates how well observed versus simulated data fits a 1:1 line, and the latter quantifies the tendency of the predicted values to be higher or lower than the measured values. The satisfactory range of NSE values is between 0.50 and 0.65 for both runoff and sediment, and the satisfactory values of PBIAS are between ±15% and ±25%, as well as between ±30% and ±55%, respectively (Moriasi et al., 2007).

2.6. Economic loss evaluation

The economic impact of ephemeral gully erosion is based on (i) the relationship between topsoil depth and corn (*Zea mays* L.) yield developed by Fenton et al. (2005), and (ii) topsoil depth change driven by ephemeral gully soil loss. The model parameters obtained in the calibration process were used. To assess the economic loss of ephemeral gully erosion, management practice of no-till with filling ephemeral gully was simulated. Management practices that replace the lost ephemeral gully soil with soil from the adjacent cropped area are assumed. The topsoil depth change estimate is derived from annual ephemeral gully sediment yields obtained from AnnAGNPS after model validation. The measured topsoil depth of 30 cm in the three watersheds is used as the initial value in the simulation. The width of soil borrow area (W, m) along the ephemeral gully from which topsoil is moved into the gully is set at 5 m, and the length of this area (L, m) is set to equal the simulated ephemeral gully length. R_{sl} (cm y^{-1}) is the annual topsoil depth change in soil borrow area, and D (cm) is the remaining topsoil layer depth, which is given by:

$$R_{sl} = \frac{A_{sl}}{\mathrm{B} \cdot \mathrm{W} \cdot \mathrm{L}} \quad (1)$$

$$D = 30 - R_{sl} \cdot y \quad (2)$$

where

A_{sl} = Simulated total soil loss by ephemeral gully erosion (Mg),
B = Bulk density (g cm^{-3}),
y = years of erosion in the ephemeral gully.

As A horizon thickness decreases due to ephemeral gully filling, the corn yield reduction accelerates as shown in Fig. 2 of Fenton et al., (2005). When D decreases from 30 cm to 20 cm and 20 cm to 10 cm, the reduction in corn yield, R_{yl}, increases from 25 to 35 kg ha^{-1} cm^{-1}, respectively.

The soil borrow area's annual economic loss (E_{sl}, \$ y^{-1}) due to the previous year's topsoil depth reduction can be written as:

$$E_{sl} = L \cdot W \cdot R_{yl} \cdot Pr \quad (2)$$

where Pr is average corn price in the Midwest United States from June 2010 to July 2014 of \$260 Mg^{-1}.

Cost associated with grass waterway installation is represented by annual farm income reductions associated with the grass waterway area since no corn could be produced in the waterway. This cost is reduced by the value of inputs (seed, herbicides, fertilizer) not added to this area since no crop could be planted there (Iowa State University Ag Decision Maker, 2014). Construction cost (distributed over grass waterway life expectancy) is also considered part of the economic liability.

3. Results and discussion

3.1. Hydrological observation

For the observation period, annual rainfall ranged between 279 mm in 2012 and 1231 mm in 2010. The corresponding annual runoff in Interim 3 (Fig. 1) ranged between 79 mm and 429 mm. Similarly in Basswood, the minimum and maximum runoff observations occurred in the two years with minimum and maximum rainfall, respectively; for the Orbweaver 3 watershed the minimum runoff occurred in 2009. The sediment yield observation period was between 2008 and 2011, two years shorter than the runoff observation record. Of interest, maximum sediment yield occurred in 2008 instead of the wettest year, 2010.

For monthly average data during the observation period, the rainfall amount in June accounted for 28% of total rainfall, which was larger than any other month (Table 1). Additionally, the percentage of runoff and sediment measured in June was also the highest on average. The proportion of runoff recorded in June to total runoff was almost 40% in these three watersheds, and corresponding values of sediment ranged from 53% in Basswood 6 to 85% in Orbweaver 3. Although August had the second highest rainfall and runoff amount, the sediment yield in this month was almost always lowest. Low sediment yields were consistently observed in April, September, and October. Indeed the sediment yield in the latter half of the year was much lower than the first half of the year. This phenomenon was reasonable because growing crop cover protected the topsoil from rainfall's splash erosion and reduced surface concentrated flow (Gyssels and Poesen 2003). The monthly percentage of erosion varied more than that of surface runoff; the coefficient of variation (CV) of sediment yield was larger than that of surface runoff. In the Interim 3 watershed, the CV of monthly surface runoff was 0.92, which was smaller than that of sediment yield, 1.86. Similar trends were observed in the Orbweaver 3 and Basswood 6 watersheds. In previous modeling work, soil erosion was shown to be more sensitive than runoff to changing rainfall and soil surface cover (Nearing et al., 2005).

Thirty six monthly rainfall events were recorded from April to October in the 2008 to 2013 time period. For the Interim 3, Orbweaver 3, and Basswood 6 watersheds, runoff occurred in 33, 30, and, 33 months, respectively, suggesting similar landscape, management, and rainfall for these experimental units. And for these respective watersheds 21, 16, and 22 monthly sediment yield observations were recorded from 2008 to 2011.

3.2. Sensitivity analysis

A linear relationship existed between variations in all input parameters and model output (Fig. 2). Total soil erosion was correlated negatively with most of the input parameters selected, but had a positive correlation with HDC. For total soil erosion, HDC was classified as a highly sensitive parameter and the remaining six parameters as having medium sensitivity (Lenhart et al., 2002). For ephemeral gully erosion, HDC was also classified as highly sensitive, while the sensitivities of the other six inputs were classified as being small to negative. Therefore only HDC was selected for calibration relative to total soil erosion simulation. This meant that only ephemeral gully erosion was calibrated in the soil erosion simulation. This was reasonable because RUSLE technology has been thoroughly researched and validated (Renard et al., 1996), and the assessment of sheet and rill erosion in AnnAGNPS using RUSLE was assumed to be reliable (Bingner et al., 2010).

3.3. Calibration test

The runoff calibration results from 2008 to 2013 in each watershed are plotted in Fig. 3. The plots illustrate the challenge of identifying a common optimum input value for both NSE and PBIAS evaluations. There were distinct ranges of input values that yielded satisfactory calibration results for each index, however, these ranges differed. The CN values yielding the optimal NSE and PBIAS values were different in each watershed (Fig. 3a). Since the soil type and management in Basswood 6 and Interim 3 were the same, the final calibrated CN value should be the same when the simulated runoff was most closely aligned with the observed

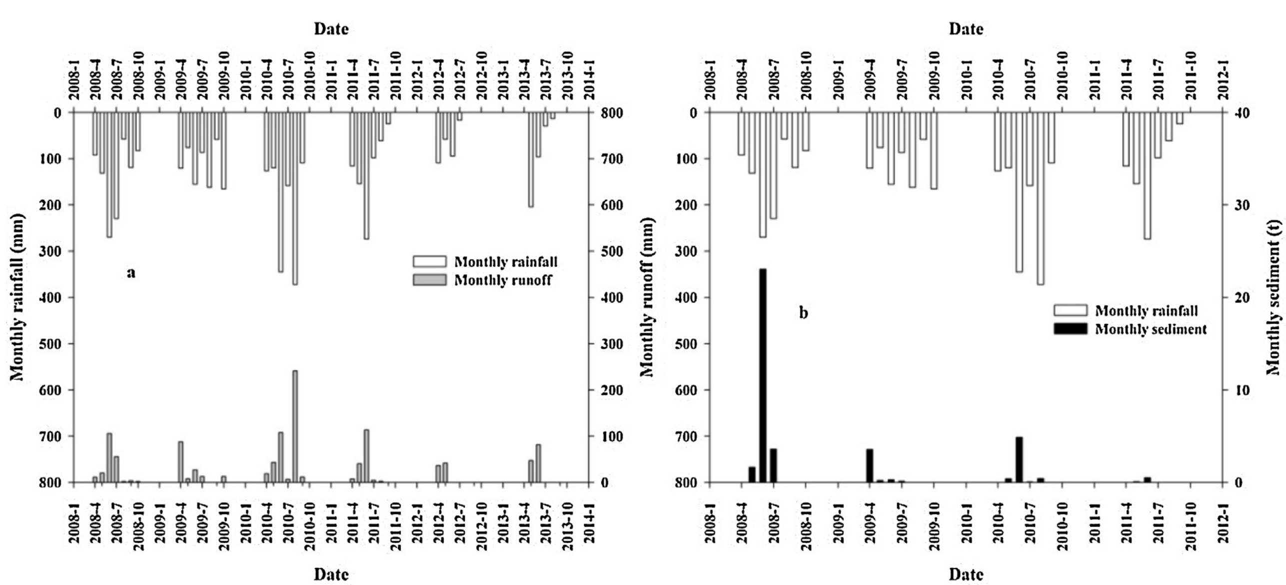

Fig. 1. Rainfall precipitation, runoff, and sediment yield under no-till system with corn-soybean rotation from 2008 to 2014 in Interim 3 watershed.

Table 1
Monthly average rainfall, runoff, and sediment yield under no-till system with corn-soybean rotation from 2008 to 2014 in three watersheds.

Month	Rainfall (mm)	Basswood 6		Interim 3		Orbweaver 3	
		Runoff (mm)	Sediment (Mg)	Runoff (mm)	Sediment (Mg)	Runoff (mm)	Sediment (Mg)
Apr	113.7	49.9	0.5	31.3	0.9	10.4	0.0
May	120.3	37.2	0.5	28.0	0.6	11.1	0.2
Jun	261.0	150.8	4.7	88.6	7.2	54.1	5.7
Jul	143.2	37.3	2.6	19.8	1.0	8.9	0.0
Aug	163.3	68.8	0.5	61.4	0.1	45.8	0.8
Sep	77.7	10.1	0.0	3.9	0.0	1.8	0.0
Oct	62.1	10.7	0.0	3.6	0.0	0.8	0.0

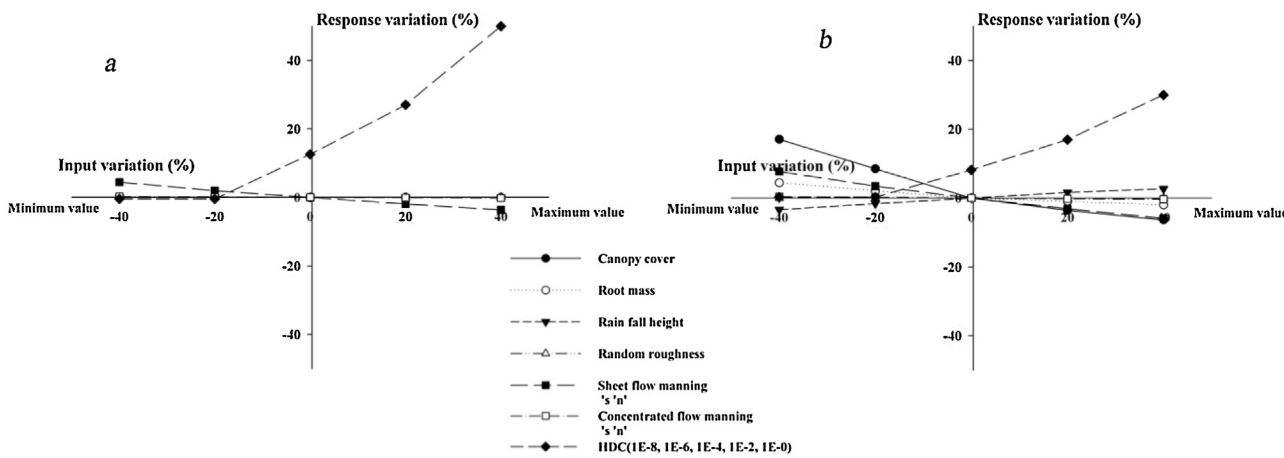

Fig. 2. Sensitivity analysis of sediment yield from ephemeral gully erosion (a) and total soil erosion (b) to selected input parameters.

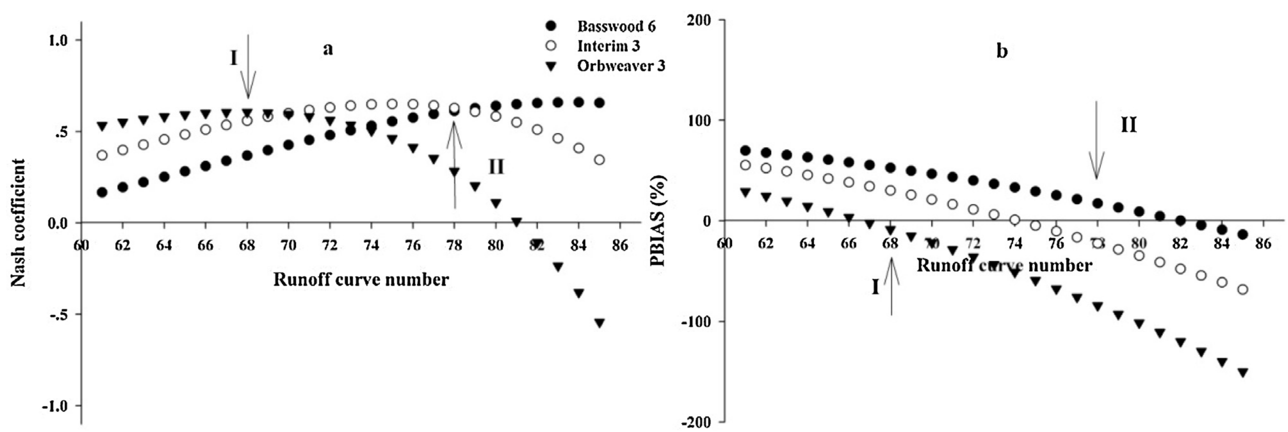

Fig. 3. Runoff calibration evaluated with NSE (a) and PBIAS (b).

value in both watersheds. The CN value of 82 yielded the best runoff simulation in Basswood 6 (0.66 and 23% for NSE and PBIAS, respectively), while the result in Interim 3 was not satisfactory as the PBIAS was −47.7% (Fig. 3b). The CN value of 75 yielded the best runoff simulation in Interim 3 (0.65 and −4.7% for NSE and PBIAS), while the result in Basswood 6 was not concurrently satisfactory, as the PBIAS was 29.3%. The optimal runoff simulation that most closely aligned with observed runoff value in both watersheds was obtained with a CN value of 78 (Fig. 3, II). The NSE and PBIAS in Basswood 6 and Interim 3 were 0.61, 17.4%, and 0.63, −22.4%, respectively, all classified as satisfactory. Additionally, the PBIAS values in both watersheds were relatively close to 0 compared with the simulated runoff yield using other CN values. Therefore the CN value of 78 was chosen for Basswood 6 and Interim 3 in the runoff calibration process. For Orbweaver 3 the CN value of 68 yielded the optimal runoff simulation since the NSE was the largest at 0.61 and the PBIAS was close to 0 with a value of −2.2% (Fig. 3, I).

Each watershed area was represented as one homogeneous cell with one soil and land use type. This meant that only one soil hydrological type needed to be identified. If the research area contained more than one soil or land use type, different soil hydrological groups would require separate calibration (Licciardello et al., 2007). Additionally the CN was assumed constant across seasons because most rainfall-induced surface runoff was observed from late spring to early autumn. In regions where rainfall runoff is observed all year, the CN variation with seasons must be considered (Chahor et al., 2014).

Sediment yield for sheet and ephemeral gully processes was calibrated by varying HDC (Fig. 4), which influences ephemeral gully development and the annual sediment yield as well as its temporal distribution (Alonso et al., 2002; Bingner et al., 2010). The initial HDC was 1, and the minimum value of HDC was 1e-8, which was the smallest value the user could input. Only when the HDC value was smaller than 1e-6 was the AnnAGNPS simulation of sediment classified as “good” in terms of trends (NSE). The model tended to overestimate sediment yield as PBIAS values were below 0 when the HDC values varied from 1e-7 to 1. The HDC value of 1e-7 yielded the optimal sediment simulation in terms of trends (NSE) and average magnitude (PBIAS) in all three watersheds. It should be noted that whether the calibrated value of HDC in this research could be applied in other regions needs to be investigated because we did not measure this value for comparison with the simulated results. This could be an important extension of improving model simulation performance that would definitely contribute to a better understanding of sediment yield from ephemeral gully erosion and its development in the field. Another probable method of improving model simulation performance through input parameters modification would involve model evaluation using the measured gully width and length data because AnnAGNPS could also be used to simulate the ephemeral gully headcut migration process temporally and spatially.

3.4. Model performance evaluation

Graphical results during calibration and validation (Figs. 5 and 6)) indicated adequate calibration and validation over the range of runoff and sediment yield observed, although the calibration results showed a better match than the validation results. NSE values for the monthly runoff calibration and validation ranged from 0.51 to 0.63 (Table 2). According to the model evaluation guidelines, the model simulated the runoff trends well. The PBIAS values varied from 8.4% to 34.3% during the calibration period and from −16.5% to 34.3% during the validation period. The average magnitude of simulated monthly runoff values was within good ranges in the calibration period. In the validation period runoff simulation in Orbweaver 3 was good while the model underestimated the runoff amount in Basswood 6 and Interim 3.

For sediment yield calibration and validation the model performances were typically classified as good in terms of NSE and PBIAS, although the NSE value during the validation in Basswood 6 was 0.43. The model tended to underestimate runoff and sediment yield in the calibration and validation periods because PBIAS values were typically greater than 0. A previous study suggests that this tendency was caused by underestimation associated with the more significant events (Helmers et al., 2012). The model tended to underestimate sediment yield, especially in small rainfall months with sediment yield less than 2 Mg (Fig. 6b). More sediment deposition would occur in small rainfall events as sediment transport capacity varies with runoff raised to the fifth power (Morgan, 2009). In our research sheet and ephemeral gully erosion were mixed in the measured sediment yield. If water and soil loss from hillslopes could be measured using a portable on-site monitoring device (Sun et al., 2014), the observed sheet erosion and ephemeral gully erosion could be separated, and hence the calibration and validation accuracy could likely be improved.

The NSE values for runoff prediction were larger than those for sediment yield prediction, indicating that the runoff volume predictions better matched the measured values than that which occurred for sediment yield. Additionally, the PBIAS values for runoff simulation were lower than those for sediment yield. Both indices confirmed that AnnAGNPS could better simulate runoff than sediment yield.

The simulated ephemeral gully development process was also compared with measured gully width and length, and sediment yield (Table 3). The ephemeral gully depth was not compared because this was one of the input parameters, i.e., the simulated gully depth was the same as the measured value. Relative differences between measured and simulated gully width were larger than that of gully length: the average measured gully widths in three watersheds were about 67% of the simulated value, while the simulated ephemeral gully lengths were around 84% of the measured value. The difference between measured and simulated gully volume were 32%, 60%, and 58% in Basswood 6, Interim 3, and Orbweaver 3, respectively, showing that the calibrated model underestimated the ephemeral gully erosion. The average magnitudes of simulated ephemeral gully erosion were within the good range (PBIAS <±55%) both in calibration and validation watersheds, except in Interim 3. The simulated ephemeral gully sediment yields ranged from 3.8 to 5.0 $Mg\,ha^{-1}\,y^{-1}$ with an average value of 4.3 $Mg\,ha^{-1}\,y^{-1}$. The average topsoil depth reduction in the adjacent region along the ephemeral gully was 1.0 $cm\,y^{-1}$, based on a bulk density of 1.4 $g\,cm^{-3}$ and the assumed adjacent borrow region width and length. EGEM, which is the forerunner of ephemeral gully erosion in AnnAGNPS, was thoroughly tested by Nachtergaele et al. (2001b) with 86 measured ephemeral gullies; a very good relationship between predicted and measured ephemeral gully volumes was found (R^2 = 0.88). Since gully length was an input parameter for EGEM, the gully cross-section is supposed to be the main source for prediction error

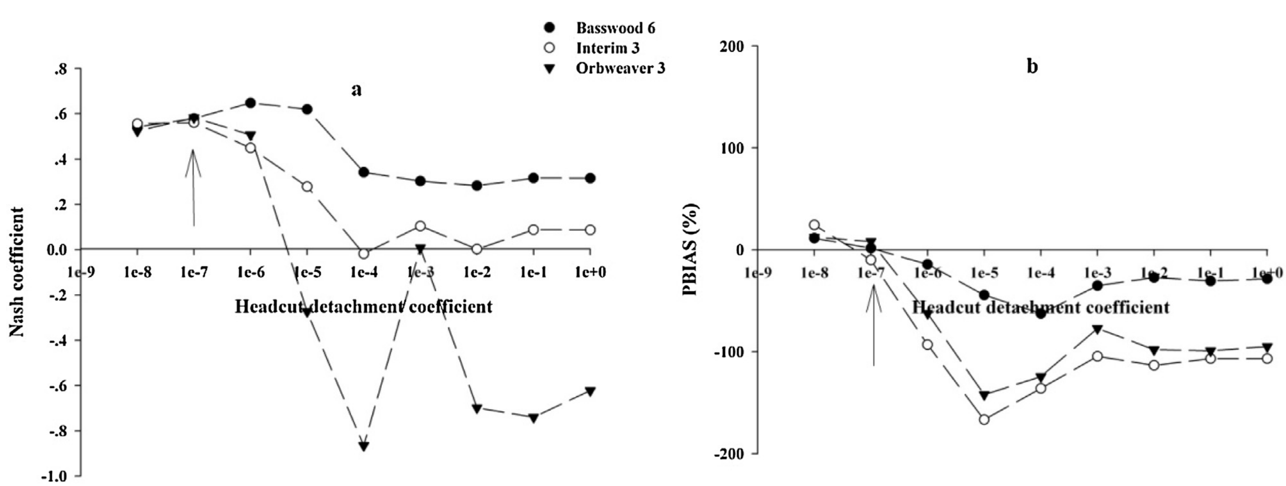

Fig. 4. Sediment yield calibration evaluated with NSE (a) and PBIAS (b).

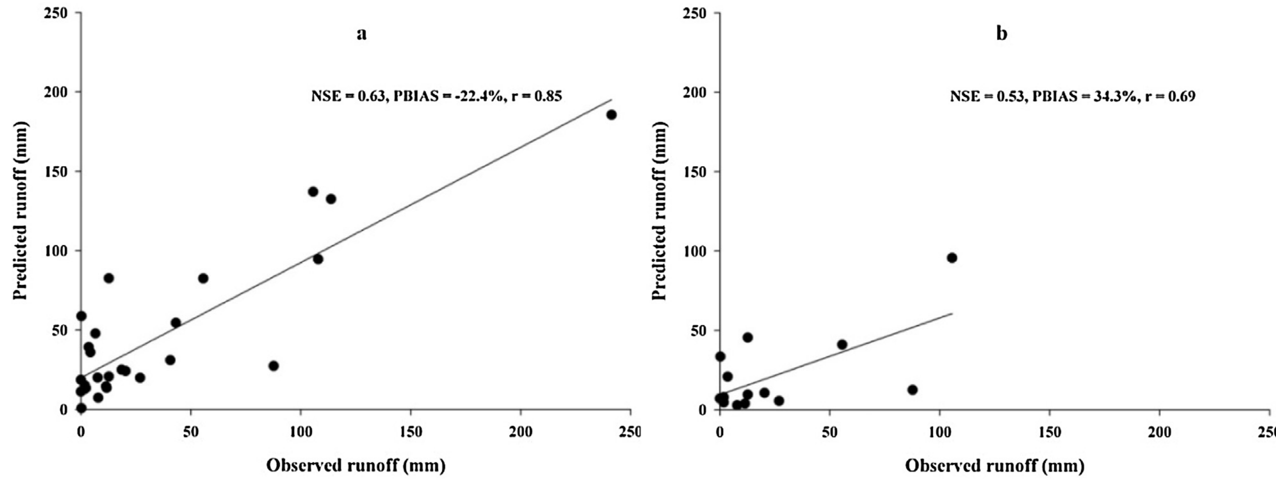

Fig. 5. Monthly observed and predicted runoff for calibration (a) and validation (b) in Interim 3.

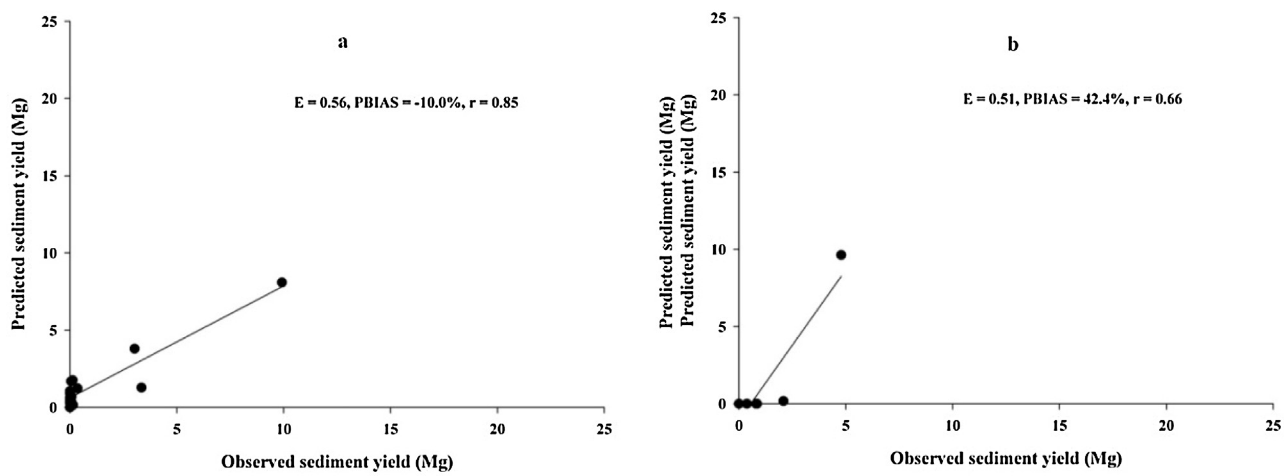

Fig. 6. Monthly observed and predicted sediment yield for calibration (a) and validation (b) in Interim.

Table 2
Calibration and validation of runoff and sediment in three watersheds.

	Runoff				Sediment			
	Calibration		Validation		Calibration		Validation	
	NSE	PBIAS (%)	NSE	PBIAS (%)	NSE	PBIAS (%)	NSE	PBIAS (%)
Basswood 6	0.61[b]	17.4[b]	0.51[b]	28.7[c]	0.58[b]	−1.5[a]	0.43[c]	45.6[c]
Interim 3	0.63[b]	−22.4[b]	0.53[b]	34.3[c]	0.56[b]	−10.0[a]	0.51[b]	42.4[b]
Orbweaver 3	0.61[b]	−8.4[a]	0.55[b]	-16.5[b]	0.58[b]	−8.0[a]	0.50[b]	26.8[b]

[a] Better than satisfactory.
[b] Satisfactory.
[c] Not satisfactory.

Table 3
Ephemeral gully morphology and erosion measurement and simulation results.

Watershed	Gully average width (m)		Gully length (m)		Sediment yield from Ephemeral gully (Mg ha^{-1} yr^{-1})		Simulated topsoil loss due to Ephemeral gully (cm yr^{-1})
	Measured	Simulated	Measured	Simulated	Estimated	Simulated	
Basswood 6	0.6	1	72.1	64.2	5.6	3.8	0.9
Interim 3	0.6	0.9	85.7	64.1	10.1	4.0	0.9
Orbweaver 3	0.8	0.9	73.3	63.2	11.9	5.0	1.3

(Woodward, 1999). After EGEM was revised and incorporated into AnnAGNPS, it better simulated ephemeral gully length and width temporally and spatially along the gully, although the relative variation of predicted gully width was still larger than that of gully length in this research.

3.5. Economic loss caused by ephemeral gully erosion and grass waterway

The annual and cumulative economic losses associated with crop yield reduction caused by soil thinning were plotted in Fig. 7, and annual profit reduction associated with an ephemeral gully or grass waterway was summarized in Table 4.

The calculated cumulative economic loss associated with ephemeral gulley erosion and corn yield reduction within 15 years was \$166 ha^{-1} with an average annual economic loss of \$11 ha^{-1} y^{-1}. Actually, the initial annual economic loss was \$6.5 ha^{-1} y^{-1}; this value would increase to \$14.3 ha^{-1} y^{-1} after 15 years as the ephemeral gully filling process decreased the topsoil layer depth gradually and hence crop yield sensitivity to topsoil depth change increases as shown by Fenton et al., (2005). Grass waterways are effective at preventing ephemeral gully development on cropland. According to the Environmental Quality Incentives Program (USDA-NRCS, 2013), grass waterway establishment cost in 2013 was \$18,298 ha^{-1}. If the life expectancy of a grass waterway was assumed to be 15 years, the temporally distributed annual cost of constructing a grass waterway would be \$1220 ha^{-1} y^{-1}, which was 111 times larger than the economic loss associated with ephemeral gully erosion (\$11 ha^{-1} y^{-1}). Annual yield loss due to no crop production in the grass waterway region was 9.8 Mg ha^{-1} y^{-1}, which was \$2548 ha^{-1} y^{-1} with the corn price of \$260 Mg^{-1}. The average cost of corn production from 2010 to 2014 was \$4.95 bu^{-1} (Iowa State University Ag Decision Maker, 2014), or \$1900 Mg^{-1}. Therefore the net economic loss in the grass waterway area due to lost crop production was \$648 ha^{-1} y^{-1}. The large difference between farm economic loss caused by ephemeral gully erosion (\$11 ha^{-1} y^{-1}) and corresponding soil conservation measures (\$648 ha^{-1} y^{-1}) was understandable since crop production in the grass waterway region was precluded. As a result, the total economic loss (economic loss from lost production plus construction cost) due to grass waterway implementation was \$1868 ha^{-1} y^{-1}, which was 170 times larger than the economic loss associated with ephemeral gully erosion (\$11 ha^{-1} y^{-1}) alone. In our research the construction cost was twice as much as farm economic loss, which accounted for more than 65 percent of total grass waterway economic impact. Taguas et al. (2012) demonstrated that the economic impact of ephemeral gully conservation with grass cover (726€ ha^{-1} y^{-1}) was considerably higher than the net profit reduction (0.71€ ha^{-1} y^{-1}) from erosion induced yield reduction, although it was considered the most environmentally friendly management practice with the annual average soil loss of 0.12 mm. The fact that the on-site economic loss associated with erosion seems rather low compared with the construction cost emphasizes the need to maintain existing soil conservation structures such as grass waterways. The significant income differences with and without grass waterways shows that farmers have no obvious financial incentive to construct and manage grass waterways in the short term without additional financial support (Lambert et al., 2007).

Table 4
Summary of economic loss associated with ephemeral gully erosion and grass waterway.

Annual economic loss	Value (\$ ha^{-1} y^{-1})
Lost crop production with filling ephemeral gully	11
Lost crop production with grass waterway	648
Grass waterway construction cost	1220

In addition to reduced crop yield, the economic loss due to erosion includes multiple other aspects not considered in this study, such as labor required to fill the gullies, and nutrient loss in the eroded soil materials. Martínez-Casasnovas et al. (2005) found that 7.5 tractor hr ha^{-1} y^{-1} was needed to restore broad base terraces and drainage channels and to fill ephemeral gullies, which comprised 5.4% of the income from farmer's grape sales. The replacement value of the N and P lost would account for 2.4% and 1.2%, respectively, of the annual income for their studied system (Martínez-Casasnovas and Ramos, 2006). Our research was focused on only on-site crop yield loss due to ephemeral gully erosion, which was only one component of the total economic loss caused by erosion. Including collateral on-site impacts as mentioned above and off-site impacts would raise ephemeral gully economic influence substantially and are required in the

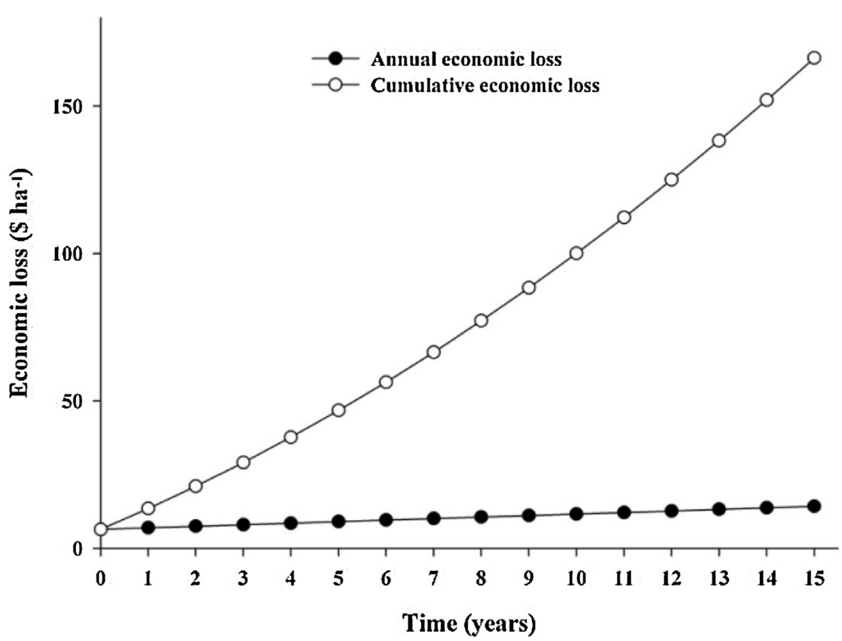

Fig. 7. Annual and cumulative economic loss caused by ephemeral gully erosion within the soil borrow area.

economic calculations to get a true picture of ephemeral gully economic implications (Ledermann et al., 2010).

4. Summary and conclusions

Ephemeral gully erosion simulated by AnnAGNPS, including runoff and sediment yield, were most sensitive to the CN and HDC parameters. We obtained optimal parameter values through model calibration; and the validation result was satisfactory but not as good as the calibration. With the calibrated CN and HDC parameters, ephemeral gully erosion amount was successfully separated from total sediment yield, and corresponding economic loss was calculated in terms of crop yield reduction by annually filling the ephemeral gully using adjacent topsoil as well as grass waterway construction.

Our results indicate that ephemeral gully erosion reduces annual farm income in the long term, but it could not offset grass waterway presence in terms of farm economic loss and construction cost. Analysis of simulation results indicates that the economic loss caused by filling ephemeral gullies accounts for less than one percent of grass waterway cost within its life expectancy (and this assumes no maintenance cost associated with the grass waterway exists during this period). Sufficient financial aid or policy incentives seems important for this soil conservation practice to be adopted.

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