

r.sim.terrain: a dynamic landscape evolution model

Brendan Alexander Harmon¹, Helena Mitasova^{2,3}, Anna Petrasova^{2,3}, and Vaclav Petras^{2,3}

¹Robert Reich School of Landscape Architecture, Louisiana State University, Baton Rouge, Louisiana, USA

²Center for Geospatial Analytics, North Carolina State University, Raleigh, North Carolina, USA

³Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina, USA

Correspondence: Brendan Harmon (baharmon@lsu.edu)

Abstract. While there are numerical landscape evolution models that simulate how steady state flows of water and sediment reshape topography over long periods of time, r.sim.terrain is the first to simulate short-term topographic change for both steady state and dynamic flow regimes across a range of spatial scales. This free and open source, GIS-based landscape evolution model uses empirical models for soil erosion at watershed to regional scales and a physics-based model for shallow 5 overland water flow and soil erosion at subwatershed scales to compute short-term topographic change. This either steady state or dynamic model simulates how overland sediment mass flows reshape topography for a range of hydrologic soil erosion regimes based on topographic, land cover, soil, and rainfall parameters. As demonstrated by a case study for Patterson Branch subwatershed on the Fort Bragg military installation in North Carolina, r.sim.terrain can realistically simulate the development of fine-scale morphological features including ephemeral gullies, rills, and hillslopes. Applications include land management, 10 erosion control, landscape planning, and landscape restoration.

Copyright statement. ...

1 Introduction

Landscape evolution models represent how the surface of the earth changes over time in response to physical processes. Most studies of landscape evolution have been descriptive, but a number of numerical landscape evolution models have been 15 developed that simulate elevational change over time (Temme et al., 2013). Numerical landscape evolution models such as the Channel-Hillslope Integrated Landscape Development (CHILD) model (Tucker et al., 2001) and SIBERIA (Willgoose, 2005) simulate steady state flows over long temporal scales. Landlab, a new Python library for numerically modeling Earth surface processes (Hobley et al., 2017), has components for simulating landscape evolution such as the Stream Power with Alluvium Conservation and Entrainment (SPACE) model (Shobe et al., 2017). There are still, however, major research questions to 20 address in the theoretical foundations of erosion modeling such as how erosional processes scale over time and space and how sediment detachment and transport interact (Mitasova et al., 2013). A dynamic landscape evolution model is needed to study fine-scale spatial and short-term temporal erosional processes such as gully formation and the development of microtopography. While most numerical landscape evolution models simulate peak flows at steady state (see Table 2), short-term erosional

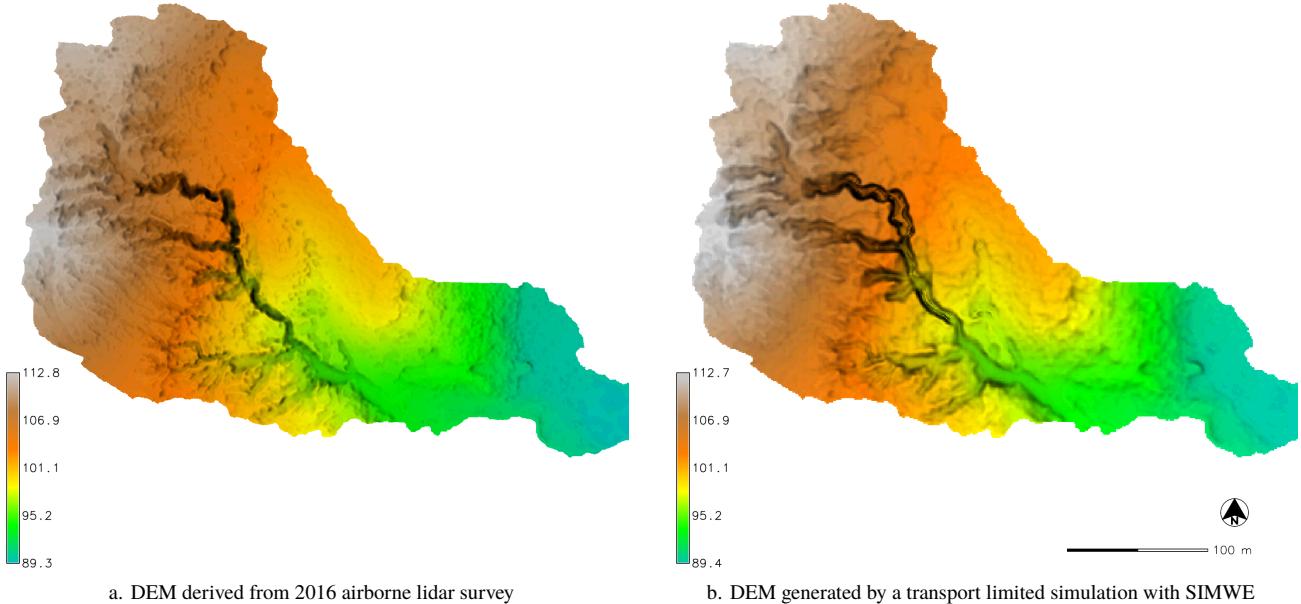


Figure 1. The digital elevation model (DEM) before (a.) and after (b.) simulated landscape evolution with r.sim.terrain. This simulation used the SIMWE model for a 120 min rainfall event with 25 mm hr^{-1} in a transport limited soil erosion regime at steady state. In the evolved DEM (b.) the gully channel has widened with depositional ridges forming along its thalweg.

processes like gully formation can be dynamic with significant morphological changes happening within minutes before flows reach steady state.

At the beginning of a rainfall event the overland water flow regime is dynamic – its depth changes at a variable rate over time and space. If the intensity of rainfall continues to change throughout the event then the flow regime will remain dynamic. If, 5 however, the overland flow reaches a peak rate then the hydrologic regime is considered to be at steady state:

$$\frac{\partial h(x, y, t)}{\partial t} = 0 \quad (1)$$

where:

(x, y) is the position [m]

t is the time [s]

10 $h(x, y, t)$ is the depth of overland flow [m]

Gullies are eroded, steep banked channels formed by ephemeral, concentrated flows of water. A gully forms when overland waterflow converges in a knickzone – a concave space with steeper slopes than its surroundings (Zahra et al., 2017) – during intense rainfall events. When the force of the water flow concentrated in the knickzone is enough to detach and transport large

amounts of sediment, an incision begins to form at the apex of the knickzone – the knickpoint or headwall. As erosion continues the knickpoint begins to migrate upslope and the nascent gully channel widens, forming steep channel banks. Multiple incisions initiated by different knickpoints may merge into a gully channel and multiple channels may merge into a branching gully system (Mitasova et al., 2013). This erosive process is dynamic; the morphological changes drive further changes in a positive

- 5 feedback loop until water flow reaches steady state. When the gully initially forms the soil erosion regime should be detachment capacity limited with the concentrated flow of water in the channel of the gully detaching large amounts of sediment and transporting it to the foot of the gully, potentially forming a depositional fan. After the initial formation of the gully the soil erosion regime may switch to erosion-deposition if the intensity of rainfall decreases. Subsequent rainfall events may trigger further knickpoint formation and upslope migration, channel incision and widening, and depositional fan and ridge formation.
- 10 Between high intensity rainfall events, lower intensity events and gravitational diffusion may gradually smooth the shape of the gully. Eventually, if detachment capacity significantly exceeds transport capacity, the gully may fill with sediment.

Gully erosion rates and evolution can be monitored in the field or modeled on the computer. Field methods include dendrogeomorphology (Malik, 2008) and permanent monitoring stakes for recording erosion rates, extensometers for recording mass wasting events, weirs for recording water and suspended sediment discharge rates, and time series of surveys using total
15 station theodolites (Thomas et al., 2004), unmanned aerial systems (UAS), airborne lidar, and terrestrial lidar (Starek et al., 2011; Bechet et al., 2016).

With terrestrial lidar, airborne lidar and UAS photogrammetry there is now sufficient resolution topographic data to morphometrically analyze and numerically model fine-scale landscape evolution in GIS including processes such as gully formation and the development of microtopography. Gully erosion has been simulated with the Revised Universal Soil Loss Equation

- 20 Version 2 (RUSLER) in conjunction with the Ephemeral Gully Erosion Estimator (EphGEE) (Dabney et al., 2014), while gully evolution has been simulated for detachment capacity limited erosion regimes with the Simulation of Water Erosion (SIMWE) model (Koco, 2011; Mitasova et al., 2013). Now numerical landscape evolution models that can simulate steady state and dynamic flow regimes and can dynamically switch between soil erosion regimes are needed to study fine-scale spatial and short-term temporal erosional processes.

- 25 The numerical landscape evolution model r.sim.terrain was developed to simulate the spatiotemporal evolution of landforms caused by shallow overland water and sediment flows at spatial scales ranging from square meters to kilometers and temporal scales ranging from minutes to years. This open source, GIS-based landscape evolution model can simulate either steady state or dynamic flow regimes, dynamically switch between soil erosion regimes, and simulate the evolution of fine-scale morphological features such as ephemeral gullies (Figure 1). It was designed as a research tool for studying how erosional
30 processes scale over time and space, comparing empirical and process-based models, comparing steady state and dynamic flow regimes, and studying the role of dynamic flow regimes in fine-scale morphological change. r.sim.terrain was tested with a subwatershed scale (450 m^2) case study and the simulations were compared against a time-series of airborne lidar surveys.

2 r.sim.terrain

The process-based, spatially distributed landscape evolution model r.sim.terrain simulates topographic changes caused by shallow, overland water flow across a range of spatiotemporal scales and soil erosion regimes using either the Simulated Water Erosion (SIMWE) model, the 3-Dimensional Revised Universal Soil Loss Equation (RUSLE 3D) model, or the Unit Stream Power

5 Erosion Deposition (USPED) model. SIMWE is a physics-based simulation that uses a Monte Carlo path sampling method to solve the water and sediment flow equations for detachment limited, transport limited, and variable erosion-deposition soil erosion regimes (Mitasova et al., 2004). With SIMWE r.sim.terrain uses the modeled flow of sediment – a function of water flow and soil detachment and transport parameters – to estimate net erosion and deposition rates. RUSLE3D is an empirical equation for sediment flows in detachment capacity limited soil erosion regimes (Mitasova et al., 1996). With RUSLE3D r.sim.terrain
10 uses an event-based erosivity factor, the slope, the flow accumulation, and a 3D topographic factor to model sediment flow. USPED is an empirical equation for net erosion and deposition in transport capacity limited soil erosion regimes. With USPED r.sim.terrain uses an event-based erosivity factor, the slope and aspect, the flow accumulation, and a 3D topographic factor to model erosion-deposition as the divergence of sediment flows. For each of the models topographic change is derived
15 at each time step from the sediment flow or net erosion-deposition rate and gravitational diffusion. The r.sim.terrain model can simulate either steady state or dynamic flow regimes. During simulations with SIMWE r.sim.terrain can switch between detachment limited, transport limited, and variable erosion-deposition soil erosion regimes.

The r.sim.terrain model can simulate the evolution of gullies including processes such as knickpoint migration, channel incision, channel widening, aggradation, and scour pool and depositional ridge formation along the thalweg of the gully.

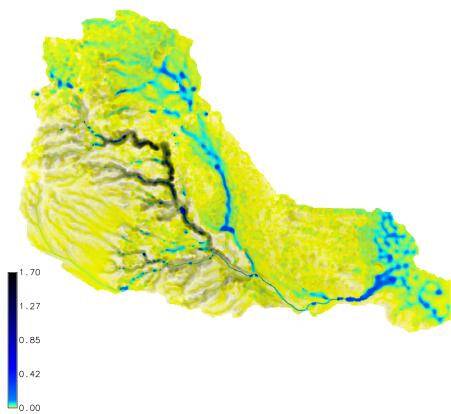
Applications include geomorphological research, erosion control, landscape restoration, and scenario development for land-

20 scape planning and management. This model can simulate landscape evolution over a wide range of spatial scales from small watersheds less than ten square kilometers with SIMWE to regional watersheds of thousands of square kilometers with USPED or RULSE3D. This model has been implemented as a Python add-on module for the free, open source Geographic Resources Analysis Support System (GRASS) GIS (GRASS Development Team). The source code is available at
25 https://github.com/baharmon/landscape_evolution under the GNU General Public License v2. It supports multithreading and parallel processing to efficiently compute simulations using large, high resolution topographic datasets. The landscape evolution model can be installed in GRASS GIS as an add-on module with the command:

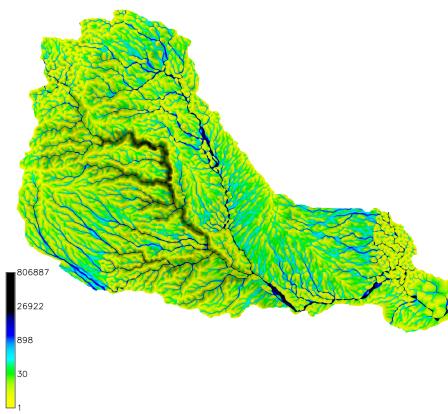
```
g.extension r.sim.terrain url=github.com/baharmon/landscape_evolution
```

2.1 Simulation of water erosion model

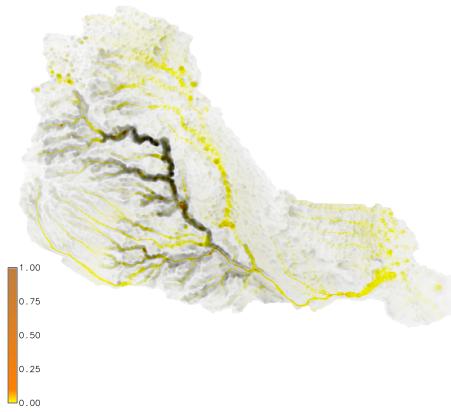
SIMWE – the Simulation of Water Erosion model – is a physics-based simulation of shallow overland water and sediment flow
30 that uses a path sampling method to solve the continuity and momentum equations with a 2D diffusive wave approximation (Mitas and Mitasova, 1998; Mitasova et al., 2004). SIMWE has been implemented in GRASS GIS as the modules r.sim.water and r.sim.sediment.



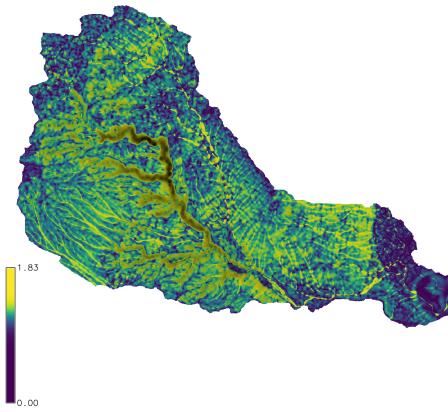
a. Water depth [m] simulated by SIMWE



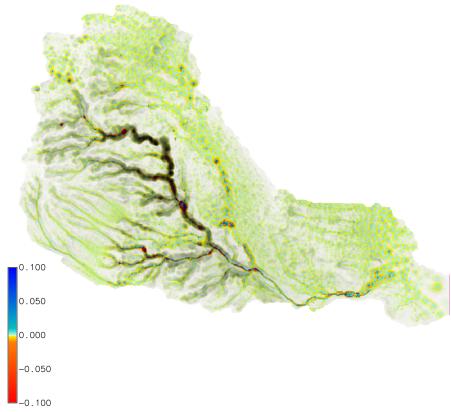
d. Flow accumulation for RUSLE3D



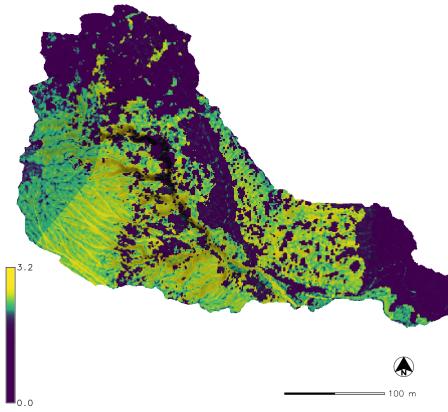
b. Sediment flux [kg m⁻¹ s⁻¹] simulated by SIMWE



e. LS3D topographic factor for RUSLE3D



c. Erosion and deposition [kg m⁻² s⁻¹] simulated by SIMWE



f. Sediment flow with spatially variable landcover modeled by RUSLE3D [kg m⁻² s⁻¹]

Figure 2. Water and sediment flows simulated by SIMWE for a 10 min event with 50 mm hr⁻¹ and by RUSLE3D with a R-factor of 310

Table 1. GIS-based soil erosion models

Model	Spatial scale	Temporal scale	Representation	Implementation	Reference
RUSLE3D	regional	continuous	raster	map algebra	(Mitasova et al., 1996)
USPED	watershed	continuous	raster	map algebra	(Mitasova et al., 1996)
SIMWE	watershed	event – continuous	raster	GRASS modules	(Mitas and Mitasova, 1998)
GeoWEPP	watershed	continuous	raster	ArcGIS module	(Dennis C. Flanagan et al., 2013)
AGWA	watershed	event – continuous	vector	ArcGIS module	(Guertin et al., 2015)

Table 2. Numerical landscape evolution models

Model	Spatial scale	Temporal scale	Representation	Dynamics	Implementation	Reference
CHILD	regional	continuous	mesh	steady state	C++ program	(Tucker et al., 2001)
SIBERIA	regional	continuous	raster	steady state	Fortran prog.	(Willgoose, 2005)
r.landscape.evol	regional	continuous	raster	steady state	GRASS module	(Barton et al., 2010)
Landlab	regional	continuous	raster + mesh	steady state	Python library	(Hobley et al., 2017)
r.sim.terrain	watershed – regional	event – continuous	raster	dynamic – steady state	GRASS module	

In SIMWE mode for each time step r.sim.terrain determines the soil erosion regime, simulates water and sediment flows, and then evolves the topography. In a variable erosion-deposition regime the model computes the partial derivatives of the topography, simulates shallow water flow and erosion-deposition, and then evolves the topography based on the erosion-deposition rate and gravitational diffusion. The same process is used in a transport capacity limited regime, except that the topography is evolved based on the transport limited erosion-deposition rate and gravitational diffusion. In a detachment capacity limited regime the model instead computes the partial derivatives of the topography, simulates shallow water flow and sediment flow, and then evolves the topography based on the sediment flow rate and gravitational diffusion. The model simulates dynamic landscape evolution when the time step is less than the travel time for a drop of water or a particle of sediment to cross the landscape. With longer time steps the model simulates steady state dynamics.

10 2.1.1 Erosion regime

This model can switch erosion regimes at each time step based on the rainfall intensity (i_r) and the balance of the sediment detachment capacity (D_c) and the sediment transport capacity (T_c) represented by the first order reaction term σ , which

depends on soil and landcover properties. The detachment capacity is the maximum potential detachment rate by overland flow, while the sediment transport capacity is the maximum potential sediment flow rate. When rainfall intensity is very high ($i_r \geq 60\text{mm hr}^{-1}$) or σ is low ($\sigma \leq 0.01\text{m}^{-1}$), then the regime is detachment capacity limited. When rainfall intensity is not very high ($i_r < 60\text{mm hr}^{-1}$) and σ is high ($\sigma \geq 100\text{m}^{-1}$), then the regime is transport capacity limited. When rainfall intensity is not very high ($i_r < 60\text{mm hr}^{-1}$) and σ is neither high nor low ($0.01\text{m}^{-1} < \sigma < 100\text{m}^{-1}$), then there is an variable erosion-deposition regime.

$$\sigma = \frac{D_c}{T_c} \quad (2)$$

where:

- 10 σ is a first order reaction term [m^{-1}]
 D_c is the sediment detachment capacity [$\text{kg m}^{-1}\text{s}^{-1}$]
 T_c is the sediment transport capacity [$\text{kg m}^{-1}\text{s}^{-1}$]

2.1.2 Shallow water flow

- 15 The SIMWE model simulates shallow overland water flow controlled by spatially variable topographic, soil, landcover, and rainfall parameters by solving the continuity and momentum equations for steady state water flow with a path sampling method (Fig. 2a). Shallow water flow $q(x, y, t)$ can be approximated by the bivariate form of the St. Venant equation:

$$\frac{\partial h(x, y, t)}{\partial t} = i_e(x, y, t) - \nabla \cdot q(x, y, t) \quad (3)$$

where:

- 20 (x, y) is the position [m]
 t is the time [s]
 $h(x, y, t)$ is the depth of overland flow [m]
 $i_e(x, y, t)$ is the rainfall excess [m s^{-1}]
(i.e. rainfall intensity – infiltration – vegetation intercept)
25 ∇ is the divergence of the flow vector field
 $q(x, y, t)$ is the water flow per unit width [$\text{m}^2 \text{s}^{-1}$].

Diffusive wave effects can be approximated so that water can flow through depressions by integrating a diffusion term $\propto \nabla^2[h^{5/3}(x, y)]$ into the solution of the continuity and momentum equations for steady state water flow. This equation is solved
30 using a Green's function Monte Carlo path sampling method.

$$-\frac{\varepsilon(x, y)}{2} \nabla^2[h^{5/3}(x, y)] + \nabla \cdot [h(x, y) v(x, y)] = i_e(x, y) \quad (4)$$

where:

$\varepsilon(x, y)$ is a spatially variable diffusion coefficient.

2.1.3 Sediment flow

- 5 In SIMWE the sediment flow rate $q_s(x, y, t)$ is estimated as a function of water flow and sediment concentration (Mitas and Mitasova, 1998) (Fig. 2b):

$$q_s(x, y, t) = \rho_s(x, y, t) q(x, y, t) \quad (5)$$

where:

$q_s(x, y, t)$ is the sediment flow rate per unit width [$\text{kg m}^{-1} \text{s}^{-1}$]

- 10 $\rho_s(x, y, t)$ is sediment mass density [kg m^{-3}].

2.1.4 Erosion-deposition

- In SIMWE the net erosion-deposition rate is estimated using the bivariate form of sediment continuity equation to model sediment storage and flow based on effective sources and sinks (Fig. 2c). Net erosion-deposition $d_s(x, y, t)$ – the difference
15 between sources and sinks – is approximated by the steady state sediment flow equation with diffusion:

$$d_s(x, y, t) = \frac{\partial[\rho_s c(x, y, t) h(x, y, t)]}{\partial t} + \nabla q_s(x, y, t) \quad (6)$$

where:

$d_s(x, y, t)$ is net erosion-deposition [$\text{kg m}^{-2} \text{s}^{-1}$].

20 2.1.5 Landscape evolution

The simulated change in elevation $\Delta z(x, y, t)$ due to water erosion and deposition is a function of the change in time, the net erosion-deposition rate, and the sediment mass density (Mitasova et al., 2013):

$$\Delta z(x, y, t) = \Delta t d_s(x, y, t) \rho_s^{-1} \quad (7)$$

- In a detachment limited erosion regime the simulated change in elevation $\Delta z(x, y, t)$ is a function of the change in time, the
25 sediment flow rate, and the mass of water carried sediment per unit area (Mitasova et al., 2013):

$$\Delta z(x, y, t) = \Delta t q_s(x, y, t) \varrho_s^{-1} \quad (8)$$

where:

ϱ_s is the mass of sediment per unit area [kg m^{-2}].

Gravitational diffusion is then applied to the evolved topography to simulate the settling of sediment particles. The simulated change in elevation $\Delta z(x, y, t)$ due to gravitational diffusion is a function of the change in time, the sediment mass density, the gravitational diffusion coefficient, and topographic divergence – i.e. the sum of the second order derivatives of elevation (Thaxton, 2004):

$$5 \quad \Delta z(x, y, t) = \Delta t \rho_s^{-1} \varepsilon_g \nabla(x, y, t) \quad (9)$$

where:

ε_g is the gravitational diffusion coefficient [$\text{m}^2 \text{ s}^{-1}$]

$\nabla(x, y, t)$ is the topographic divergence [m^{-1}].

10 2.2 Revised universal soil loss equation 3D model

The Revised Universal Soil Loss Equation for Complex Terrain (RUSLE3D) is an empirical equation for computing erosion in a detachment capacity limited soil erosion regime for watersheds with complex topography (Mitasova et al., 1996). It is based on the Universal Soil Loss Equation (USLE), an empirical equation for estimating the average sheet and rill soil erosion from rainfall and runoff on agricultural fields and rangelands with simple topography (Wischmeier et al., 1978). It models erosion dominated regimes without deposition in which sediment transport capacity is uniformly greater than detachment capacity. As an empirical equation the predicted soil loss is spatially and temporally averaged. In USLE soil loss per unit area is determined by an erosivity factor R , a soil erodibility factor K , a slope length factor L , a slope steepness factor S , a cover management factor C , and a prevention measures factor P . These factors are empirical constants derived from an extensive collection of measurements on 22.13 m standard plots with an average slope of 9%. RUSLE3D was designed to account for more complex, 15 3D topography with converging and diverging flows. In RUSLE3D the topographic potential for erosion at any given point is represented by a 3D topographic factor LS_{3D} , which is a function of the upslope contributing area and the angle of the slope.

In this spatially and temporally distributed model RUSLE3D is modified by the use of a event-based r-factor derived from the rainfall intensity at each time step. For each time step this model computes the parameters for RUSLE3D – an event-based erosivity factor, the slope of the topography, the flow accumulation, and the 3D topographic factor – and then solves the 20 RUSLE3D equation for sediment flow. The sediment flow is used to simulate landscape evolution in a detachment capacity limited soil erosion regime.

2.2.1 Event-based erosivity factor

The erosivity factor R in USLE and RUSLE is the combination of the total energy and peak intensity of a rainfall event, representing the interaction between the detachment of sediment particles and the transport capacity of the flow. It can be 30 calculated as the product of the the kinetic energy of the rainfall event E and its maximum 30 min intensity I_{30} (Brown and Foster, 1987; Renard et al., 1997). In this model, however, the erosivity factor is derived at each time step as a function of kinetic energy, rainfall volume, rainfall intensity, and time. First rain energy is derived from rainfall intensity (Brown and

Foster, 1987):

$$e_r = 0.29 (1. - 0.72 \exp(-0.05 i_r)) \quad (10)$$

where:

e_r is unit rain energy [$\text{MJ ha}^{-1} \text{ mm}^{-1}$]

5 i_r is rainfall intensity [mm h^{-1}].

Then the event-based erosivity index R_e is calculated as the product of unit rain energy, rainfall volume, rainfall intensity, and time:

$$R_e = e_r v_r i_r t_r \quad (11)$$

10 where:

R_e is the event-based erosivity index [$\text{MJ mm ha}^{-1} \text{ hr}^{-1}$]

v_r is the rainfall volume [mm] derived from $v_r = i_r t_r$

t_r is the time interval [s].

2.2.2 Flow accumulation

15 The upslope contributing area per unit width is determined by flow accumulation times grid cell width (Fig. 2d). Flow accumulation is calculated using a multiple flow direction algorithm (Metz et al., 2009) based on A^T least cost path searches (Ehlschlaeger, 1989). The multiple flow direction algorithm implemented in GRASS GIS as the module r.watershed is computationally efficient and can navigate nested depressions and other obstacles.

2.2.3 3D topographic factor

20 The 3D topographic factor $LS_{3D}(x, y)$ is calculated as a function of the flow accumulation, representing the upslope contributing area, and the slope (Fig. 2e). The empirical coefficients m and n for the upslope contributing area and the slope can range from 0.2 to 0.6 and 1.0 to 1.3 respectively with low values representing dominant sheet flow and high values representing dominant rill flow.

$$LS_{3D}(x, y) = (m + 1.0) (a(x, y) a_0^{-1})^m (\sin(\beta) \beta_0^{-1})^n \quad (12)$$

25 where:

LS_{3D} is the dimensionless topographic (length-slope) factor

a is upslope contributing area per unit width [m]

a_0 is the length of the standard USLE plot [22.1 m]

β is the angle of the slope [$^\circ$]

30 m is an empirical coefficient

n is an empirical coefficient

β_0 is the slope of the standard USLE plot [0.09°]

2.2.4 Sediment flow

- 5 Sediment flow is a function of the event-based erosivity factor, the soil erodibility factor, the 3D topographic factor, cover factor, and the prevention measures factor (Fig. 2f):

$$E = R_e K LS_{3D} C P \quad (13)$$

where:

E is sediment flow [$\text{kg m}^{-2} \text{ min}^{-1}$]

10 R_e is the event-based erosivity factor [$\text{MJ mm ha}^{-1} \text{ hr}^{-1}$]

K is the soil erodibility factor [$\text{ton ha hr ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$]

LS_{3D} is the dimensionless topographic (length-slope) factor

C is the dimensionless land cover factor

P is the dimensionless prevention measures factor.

15

For RUSLE3D the simulated change in elevation $\Delta z(x, y, t)$ is derived from equation 8 for landscape evolution in an detachment limited soil erosion regime and then equation 9 for the settling of sediment particles due to gravitational diffusion.

2.3 Unit strempower erosion deposition model

The Unit Stream Power Erosion Deposition (USPED) model estimates net erosion-deposition as the divergence of sediment flow in transport capacity limited soil erosion regimes. At transport capacity shallow flows of water are carrying as much sediment possible – more sediment is being detached than can be transported. As a transport capacity limited model USPED predicts erosion where transport capacity increases and deposition where transport capacity decreases. The influence of topography on erosion and deposition in USPED is represented by a topographic sediment transport factor, while the influence of soil and landcover are represented by factors adopted from USLE and RUSLE (Mitasova et al., 1996). Net erosion-deposition is estimated by computing the event-based erosivity factor (R_e) using Eq. 11, the slope and aspect of the topography, the flow accumulation with a multiple flow direction algorithm, the topographic sediment transport factor, the sediment flow at transport capacity, and the divergence of the sediment flow.

The 3D topographic factor (Eq. 12) for RUSLE3D is adapted to represent the topographic sediment transport factor (LST) – the topographic component of overland flow at sediment transport capacity:

$$30 LST = a^m (\sin \beta)^n \quad (14)$$

where:

LST is the topographic sediment transport factor

a is the upslope contributing area per unit width [m]

β is the angle of the slope [$^\circ$]

5 m is an empirical coefficient

n is an empirical coefficient.

The sediment flow at transport capacity is a function of the event-based rainfall factor, the soil erodibility factor, the topographic component of overland flow, the landcover factor, and the prevention measures factor:

10 $T = R_e K C P LST$ (15)

where:

T is sediment flow at transport capacity [$\text{kg m}^{-1} \text{ s}^{-1}$]

R_e is the event-based rainfall factor [$\text{MJ mm ha}^{-1} \text{ hr}^{-1}$]

K is the soil erodibility factor [$\text{ton ha hr ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$]

15 C is the dimensionless land cover factor

P is the dimensionless prevention measures factor.

Net erosion-deposition at transport capacity is estimated as the divergence of sediment flow:

$$d_s(x, y, t) = \frac{\partial(T \cos \alpha)}{\partial x} + \frac{\partial(T \sin \alpha)}{\partial y} \quad (16)$$

20 where:

$d_s(x, y, t)$ is net erosion-deposition [$\text{kg m}^{-2} \text{ s}^{-1}$]

α is the aspect of the topography [$^\circ$].

With USPED the simulated change in elevation $\Delta z(x, y, t)$ is derived from equation 7 for landscape evolution and then equation

25 9 for the settling of sediment particles due to gravitational diffusion.

3 Case study

Military activity is a high-impact land use that can cause significant physical alteration to the landscape. Erosion is a major concern for military installations, particularly at training bases, where the land surface is disturbed by off-road vehicles, foot traffic, and munitions. Off-road vehicles and foot traffic by soldiers cause the loss of vegetative cover, the disruption of soil structure, soil compaction, and increased runoff due to reduced soil capacity for water infiltration (Webb and Wilshire, 1983; McDonald, 2004). Gullies – ephemeral channels with steep headwalls that incise into unconsolidated soil to depths of meters –

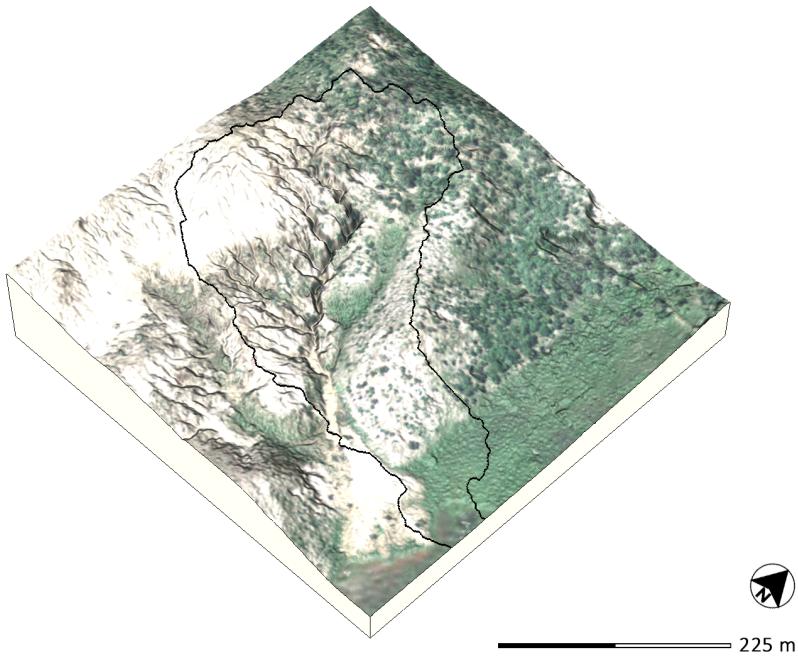


Figure 3. Subwatershed with 2014 orthoimagery draped over 2016 digital elevation model, Patterson Branch Creek, Fort Bragg, NC, USA

are a manifestation of erosion common to military training installations like Ft. Bragg in North Carolina and the Piñon Canyon Maneuver Site in Colorado. While the local development of gullies can restrict the maneuverability of troops and vehicles during training exercises, pervasive gullying across a landscape can degrade an entire training area (Huang and Niemann, 2014).

To test the effectiveness of the different models in r.sim.terrain we compared the simulated evolution of a highly eroded subwatershed of Patterson Branch Creek on Fort Bragg, North Carolina against a timeseries of airborne lidar surveys. The models – SIMWE, RUSLE3D, and USPED – were tested in steady state and dynamic modes for constant rainfall, design storms, and recorded rainfall.

3.1 Patterson Branch Creek

With 650 km² of land Fort Bragg is the largest military installation in the US and has extensive areas of bare, erodible soils on impact areas, firing ranges, landing zones, and dropzones. It is located in the Sandhills region of North Carolina with a Longleaf Pine and Wiregrass Ecosystem (Sorrie et al., 2006). The study landscape – a subwatershed of Patterson Branch Creek in the Coleman Impact Area – is pitted with impact craters from artillery and mortar shells and has an active, approximately 2 m deep gully. It is a Pine-Scrub Oak Sandhill community composed primarily of Longleaf Pine (*Pinus palustris*) and Wiregrass

(*Aristida stricta*) on Blaney and Gilead loamy sands (Sorrie, 2004). Throughout the Coleman Impact Area frequent fires ignited by live munitions drive the ecological disturbance regime of this fire adapted ecosystem. In 2016 the 450 m² study site was 5 43.24% bare ground with predominately loamy sands, 39.54% covered by the Wiregrass community, and 17.22% forested with the Longleaf Pine community (Figure 4c). We hypothesize that the elimination of forest cover in the impact zone triggered extensive channelized overland flow, gully formation, and sediment transport into the creek.

Timeseries of digital elevations models and landcover maps for the study landscape were generated from lidar pointclouds and orthophotography (Figure 4a-c). The digital elevations models for 2004, 2012, and 2016 were interpolated at 0.3 m resolution using the regularized spline with tension function (Mitasova and Mitas, 1993; Mitasova et al., 2005) from airborne lidar surveys collected by the NC Floodplain Mapping program and Fort Bragg. Unsupervised image classification was used 10 to identify clusters of spectral reflectance in a timeseries of 1 m resolution orthoimagery collected by the National Agriculture Imagery Program. The landcover maps were derived by fusing the classified lidar point clouds with the classified orthoimagery. Spatially variable soil erosion factors – k-factor, c-factor, manning's, and runoff rates – were derived from the landcover and soil maps. The dataset for this study is hosted at https://github.com/baharmon/landscape_evolution_dataset under the ODC Open Database License (ODbL). The data is derived from publicly available data from the US Army, USGS, USDA, Wake County 15 GIS, NC Floodplain Mapping Program, and the NC State Climate Office.

We used the geomorphons method of automated landform classification based on the openness of terrain (Jasiewicz and Stepinski, 2013) and the difference between the digital elevation models to analyze the changing morphology of the study area (Figure 4d-f). The 2 m deep gully – its channels classified as valleys and its scour pits as depressions by geomorphons – has multiple mature branches and ends with a depositional fan. The gully has also developed depositional ridges beside the 20 channels. Deep scour pits have developed where branches join the main channel and where the main channel has sharp bends. A new branch has begun to form in a knickzone classified as a mix of valleys and hollows on a grassy swale on the northeast side of the gully. Between 2012 and 2016 a depositional ridge has developed at the foot of this nascent branch where it would 25 meet the main channel. The difference in elevation between 2012 and 2016 (Figure 4d) shows a deepening of the main channel by approximately 0.2 m and the scour pits by approximately 1 m, while depositional ridges have formed and grown up to approximately 1 m or more.

3.2 Simulations

We ran a sequence of r.sim.terrain simulations for the Patterson Branch Creek subwatershed study area to test dynamic and steady state flow regimes in the SIMWE, RUSLE3D, and USPED models (Table 3). RUSLE3D was used to simulate 120 min events with rainfall intensities of 50 mm hr⁻¹ for detachment capacity limited soil erosion regimes for both dynamic and 30 steady state flow regimes using RUSLE3D (Figure 5a-c). USPED was used to simulate 120 min events with rainfall intensities of 50 mm hr⁻¹ for transport capacity limited soil erosion regimes for both dynamic and steady state flow regimes (Figure 5d-f). SIMWE was used to simulate 120 min events with rainfall intensities of 50 mm hr⁻¹ for erosion-deposition and detachment limited soil erosion regimes in steady state flow regimes (Figure 6). In all of the simulations a sink filling algorithm – an

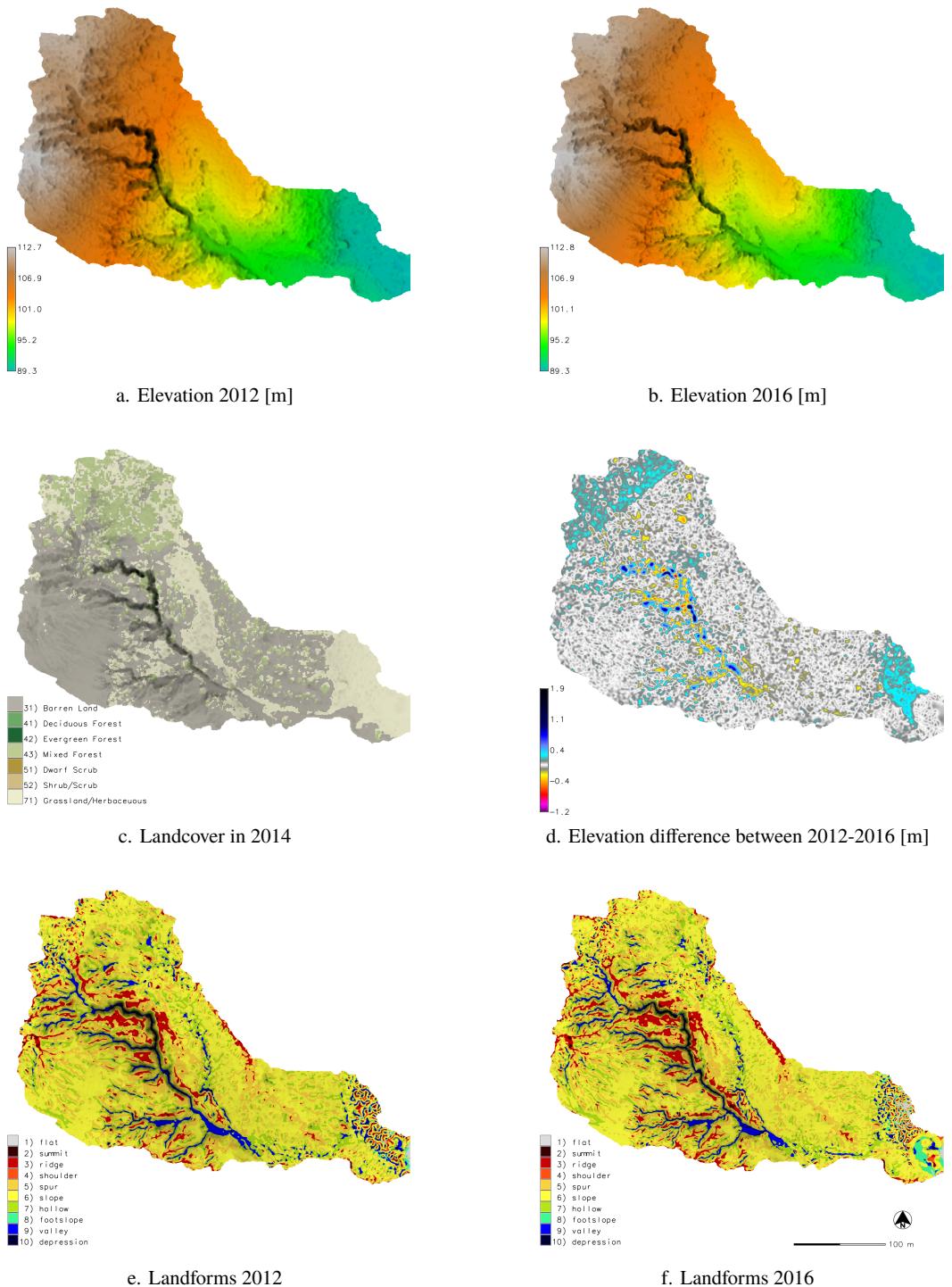


Figure 4. Subwatershed, Patterson Branch Creek, Fort Bragg, NC, USA

optional parameter in r.sim.terrain – was used to reduce the effects of positive feedback loops that cause the over-development of scour pits.

The simulations were automated and run in parallel using Python scripts that are available in the software repository. The simulations can be reproduced using these scripts and the study area dataset by following the instructions in the Open Science Framework repository at <https://osf.io/tf6yb/>. The simulations were run in GRASS GIS 7.4 on a desktop computer with 64-bit Ubuntu 16.04.4 LTS, 8 x 4.20 GHz Intel Core i7 7700K CPUs, and 32 GB RAM. Simulations using SIMWE are far more computationally intensive than RULSE3D or USPED, but support multi-threading when compiled with OpenMP. Dynamic simulations of RUSLE3D and USPED each took 3 min 14 s to run on a single thread, while steady state simulations for SIMWE each took 84 min 13 s running on 6 threads (Table 3).

10 3.3 Results

The dynamic RUSLE3D simulation deepened the main channel of the gully, while the dynamic USPED simulation eroded the banks of the gully and deposited in channels causing the gully grow wider and shallower (Figure 5). As a detachment capacity limited model RUSLE3D’s results were dominated by erosion and thus negative elevation change. RUSLE3D carved a deep incision in the main gully channel where water and sediment flow accumulated (Figure 5c). As a transport capacity limited model USPED generated a distributed pattern with both erosion and deposition and thus negative and positive elevation change. While USPED’s pattern of elevation change was grainy and fragmented, it captured the process of channel filling and widening expected with a transport capacity limited soil erosion regime (Figure 5f).

The steady state SIMWE simulations predicted more realistic patterns of landscape evolution (Figure 6). For transport limited and variable erosion-deposition regimes SIMWE simulated channel widening and the formation of depositional ridges along the thalweg of the channel (Figure 6c). For a detachment limited soil erosion regime SIMWE simulated major erosion driving the continued development of the gully network including the spread of rills and the evolution of the nascent branch into a full fledged channel (Figure 6f). The detachment limited simulation also formed extensive ridges beside the gully channels (Figure 6f), continuing the development of channel-side ridges observed in the 2012 and 2016 landform maps (Figure 4e-f).

Given the presence of an active gully with ridges along its banks, this landscape is dominated by a detachment limited soil erosion regime. The detachment limited SIMWE simulation generated the morphological features – the deeply incised gully channels, scour pits, and ridges along the channels – characteristic of its erosion regime, realistically simulating landscape evolution at the scale of a subwatershed. The erosion-deposition and transport limited SIMWE simulations also generated the morphological processes and features that would be expected in these regimes – gradual aggradation and the formation of a depositional ridge along the thalweg of the channel.

While RUSLE3D and USPED produced less realistic patterns of landscape evolution than SIMWE, these models were much faster and still generated the key morphological patterns and processes – channel incision, filling, and widening. Given their speed and approximate modeling of erosive processes, RUSLE3D and USPED are effective for simulating landscape evolution at regional scales, i.e. for landscapes greater than 10 km². RUSLE3D for example has been used to model erosion for the entire 650 km² Fort Bragg installation at 9 m resolution (Levine et al., 2018).

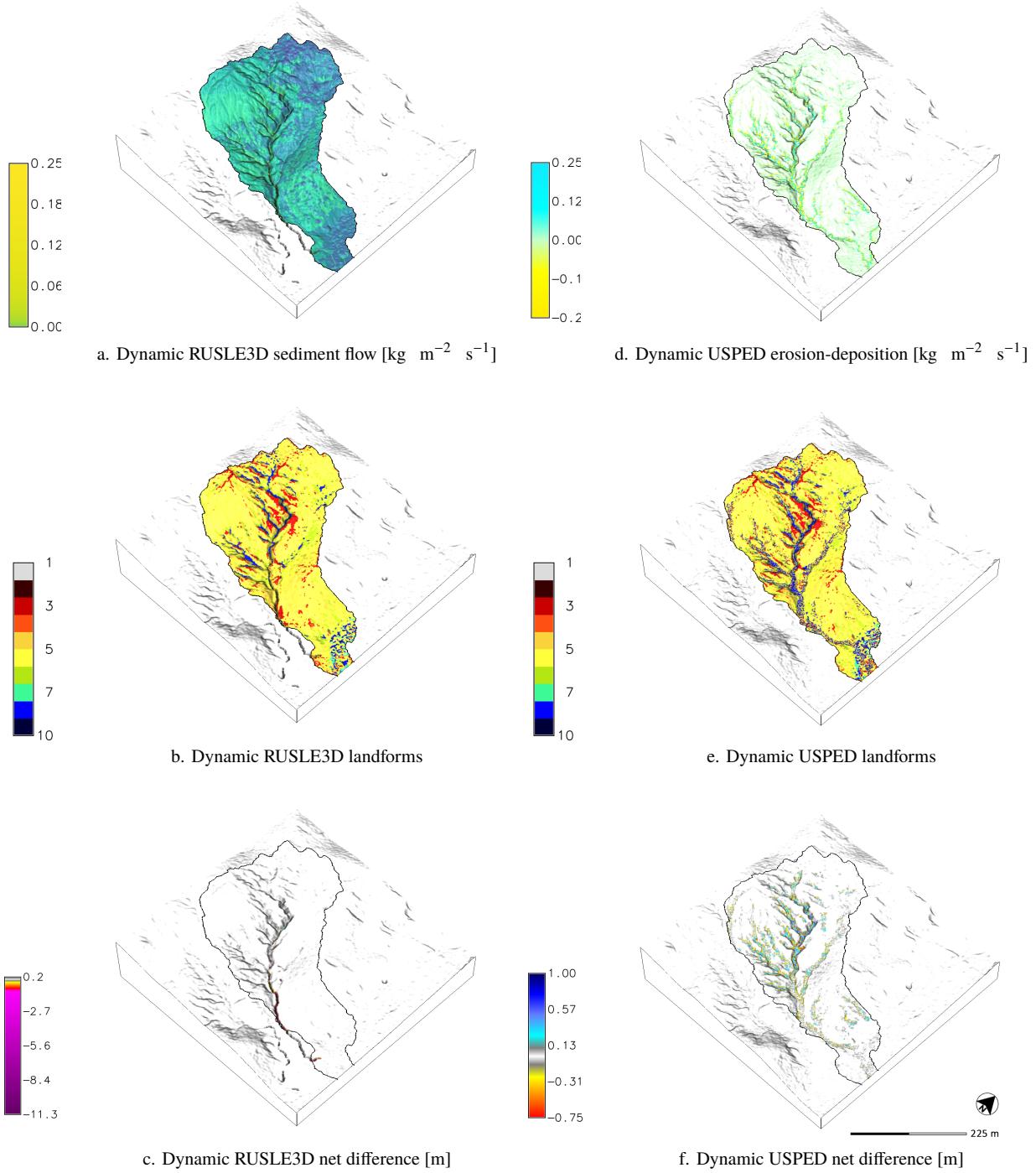


Figure 5. Dynamic RUSLE3D and USPED simulations for a 120 min event with a rainfall intensity of 50 mm hr⁻¹

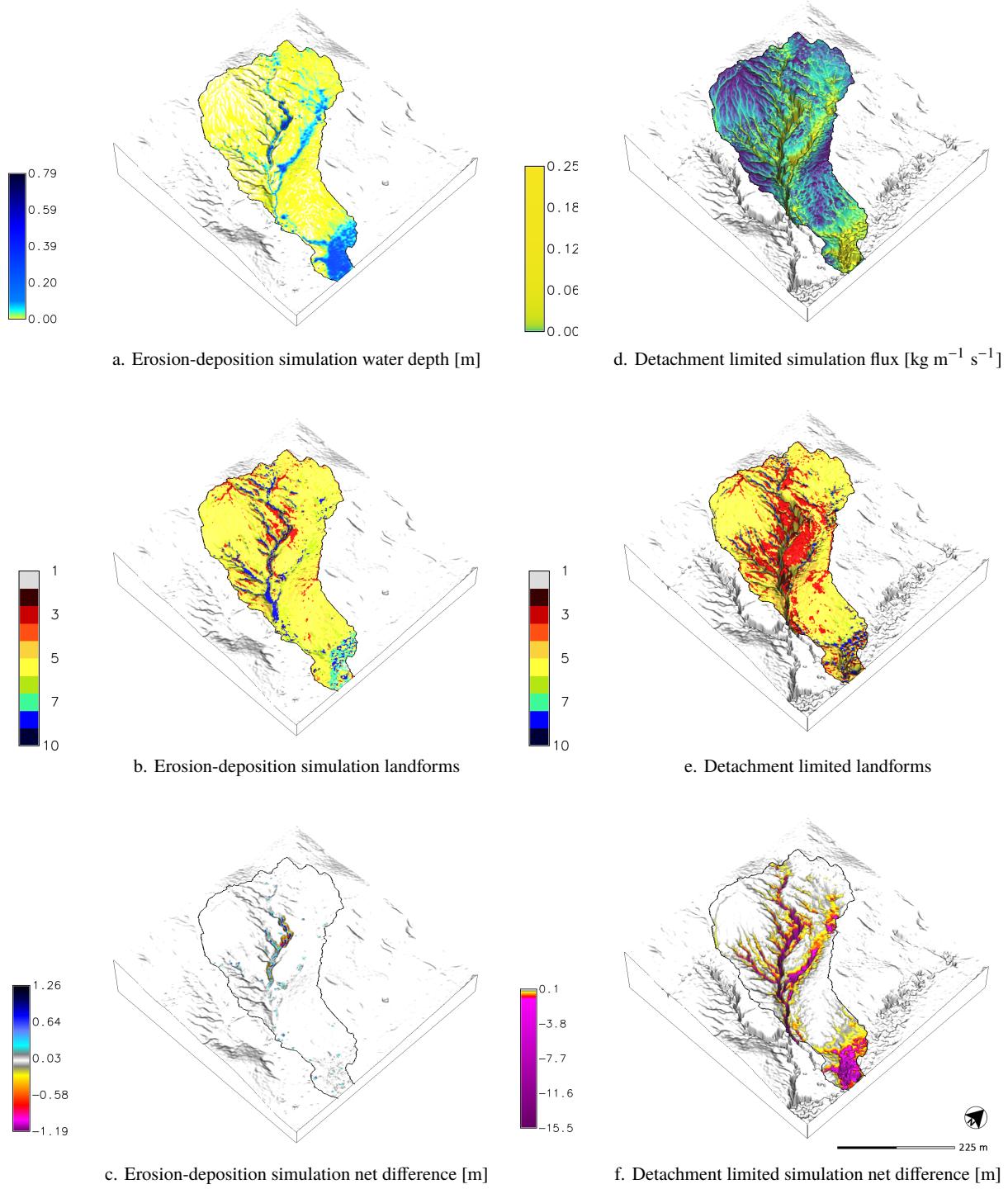


Figure 6. Steady state SIMWE simulations for 120 min events with rainfall intensities of 50 mm hr⁻¹ and 25 mm hr⁻¹

Table 3. Landscape evolution simulations

Dynamics	Model	Intensity	Duration	Interval	D_c	T_c	m	n	ρ_s	Threads	Runtime
Dynamic	RUSLE3D	50 mm hr ⁻¹	120 min	3 min			0.4	1.3			2 min 36 s
Dynamic	USPED	50 mm hr ⁻¹	120 min	3 min			1.5	1.2	1.6		3 min 14 s
Steady state	SIMWE	50 mm hr ⁻¹	120 min	120 min	0.001				1.6	6	84 min 13 s
Steady state	SIMWE	25 mm hr ⁻¹	120 min	120 min	0.0001	0.01			1.6	6	84 min 13 s

4 Conclusions

The short-term landscape evolution model r.sim.terrain can realistically simulate the development of gullies, rills, and hillslopes by overland water erosion for a range of hydrologic and soil erosion regimes. The landscape evolution model was tested with a series of simulations for different hydrologic and soil erosion regimes for a highly eroded sub-watershed on Fort Bragg 5 with an active gully. For each regime it generated the morphological processes and features expected. The physics-based SIMWE model realistically simulated short-term topographic change for steady state hydrologic regimes at sub-watershed to watershed scales. For detachment limited soil erosion regimes it simulated morphological processes including channel incision, channel widening, and the development of knickzones, rills, and scour pits. For transport limited and variable erosion-deposition regimes, it simulated processes such as channel aggradation, scouring, and the development of depositional ridges 10 along the thalweg. The empirical RUSLE3D and USPED models approximated short-term topographic change at watershed to regional scales. For detachment limited soil erosion regimes RUSLE3D simulated channel incision, while for transport limited regimes USPED simulated channel widening and filling. Since it is a GIS-based model that realistically simulates fine-scale morphological processes and features, r.sim.terrain can easily and effectively be used in conjunction with other GIS-based tools for geomorphological research, land management and conservation, erosion control, and landscape restoration.

15 *Code and data availability.* As a work of open science this study is reproducible, repeatable, and recomputable. Since the data, model, GIS, dependencies are all free and open source, the study can easily be reproduced. The landscape evolution model has been implemented in Python as module for GRASS GIS, a free and open source GIS. The source code for the model is hosted on GitHub at https://github.com/baharmon/landscape_evolution under the GNU General Public License version 2. The code repository also includes Python scripts for running and reproducing the simulations in this paper. The geospatial dataset for the study area is available on GitHub at https://github.com/baharmon/landscape_evolution_dataset under the Open Database License. The source code, scripts, data, and results are also hosted on the 20 Open Science Framework at <https://osf.io/tf6yb/>.

Author contributions. Brendan Harmon developed the models, code, data, case studies, and manuscript. Helena Mitasova contributed to the development of the models and case studies and revised the manuscript. Anna Petrasova and Vaclav Petras contributed to the development of the code. All authors read and approved the final manuscript.

Competing interests. The authors declare that they have no conflict of interest.

5 *Acknowledgements.* We acknowledge the GRASS GIS Development Community for developing and maintaining GRASS GIS.

References

- Barton, C. M., Ullah, I., and Mitasova, H.: Computational Modeling and Neolithic Socioecological Dynamics: a Case Study from Southwest Asia, *American Antiquity*, 75, 364–386, <http://www.jstor.org/stable/25766199>, 2010.
- Bechet, J., Duc, J., Loyer, A., Jaboyedoff, M., Mathys, N., Malet, J. P., Klotz, S., Le Bouteiller, C., Rudaz, B., and Travelletti, J.: Detection of seasonal cycles of erosion processes in a black marl gully from a time series of high-resolution digital elevation models (DEMs), *Earth Surface Dynamics*, 4, 781–798, <https://doi.org/10.5194/esurf-4-781-2016>, 2016.
- 5 Brown, L. C. and Foster, G. R.: Storm Erosivity Using Idealized Intensity Distributions, *Transactions of the American Society of Agricultural Engineers*, 30, 0379 –0386, <https://doi.org/http://dx.doi.org/10.13031/2013.31957>, 1987.
- Dabney, S., Vieira, D., Bingner, R., Yoder, D., and Altinakar, M.: Modeling Agricultural Sheet , Rill and Ephemeral Gully Erosion, in: ICHE 10 2014. Proceedings of the 11th International Conference on Hydroscience & Engineering, pp. 1119–1126, Karlsruhe, 2014.
- Dennis C. Flanagan, James R. Frankenberger, Thomas A. Cochrane, Chris S. Renschler, and William J. Elliot: Geospatial Application of the Water Erosion Prediction Project (WEPP) Model, *Transactions of the ASABE*, 56, 591–601, <https://doi.org/10.13031/2013.42681>, <https://www.fs.usda.gov/treesearch/pubs/43830>, 2013.
- Ehlschlaeger, C.: Using the A^T Search Algorithm to Develop Hydrologic Models from Digital Elevation Data, in: Proceedings of International 15 Geographic Information Systems (IGIS) Symposium '89, pp. 275–281, Baltimore, MD, 1989.
- GRASS Development Team: GRASS GIS, <https://grass.osgeo.org>.
- Guertin, D. P., Goodrich, D. C., Burns, I. S., Korgaonkar, Y., Barlow, J., Sheppard, B. S., Unkrich, C., and Kepner, W.: Automated Geospatial Watershed Assessment Tool (AGWA), <https://doi.org/10.1061/9780784479322.012>, 2015.
- Hobley, D. E., Adams, J. M., Siddhartha Nudurupati, S., Hutton, E. W., Gasparini, N. M., Istanbulluoglu, E., and Tucker, G. E.: Creative 20 computing with Landlab: An open-source toolkit for building, coupling, and exploring two-dimensional numerical models of Earth-surface dynamics, *Earth Surface Dynamics*, 5, 21–46, <https://doi.org/10.5194/esurf-5-21-2017>, 2017.
- Huang, X. and Niemann, J. D.: Simulating the impacts of small convective storms and channel transmission losses on gully evolution, in: Military Geosciences in the Twenty-First Century, edited by Harmon, R. S., Baker, S. E., and McDonald, E. V., Geological Society of America, https://doi.org/10.1007/978-1-4020-3105-2_18, 2014.
- 25 Jasiewicz, J. and Stepinski, T. F.: Geomorphons - a pattern recognition approach to classification and mapping of landforms, *Geomorphology*, 182, 147–156, <https://doi.org/10.1016/j.geomorph.2012.11.005>, 2013.
- Koco, Š.: Simulation of gully erosion using the SIMWE model and GIS, *Landsurface Analysis*, 17, 81–86, 2011.
- Levine, J., Wegmann, K., Mitasova, H., Eads, C., Lyons, N., Harmon, B., McCarther, C., Peart, S., Oberle, N., and Walter, M.: Freshwater Bivalve Survey for Endangered Species Branch Fort Bragg, NC, Tech. rep., North Carolina State University, Raleigh, NC, 30 <https://doi.org/10.13140/RG.2.2.17512.11521>, 2018.
- Malik, I.: Dating of small gully formation and establishing erosion rates in old gullies under forest by means of anatomical changes in exposed tree roots (Southern Poland), *Geomorphology*, 93, 421–436, <https://doi.org/10.1016/j.geomorph.2007.03.007>, 2008.
- McDonald, K. W.: Military Foot Traffic Impact on Soil Compaction Properties, pp. 229–242, Springer Netherlands, Dordrecht, https://doi.org/10.1007/978-1-4020-3105-2_18, 2004.
- 35 Metz, M., Mitasova, H., and Harmon, R. S.: Fast Stream Extraction from Large , Radar- Based Elevation Models with Variable Level of Detail, pp. 237–242, 2009.

- Mitas, L. and Mitasova, H.: Distributed soil erosion simulation for effective erosion prevention, *Water Resources Research*, 34, 505–516, <https://doi.org/10.1029/97wr03347>, 1998.
- Mitasova, H. and Mitas, L.: Interpolation by regularized spline with tension: I. Theory and implementation, *Mathematical Geology*, 25, 641–655, <https://doi.org/10.1007/BF00893171>, 1993.
- 5 Mitasova, H., Hofierka, J., Zlocha, M., and Iverson, L. R.: Modelling topographic potential for erosion and deposition using GIS, *International Journal of Geographical Information Science*, 10, 629–641, <https://doi.org/10.1080/02693799608902101>, <http://dx.doi.org/10.1080/02693799608902101>, 1996.
- Mitasova, H., Thaxton, C., Hofierka, J., McLaughlin, R., Moore, A., and Mitas, L.: Path sampling method for modeling overland water flow, sediment transport, and short term terrain evolution in Open Source GIS, *Developments in Water Science*, 55, 1479–1490, 10 [https://doi.org/10.1016/S0167-5648\(04\)80159-X](https://doi.org/10.1016/S0167-5648(04)80159-X), 2004.
- Mitasova, H., Mitas, L., and Harmon, R. S.: Simultaneous spline approximation and topographic analysis for lidar elevation data in open-source GIS, *IEEE Geoscience and Remote Sensing Letters*, 2, 375–379, <https://doi.org/10.1109/LGRS.2005.848533>, 2005.
- Mitasova, H., Barton, M., Ullah, I., Hofierka, J., and Harmon, R.: 3.9 GIS-Based Soil Erosion Modeling, in: *Treatise on Geomorphology*, edited by Shroder, J. F., chap. 3.9, pp. 228–258, Elsevier, San Diego, California, USA, <https://doi.org/10.1016/B978-0-12-374739-15-6.00052-X>, <http://www.sciencedirect.com/science/article/pii/B978012374739600052X>, 2013.
- Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., and Yoder, D. C.: Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE), Tech. Rep. 703, US Government Printing Office, Washington, DC, https://www.ars.usda.gov/ARSUserFiles/64080530/rusle/ah_703.pdf, 1997.
- Shobe, C. M., Tucker, G. E., and Barnhart, K. R.: The SPACE 1.0 model: A Landlab component for 2-D calculation of sediment transport, 20 bedrock erosion, and landscape evolution, *Geoscientific Model Development*, 10, 4577–4604, <https://doi.org/10.5194/gmd-10-4577-2017>, 2017.
- Sorrie, B. A.: An Inventory of the Significant Natural Areas of Hoke County, North Carolina, Tech. rep., North Carolina Natural Heritage Program, 2004.
- Sorrie, B. A., Gray, J. B., and Crutchfield, P. J.: The Vascular Flora of the Longleaf Pine Ecosystem of Fort Bragg and Weymouth Woods, 25 North Carolina, *Castanea*, 71, 129–161, <https://doi.org/10.2179/05-02.1>, 2006.
- Starek, M. J., Mitasova, H., Hardin, E., Weaver, K., Overton, M., and Harmon, R. S.: Modeling and analysis of landscape evolution using airborne , terrestrial , and laboratory laser scanning, *Geosphere*, 7, 1340–1356, <https://doi.org/10.1130/GES00699.1>, 2011.
- Temme, A., Schoorl, J., Claessens, L., and Veldkamp, A.: 2.13 Quantitative Modeling of Landscape Evolution, vol. 2, Elsevier Ltd., <https://doi.org/10.1016/B978-0-12-374739-6.00039-7>, <http://linkinghub.elsevier.com/retrieve/pii/B9780123747396000397>, 2013.
- 30 Thaxton, C. S.: Investigations of grain size dependent sediment transport phenomena on multiple scales, Phd, North Carolina State University, <http://www.lib.ncsu.edu/resolver/1840.16/3339>, 2004.
- Thomas, J. T., Iverson, N. R., Burkart, M. R., and Kramer, L. A.: Long-term growth of a valley-bottom gully, Western Iowa, *Earth Surface Processes and Landforms*, 29, 995–1009, <https://doi.org/10.1002/esp.1084>, 2004.
- Tucker, G., Lancaster, S., Gasparini, N., and Bras, R.: The channel-hillslope integrated landscape development model (CHILD), in: *Landscape erosion and evolution modeling*, pp. 349–388, Springer, Boston, MA, https://doi.org/10.1007/978-1-4615-0575-4_12, 2001.
- 35 Webb, R. and Wilshire, H.: Environmental Effects of Off-Road Vehicles: Impacts and Management in Arid Regions, *Environmental Management Series*, Springer New York, <https://doi.org/10.1007/978-1-4612-5454-6>, 1983.

Willgoose, G.: Mathematical Modeling of Whole Landscape Evolution, Annual Review of Earth and Planetary Sciences, 33, 443–459, <https://doi.org/10.1146/annurev.earth.33.092203.122610>, <http://www.annualreviews.org/doi/10.1146/annurev.earth.33.092203.122610>, 2005.

Wischmeier, W. H., Smith, D. D., Science, U. S., Administration, E., and Station, P. U. A. E.: Predicting Rainfall Erosion Losses: A Guide
5 to Conservation Planning, Tech. rep., Washington, D.C., <https://naldc.nal.usda.gov/download/CAT79706928/>, 1978.

Zahra, T., Paudel, U., Hayakawa, Y., and Oguchi, T.: Knickzone Extraction Tool (KET) – A New ArcGIS toolset for automatic extraction of knickzones from a DEM based on multi-scale stream gradients, Open Geosciences, 9, <https://doi.org/10.1515/geo-2017-0006>, 2017.