Erosion Modeling:

Use of Multiple-Return and Bare-Earth LIDAR Data to Identify Bare Areas Susceptible to Erosion

MacRidge, Training Area J, Fort Bragg, NC

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Abstract

Accelerated erosion of military training lands is one of the largest environmental challenges encountered by U.S. Army land managers. Many military installations experience common erosion-related problems. Only a handful of installations track erosion through quantified methods. Given the mission and the right tools, land managers could explicitly quantify the erosion effects on their installation. Controlling erosion is achieved in only two ways: reduce the erosive forces applied to the soil, or reduce the erodibility of the soil. Indefinitely halting military training on these lands is contrary to their intended use, so land managers must find the delicate balance of mitigating soil erosion without significantly impeding Soldier training opportunities.

This study was initiated to quantify the effects and rates of soil erosion on military training lands through the exploration of new techniques utilizing a Geographic Information System (GIS). The primary objective is to develop a simplified land cover classification to identify bare areas susceptible to erosion. This method computes the difference between multiple return Light Detection and Ranging (LIDAR) data and bare-earth LIDAR to derive a vegetation-height raster map. The derived vegetation-height raster is recoded and applied to a modified Revised Universal Soil Loss Equation (RUSLE3d) as the cover factor, or C-factor. This analysis will serve as a decision-making tool that will aid land managers in their decision process.

Introduction

Accelerated erosion of military training lands is one of the largest environmental challenges encountered by U.S. Army land managers. Many military installations experience common erosion-related problems. Only a handful of installations track erosion through quantified methods. Most installations track erosion through qualified methods (Harmon and Doe, 2001). In these cases, descriptors are used and temporal comparisons made without scientific monitoring. Given the mission and the right tools, land managers could explicitly quantify the erosion effects on their installation. They would provide reputable advice to garrison commanders and their staff concerning best management practices to preserve these valuable training resources.

Soil erosion can be categorized into three stages: detachment, transport and deposition. The first two stages define the mechanics of soil erosion, while the third occurs only when sufficient energy is no longer generated to transport particles (Morgan, 2005). Two factors determine the magnitude of erosion: erosivity of the rainfall, runoff, and wind; and erodibility of the soil. Explained well by Toy, Foster and Renard, 2002: “Erosivity is a measure of the forces applied to the soil that cause erosion, and erodibility is a measure of the susceptibility of the soil to erosive forces.” Detachment occurs when the erosive force(s) energy surpasses the erodibility threshold of the soil at which point particles become detached and are susceptible to transport. Transport occurs while the energy retained by the erosive force(s) is greater than the friction created by the surface over which the agent moves.

Controlling erosion is achieved in only two ways: reduce the erosive forces applied to the soil, or reduce the erodibility of the soil. When the problem is identified and quantified, the delicate balance between enacting conservation and training priorities ensues. Removing

Soldier-induced erosive forces indefinitely from military training sites is counterproductive to their purpose, so land managers must consider alternative options to supplement management even when erosive forces may be reduced. Land managers will likely implement a combination of these principles using a variety of methods.

Many erosion modeling techniques have been developed to quantify the effects of erosion. A plethora of equations are associated with these methods. While no particular method maintains fame as the perfect model, the original Universal Soil Loss Equation (USLE) developed in 1954 by the Science and Education Administration in cooperation with Purdue University (USDA Ag Handbook 537) and the new Revised Universal Soil Loss Equation (RUSLE) is a launch point for detachment capacity limited erosion modeling. The RUSLE computes the average annual erosion expected on field slopes as:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (1)$$

Where *A* is the computed soil loss per unit of area, *R* is rainfall and runoff erosivity factor, *K* is the soil-erodibility factor, *L* is slope-length factor, *S* is slope-steepness factor, *C* is the cover and management factor and *P* is the erosion-control practice factor (Wischmeier and Smith, 1978).

The erosion models in this project use a modification of RUSLE, referred to as RUSLE3d, in which the slope length and slope steepness are combined into an LS-factor that replaces slope length with upslope area:

$$LS = (m + 1) \left(\frac{\mathrm{U}}{22.1}\right)^{m} \left(\frac{\sin\beta}{0.09}\right)^{n} \qquad (2)$$

Where *U* is the upslope area per unit width (measure of water flow, m^2/m), β is the slope angle in degrees, 22.1m is the length of the standard USLE plot, 0.09=9% is the slope of the standard USLE plot, *m* and *n* are empirical constants. Exponential constants have range m = 0.2 – 0.6 and n = 1.0 – 1.3 (Neteler and Mitasova, 2008).

A second model is used to predict the spatial distribution of erosion and deposition. The Unit Stream Power-based Erosion Deposition (USPED) model assumes steady state overland flow with uniform rainfall and that the erosion process is transport capacity limited (Mitasova, et al., 2002). Neteler and Mitasova, 2008, and Mitasova, et al., 2002, set up the model in the form of two equations. The model combines the RUSLE parameters and upslope contributing area per unit width U to estimate sediment flow as:

$$T \approx R \cdot K \cdot C \cdot P \cdot A^{m} (sin\beta)^{n} \quad (3)$$

Where $R \sim i^{m}$, $KCP \sim Kt$ and $LS = A^{m} (sin\beta)^{n}$ and m=1.0 – 1.6, n=1.0 – 1.3. The exponents *m* and *n* control the relative influence of water and slope to reflect the impact of different types of flow. The net erosion/deposition is computed as a change in sediment flow rate expressed by a divergence in sediment flow in the x and y directions:

$$D = \nabla \cdot (Ts_{o}) = \frac{\partial(T\, cos\alpha)}{\partial x} + \frac{\partial(T\, sin\alpha)}{\partial y} \quad (4)$$

Where α is aspect in degrees.

This study was initiated to quantify the effects and rates of soil erosion on military training lands through the exploration of new techniques utilizing a Geographic Information System (GIS). The Geographic Resources Analysis Support System, or GRASS, is the GIS used to compute the erosion models and analyze the results. The primary objective is to develop a simplified land cover classification to identify areas void of vegetation and thus susceptible to erosion. This method computes the difference between multiple-return LIDAR (Light Detection and Ranging) and bare-earth LIDAR to derive a vegetation-height raster map. The derived vegetation-height raster is recoded and applied to the RUSLE as the cover factor, or C-factor. The goal is to derive a raster that distinguishes cover types well enough to be applied to the RUSLE3d as parameter *C*. Additionally, deriving the raster should be more efficient then other land classification methods. Other classification methods include supervised and unsupervised classification and are supported by several software, including GRASS, ArcInfo Workstation by Environmental Systems Research Institute (ESRI), and IMAGINE by ERDAS, Inc.. Conducting classifications in these systems can be cumbersome and requires a level of user interaction commensurate with the desired fidelity of the outcome.

Study Area

The study area comprises 55 acres along MacRidge in Training Area J on Fort Bragg Military Reservation, North Carolina.   The training area is heavily used due to its easy access and close proximity to the cantonment area. Heavy use by has caused significant erosion, particularly in the area just south of the landing zone near MacRidge.

Figure 1. The study site. MacRidge, Training Area J, Fort Bragg, NC.

The 30-year average (1971-2000) annual rainfall at Fort Bragg is 47.34 inches. Rainfall is fairly evenly distributed throughout the year. The wettest month is July, averaging 5.74 inches (NOAA).

FT BRAGG WATER PLA (313168)
Monthly Totals/Averages
Precipitation (inches)
Years: 1971-2000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average	4.18	3.53	4.30	3.34	3.82	4.56	5.74	4.54	4.05	3.07	3.00	3.21	47.34

Table 1. 30-year average rainfall at Fort Bragg.

The soils in this area are Ultisols. A representative sample of Ultisols soil from a different location revealed that at a depth interval of 0-12 cm, the soil is composed of 72.4 percent sand, 15.3 percent silt, and 12.3 percent clay (USDA Handbook 436, p. 721-725). The soil can be characterized as fine sandy loam. The area with the least vegetation and most susceptible to erosion is on high ground. The fact that there is no canopy, very little vegetation, fine sandy loam soil and gentle slopes in all directions indicate the area is subjected to rill erosion.

Data

Bare-earth LIDAR data from 2004 was retrieved from the North Carolina Floodplain Mapping Information System (online). One tile was required for the study site (be3710948900go20041018.txt). The data is ASCII text files in comma-delimited X,Y,Z coordinates. The coordinate system is North Carolina State Plane feet (FIPS 3200) referenced to the North American Datum of 1983 (NAD83), GRS80 ellipsoid.

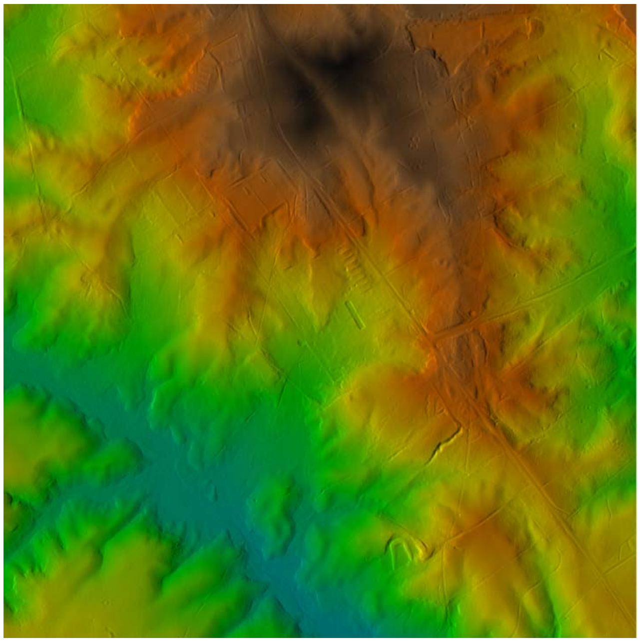


Figure 2. Bare-earth LIDAR of the tile at 1-meter resolution.

The multiple return data is from the North Carolina and FEMA coordinated LIDAR-based floodplain mapping project beginning in 2001. The data set is from Phase1B (NC_Phase1b_35079a1b3.txt). Credit is to Dr. Mitasova for securing the dataset and conducting some of the pre-processessing tasks, such as conversion to ASCII through LAS and projecting in state plane meters.

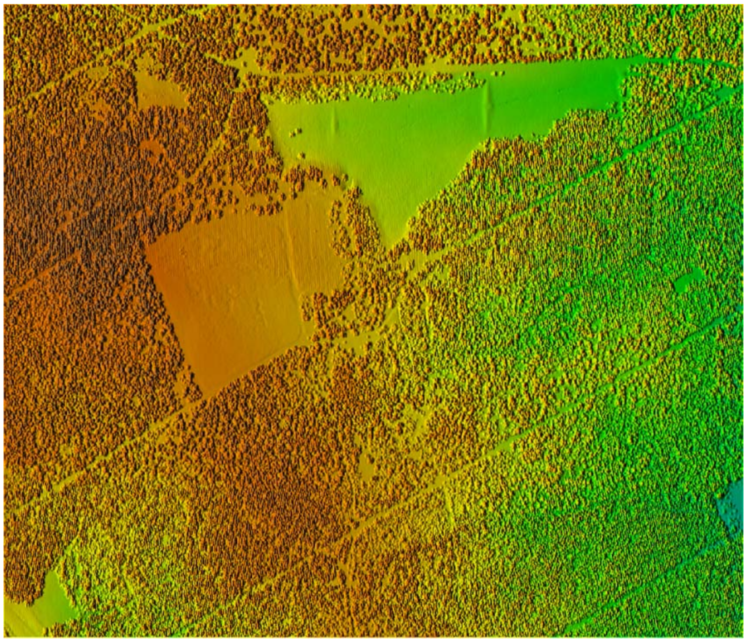


Figure 3. Multiple-return LIDAR of a subset of the tile at 1-meter resolution.

Orthophotographs were not immediately available due to the secure nature of the military installation. Imagery used for general reference and general land cover comparison were obtained through Google Earth.

A paper military installation map is a useful reference for man-made features, as most digital data sets are masked by the installation boundary. Map: 1:50,000 Fort Bragg East Military Installation Map (1998), Edition 1-NIMA, Series V742S, Sheet Fort Bragg East, Projection Transverse Mercator, Horizontal Datum and Ellipsoid WGS84 .

Methods

Preprocessing

The bare-earth LIDAR data were downloaded as ASCII text files in comma-delimited X,Y,Z coordinates. The study area region boundaries are contained within one dataset, negating the need for batch processing several files. A region extent larger than the study area is defined and the resolution set to six feet. The file is imported into GRASS using the mean method. GRASS computs the binned DEM in which the output is a vector point file. The region is set to the new DEM and resolution set to six feet. The new DEM is interpolated using regularized spline with tension and smoothing set to default parameters (tension=40 and no smoothing). The minimum number of points for approximation in a segment is set to 120 and maximum number of points in a segment set to 35. The resulting DEM displayed with shaded relief, reveals a high resolution image of the study area and indicates that the data was useable. Upon further processessing, it was decided in consultation with Dr. Mitasova to project the data to NC State Plane meters in order for the GRASS modules to properly process the data in metric distance measurements.

Additional processing is required to project the data into NC State Plane meters. The vector point file is projected to NC State Plane meters by running the command from a GRASS Project Location in NC State Plane meters. The Z-values (elevation) are scaled from feet to meters. The region is set to the new DEM and resolution set to one meter. The DEM is interpolated several times using regularized spline with tension, adjusting the tension and smoothing factors for the iterations. The first DEM interpolated tension=30, smoothing=0.5 and is viewed as a shaded relief map to see what is there (Fig. 4). The data appears suitable for modeling. The next DEM interpolated has tension=500, smoothing=1.5 (Fig. 5). The third DEM interpolated has tension=900 and smoothing=2.0 (Fig. 6). This DEM is selected for the initial erosion model.

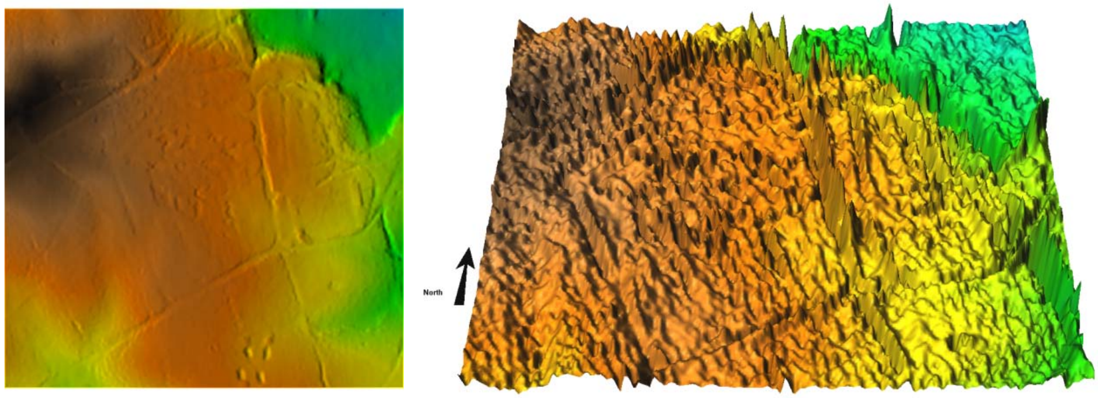


Figure 4. 2D and 3D bare-earth LIDAR at 1-meter resolution, tension=30, smoothing=0.5

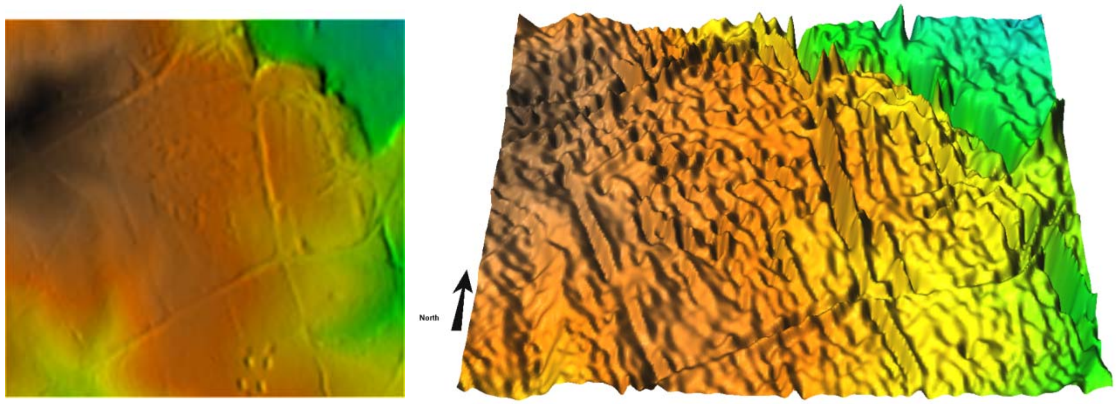


Figure 5. 2D and 3D bare-earth LIDAR at 1-meter resolution, tension=500, smoothing=1.5

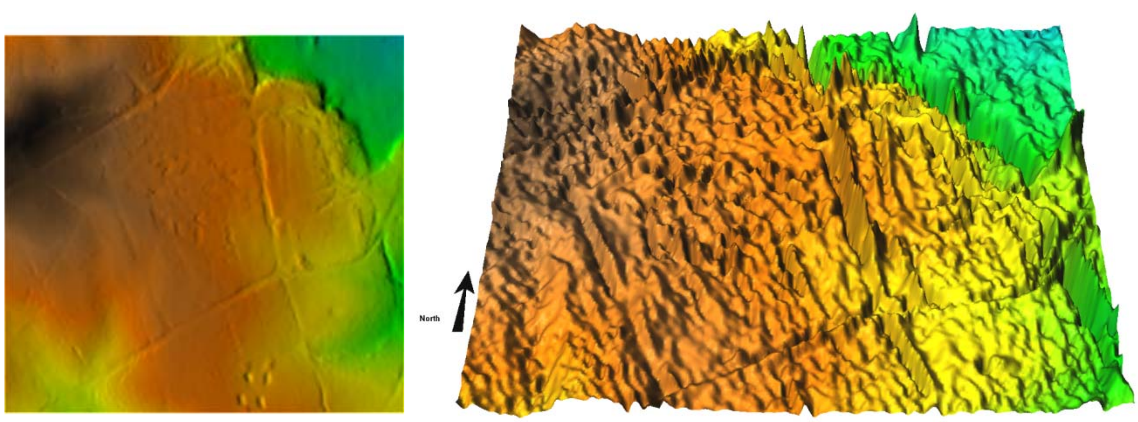


Figure 6. 2D and 3D bare-earth LIDAR at 1-meter resolution, tension=900, smoothing=2.0

An additional set of DEMs are interpolated at two-meter resolution to facilitate modeling. The DEM interpolated with tension=350 and smoothing=2.5 is ultimately used in a second erosion model (Fig. 7).

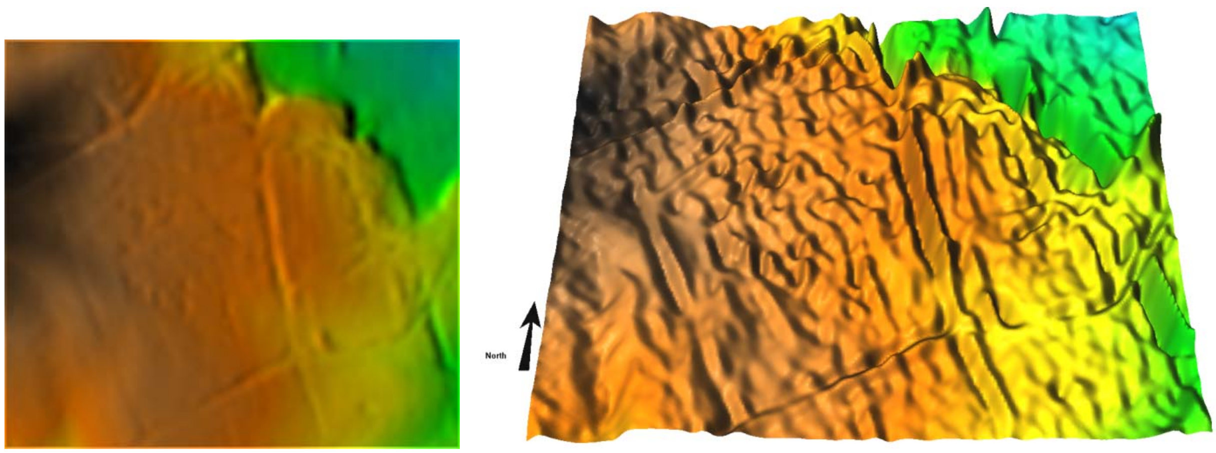


Figure 7. 2D and 3D bare-earth LIDAR at 2-meter resolution, tension=350, smoothing=2.5

Trial erosion model

This initial erosion model is a useful gauge to determine the appropriate DEM resolution and C-factor recode table values. This model was conducted with a 1-meter resolution DEM. The model accounts for all the elements of the RUSLE3d as:

R = 270

K = 0.35

LS (computed as 3D LS-factor with exponential values m=0.6 and n=1.2)

C = recoded result of (MR LIDAR) – (BE LIDAR) (see Appendix A for C_factor_recode_table_for_MR_BE_mt900.txt)

P = 1

The sharp change from red to green in the derived C-factor raster may be a result of varying data points per grid cell (Fig. 9b). This phenomenon was the primary deciding factor to conduct the model with a 2-meter resolution DEM.

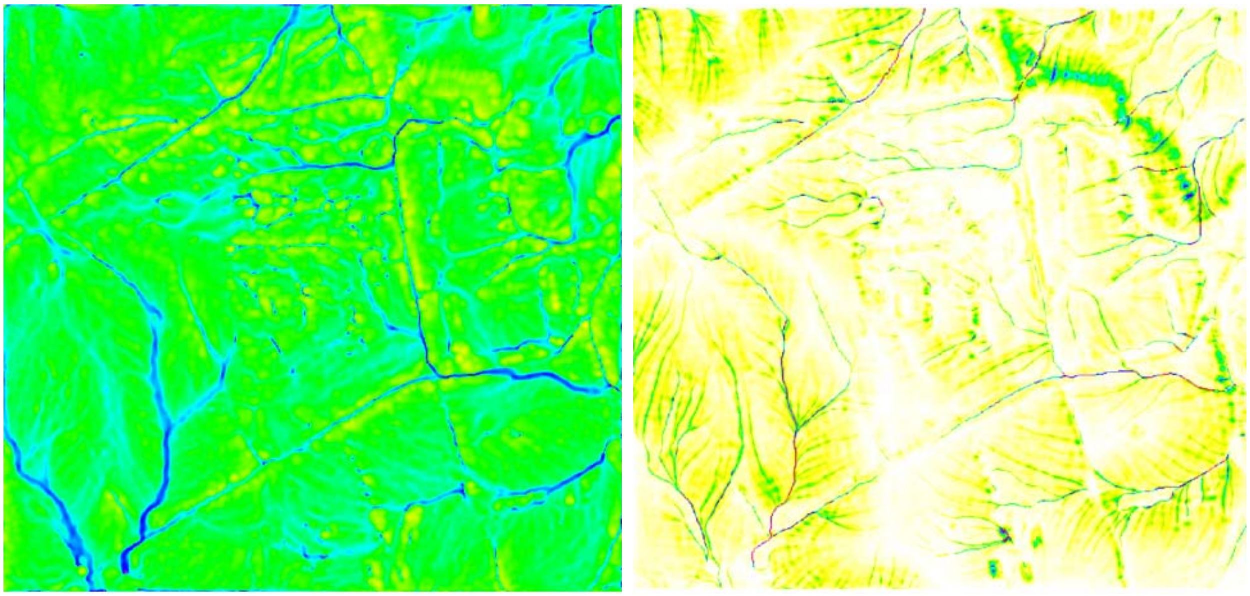
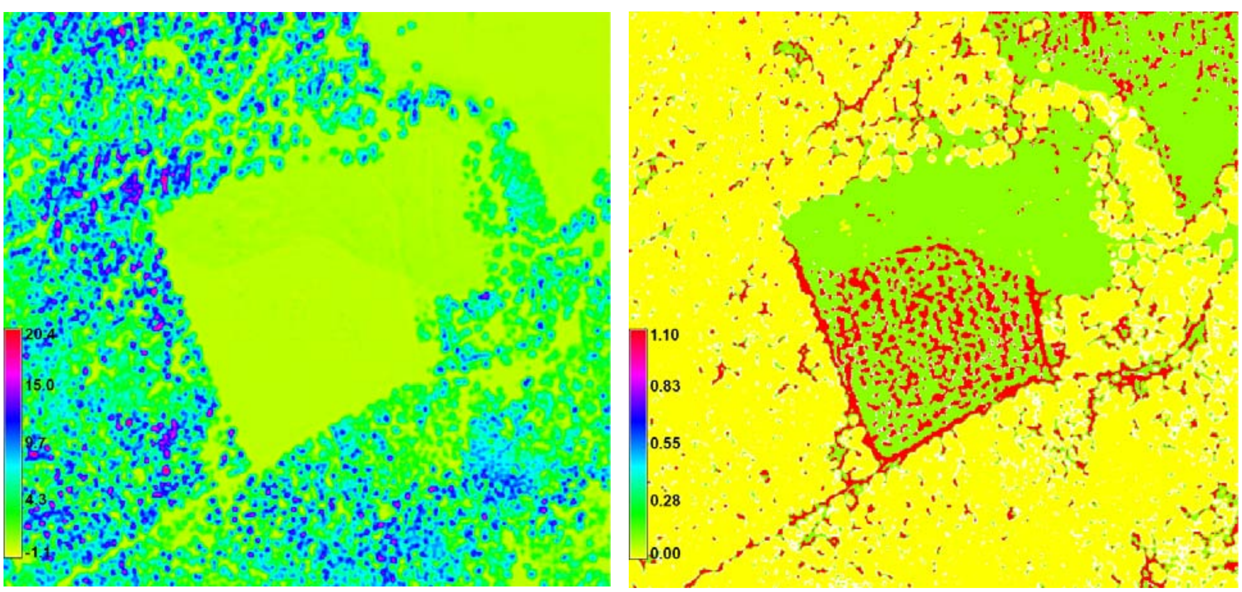
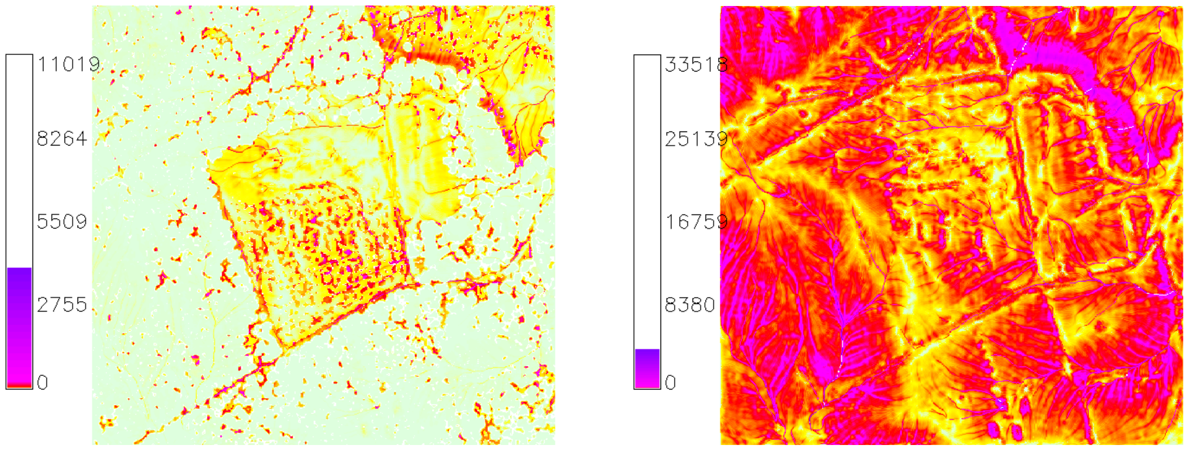


Figure 8. (a) Wetness index for study area at 1-meter resolution. (b) 3d LS-factor. Red areas in the flow paths indicate greater erosion potential.



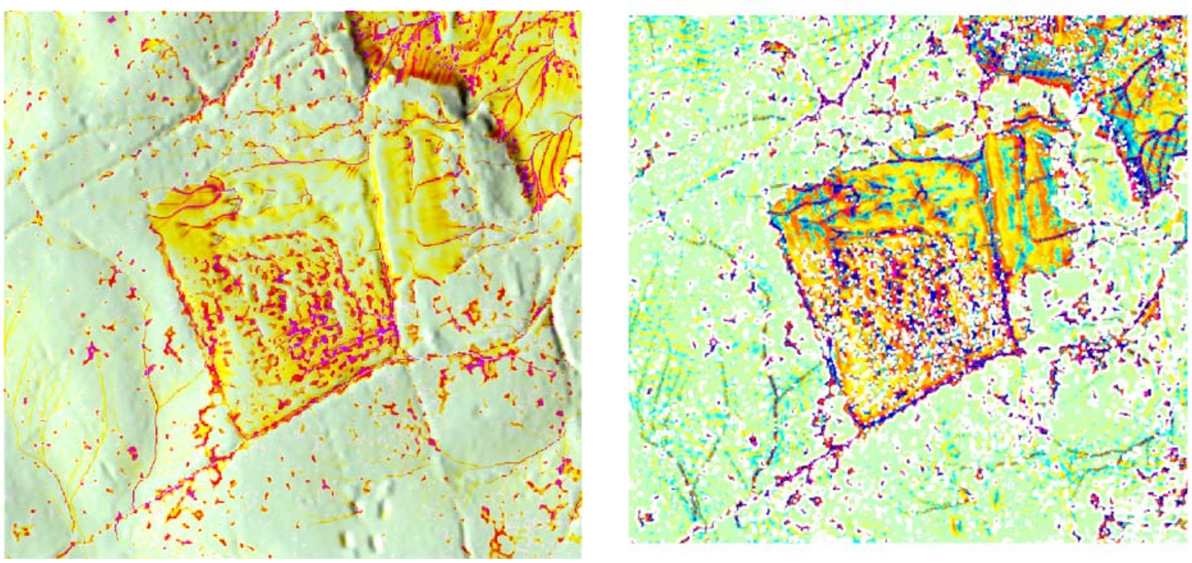
(a) (b)

Figure 9. (a) Resulting raster from MR-BE LIDAR. (b) Recoded MR-BE LIDAR for us in RUSLE3d as the C-factor.



(a) (b)

Figure 10. Soil loss comparison. (a) soil loss computed with derived C-factor. (b) soil loss computed with a standard C-factor of 1.1 (bare soil).



(a) (b)

Figure 11. (a) Sediment flow rate. Magenta areas indicate greater sediment flow. (b) Net erosion and deposition. Red areas indicate more erosion and blue areas indicate more deposition.

Improved erosion model

The two-meter resolution DEM erosion model renders a smoother and more fluid model than the previous one-meter resolution model. The research undertaken during the course of this project resulted in a familiarity and knowledge of the RUSLE3d variables which aided their refinement. The updated RUSLE3d model components were:

R = 310

K = 0.28

LS (computed as 3D LS-factor with exponential values m=0.6 and n=1.0)

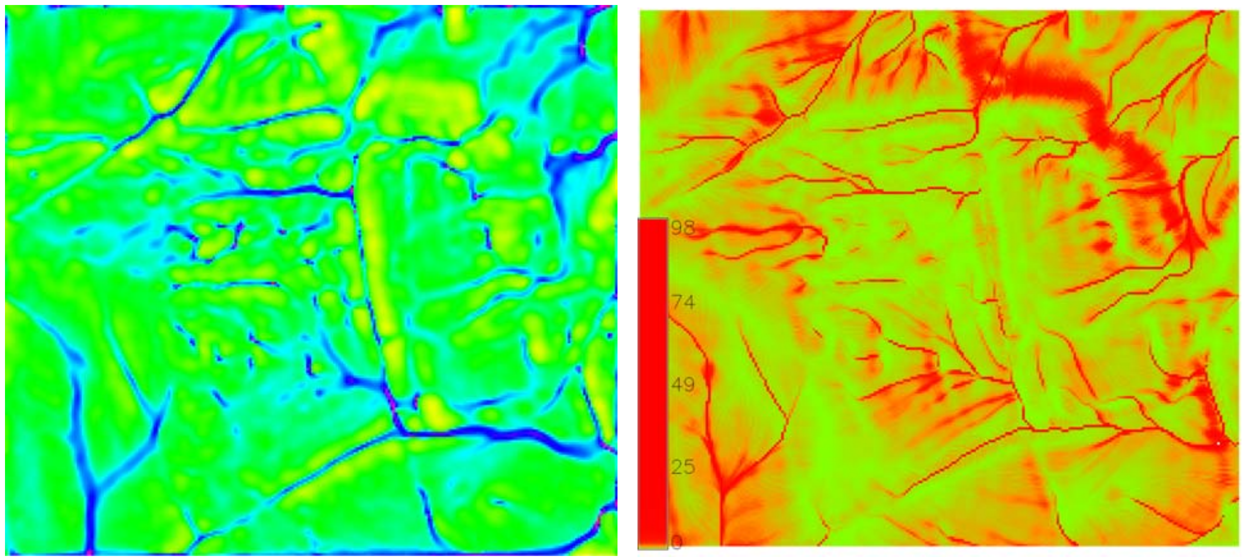
C = recoded result of (MR LIDAR) – (BE LIDAR) (see Appendix A for C_factor_recode_table_for_MR_BE_2m.txt)

P = 1

The R-factor for this area is visually interpolated as 310 from the adjusted R_R-factor isoerodent map of the Eastern United States (Renard et al., 1996). The manner in which K-factor is derived is very complicated and some level of subjectivity is apparently necessary. When computing the USLE, the relative erodibilities of key soils table (Wischemeier and Smith, 1965) in the U.S. Dept of Interior's Erosion and Sedimentation Manual list the K-factor for fine sandy loam between 0.22 and 0.25. The revised equation results in a larger K-factor. Based on the soil description at the study site, and interpolation from several K-factor tables describing "fine sandy loam", a K-factor of 0.28 is used. LS exponential value *m* is associated with rill formation. The MR-BE raster reveals that over 45 percent of the study area has vegetation height equal to or near zero, indicating bare ground (Table 2). For the purposes of this model, bare ground is equated to disturbed areas; therefore, *m*=0.6 (Mitasova, et al., 2002). Due to the fact that slopes angles are below the standard plot slope angle of 9 percent, the LS exponential value *n*=1.0 is used. The C-factor is employed dynamically across the study areas. The resulting cell values from MR-BE LIDAR rasters are recoded based on land cover height. Recoded value for each cell is the C-factor for that cell.

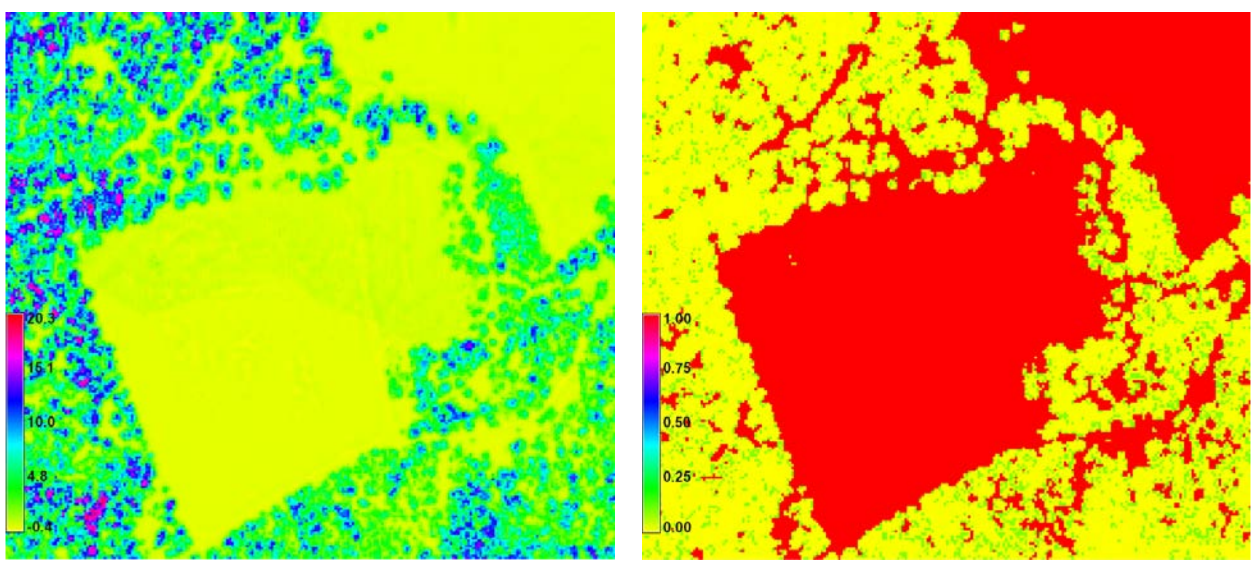
```
+-----------------------------------------------------------------------------+
|                         RASTER MAP CATEGORY REPORT                          |
|LOCATION: nc_spm_08                                Mon Apr 27 10:31:12 2009|
|-----------------------------------------------------------------------------|
|          north: 152250    east: 605700                                      |
|REGION    south: 151804    west: 605204                                      |
|          res:        2    res:       2                                      |
|-----------------------------------------------------------------------------|
|MASK:none                                                                    |
|-----------------------------------------------------------------------------|
|MAP: (untitled) (cfac_mrbe2m in Bragg_m)                                     |
|-----------------------------------------------------------------------------|
|         Category Information           |           |          |   %  |
| #|description                           |      acres|  hectares| cover|
|-----------------------------------------------------------------------------|
| 0| . . . . . . . . . . . . . . . . . . .| 25.084161| 10.151200| 45.89|
| 1| . . . . . . . . . . . . . . . . . . .|  5.244565|  2.122400|  9.59|
| 2| . . . . . . . . . . . . . . . . . . .|  4.022876|  1.628000|  7.36|
| 3| . . . . . . . . . . . . . . . . . . .|  3.531630|  1.429200|  6.46|
| 4| . . . . . . . . . . . . . . . . . . .|  3.057188|  1.237200|  5.59|
| 5| . . . . . . . . . . . . . . . . . . .|  2.588676|  1.047600|  4.74|
| 6| . . . . . . . . . . . . . . . . . . .|  2.256566|  0.913200|  4.13|
| 7| . . . . . . . . . . . . . . . . . . .|  1.951144|  0.789600|  3.57|
| 8| . . . . . . . . . . . . . . . . . . .|  1.666479|  0.674400|  3.05|
| 9| . . . . . . . . . . . . . . . . . . .|  1.376871|  0.557200|  2.52|
|10| . . . . . . . . . . . . . . . . . . .|  1.170291|  0.473600|  2.14|
|11| . . . . . . . . . . . . . . . . . . .|  0.930105|  0.376400|  1.70|
|12| . . . . . . . . . . . . . . . . . . .|  0.651370|  0.263600|  1.19|
|13| . . . . . . . . . . . . . . . . . . .|  0.478396|  0.193600|  0.88|
|14| . . . . . . . . . . . . . . . . . . .|  0.269839|  0.109200|  0.49|
|15| . . . . . . . . . . . . . . . . . . .|  0.160124|  0.064800|  0.29|
|16| . . . . . . . . . . . . . . . . . . .|  0.114657|  0.046400|  0.21|
|17| . . . . . . . . . . . . . . . . . . .|  0.059305|  0.024000|  0.11|
|18| . . . . . . . . . . . . . . . . . . .|  0.033606|  0.013600|  0.06|
|19| . . . . . . . . . . . . . . . . . . .|  0.008896|  0.003600|  0.02|
|20| . . . . . . . . . . . . . . . . . . .|  0.006919|  0.002800|  0.01|
|-----------------------------------------------------------------------------|
|TOTAL                                    | 54.663664| 22.121600|100.00|
+-----------------------------------------------------------------------------+
```

Table 2. Percent of land area vegetation height from MR-BE LIDAR.



(a) (b)

Figure 12. (a) Wetness index for study area at 2-meter resolution. (b) 3d LS-factor. Red areas indicate greater erosion potential.



(a) (b)

Figure 13. (a) Resulting raster from MR-BE LIDAR. (b) Recoded MR-BE LIDAR for us in RUSLE3d as the C-factor.

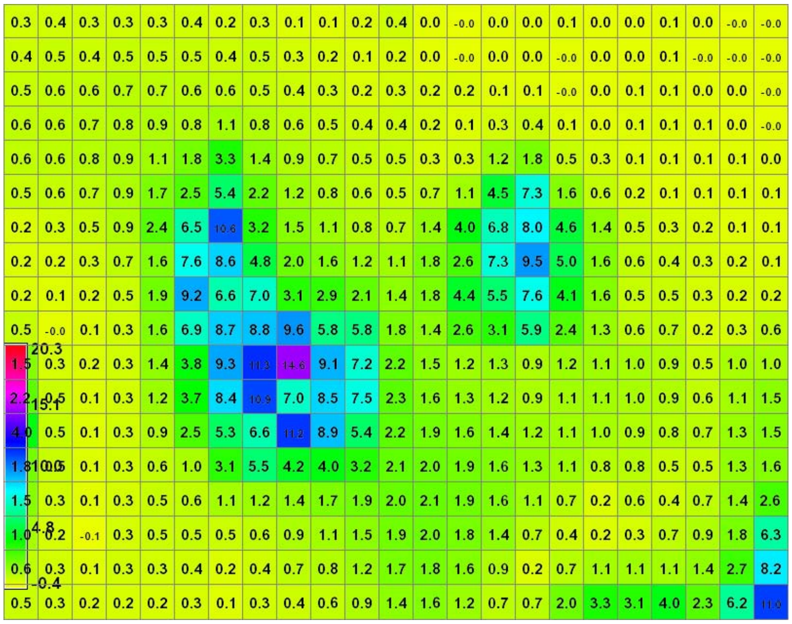
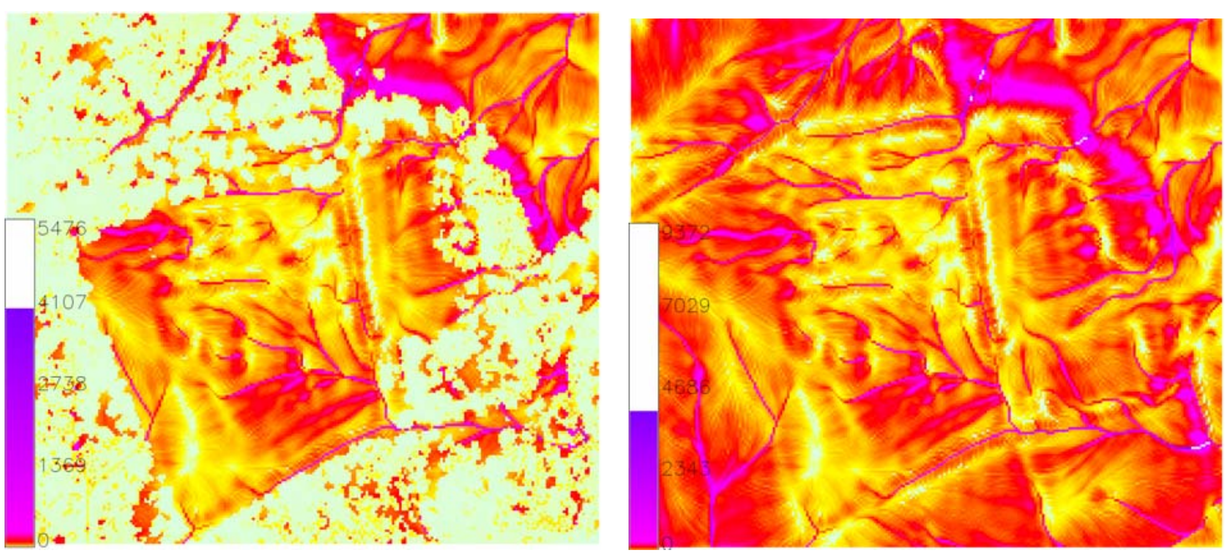


Figure 14. A subset of the resulting raster from MR-BE LIDAR (Fig. 13a) that depicts vegetation height at the particular cell. The area at the top-right is grass, but has values of zero indicating bare ground.



(a) (b)

Figure 15. Soil loss comparison. (a) soil loss computed with derived C-factor. (b) soil loss computed with a standard C-factor of 1.1 (bare soil).

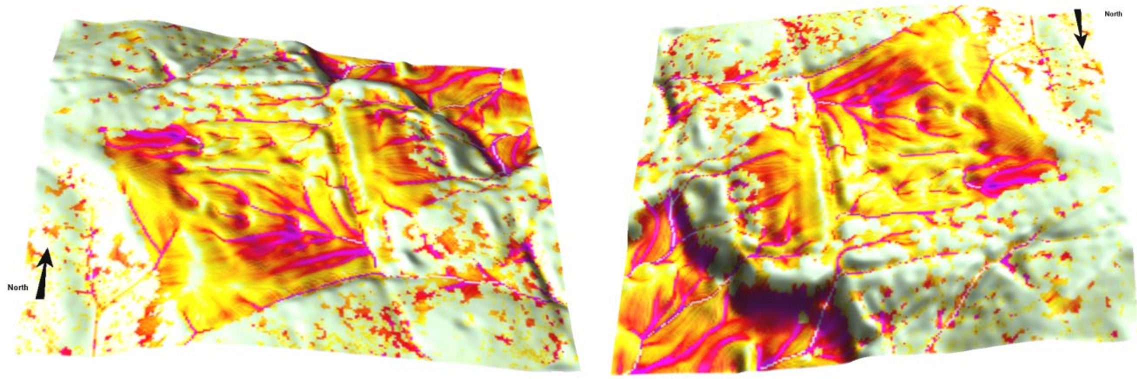


Figure 16. Sediment flow rate. Magenta areas indicate greater sediment flow. (Views north and south as indicated by north arrow).

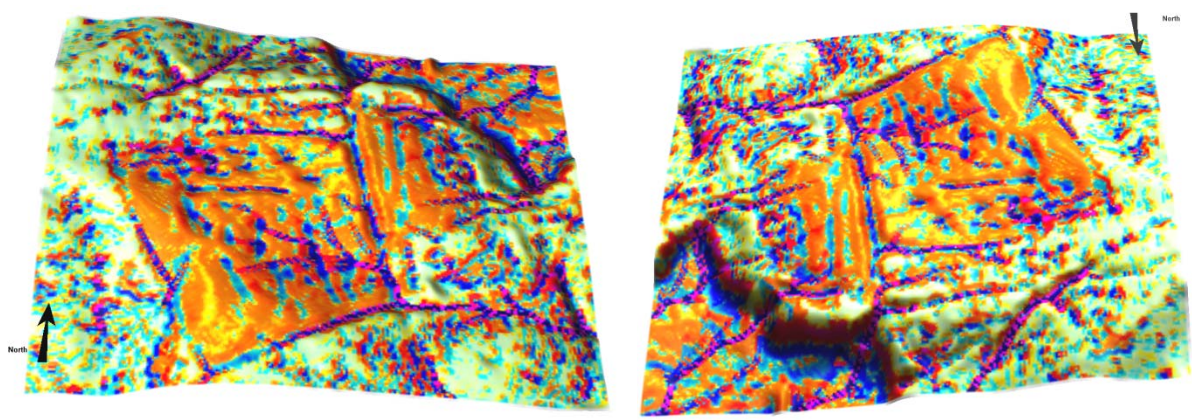


Figure 17. Net erosion and deposition. Red areas indicate more erosion and blue areas indicate more deposition. (Views north and south as indicated by north arrow).

Results

Deriving the C-factor dynamically across all raster cells is a challenging proposition. The resulting raster from the MR-BE LIDAR produces promising images. The bare spots as viewed from imagery are in fact rendered as cell value 0, or near zero as expected. The highest values of 20 meters are reasonable, as there are some tall pine trees bordering the study site. From this perspective, the process certainly returns vegetation height and is an indicator of vegetation presence or absence. What this model fails to recognize in its current state is the difference between bare ground (disturbed soil) and low-lying vegetation, such as grass (Fig. 14). Areas with very short grass were recognized by the model as bare ground, when in fact they likely have a C-factor of 0.012 – 0.003 as opposed to bare soil values of 1.2 – 0.900 (smaller number equates to less erosion potential) (Haan, Barfield and Hayes, 1994).

GRASS version 6.3.0 (native install for Windows) was used to execute the models. GRASS version 6.4 (express install) was available at the time of this study and attempts to complete an erosion model failed. Primarily, the command r.watershed fails to execute. Additionally, visualization production was made cumbersome due to problems with legend text and the inability to launch NVIZ, the 3D-viewer.

Conclusion

The recoding process for C-factor is a task that requires much attention to detail and great familiarity with the land cover of the study area. Refinements must be made to capitalize on the method of using MR-BE LIDAR. It is unclear if refinements in recoding the MR - BE LIDAR raster will solely suffice to serve the purpose of land cover type as relates to soil erodibility. Further experimentation with recoding and tuning the tension of the DEMs is required to confirm or rule out the use of this technique in erosion modeling.

Future work includes developing a “military training erosion ramp chart.” to quantify the effects of varying military training practices, so that commanders and U.S. Army land managers can plan collaboratively concerning training intensity, type and duration in respective training areas. The idea is to apply a P-factor to the RUSLE to account for training events that have been categorized and valued based on their erosivity. Table 7-3 in Soil Erosion by Toy, et al. which summarizes water erosion-control practices (Toy, et al., 2002) inspired the idea of using this erosion ramp chart as a P-factor value when calculating erosion with RUSLE3d. Initial values will be extrapolated from text until such time that empirical data is collected.

The values in the table below were used as a guide to develop the subsequent recode tables.

C_factor_values_landcover.txt - Notepad

File Edit Format View Help

```
C-factor values for different types of land cover

Source (see for more detailed values and descriptions):
Haan, Barfield, Hayes: Design Hydrology and Sedimentology for Small Catchments

Dense Forest       0.0001 - 0.001 values depend on effective canopy 100-75% and at least 5cm litter
Sparse Forest      0.002  - 0.009 canopy 75-20%

Pasture, idle land 0.100  - 0.011 cover 40-100%
Grassland          0.012  - 0.003 cover 40-100%

Bare soil          1.200  - 0.900 buldozed, freshly disturbed, or compacted
Mulch on bare soil 0.100  - 0.200

Corn, soy          0.650  - 0.20  from tilled seedbed to grown crop

wetland, water, developed paved area has C=0 as there is no soil.
```

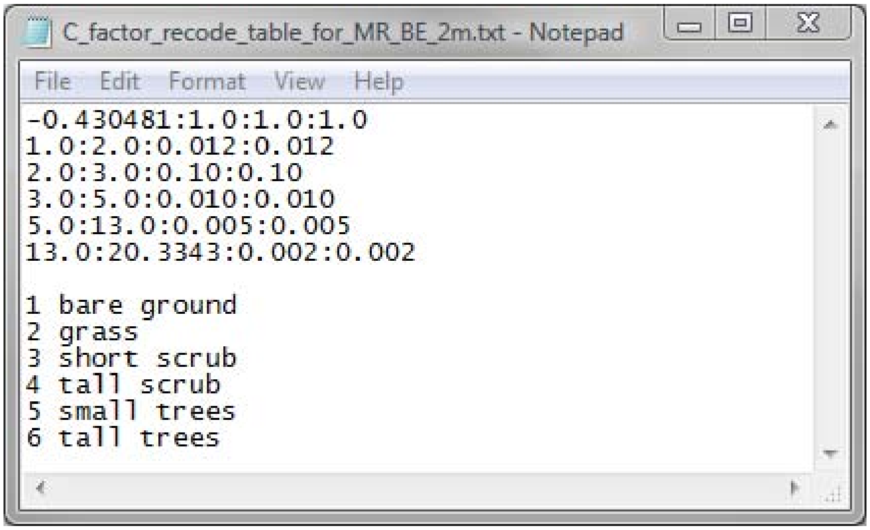
The following recode table was used to recode the MR-BE LIDAR raster map for the 1-meter resolution erosion model.

C_factor_recode_table_for_MR_BE_mt900.txt - Notepad

File Edit Format View Help

```
-1.112129:0.0:1.1:1.1
0.005:0.005:0.012:0.012
0.006:0.5:0.10:0.10
0.51:1.0:0.010:0.010
2.0:10.0:0.002:0.002
10.1:20.412712:0.001:0.001

1 bare ground
2 grass
3 short scrub
4 tall scrub
5 small trees
6 tall trees
```

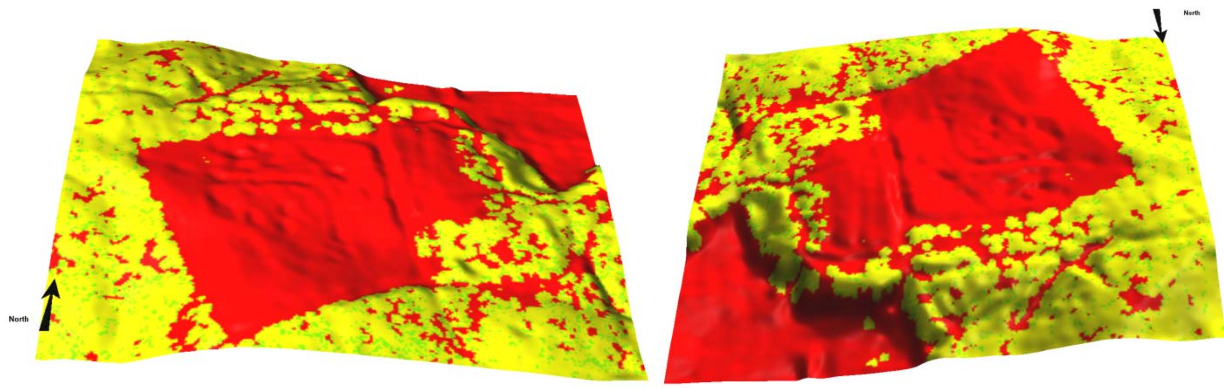
The following recode table was used to recode the MR-BE LIDAR raster map for the 2-meter resolution erosion model.



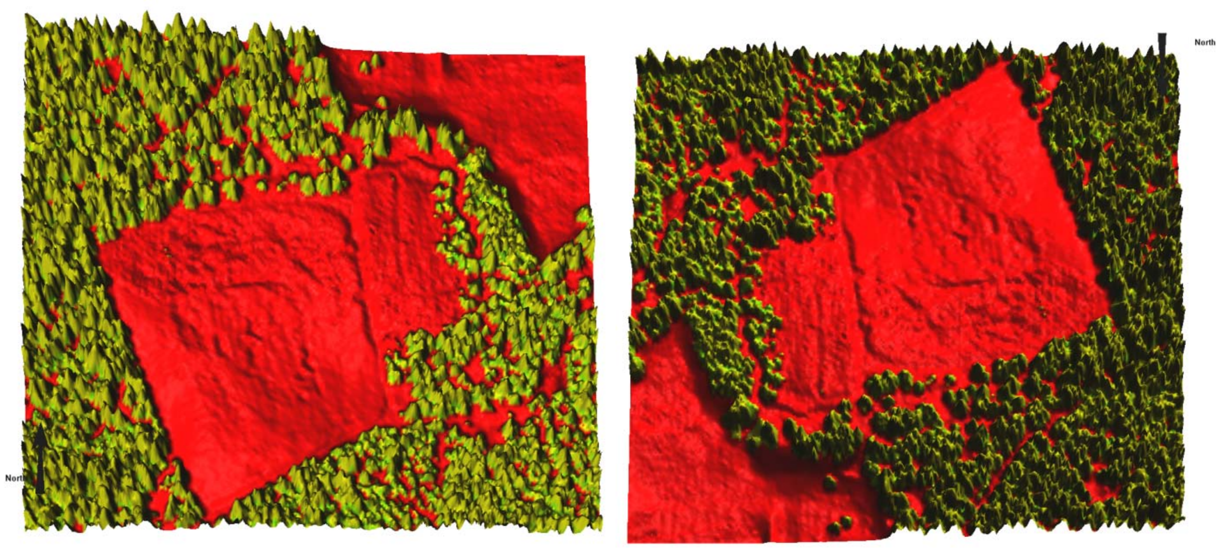

```
-0.430481:1.0:1.0:1.0
1.0:2.0:0.012:0.012
2.0:3.0:0.10:0.10
3.0:5.0:0.010:0.010
5.0:13.0:0.005:0.005
13.0:20.3343:0.002:0.002

1 bare ground
2 grass
3 short scrub
4 tall scrub
5 small trees
6 tall trees
```

Appendix B: Additional Images

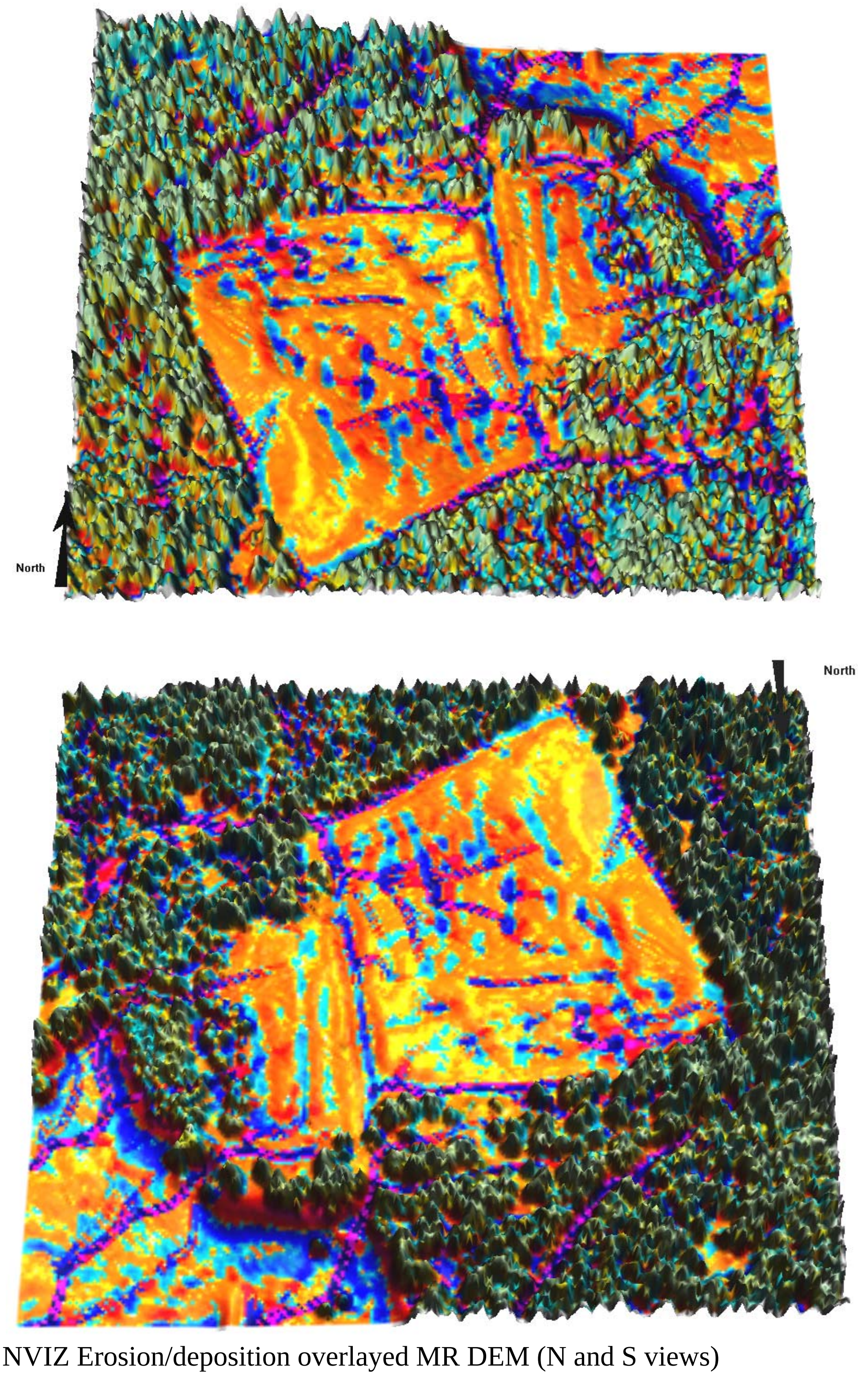
The following 3D images further depict the results from the 2-meter resolution erosion model.



NVIZ recoded C-factor over BE DEM (N and S views)



NVIZ recoded C-factor over MR DEM (N and S views)



NVIZ Erosion/deposition overlayed MR DEM (N and S views)

Appendix C: GRASS Commands and Rules

Grass commands and rules are included in the digital portfolio.

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