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14. ABSTRACT

Fort Bragg military post in the Sandhills of North Carolina's Piedmont is situated on more than 150,000 acres. Sections of the base are used for military training, others serve as refugia for endangered and threatened species. Prior stream surveys conducted at Fort Bragg documented the presence, abundance and distribution of freshwater mussels on Post. Stream channel substrate size, availability, and stability were the primary factors contributing to habitat suitability for freshwater mussel species. The studies confirmed the presence of freshwater mussels in the headwater streams supporting streams on Fort Bragg as well in the streams of the military post. Diversity and abundance of mussels in the headwater streams exceeded that of Fort Bragg streams. Headwater streams contained more course substrate compatible with sustaining stable streambeds for freshwater mussel populations. Headwater stream pH was higher than that of the pH of Fort Bragg streams. A tangible landscape model that was developed provides a means of assessing potential physical changes to the streambed that can be anticipated overtime. The models developed provide an opportunity to examine alternative approaches to stream restoration that could be used to guide restoration projects as they are initiated to restore stream habitat on Fort Bragg.

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Freshwater mussels, survey, streams, landscape model, substrate, erosion, sedimentation

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Title: Freshwater Bivalve Survey for Endangered Species Branch Fort Bragg, NC

Subtitle: Freshwater Bivalve Survey

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Project Summary

Fort Bragg military base in the Sandhills of North Carolina's Piedmont is situated on more than 150,000 acres. Sections of the base are used for military training, others serve as refugia for endangered and threatened species. Recent stream surveys conducted at Fort Bragg documented the presence, abundance and distribution of freshwater mussels on Post. *Villosa delumbis*, a species listed as state endangered was found in the Little River, which is part of the Cape Fear River basin. *Ellipitio complanata, and Uniomerus caroliniana* were found in both the Little River and in Drowning Creek, which is part of the Lumber River basin. Stream channel substrate size, availability, and stability were the primary factors contributing to habitat suitability for freshwater mussel species. Measurements of stream channel grain size distributions from study reaches were used to calibrate a sediment transport model. The model serves as a predictive tool for identifying areas with greater potential for future in-channel mussel augmentation and enhancement efforts. Catchment-average erosion rates, measured from in-situ cosmogenic nuclide ^{10}Be extracted from quartz-bearing stream sediments indicates that the Little River basin is eroding at about 10 m/Ma (0.001 cm/yr.) over timescales of ~10^4 years. These first ^{10}Be results from the Sandhills region of North Carolina provided baseline reference frame estimates of the upland erosion and sediment transport rate through the Little River basin prior to anthropogenic modifications of the landscape. This project built on these prior studies and continued assessment of freshwater mussels populations on Fort Bragg and assessed river and hillslope landscape factors important to their present distribution and future fate on the military Post. Specific Objectives of the project included: *1) Establish a routine monitoring program to document the presence of freshwater mussel fauna in Fort Bragg streams; 2) Survey streams upriver of Fort Bragg to determine if they can serve as sources of freshwater mussel stock for population augmentation*; *3) Determine the value of using freshwater mussels as environmental monitors; 4) Develop a dynamic model of upland soil erosion potential paired with tributary stream sediment transport and delivery to the Little River and Drowning Creek trunk channels, which can be used to predict the potential viability of stream sites for sustainable restoration; 5) Estimating upland soil erosion potential; 6) Develop Lidar and Sediment Transport Models; and 7) Develop and Demonstrate a Tangible Landscape system as a collaborative environment for communication of spatial patterns and sediment transport.* The studies confirmed the presence of freshwater mussels in the headwater streams supporting streams on Fort Bragg as well in the streams of the military post. The diversity and abundance of mussels in the headwater streams exceeded that of what was present in Fort Bragg streams. Headwater streams contained course substrate compatible with sustaining stable stream beds for freshwater mussel populations. Streams substrate character on Fort Bragg was more variable and contained more sand and provided less desirable substrate for freshwater mussel populations. The pH of streams in the headwaters was higher than that of the pH of Fort Bragg streams and there is a marked transition to a lower pH in Fort Bragg streams that may reflect a change in the character of the canopy in riparian areas. Riparian areas on Fort Bragg are more heavily populated with pines that may be contributing tannins that lower stream pH. Sustained spatially averaged human induced erosion rates in excess of about 0.001 cm/yr are likely to introduce more sediment to the Little River and its tributaries than the stream network is capable of transporting efficiently downstream, potentially resulting in unstable channel substrates and a reduction in mussel habitat suitability. The tangible landscape model that was developed provides a means of assessing potential physical changes to the stream bed that can be anticipated overtime. A recent SERDEP project identified streams on Fort Bragg that are potential targets for restoration. The models developed provide an opportunity to examine alternative approaches to stream restoration that could be used to guide these restoration projects as they are initiated to restore stream habitat on Fort Bragg.

Conclusions and Implications for Future Research and Implementation (from page 44,45)

1. Conduct bi-annual spring freshwater mussel surveys.
   Based on the two survey projects conducted to assess the diversity and abundance of freshwater mussels on Fort Bragg freshwater routine mussel surveys should be conducted. Little change was observed during the two series of studies and bi-annual surveys should be sufficient to provide a representative assessment of reshwater mussel populations on Fort Bragg. If population augmentation is attempted after stream restoration then a more frequent schedule of freshwater mussel surveys should be implemented in the restored stream reaches. Since freshwater mussel reproduction is tied to the presence of fish species that can serve as fish-hosts, routine fish surveys should be conducted to ensure the needed fish species are present in Fort Bragg streams.

2. The low pH observed in the Little River and tributaries on the base may be incompatible with freshwater mussel shell development. Although the threshold values for shell development need further study, a study to determine the reasons for the pH reduction on Fort Bragg is warranted. The low pH may be derived from base flow from areas with vegetation producing tannins or direct deposition of tannins. A study should be conducted to identify factors contributing to the marked change in freshwater mussel diversity and abundance at the confluence of James creek and the Little River.

3. Propagate *Villosa delumbis* and Release into Restored Streams. The Eastern Creekshell, *Villosa delumbis* is listed as state endangered. During our previous project we also identified the species on the post. *Villosa delumbis* is a species that can be propagated in captivity and then released back into streams. However, releasing captive reared animals into degraded habit is of little conservation value. If stream restoration is undertaken adult *V. delumbis* can be collected upriver of Fort Bragg, propagated in the laboratory and then released back into restored streams.

4. Establish Groundwater Monitoring Wells to Determine if Low Stream pH is Associated with Low pH base-flow or Vegetation. There is a drop in stream pH as tributaries enter Fort Bragg. The origin of the low stream pH that could potential limit freshwater mussel shell development and limit freshwater mussel population could be derived from riparian vegetation releasing tannins into streams or base flow from areas with tannin releasing vegetation. A series of groundwater monitoring wells would need to be established and the pH of groundwater monitored to identify the origin of the low pH problem.

5. Conduct a Collaborative Exploration of Alternative Stream Ecosystem Recovery Design Scenarios for Fort Bragg Streams. A comprehensive study of military bases was conducted by another institution to identify streams on military property that could be and should be restored. We suggest accessing this study, when available, and then using the tangible landscape technology refined during the course of this study to develop a comprehensive plan for stream restoration on Fort Bragg. Restoration efforts should be paired with efforts to mitigate continued erosion and sand deposition into Fort Bragg streams.

6. Study Suitability of Jumping Run Creek Restoration and Mitigation of Erosion and Sand Loading from Landing Zones and Implement Erosion Control Measures to Minimize Sand Loading into Streams. Jumping Run Creek was identified as a degraded stream that could potentially be restored if steps are taken to mitigate erosion and sand sedimentation into the stream.

7. Study Suitability of Tank Creek Restoration by physical reworking of the channel. Tank Creek is completely contained within Fort Bragg. It is species depauperate lacking both freshwater macroinvertebrate and vertebrate diversity and abundance. It has been severely degraded by military activity and is a relatively straight channel with limited riparian vegetative buffer protection. Restoration efforts should include an effort to create a restored stream channel with meandering flow and include efforts to mitigate erosion and sand deposition in the stream.

8. Establish Vegetative Landcover Over Berms Adjacent to Landing Zones. Landing zones adjacent to Fort Bragg stream include soil berms that are not protected with vegetation from erosion. If feasible, without disrupting troop training, vegetative cover should be established to mitigate erosion and deposition of sand into adjacent streams.

Table of Contents

List of Tables

List of Figures

List of Acronyms and Abbreviations

Acronym	Definition
ARCGIS	ESRI geographic Information Software
^{10}BE	Cosmogenic nuclide Beryllium
CNC	Computer numerical control
CPUE	Catch per unit effort
CRN	cosmogenic radionuclides
CRONUS	On-line calculator
DEM	Digital elevation models
D_{50}	Medium
PRIME	Purdue University Rare Isotope Measurement Laboratory

Keywords

Freshwater mussels, unionids, streams, erosion, erosion rate, sedimentation, landscape model

Objectives

Our initial studies conducted at Fort Bragg identified three species of freshwater mussels, one of which, *Villosa delumbis*, is listed as state endangered. The studies prompted a series of recommendations that guided development of the following specific objectives for this project to: ***1) Establish a routine monitoring program to document the presence of freshwater mussel fauna in Fort Bragg streams; 2) Survey streams upriver of Fort Bragg to determine if they can serve as sources of freshwater mussel stock for population augmentation; 3) Determine the value of using freshwater mussels as environmental monitors; 4) Develop a dynamic model of upland soil erosion potential paired with tributary stream sediment transport and delivery to the Little River and Drowning Creek trunk channels, which can be used to predict the potential viability of stream sites for sustainable restoration; 5) Estimating upland soil erosion potential and relationship with freshwater mussels counts; 6) Develop Lidar and Sediment Transport Models; and 7) Develop and Demonstrate a Tangible Landscape system as a collaborative environment for communication of spatial patterns and sediment transport.***

Background/Introduction

Freshwater mussels are among the more highly endangered faunal groups with approximately 70% of the 297 species historically present in North America being designated with some degree of imperilment (Williams et al. 1993). North Carolina is home to approximately 55 species, and those are similarly threatened (Bogan 2002). In North Carolina, habitat degradation and loss through expansion of urban landscapes and poor historical land use practices have likely contributed the most to their decline. Erosion, sedimentation and destabilization of stream channels are among the greatest threats to these animals because they are heavily reliant on stable substrates (Strayer 1999, Johnson and Brown 2000).

Objective 1: Establish a routine monitoring program to document the presence of freshwater mussel fauna in Fort Bragg streams;

Active routine surveying of freshwater mussel populations helps assess the status of existing populations and increases or decreases in species abundance and diversity moving forward. We sought to survey the freshwater mussel communities of the Little River watershed on and upstream of Fort Bragg in North Carolina to identify species present in the watershed. We also searched for sites that could serve as potential restoration sites for more rare species in the watershed. Previous work (Levine and Wegmann 2015) included survey of several streams across Fort Bragg and found that the Little River (Fig 1) was the most diverse, containing *Elliptio complanata*, *Uniomerus carolinianus*, as well as a single specimen of *Villosa delumbis*. *Villosa delumbis* is currently listed as Endangered in the state of North Carolina.

Materials and Methods

Linear stretches of each stream site were surveyed with either bathyscopes (viewscopes) or snorkeling for identification of freshwater mussel in the stream substrate.

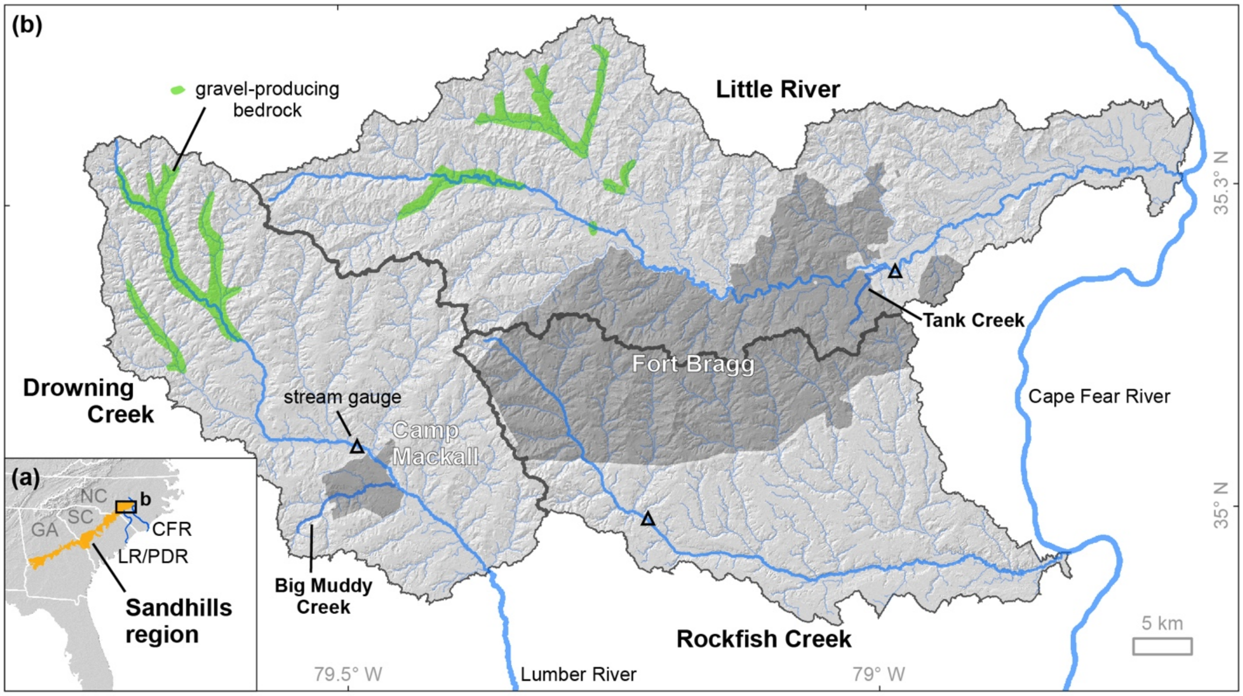

Figure 1. *Bedrock and stream map of Fort Bragg area.* ***(a)*** *The Sandhills region spans the states of North Carolina (NC), South Carolina (SC) and Georgia (GA) and represents the upper (innermost) portion of the Atlantic Coastal Plain physiographic province. Fort Bragg proper is drained by the Cape Fear (CFR). Camp McCall is drained by Drowning Creek, part of the Lumber River (LR), and itself a tributary of the Pee Dee River (PDR).* ***(b)*** *Mussel surveys, denoted by black dots along the streams were spread throughout these river systems. Stream sediment samples (S1–S4) for catchment-average erosion rate analysis were collected in the Little River basin. Bedrock that can erode to produce gravel-sized sediment (green polygons) crops out in the headwaters of Drowning Creek and the Little River. US Geological Survey stream gages (triangles) were used in the sediment grain size modeling.*

Results and Discussion

Three species of freshwater mussels were observed during the survey. No mussels were found in James Creek at the two sites surveyed despite some physical habitat that appeared to be suitable for Unionids. Crane Creek held mostly *Uniomerus carolinianus* but also yielded two *V. delumbis* (Fig. 3&4). Despite only finding two live *E. complanata* in Crane Creek, we did find a relatively large amount of shell of that species in the stream. Sixteen stream sites (4-18, 20) on Fort Bragg were surveyed. Sites 1-3 and 19 were located upstream of the post and survey results are noted in Objective 2. Surveys were timed to assess the number of survey person-hours in each stream (Table 1) and catch/unit effort (Fig. 2)). Geographic location was recorded at the beginning and ending of each survey run.

Table 1. *Site descriptors, coordinates and site-specific survey effort at survey sites.*

Date	Stream	Location	Starting Latitude	Starting Longitude	Ending Latitude	Ending Longitude	Person-Hours
8/11/2016	Little R	Downstream of Long Point	35.23317	-79.27769	35.23365	-79.27891	7.5
8/5/2016	Little R	Upstream of Lakebay Rd	35.20394	-79.21614	35.20555	-79.21577	4.5
8/31/2016	Little R	Just upstream of James Cr	35.19771	-79.21631	35.19874	-79.21584	3
8/31/2016	Little R	Just downstream of James Cr	35.19637	-79.21492	35.19771	-79.21631	1.67
8/31/2016	Little R	near Pre-Ranger Course	35.19395	-79.20387	35.19561	-79.20405	2
9/1/2016	Little R	Upstream of Morrison Bridge Rd	35.19284	-79.18872	35.19245	-79.18981	1.33
8/19/2016	Little R	Downstream of Morrison Bridge Rd	35.19073	-79.18349	35.19354	-79.18477	3.5
8/19/2016	Little R	Upstream of Flat Creek	35.18773	-79.17322	35.18894	-79.17223	2
7/19/2016	Little R	Between Crane Cr and Deep Cr	35.17891	-79.16119	35.17973	-79.16143	3
7/19/2016	Little R	Between Crane Cr and Deep Cr	35.18063	-79.15952	35.17991	-79.15945	1
7/19/2016	Little R	Between Crane Cr and Deep Cr	35.18190	-79.16051	35.18063	-79.15952	3
7/29/2016	Little R	Between Crane Cr and Deep Cr	35.17660	-79.15497	35.17737	-79.15463	1.5
7/29/2016	Little R	Between Crane Cr and Deep Cr	35.17547	-79.15034	35.17508	-79.15313	4
7/29/2016	Little R	Between Crane Cr and Deep Cr	35.17424	-79.14852	35.1762	-79.14811	4.5
7/14/2016	Little R	Between Deep Cr and Buffalo Cr	35.17147	-79.13741	35.17109	-79.13798	2
7/14/2016	Little R	Between Deep Cr and Buffalo Cr	35.17398	-79.13651	35.17306	-79.13676	2
7/14/2016	Little R	Between Deep Cr and Buffalo Cr	35.17718	-79.13616	35.17654	-79.13555	1
7/14/2016	Little R	Downstream of Buffalo Creek	35.17775	-79.13308	35.17738	-79.13473	2
9/1/2016	Crane Cr	Upstream of McGill Rd	35.20866	-79.18635	35.20966 5	-79.18465	3
9/1/2016	James Cr	Upstream	35.20144	-79.21973	35.20209	-79.21949	1
9/1/2016	James Cr	Just upstream of Little R	35.19771	-79.21631	35.19824	-79.21653	1.2

Table 2. *Results of surveys conducted in the Little River watershed on Fort Bragg in 2016.*

Site #	Stream	Location	Effort (Person-Hours)	*Elliptio complanata*	*Uniomerus carolinianus*	*Villosa delumbis*	Total Mussels Found	CPUE (Mussels per hour)
4	Little R	Just downstream of James Cr	1.67	18	2	0	20	12.0
5	Little R	near Pre-Ranger Course	2	4	7	0	11	5.5
6	Little R	Upstream of Morrison Bridge Rd	1.33	1	0	0	1	0.8
7	Little R	Downstream of Morrison Bridge Rd	3.5	2	2	0	4	1.1
8	Little R	Upstream of Flat Creek	2	4	13	0	17	8.5
9	Little R	Between Crane Cr and Deep Cr	3	3	1	0	4	1.3
10	Little R	Between Crane Cr and Deep Cr	1	22	0	0	22	22.0
11	Little R	Between Crane Cr and Deep Cr	3	19	1	0	20	6.7
12	Little R	Between Crane Cr and Deep Cr	1.5	9	0	0	9	6.0
13	Little R	Between Crane Cr and Deep Cr	4	40	30	0	70	17.5
14	Little R	Between Crane Cr and Deep Cr	4.5	28	1	0	29	6.4
15	Little R	Between Deep Cr and Buffalo Cr	2	40	8	0	48	24.0
16	Little R	Between Deep Cr and Buffalo Cr	2	9	1	0	10	5.0
17	Little R	Between Deep Cr and Buffalo Cr	1	2	1	0	3	3.0
18	Little R	Downstream of Buffalo Cr	2	5	0	0	5	2.5
20	James Cr	Upstream	1	0	0	0	0	0.0
21	James Cr	Just upstream of Little R	1.2	0	0	0	0	0.0

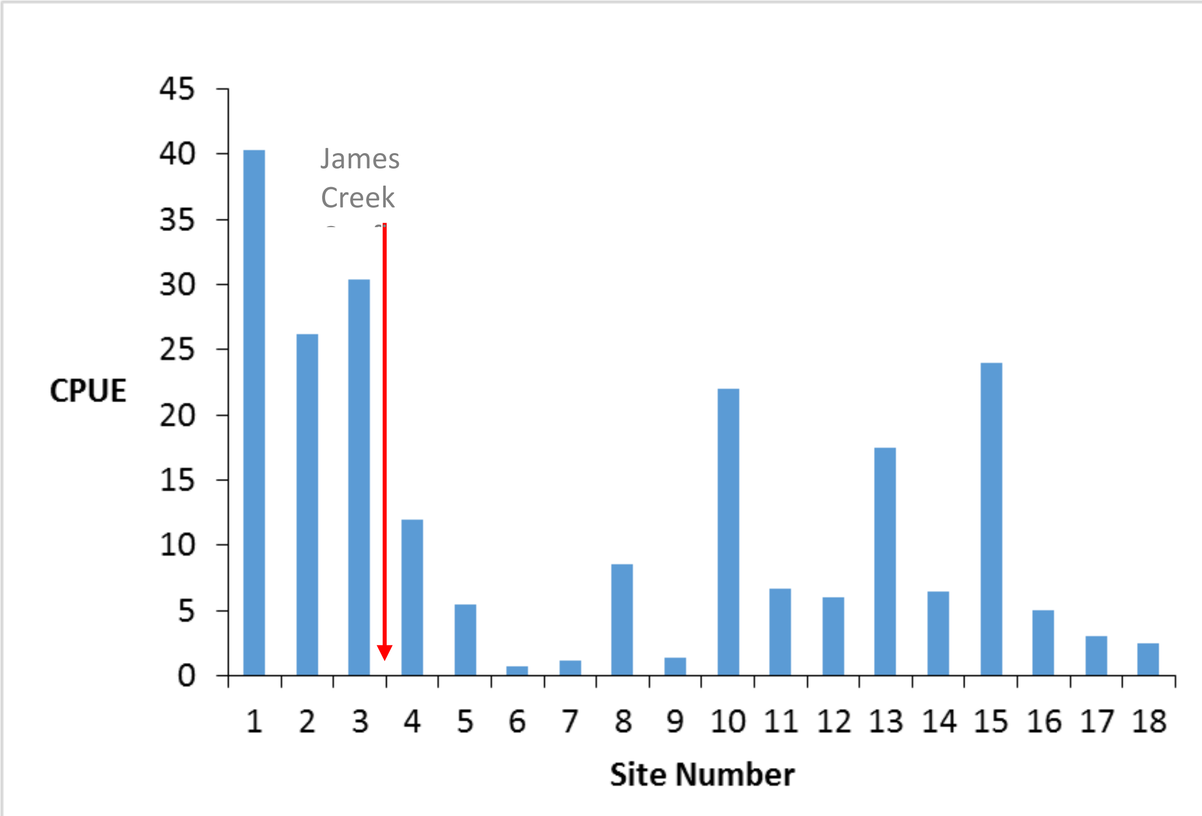

Figure 2. *Catch Per Unit Effort (CPUE) as total number of mussels found per person-hour at 18 sites along the Little River. Sites are oriented upstream to downstream with Site 1 being at Long Point Rd, Site 3 being just above the confluence with James Creek, and Site 18 being immediately downstream of Buffalo Creek.*

Figure 3. *Villosa delumbis found downstream of Long Point Rd on 11 August 2016.*

Figure 4. *Villosa delumbis found upstream of Lakebay Rd on 5 August 2016.*

Monitoring of pH revealed that the Little River upstream of Fort Bragg has a pH around 6.3. James Creek and other streams on the base flowing into the mainstem are more acidic, and we observed a general decrease in the pH in the Little River as it was fed by these tributaries (Table 3).

Table 3. *Results of pH measurements in the Little River watershed on 27 July 2017.*

Stream	Location	Latitude	Longitude	pH
Buffalo Creek	Lobelia Rd	35.18971	-79.13579	4.9
Crane Creek	McGill Rd	35.19637	-79.21492	6.1
Deep Creek	Manchester Rd	35.16773	-79.15294	5.1
Flat Creek	Manchester Rd	35.18268	-79.17737	5.0
James Creek	Upstream Site	35.20144	-79.21973	5.7
Jumping Run Creek	Manchester Rd	35.16362	-79.11706	5.6
Little Creek	Manchester Rd	35.17161	-79.08783	5.5
Little River	Long Point Rd	35.23317	-79.27769	6.3
Little River	Lakebay Rd	35.20394	-79.21614	6.3
Little River	Below James Cr Mixing Zone	35.19364	-79.21193	6.2
Little River	Below James Cr (Ranger Camp)	35.19738	-79.21615	6.1
Little River	Morrison Bridge Rd	35.19185	-79.18347	6.3
Little River	Below Jumping Run Creek	35.17560	-79.10517	6.0
Little River	Downstream of Flat Creek	35.18016	-79.16195	6.0
Tank Creek	Downstream of MacFayden Lake	35.15728	-79.01111	7.1

Relative to other watersheds within the Cape Fear River Basin, the Little River sub-basin that flows through Fort Bragg does not have a particularly diverse mussel assemblage. Only three species were found in total, and one of those species – *Villosa delumbis* – was quite rare. This may be due to the low pH of the streams or the historical land use practices on base and in surrounding towns that have contributed excess sediment load to the river. Generally, acidic waters are inhospitable for organisms that construct a shell of calcium carbonate ($CaCO_3$). Water of pH 5.25 has been shown to tax the calcium reserves of *Margaritifera margaritifera* in only a few days (Heming et al. 1988). Additionally, food quality of the particulate organic matter in watersheds dominated by coniferous forest is also reduced (Omerod et al. 1993, Riipinen and Dobson 2010). We suspect the factors of low pH, stream sedimentation and erosion as well as potentially suboptimal food quality may be limiting the overall abundance and diversity of mussels in the Little River watershed.

Reduced abundance was especially the case in the Little River downstream of the confluence with James Creek. The point at which these two streams meet is the point at which the Little River reaches Fort Bragg. Below this confluence, mussel abundance is markedly decreased relative to the Little River upstream of the base. The reach between James Creek and Buffalo Creek was characterized by large amounts of gravel with sand as a subdominant substrate similar to that upstream of James Creek. Large sections of bedrock were also present. Unlike the upstream reaches, however, the only significant concentrations of mussels downstream were primarily found near flow refugia next to instream bedrock walls and sometimes near certain stream banks (Fig 5). These narrow stretches of stream appeared to provide stable patches of substrate for mussels to colonize. The high concentration of mussels in those areas relative to the rest of the channel suggests that much of the stream channel may be unstable or otherwise physically unsuitable for mussels. Downstream of Buffalo Creek, the Little River becomes even more degraded, homogenous, dominated by sand substrates, and unsuitable for mussels.

Figure 5. *The base of an instream bedrock wall in the Little R. In many cases, these provided the only apparently stable habitat in the Little River downstream of James Creek.*

While these factors may limit overall mussel abundance on Fort Bragg, there are still opportunities for mussel restoration efforts in this reach where those rock walls exist. Namely, sites 10, 13, and 15 all have patches of substrate that are highly stable and support relatively dense aggregations. *Villosa delumbis* is extant in the watershed and was found in this reach of river in our original study (Levine and Wegmann 2015). By its presence in Crane Creek we know that pH 6.1 is not too low to support the species. Freshwater mussel reproduction is dependent on the sympatric presence of fish species that serve as hosts for the larval stage, glochidia. We regularly observed the presence of its host fish species, Redbreast sunfish (*Lepomis auritus*) and bluegill (*Lepomis macrochirus*), during mussel surveys. If efforts are initiated to restore freshwater mussel populations on Fort Bragg, we would recommend propagation and culture of *V. delumbis* from the watershed and release into these three sites in patches currently holding the aggregations of *E. complanata* and *U. carolinianus*. With some effort, brood stock could likely be found in Crane Creek or potentially the upper reaches of the Little River. Except for Tank Creek, which had a pH of 7.1 at the time of sampling, all other sampled tributaries on the base had very low pH, and we would not recommend these for restoration. Due to the high amount of channel alteration and development around Tank Creek, we suggest that be deemed as a low priority for population augmentation unless a major restoration effort was initiated to restore the stream bed and restore stream banks in a manner that minimizes future erosion and sedimentation.

Objective 2: Survey streams upriver of Fort Bragg to determine if they can serve as sources of freshwater mussel stock for population augmentation;

Freshwater mussels populations are most stable in streambeds with rock and cobble and less stable in streams where small grain gravel and sand predominate. In our initial studies, we noted low abundance and little diversity in mussel populations on Fort Bragg. Stream substrates in many locations were unstable with sand rather than cobble comprising the majority of the streambeds. However, we identified from satellite imagery that streams upriver from Fort contained sites with gravel and cobble that are more suitable for mussel populations. We hypothesized that these sites might contain a great diversity of mussel fauna. If restoration efforts are initiated on Fort Bragg to improve habitat quality in currently degraded streams, these upstream sites could potentially serve as nursery areas for repopulated downstream sites on the Post after stream habitat is restored into habitat suitable for freshwater mussels. Accordingly, we conducted an initial reconnaissance effort to identify potential sites with physical conditions (e.g. substrate) more suitable for freshwater mussel populations. After these initial site assessments, we then conducted more thorough population surveys to determine mussel diversity and abundance at selected sites that may be supporting mussel populations.

Methods

Geologic maps of Fort Bragg and surrounding communities suggest that stream substrate upstream of Fort Bragg may be more suitable freshwater mussel habitat. These locations appear to provide a source of courser grain substrate (cobble and gravel) that is then washed downstream. Selected upriver sites were assessed to determine if they can serve as a local source of freshwater mussels for reviving Fort Bragg mussel population diversity.

To locate streams in the upper Little River watershed that might be suitable to support freshwater mussels, we performed site reconnaissance at 15 sites across 7 streams above Fort Bragg (Table 4). Potential sites potentially compatible with freshwater mussels populations were surveyed by walking the stream bed with bathyscopes to search for mussels. One person-hour of effort was conducted at each site to identify habitat that looked suitable for freshwater mussels.

Follow-up surveys were conducted with bathyscopes and by snorkeling at four sites with potential freshwater mussel populations. Linear reaches of stream with surveyed. Person-time was recorded and the catch/unit effort noted.

Table 4. *Upper Little River watershed sites evaluated for the potential presence of freshwater mussels.*

Stream	Latitude	Longitude	Comments
Beaver Creek	35.26999	-79.227181	Very tannic. Stream channel in good condition. Gravel, sand, some cobble. No mussels
Crane Creek	35.19536	-79.169714	Deep, homogenous habitat. Dominated by bedrock. ATV access degrading stream banks. Heavily used swimming hole with rope swing and no evidence of mussels. No mussels found.
Crane Creek	35.213187	-79.18372	Sand-gravel stream with silt covering. Shells of Elliptio and Uniomerus common but no live mussels.
Crane Creek	35.28477	-79.271596	Sandy, muddy, poor habitat, no mussels.

Little Crane Creek	35.28997	-79.266991	Beaver impoundment, silty-sandy and homogenous. Poor habitat. No mussels
Little River	35.24969	-79.300557	Wetland/beaver Impoundment. Not good for mussels
Little River	35.26971	-79.416739	Downstream is channelized and sedimented in with sand and silt. Very straight with poor habitat. One *Uniomerus* shell found downstream. Upstream had some live *Uniomerus* present in one small patch upstream of the golf course. Habitat is very patchy. Lots of gravel upstream.
Little River	35.26854	-79.469542	Heavy beaver activity and sandier. A large dam upstream of the road crossing. The downstream area appears to be previously dammed and shows evidence of beaver dams blowing out with channel braiding and degradation. No signs of mussels.
Little River	35.235336	-79.278548	Good run/shoal habitat from approximately 50-250 m downstream of the road. Live *Elliptio* and *Uniomerus*. Sand-gravel mix. Water is clear.
Little River	35.20386	-79.216309	Great habitat upstream with long gravel runs. Live *Elliptio* and *Uniomerus*
Mill Creek	35.23524	-79.335768	Sandy/silty with some clay. Poor mussel habitat and no mussels found
Nicks Creek	35.25346	-79.412853	Below reservoir. Gravel with some cobble. Stable habitat with very black water. No mussels found
Nicks Creek	35.2376	-79.447262	Sandy, deep and low gradient. Runs through power line right of way. No signs of mussels.
Nicks Creek	35.23253	-79.487427	Very low gradient and sandy. Almost swampy. No signs of mussels.
Wad's Creek	35.28198	-79.431243	Very small. A muddy mess. Heavily sedimented with eroded banks. Mid-channel bars present. No mussels found.

Results

Freshwater mussels were at each of the four sites. The same species of mussels, U. *carolinianus,* and *E. complanata* were observed at all three of the sites. *Villosa delumbis* was observed downstream at Long Point, Upstream of Lakebay Rd, and upstream of McGill Rd. Although *U. carolinianus,* and *E. complanata* were observed upstream of James Creek, V. delumbis was not observed at the site.

Table 5. *Site list for full mussel surveys upstream of Fort Bragg.*

Site #	Date	Stream	Location	Starting Latitude	Starting Longitude	Ending Latitude	Ending Longitude	Person-Hours
1	8/11/2016	Little R	Downstream of Long Point	35.23317	-79.27769	35.23365	-79.27891	7.5
2	8/5/2016	Little R	Upstream of Lakebay Rd	35.20394	-79.21614	35.20555	-79.21577	4.5
3	8/31/2016	Little R	Just upstream of James Creek	35.19771	-79.21631	35.19874	-79.21584	3
19	9/1/2016	Crane Cr	Upstream of McGill Rd	35.20866	-79.18635	35.209665	-79.18465	3

Table 6: *Mussel survey results from streams in the upper section of the watershed branching into tributaries on Fort Bragg.*

Site #	Stream	Location	Sampling Effort (Person-Hours)	*Elliptio complanata*	*Uniomerus carolinianus*	*Villosa delumbis*	Total Mussels Found	CPUE (Mussels per hour)
1	Little R	Downstream of Long Point Rd	7.5	226	75	1	302	40.3
2	Little R	Upstream of Lakebay Rd	4.5	97	20	1	118	26.2
3	Little R	Just upstream of James Cr	3	70	21	0	91	30.3
19	Crane Cr	Upstream of McGill Rd	3	2	21	2	25	8.3

Objective 3: Determine the value of using freshwater mussels as environmental monitors;

Various miniaturized sensors have been adapted to monitor pulse, heart rate and in bivalves shell movement. Prior efforts had focused on collecting data from oysters or mussels fixed on a pedestal and the use of Hall effect sensors and magnetic distance between open or closed shell and the sensor to assess shell movement. We had proposed conducting a preliminary study in which we would attach backpack physiologic sensors that facilitated wireless data recovery. Funds were budgeted to purchase the backpack sensors from a research laboratory at the University of Iowa. We had intended to use the sensors to monitor shell gaping activity to assess periods when mussels were feeding. In addition, the sensors we had selected were to be capable of monitoring heart rate. In theory, individual animals in a population should be feeding asynchronously. If a noxious stressor is introduced into a system, we anticipated that they would stop feeding synchronously. In this manner, we hypothesized we could use the synchronous cessation of feeding as an indicator of stressors being released into the stream that are potentially a detriment to freshwater mussel health.

Although an initial prototype was provided the designer could not provide us with the sensors to conduct the studies. We had hoped to deploy sensors on the shells of muscles that provided a wireless means of data retrieval. The designer failed in efforts to develop a wireless sensor sufficiently robust to accommodate field deployment and wireless data recovery. Sensor size reduction limited battery-life. Consequently the majority of funds allocated for sensor purchase were not used and field -testing was not feasible. We however have continued to work on sensor development with a different designer. The notion of a completely wireless sensor pack has been abandoned until new long-life miniaturized batteries are developed that can provide continuous data collection without power interruption. As an alternative, we are now working with a new designer to produce a sensor that is tethered between a freshwater mussel and a solar power source. Unlike prior designs, as envisioned the new design will facilitate mussel movement in the substrate and solar sustained battery power.

Objective 4: Develop a dynamic model of upland soil erosion potential paired with tributary stream sediment transport and delivery to the Little River and Drowning Creek trunk channels, which can be used to predict the potential viability of stream sites for sustainable restoration;

Cobble and gravel provide more stable streambed substrate for mussel populations. Many of the streams on Fort Bragg are covered with fine grain sand that does not provide stable substrate for freshwater mussels. Freshwater mussel populations are dependent on the presence of fish that serve as hosts for larval freshwater mussels. Erosion and sedimentation also has a negative impact on fish reproduction and other stream invertebrates. Streams such as Tank Creek lack overall faunal diversity but a paucity of species does not necessarily imply that a specific stream or stream reach is a suitable site for stream restoration. Stream restoration is needed to establish viable habitat for freshwater mussels, other invertebrates and fish species. But stream site selection should take into account the potential for upland soil erosion and sedimentation that can diminish the value of an investment in stream restoration. Accordingly, we modeled stream sediment size and determined basin-wide average erosion rates from the accumulation of the terrestrial in-situ cosmogenic nuclide ^{10}Be in quartz to test and quantify the above observations.

Methods

Stream-wide distribution of sediment sizes –

Construction of stream sediment bedload samplers was completed by the NC State University College of Sciences Machine Shop in May, 2016. These samplers were deployed at locations along the Little River, upstream from Fort Bragg (Fig. 6; Table 7). We deployed sediment load samplers and pressure sensor loggers at 10 sites (Table 7). One sediment sampler and its attached stream level pressure sensor (Solinst levelogger) were lost during a high discharge event in early June, 2016. Stream channel geometry data was collected at each bed load sampling site. Bedload sediment transport measurements were conducted during the following days: May 10 – 15; May 19 – 21; and June 2 – 6 (Fig. 7). These collection periods corresponded with falling, rising, and peak hydrograph conditions, respectively (Fig.8).

Figure 6. *Bedload sediment sampler deployed in Little River, May 2016.*

Table 7. *Median (D_{50}) size of bedload samples at locations along the Little River between 54 and 95 km upstream from the Cape Fear River Confluence. Downstream of the LR-7 site, the median bedload size fraction is consistently < 2 mm (sand).*

Location ID	Latitude (°N)	Longitude (°W)	Distance upstream from Cape Fear River confluence (km)	Stream Substrate D_{50} Min (mm)	Stream Substrate D_{50} Max (mm)
LR-7	35.171433	79.116233	54.721	4	8
LR-8	35.172083	79.129083	56.6585	4	8
LR-6	35.172550	79.146983	59.8735	0	1
LR-5	35.172383	79.147533	59.923	2	4
LR-4	35.185100	79.167950	64.226	4	8
LR-2	35.203867	79.215417	72.8205	4	8
LR-3	35.185917	79.168367	64.278	4	8
NiagaraCarthrage-87	35.263560	79.358195	95.4645	8	16
NiagaraCarthrage-107	35.263454	79.358184	95.456	8	16
LR-1	35.262750	79.358050	95.352	8	16

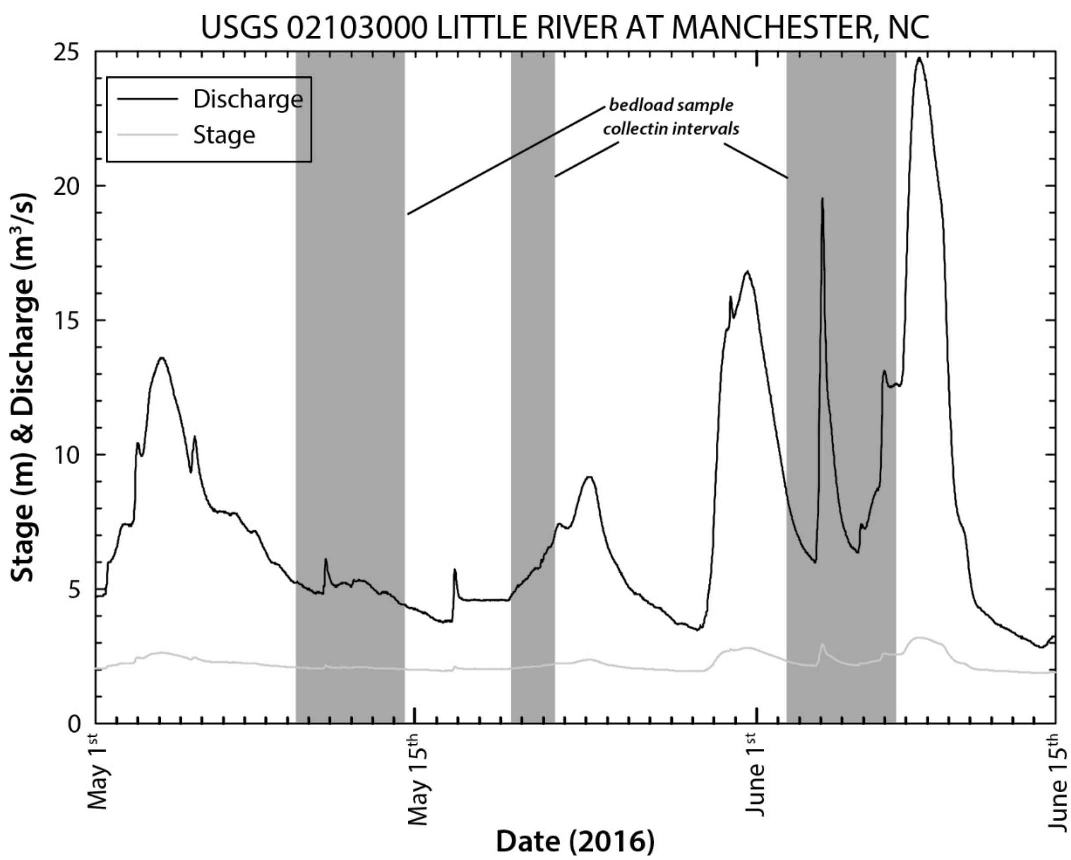

Figure 7. *Time span of bedload sediment samples collected from the Little River as a function stage and discharge measured at the USGS gage at Manchester, NC. Bedload sampling occurred during rising, falling, and peak flow conditions.*

Sediment collected in the traps was returned to the lab, dried, sieved by size class and weighed. The Baralogger on station at Fort Bragg measured ambient atmospheric pressure levels during the deployment of the bedload sediment samplers. The Baralogger was retrieved and the data downloaded. The regional atmospheric pressure measurements were used to correct for the stream stage (levelogger) measurements that were made at the time of the bedload sampling in order to improve the sediment transport modeling. The mass of bedload sediment collected in the traps was normalized by the stream discharge at each sampling site in order to derive a bedload flux rate as a function of stream discharge and position in the channel network. These were used to calibrate and improve our model for sediment transport and grain size distribution along the Little River as it relates to the current distribution of Unionids and for guiding future restoration opportunities.

Stream substrate sediment size distributions were modeled for the Little River, based upon fish habitat studies that proved successful in identifying stream reaches with sediment size within the range that salmonids require for redd (spawning nest) construction, and is similar to the range of bedload sizes observed in the Little River. By adopting the model to the Little River, as detailed in Lyons (2014), we were able to provide an independent means of evaluation for the suitability of substrate sediment size distributions to mussels (Fig. 8). Maps of expected sediment size based upon topography and sediment source were produced using well-established solutions to sediment transport equations (Lyons, 2014). The sediment distribution maps were compared to mussel surveys and can then be used as a tool to predict stream reaches where suitable habitat may exist. Evaluation of model output indicated that the method reasonably accurately predicted measured grainsize and mussel abundance and diversity at majority of reaches. We observed an overall increase in both the total number of mussels counted at a given survey reach as well as the count-per-unit-effort at sites increased substrate size (Fig. 9).

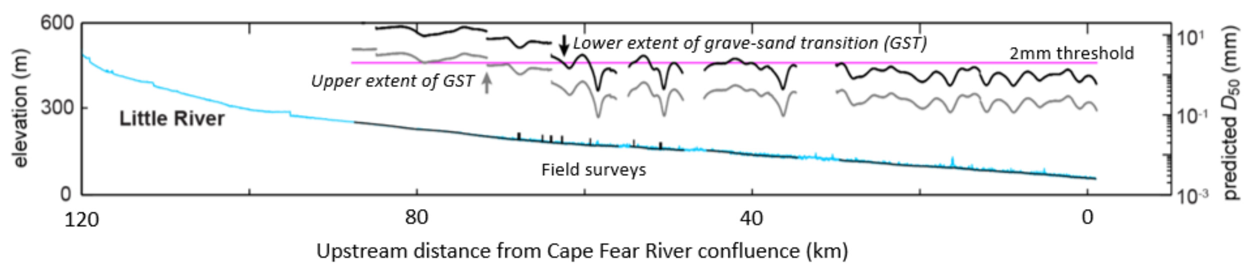

Figure 8. *Stream longitudinal profile and modeled (predicted) median grain size (D50) for the Little River. Smoothed longitudinal profile (black line) originated at the drainage area threshold of 200 km2 and is shown only where grain size was predicted. The non-smoothed portion of the profile (blue line) originate at a drainage area threshold of 10 km2 and are shown here only for reference. Both the upstream and downstream limits of D50 predictions (black and gray points) are shown. The location where the predicted D50 crosses the 2 mm threshold of sand was defined at the gravel-to-sand transition (GST; purple horizontal line). Locations of mussel surveys along the stream are indicated. Modified from Lyons (2014).*

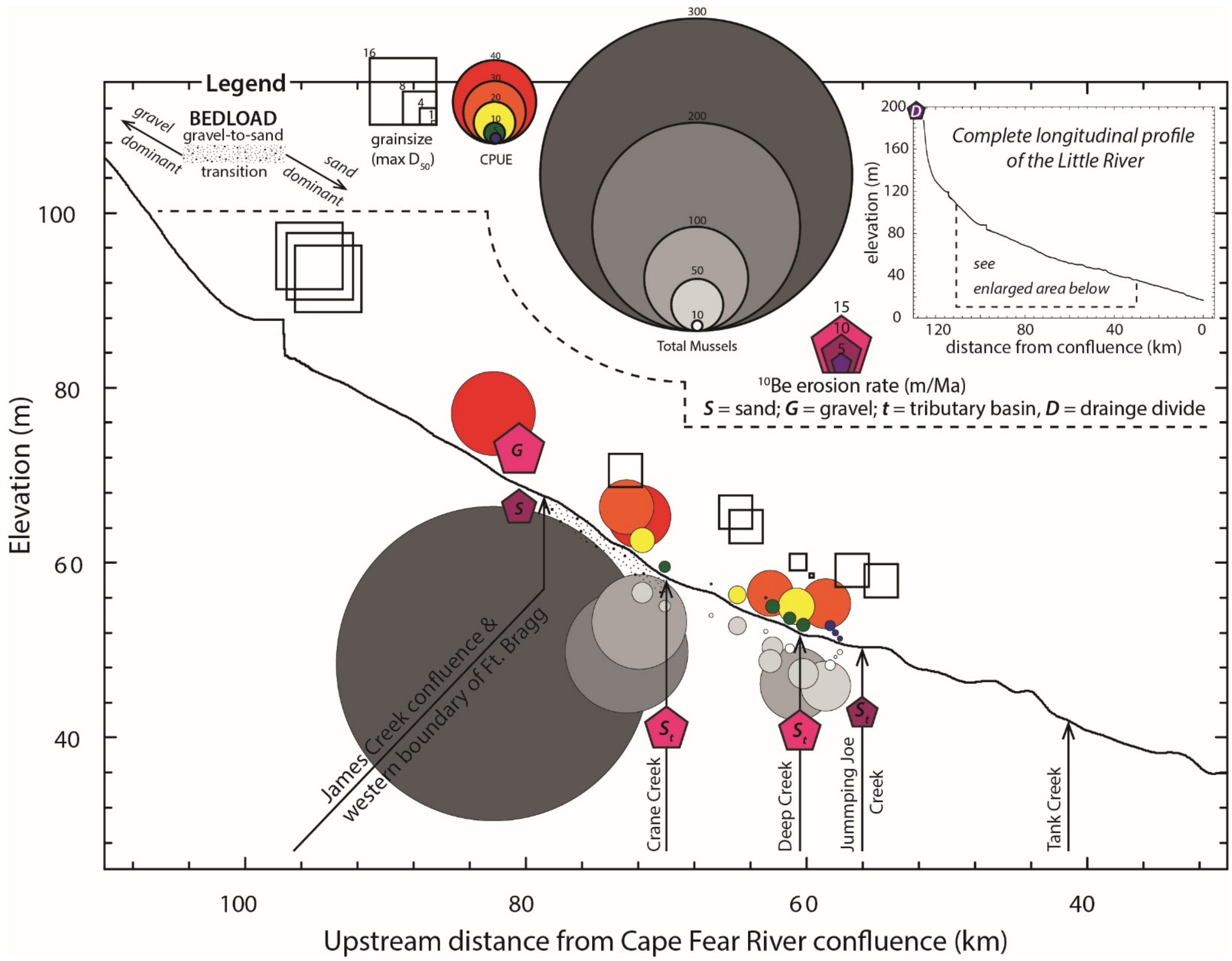

Figure 9. *Sediment grain size, mussel counts, and basin average erosion rates for the Fort Bragg section of the Little River. The complete longitudinal profile of the Little River is shown in the inset diagram, while the main image portrays an 80 km section of the stream from river km 30 to 110 (upstream from the Cape Fear River confluence). All of the shapes on the figure are scaled relative to their size, number, or rate. The maximum measured D50 bedload size fraction collected at 10 sampling sites (Table KW-X) are denoted by scaled-hollow squares. Note the observable bedload size increase upstream of the gravel-to-sand transition that occurs between where James and Crane Creek enter the Little River. The total number of mussels observed at each of 17 survey reaches are represented by gray circles situated beneath the longitudinal profile. Values for the catch-per-unit effort (CPUE) at each of the mussel survey sites are shown above the longitudinal profile as colored circles. Both the total number and CPUE values increase in an upstream direction. Beryllium-10 basin average erosion rates for sand (s), gravel (g) size fractions are plotted as color-coded pentagons. Tributary erosion rate values are denoted by a subscript "t".*

Basin-wide average erosion rates –

In our 2014 study we initiated a reconnaissance evaluation of the effectiveness of using in situ-produced cosmogenic ^{10}Be radionuclide dating to: 1) Estimate background (10^4 yrs) catchment-average erosion rates across the study area, and 2) test whether or not land use activities on the Post have altered upland sediment erosion and delivery to the channel network significantly enough to result in observable decreases in ^{10}Be inventories for streams draining the Post versus streams originating off-Post. In this study, we collected additional ^{10}Be samples and recalculated basin average erosion rate estimates, including those from the 2014 studies in order to better parameterize the two objectives of this research component.

The idea behind these analyses was that cosmic rays that reach the surface of the earth produce cosmogenic radionuclides (CRN) in minerals (Lal, 1991). The accumulation rate of CRN in rocks and soil is determined primarily by the latitude and elevation of the catchment, and there are a number of modeling schemes available to estimate the local nuclide production rate per gram of quartz at the Earth's surface (e.g., Gosse and Phillips, 2001; Balco et al., 2008; Dunai, 2010). Production of CRN occurs only within the upper few meters of the ground surface. In contrast, the concentration of ^{10}Be is homogenized in the upper ~1 m of Earth's surface as soil materials are mixed by physical and biological processes (Jungers et al. 2009). This makes erosion rate estimates insensitive to all but the most deeply penetrating forms of upland erosion and mass wasting (e.g., Niemi et al., 2005). Erosion strips off the upper soil and rock layer, which loads streams with minerals that are both high (sediment comprising the previously stable ground prior to rapid erosion – perhaps induced by intensive land use) and low (sediment or rock recently exposed to cosmogenic rays) in ^{10}Be concentration. Thus, in most instances, ^{10}Be measurements of modeled erosion rates derived from modern river sediments still record the isotopic signature of longer-term hillslope erosion (10^3–10^4 yr) and constitute a useful metric for comparison to human-induced rates of erosion (von Blanckenburg et al., 2006; Reusser et al., 2015).

Erosion rates were determined from in situ cosmogenic ^{10}Be measured in present-day river sediment samples (n = 5) and from the upland watershed divide of the Little River (n=1) to estimate spatially averaged, millennial-scale rates of sediment production and landscape erosion (e.g., Portenga and Bierman, 2011). Stream sediment samples were also collected from the Drowning Creek basin at Camp McCall; however unfortunately, the geochemists at PRIME lab were unable to isolate and concentrate ^{10}Be from these samples, therefore our results are for the Little River basin only. To our knowledge, these are the first basin-average cosmogenic erosion rate estimates for the upper Coastal Plain (Sandhills) physiographic province in North Carolina. Samples of active-channel sediment were collected from four sites in the study area (Fig. 10, Tables 8, 9).

The stream sediment was dried and sieved in the lab to the 250-500 μm size fractions and the minor non-quart fraction was reduced by passing the samples through a Frantz magnetic separator. Geographic statistics for the catchments upstream from each collection point were calculated in ArcGIS software (www.esri.com) using 20-foot (6.096 m) pixel resolution digital elevation models (downloaded from www.ncfloodmaps.com/lidar.htm) using the technique reported in Portenga and Bierman (2011). This determined the catchment weighted-average location (latitude, longitude) and elevation for production rate scaling estimates. Because basin slopes are gentle, and the elevation range is minimal, we did not apply a topographic shielding correction factor to the modeling of catchment-averaged isotope production rates. We assumed standard density of quartz (2.65 g/cm^3) in the isotope production rate calculations.

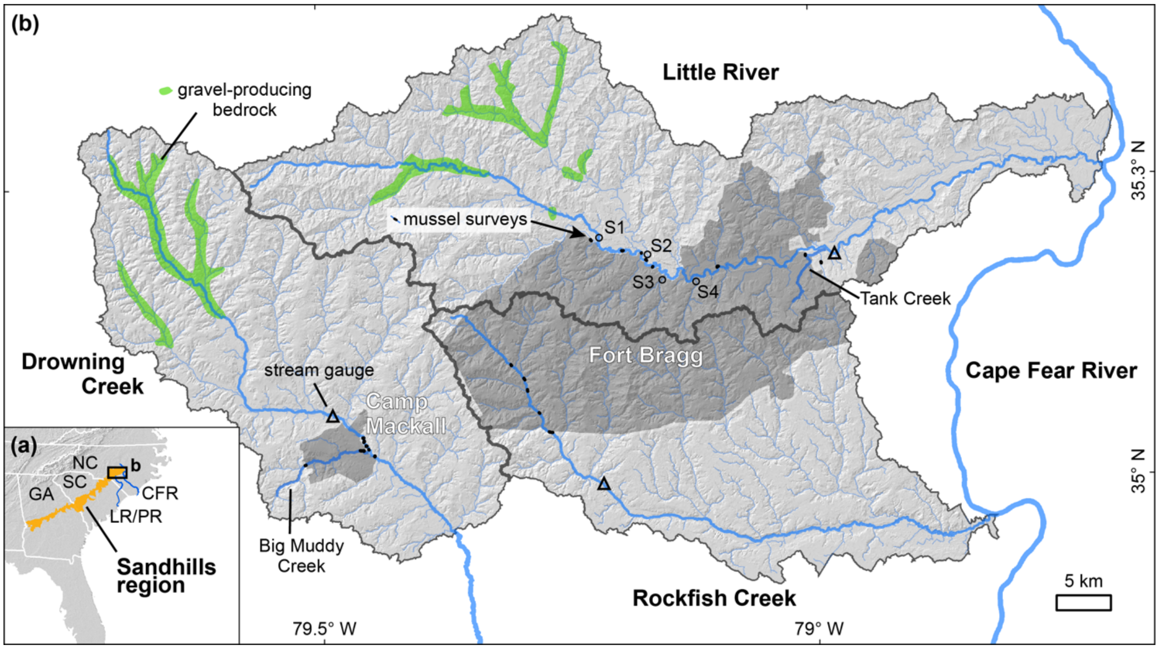

Figure 10. *Bedrock and stream map of Fort Bragg area.* ***(a)*** *The Sandhills region spans the states of North Carolina (NC), South Carolina (SC) and Georgia (GA) and represents the upper in conjunction with mussel surveys; two from the main stem of the Little River, and one each from the tributary mouths of Crane, Deep, and Jumping Run Creeks. In theory, sediment collected at Sites 1 – 4 should be a well-mixed representation of sediment erosion within the entire catchment area upstream of the collection site. Areas of faster erosion contribute proportionally more grains of quartz with lower concentrations of ^{10}Be. Areas of slower erosion contribute fewer grains of quartz that has higher concentrations of ^{10}Be.*

The sieved and magnetically-separated quartz-sand samples were sent to the Purdue University Rare Isotope Measurement (PRIME) Laboratory for quartz purification and ^{10}Be extraction using selective acid etching (Kohl and Nishiizumi, 1992) and HF dissolution and ion exchange chromatography (Corbett et al. 2011). Isotopic measurements were made on the PRIME Lab accelerator mass spectrometer (Table 8). Errors in nuclide concentrations included only 1□ ratio measurement uncertainties. Measured ratios of ^{10}Be/^{9}Be were normalized to the 07KNSTD3110 standard (Nishiizumi et al., 2007) with an assumed ratio of 2850 x 10^{-15} and corrected using process blanks Cblk-03232-1 (FB-14 samples) and CBlk-4135-1 (FB-16 samples). ^{10}Be erosion rates were estimated with the CRONUS online calculator (http://hess.es.washington.edu, version 2.3) using the constant production rate model of Lal (1991) and Stone (2000). ^{10}Be production (per gram SiO_2 per year) and modeled catchment average erosion rates (in m/My and mm/yr) are presented in Tables 8 and 9.

Table 8. *Summary data for in-situ ^{10}Be catchment-average erosion rate samples.*

Sample	grain size	Latitude (°N)	Longitude (°W)	Upstream drainage area (km^2)	Catchment Weighted Average Soil Bulk Density (g/cm^3)	Mean catchment slope (°)	Erosion rate (m/My)	Erosion rate (mm/y)
FB-14-**S1**	sand	35.2039	79.2157	289.4	2.65	3.5	8.4 ± 0.7	0.0084 ± 0.0007
FB-14-**S2**	sand	35.1859	79.1684	258.8	2.65	3.3	10.7 ± 0.9	0.0107 ± 0.0009
FB-14-**S3**	sand	35.1713	79.1492	20.2	2.65	3.3	10.4 ± 0.9	0.0104 ± 0.0009
FB-16-**S3**	gravel	35.2039	79.2157	289.4	2.65	3.5	12.6 ± 1.1	0.0126 ± 0.0011
FB-14-**S4**	sand	35.167	79.1183	13.1	2.65	3.5	7.7 ± 0.6	0.0077 ± 0.0006
FB-16-**07**	sand	35.2255	79.5435	0	2.65	0.5	4.2 ± 0.4	0.0042 ± 0.0004

Table 9. *Detailed data for in-situ 10Be catchment-average erosion rate samples collected from the Little River, tributaries, and drainage divide. AMS determinations were completed at the Purdue Rare Isotope Measurement Laboratory (http://science.purdue.edu/primelab/) and production rate and basin average denudation (erosion) rate estimates were modeled with the Cronus on-line calculator v. 2.3 (http://hess.ees.washington.edu/).*

Field ID	PRIME Lab ID	Sample Site					Quartz mass
		Mean Basin Elevation (m)	Latitude (°N)	Longitude (°W)	Basin Area (km^2)	Description	(g)
FB-14-S1	201402229	122	35.20388	79.215706	289.4	Sand from Little River	53.990
FB-14-S2	201402230	110	35.18592	79.2564	258.8	Sand from Crane Creek, 50 m upstream of Little River confluence	30.083
FB-14-S3	201402231	95	35.17134	79.149248	20.2	Sand from Deep Creek, 225 m upstream of Little River confluence	54.495
FB-14-S4	201402232	96	35.16698	79.118333	13.1	Sand from Jumping Run Creek, 550 m upstream of Little River confluence	49.017
Cblk-3232-1	201402233	na	na	na	na	2014 Prime Lab blank	na
FB-16-03	201601920	122	35.20388	79.215706	289.4	Gravel from Little River; same locaiton as FB-14-S1 sand sample	18.42
FB-16-07	201601924	172	35.2255	79.5435	0	sand from soil pit excavated at 22 cm below ground surface along catchment divide	46.553
Cblk-4135-1	201601922	na	na	na	na	2016 Prime Lab blank	na

Table 9. Continued.

Field ID	PRIME Lab ID	Carrier			AMS					
		^{9}Be Carrier (mg)	Atoms ^{10}Be per mg of ^{9}Be Carrier	Std Dev	^{10}Be Ratio ($x10^{-15}$)	^{10}Be Std Dev ($x10^{-15}$)	Total ^{10}Be Atoms	Std Dev	Carrier-Corrected Total ^{10}Be Atoms	Carrier-Corrected Std Dev
FB-14-S1	201402229	0.2573	223075	49966	983.24	18.46	16907577	317350	16850179	317610
FB-14-S2	201402230	0.2591	223075	49966	445.09	10.35	7707125	179277	7649326	179744
FB-14-S3	201402231	0.2578	223075	49966	820.93	19.03	14143979	327934	14086470	328186
FB-14-S4	201402232	0.2592	223075	49966	963.35	21.29	16687810	368725	16629989	368953
Cblk-3232-1	201402233	0.2577	223075	49966	3.338	0.748	na	na	na	na
FB-16-03	201601920	0.2605	55713	51694	233.309	7.55994	4061826	131616	4047312	132303
FB-16-07	201601924	0.2574	55713	51694	1452.61	34.2748	24988467	589611	24974127	589761
Cblk-4135-1	201601922	0.2572	55713	51694	0.833625	0.7735	na	na	na	na

Results and Discussion

Stream-wide distribution of sediment sizes

The model sufficiently predicted grain size in sand and gravel fractions (Fig. 8). Under-predicted samples were collected immediately downstream of a reach of Little River that was partially rerouted around a breached dam. This indicates that this reach is expected to have finer sediment given the slope of the river, although channel changes due to the dam led to localized coarser streambed sediment size. This also demonstrated that the accuracy of the model was sensitive to stream reaches with altered channel gradients. The transition from gravel-to-sand sized sediment is located between James and Crane Creek both in the model as well as in the reduction of substrate D50 values between river km 100 and 70 (Fig. KW-4). The reduction in grain size is consistent with the concept of down-stream fining as well as the observation that lithologies capable of producing gravel-sized clasts exist exclusively upstream of Fort Bragg (Figs. 1, 10). Tributaries entering the Little River from Fort Bragg transport only sand and finer grain sizes

Basin-wide erosion rates –

Intensive land use practices that have reduced vegetative cover and concentrated water flow have increased the potential for stream incision and mobilization of sediment across the Coastal Plain and Piedmont Physiographic provinces of North Carolina (e.g.

Trimble, 1974; Phillips, 1993) and on Fort Bragg (e.g., Fogleman, 2009; Tateosian et al., 2010). Since mobilization of sand into tributaries can blanket gravel substrate in rivers downstream, the amount of available mussel habitat has apparently decreased where intensive land uses have increased surface erosion and sediment transport across Fort Bragg. Our initial hypothesis for the ^{10}Be analysis was that sediment collected at points along the rivers will exhibit a decrease in ^{10}Be concentration in the downstream direction, indicating that erosion and sediment influx rate into rivers is increasing as tributaries deliver increased loads of sandy sediment derived from zones of upland erosion that exceed the depth of ^{10}Be production (~2.5 to 3 m).

The concentration of ^{10}Be in stream sands and gravels collected from the Little River and from the lower reaches of Crane, Deep, and Jumping Run Creeks ranged from 2.54 to 3.39 x 10^5 atoms ^{10}Be g^{-1} SiO_2 (Table 9). The concentration of ^{10}Be from the drainage divide sample (FB-16-07) was 5.36 x 10^5 g^{-1} SiO_2 yr^{-1}, or about two times greater than the stream transported sediments (Table 9). The modeled basin-average production of ^{10}Be (spallation + muon capture) varied between 3.82 and 4.09 atoms g^{-1} SiO_2 yr^{-1} (Table9). Calculated background erosion rates from the four catchments (S1-S4) ranged between 7.7 to 10.7 m/My for sand-sized samples and 12.6 m/My for the gravel fraction, as collected from the Little River at site S1 (Fig.11). The sample collected from the low-relief drainage divide of the Little River (FB-16-07) provides an approximate estimate of the rate of upland soil production and landscape lowering of 4.2 ± 0.4 m/My (Table 8) that is consistent with the rate of upland lowering also determined from ^{10}Be accumulation in quartz of ~ 4.5 m /My as determined for a site in the Piedmont of Virginia (Pavic et al., 1985). The basin-average stream erosion rates suggest that the Little River and its tributaries have been eroding at about 2 to 3 times (8 to 12 m/My) the rate of upland landscape lowering, at least for the last tens of thousands of years. If true, this suggests that relief during the late Quaternary is very slowly increasing in the Little River catchment. These rates can be used to set the bounds for more site-specific upland erosion modeling such that the minimum background (geologic) rate of basin-average erosion could be set to about 4 m/My (0.004 mm/yr), and probably should not exceed 15 m/my (0.015 mm/yr).

As a test of the impact of grainsize on derived basin-average erosion rates, we collected a gravel sample (FB-16-S3) at the same location where we had previously determined the ^{10}Be concentration from the sand-sized bedload fraction of the Little River (FB-14-S1) (Fig. 11, Tables 8, 9). The basin average erosion rate derived from the gravel sample is 50% greater than that derived from sand. While both are very slow rates (8.4 and 12.6 m/My), the increase observed in the gravel fraction may reflect increasing basin relief, as discussed above, and, or the landscape position of the geologic units capable of delivering gravel-sized clasts to the Little River and its tributaries (Fig. 10). Because the geologic units capable of delivering gravel to the stream are all located in the valley bottoms, the transport time (and thus potential exposure to cosmic rays) needed for gravel clasts to become bedload in the stream may be less, on average, than for sand-sized particles, some of which will be derived from geologic units located at a greater distance from the stream network (e.g. interfluves and drainage divides).

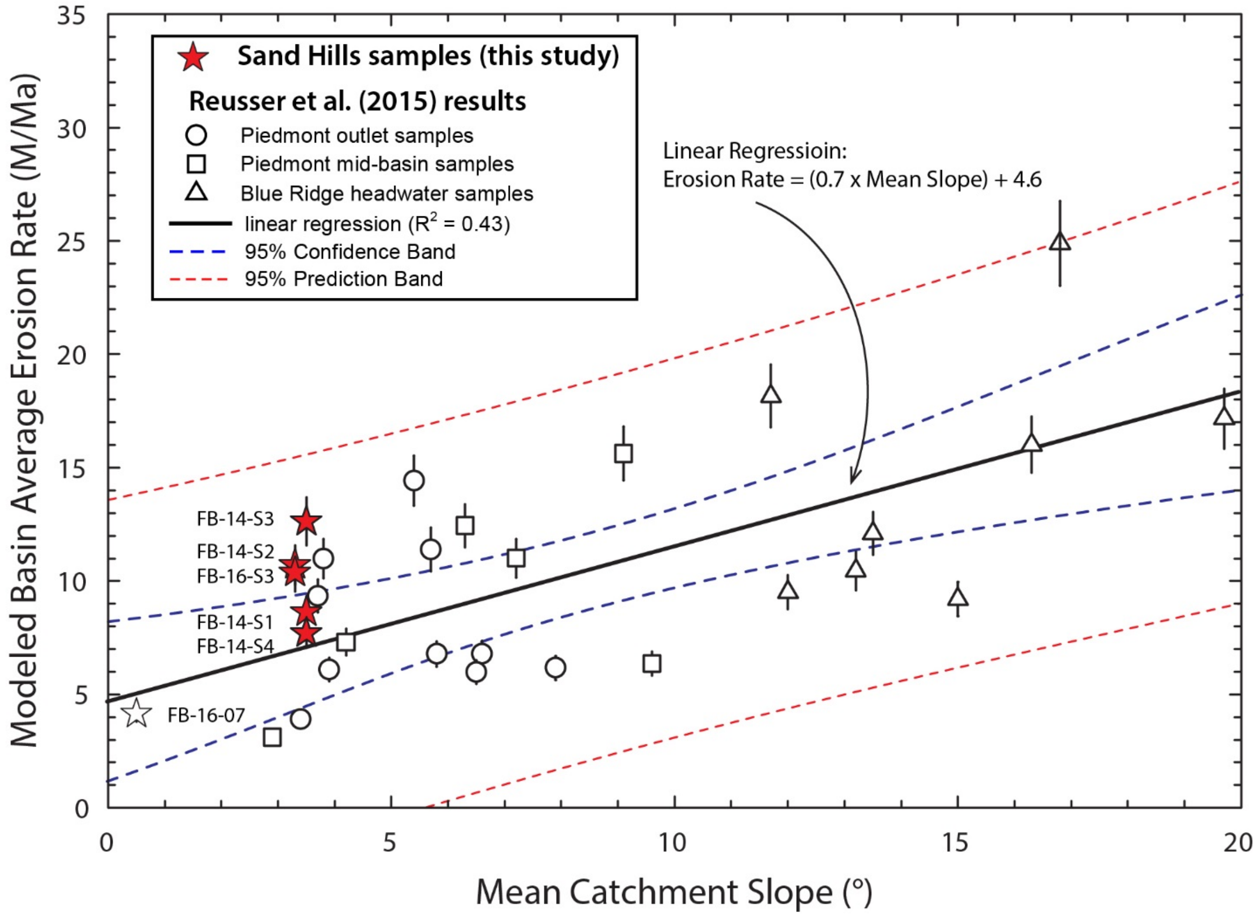

Figure 11. *Catchment average ^{10}Be erosion rate plotted versus mean catchment slope for the four selected sub-basins (red stars) and from the watershed divide (white star) compared to similar results from large rivers draining the Piedmont from Georgia to Virginia as reported by Reusser et al. (2015). The vertical bars are 1-sigma errors. The results from this study fall within the predicted range (2-sigma) for basin average erosion rate as function of mean catchment slope, as is often observed for mid-latitude drainage basins (e.g., Ahnert, 1970).*

Neither basin size nor mean slope were predictable determinants of the basin-average erosion rates. For example, the largest and smallest basins (Little River and Jumping Run Creek, respectively) have the two slowest calculated average rates (Table 8; Fig. 11). Similarly, Deep and Jumping Run Creeks (basins S3 and S4), the two tributaries draining to the Little River from Fort Bragg did not result in faster background erosion rates as originally hypothesized when compared to portions of the Little River basin draining lands to the north (S2) and west (S1) of Fort Bragg. Therefore, the amount of anthropogenic erosion, as it affects catchment average ^{10}Be erosion rates from Fort Bragg have been no more severe than in the rest of the Little River catchment draining areas off Post.

A 2015 study by Reusser and colleagues reported the catchment-averaged erosion rates for 24 ^{10}Be samples of modern stream sediment collected in large Piedmont basins (Fig. 11). Predictably, their results suggested that millennial-scale erosion rates decrease from the steeper headwater basins draining eastward off the Blue Ridge Escarpment (mean = 14.7 ± 1.1 m/My) to the basin outlets where the rivers transition from the Piedmont across the Fall Zone to the Coastal Plain (mean = 8.2 ± 0.7 m/My). The mean catchment-averaged erosion rate for the sand-sized samples from basins in our study (9.3 ± 1.3 m/My) is the same within uncertainty to the lower Piedmont basin erosion rates calculated by Reusser et al. (2015). Using our data combined with that of Reusser et al. (2015), we estimate that the basin average erosion rate can be approximated as 0.7 times the mean catchment slope with a y-intercept of 4.6 (Fig. 11). This relationship has an r^2 value of 0.43, and can be applied as an initial quick and inexpensive means to estimate the background rate of erosion for drainage basins spanning the Piedmont and Sand Hills physiographic provinces.

Background erosion rates, determined through the measurement of in situ-produced ^{10}Be, provide the context from which to assess nearly all other measures of erosion germane to a human time scale. They hold the potential to inform a variety of landscape management strategies. For example, such isotopic estimates could serve as benchmarks to determine whether rates of soil loss are sustainable (Montgomery, 2007). They could also be used to establish sediment Total Maximum Daily Load (TMDL) strategies for rivers that are consistent with the natural rates of sediment supply prior to the period of more intensive land use modification (e.g., Reusser et al., 2015).

Objective 5: Estimating upland soil erosion potential and relationship with freshwater mussels counts.

In North Carolina, habitat degradation and loss through expansion of urban landscapes and poor historical land use practices have likely contributed the most to their decline. Erosion, sedimentation and destabilization of stream channels are among the greatest threats to these animals because they are heavily reliant on stable substrates (Strayer 1999, Johnson and Brown 2000).

Relationship between Mussel counts, erosion rates, and bedload sediment distribution

Results and Discussion

Reach-scale surveys of endemic freshwater mussels in the Little River demonstrate an overall increase in both the total number of individuals observed as well as the count-per-unit-effort (CPUE) (Fig. 9). Higher total mussel counts and CPUEs were found upstream of the Crane Creek confluence, above Fort Bragg, beginning essentially with the location of the gravel-to-sand bedload transition (Figs. 8, 9). The greatest total number of mussels counted, and the location requiring the least cumulative effort occurred at the survey site upstream of James Creek, coinciding approximately with the upstream end of the gravel-to-sand transition. Between the Crane Creek junction and river km 95, the stream bed substrate becomes predominately gravel as the D_{50max} increases from 8 to 16 mm, well into the gravel size fraction. When the channel gradient of each survey reach is plotted against the cumulative mussel CPUE, a positive trend is observed above a threshold slope of ~ 0.03 (Fig. 12), correspond with streambeds either within the gravel-to-sand transition or dominated by gravel-sized bedload, which apparently are “preferred” by mussels. The apparent breakdown at lower channel gradients in the slope-to-CPUE relationship could indicate that sediment size, and by inference streambed stability, is less of a habitat controlling factor. When slopes are above ~ 0.04, streambeds consisting of gravel are generally stable enough for mussels, and this component of their environmental needs only gets better moving upstream.

Below this threshold, some stream segments are still steeper and more gravelly than adjacent ones, but other habitat factors (e.g. food availability, pH, etc.) are a stronger control by proportion at the stream-reach scale that is greater (longer) than we choose to measure the reach gradients. Another way to interpret the data presented on Figures 9 and 12 is that mussels are denser per unit area within and upstream from the gravel-to-sand transition because substrate size along this portion of the Little River is not another limiting factor in their sustainability. In contrast mussels living in reaches below the gravel-to-sand transition have to deal with more unstable stream beds in addition to other limiting environmental factors. Downstream of the gravel-to-sand transition, mussels may be more sensitive to water quality and food quality and availability issues because streambed stability is already a challenging variable. Downstream of the gravel-to-sand transition, substrate augmentation (e.g. addition of gravel to the active channel) is unlikely to be a successful strategy for improvement in mussel habitat characteristics, as the gravel will be volumetrically overwhelmed by the more mobile sand fraction; however, large-scale environmental mitigation efforts on the Post that improve stream water quality parameters may increase the resiliency of endemic mussel populations within the Little River.

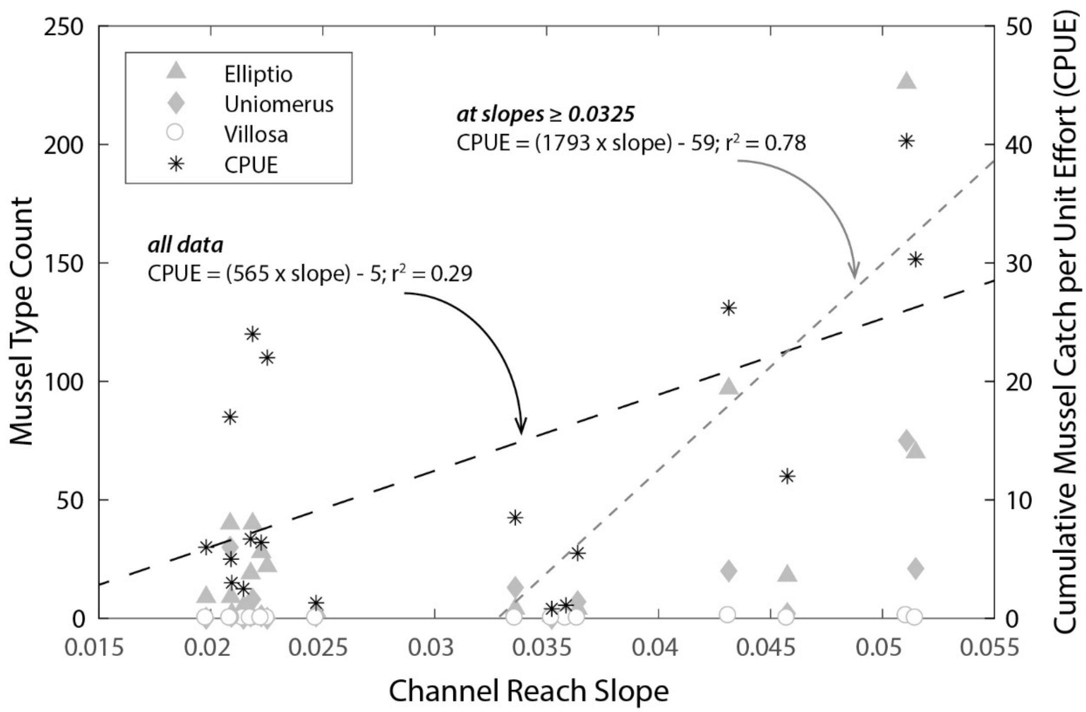

Figure 12. *Plot of Channel Reach Slope for the Little River versus counts of mussels by genus as well as cumulative mussel count per unit effort (CPUE) expended by the survey team. There is a general increase in CPUE in relation to channel reach slope (r^2 = 0.3) for the entire data set that becomes stronger (r^2 = 0.78) for channel reach gradients > 0.0325.*
with the strongest relationship observed for channel reach slopes above 0.05. The sections of the channel with slopes > 0.0325

6) Develop a demonstration of a Tangible Landscape system as a collaborative environment for communication of spatial patterns and sediment transport.

Conduct reach-scale sediment transport modeling to predict which reaches will be best suited to gravel and cobble substrate augmentation for mussel enhancement efforts (see item 5 above). Incorporate the newest soil erosion models with high-resolution lidar topographic datasets. Land use classification maps should be created to predict areas of enhanced soil erosion within Fort Bragg and surrounding areas that might negatively impact mussel populations should the eroded sediment enter the channel network. Incorporate catchment average ^{10}Be erosion rate estimates into upland erosion modeling and seek to identify if the high rates of erosion identified for the Sandhills region, including Fort Bragg, is due to natural or anthropogenically-enhanced factors.

Background

To create resilient mussel habitats the sediment sources and sinks and spatial pattern of sediment transport need to be analyzed. Identification of stream reaches suitable for mussel habitat restoration requires understanding of sediment delivery from contributing areas to the stream. The amount of sediment carried to the stream is function of a complex relationship between the rainfall intensity, surface runoff, soil properties, land cover and topography and is often difficult to estimate accurately. GIS-based modeling methods (Warren et al. 2005, Mitasova et al. 2005) were proposed to map the spatial distribution of soil erosion and deposition and sediment transport from the contributing areas across the installation.

Methods

Geospatial data were acquired from public repositories and the Fort Bragg base GIS, and further processed to provide inputs for estimation of spatial pattern of upland erosion. Erosion, sediment transport and deposition modeling was performed for the entire installation at 9 m resolution using the digital elevation models (DEM) and land cover map layers derived from lidar and spatially aggregated soil and rainfall factors. Surface runoff pattern, sediment transport and erosion/deposition were then modeled at 1m resolution for selected areas, identified in the installation-wide result as potentially high sediment sources.

Processing point cloud lidar data – Point cloud data and DEM from two lidar surveys were processed to provide two snapshots of bare ground elevation surface for the years 2012 and 2015. The installation wide DEM for the year 2012 (Figure 13) was re-interpolated at 9 m resolution to provide input for watershed boundaries and stream network extraction and to derive basic topographic inputs for erosion modeling. In addition to installation-wide DEM, point cloud lidar data for both 2012 and 2015 were interpolated at 1m resolution to support modeling in selected test areas at the Sicily drop zone, Patterson Branch Creek, and Tank Creek. The high resolution DEMs were needed to capture the impact of erosion control measures such as berms and to provide adequate representation of gullies. The interpolation was performed by the RST spline function (Mitasova et al., 2005) to smooth-out the noise typical for lidar data while preserving surface geometry important for erosion/deposition modeling. The two high-resolution DEM snapshots were also used to evaluate the potential for using these data to quantify and map short term erosion/deposition rates by differencing these DEMs and to create 3D physical model for Tangible Landscape system. Classified point cloud lidar data were used to derive an updated land cover map layer (Figure 14) by binning the classified points into bare ground, above ground vegetation, buildings and surface water raster representation.

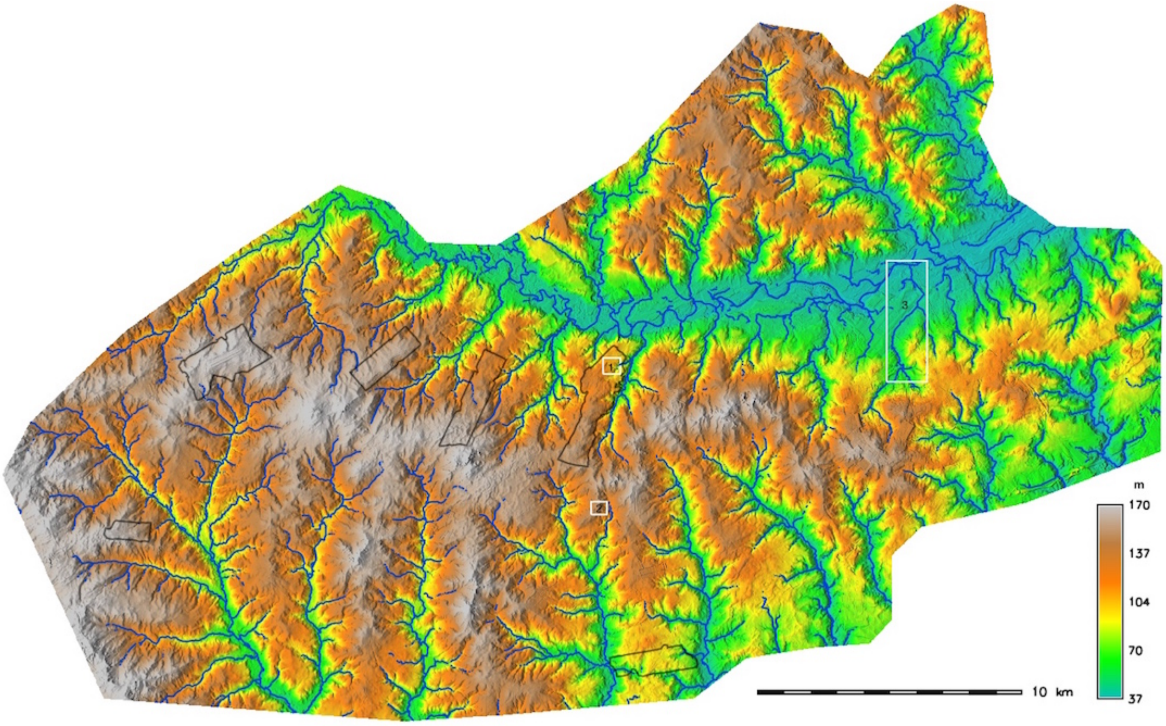

Figure 13 *Digital elevation model of the installation with streams (blue), drop zones (black) and study sites at (1) the Sicily drop zone, (2) Patterson creek target area, (3) Tank creek.*

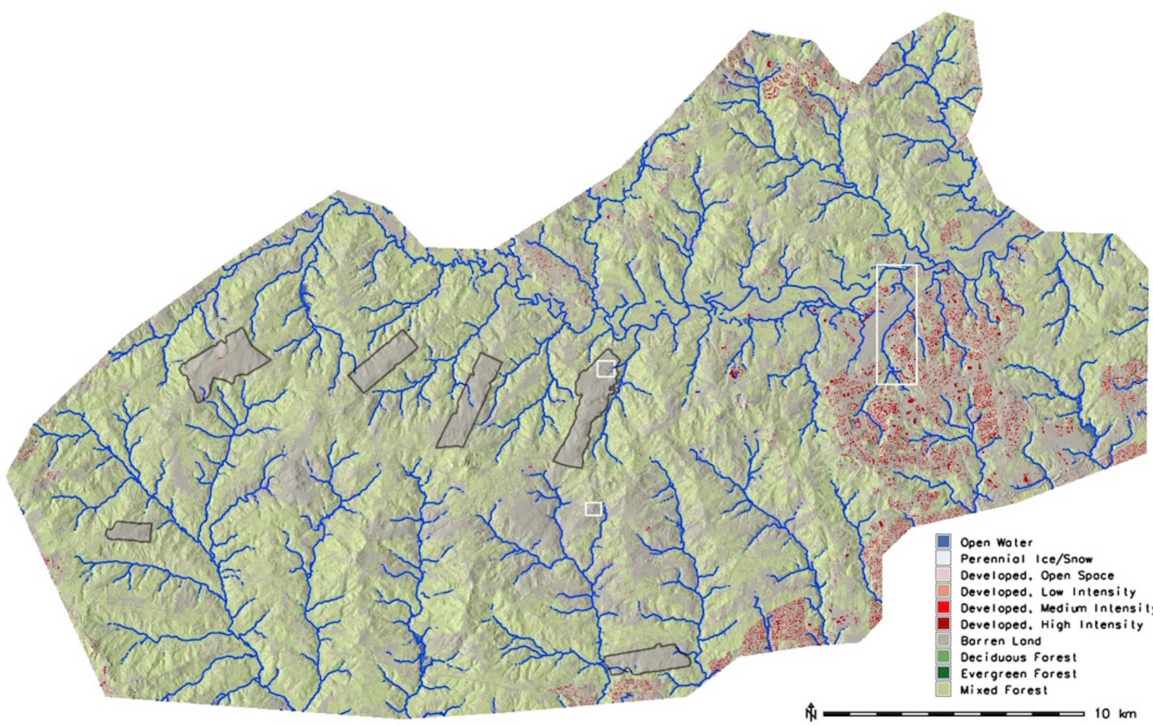

Figure 14. *Land cover map layer derived from the classified lidar data.*

Modeling spatial distribution of erosion, sediment transport and deposition – Spatial distribution of sediment sources, sediment transport and deposition was analyzed at the installation and site scales by GIS-based modeling techniques. The mathematical and physical foundations of the models can be found in Mitasova et al. (2013). Generalized, 3D modification of Universal Soil Loss Equation (USLE) was used to estimate spatial distribution of detachment capacity limited erosion rates and the USLE-based erosion-deposition model was applied to estimate net erosion / deposition potential for the entire installation. Both models incorporate the effects of complex topography and spatial variability in land cover, with the generalized USLE providing detachment limited soil loss estimates while the erosion-deposition model represents transport capacity limited, net erosion and deposition rates. More detailed, process-based modeling of surface water flow and sediment transport was then performed for the selected sites using path sampling method applied at high resolution of 1m to capture the effects of topography-based sediment control measures, such as contour berms on the distribution of surface runoff and sediment transport.

Results and Discussion

Watershed boundaries and stream network derived from the DEM highlight the topographic position of drop zones along ridges defining the watershed divides (Figure 15). Watersheds directly impacted by drop zones were identified along with the reaches of streams that may be influenced by increased runoff from these areas. Similar polygon overlay can be used to identify watersheds and streams impacted by target areas.

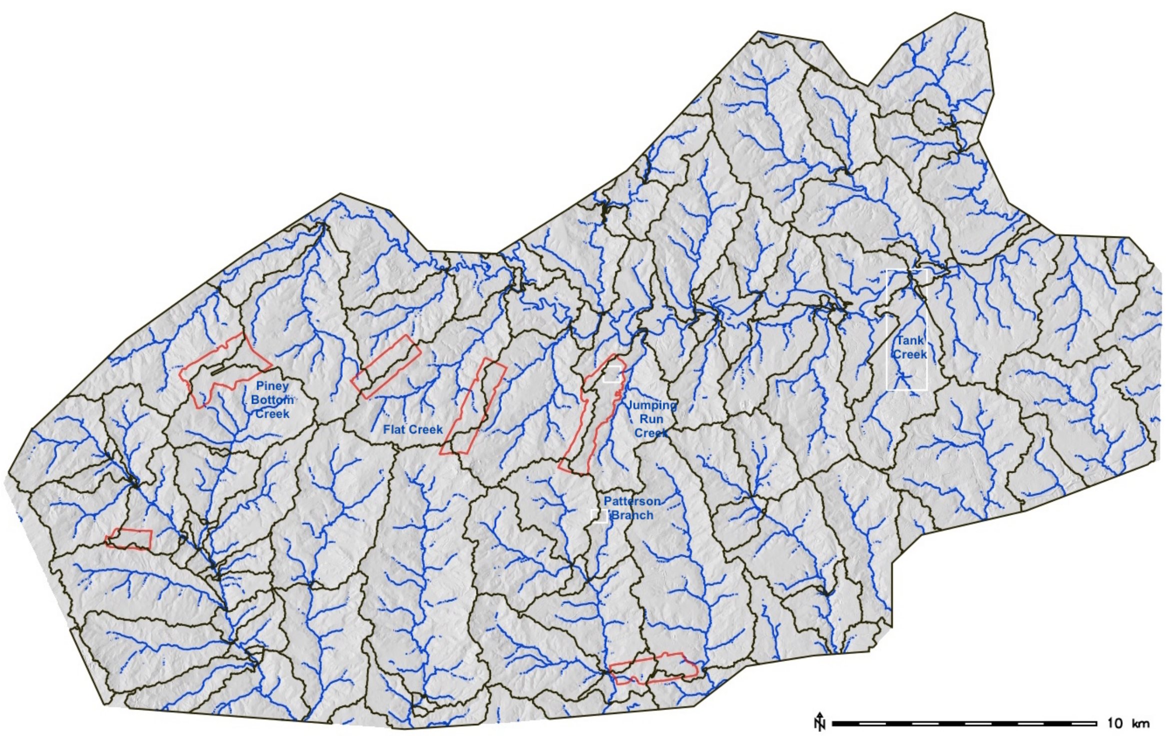

Figure 15. *Watershed boundaries (black) derived from the DEM, streams (blue), drop zones (red) and overland erosion study sites (white). The drop zones are located on the watershed divides, splitting the impacts towards two adjacent streams.*

Erosion potential at installation-wide scale – Preliminary results based on the generalized USLE model indicate significant soil detachment potential across the installation, mostly driven by reduced vegetation in landing zones and target areas. These preliminary results indicate that although 65% area is relatively stable, almost 30% of the installation area can become sediment sources (Table 10, Figure 16) without effective conservation measures. However, impact of these sediment sources on streams is limited by the currently installed sediment control measures, natural and anthropogenic terrain configuration, and vegetation.

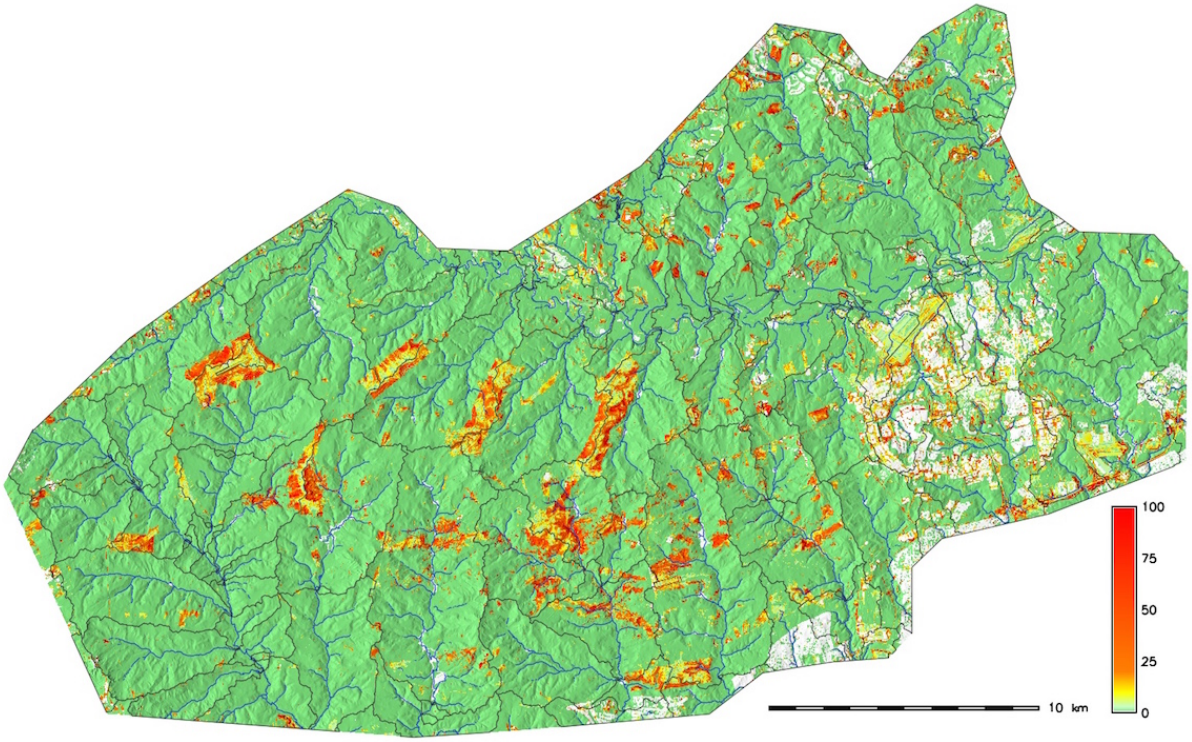

Figure 16. *Spatial pattern of detachment limited erosion rates with highest rates in drop zones and target areas with limited vegetation. The estimates are approximate, based on limited input data.*

Table 10. *Spatial extent of areas with detachment limited erosion rates classes*

Category Information	Land Cover	
Description	(%)	(hectares)
stable	64.8	47,909
low	4.5	3,314
moderate	20.0	14,854
high	8.8	6,515
extreme	1.9	1,415

The preliminary results from the erosion-deposition model indicate relatively balanced erosion and deposition rates, therefore, most of the detached sediment can be deposited within the watersheds, relatively close to the source. (This also means that most of the sediment in streams would be from the stream banks, mostly caused by storm water runoff and high water flow rates during major storm events). The area with the largest spatial extent of both erosion and deposition (Table 11), including gullies is the target area in the Black creek and Patterson branch watershed (Figures 17, 18) and in the landing zones. In spite of relatively low resolution (9m), the model successfully predicted erosion/deposition pattern of the sediment control berms around landing zones which appear to be effective in capturing some of the eroded soil. However, concentrated flow erosion and gully formation may be still problem in these areas during extreme events and, as shown in the next chapter, Tangible Landscape system can be used to test different configuration of berms, check dams or ponds to address this issue.

Table 11. *Spatial extent of erosion and deposition rates classes*

Category Information	Land Cover	
Description	(%)	(hectares)
high erosion	2.5	1,707
moderate erosion	1.9	1,268
low erosion	12.5	8,565
stable	73.1	49,997
low deposition	7.2	4,950
moderate deposition	0.9	620
high deposition	1.9	1,317

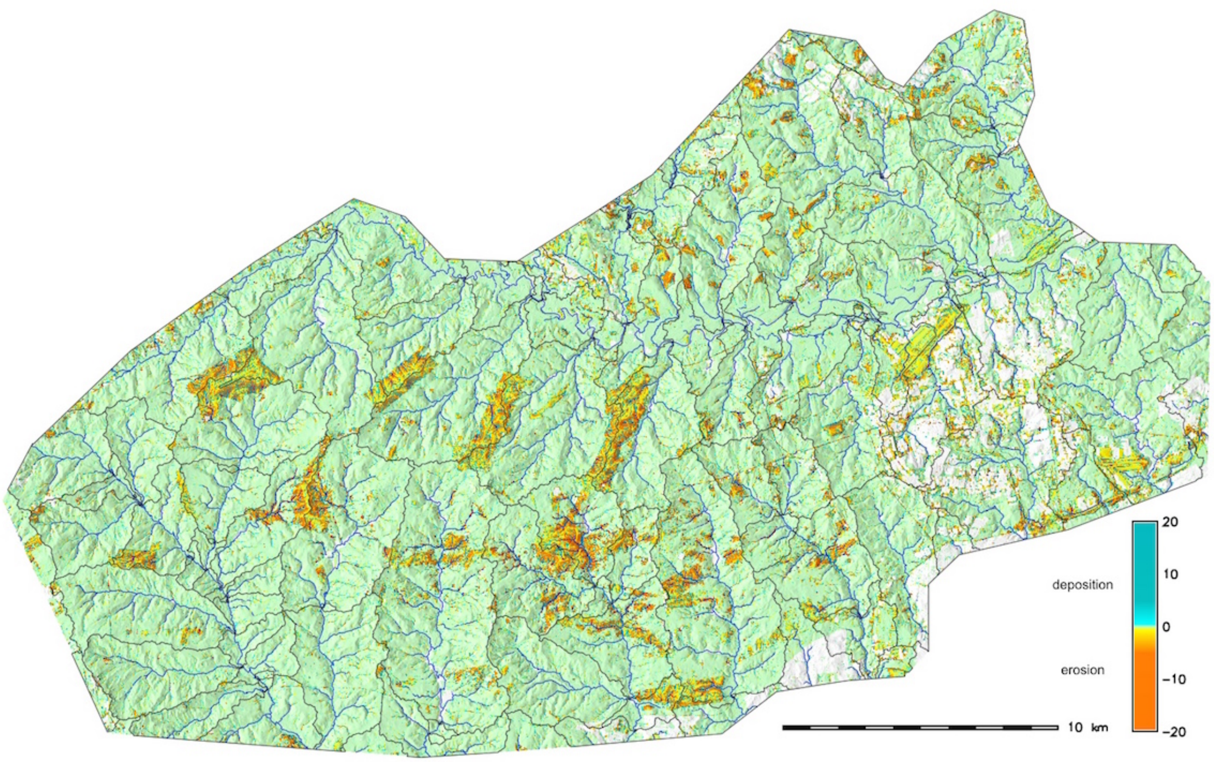

Figure 17. *Spatial pattern of erosion and deposition with both high erosion and deposition modeled in the areas with limited vegetation. The values represent a relative index estimated with limited input data.*

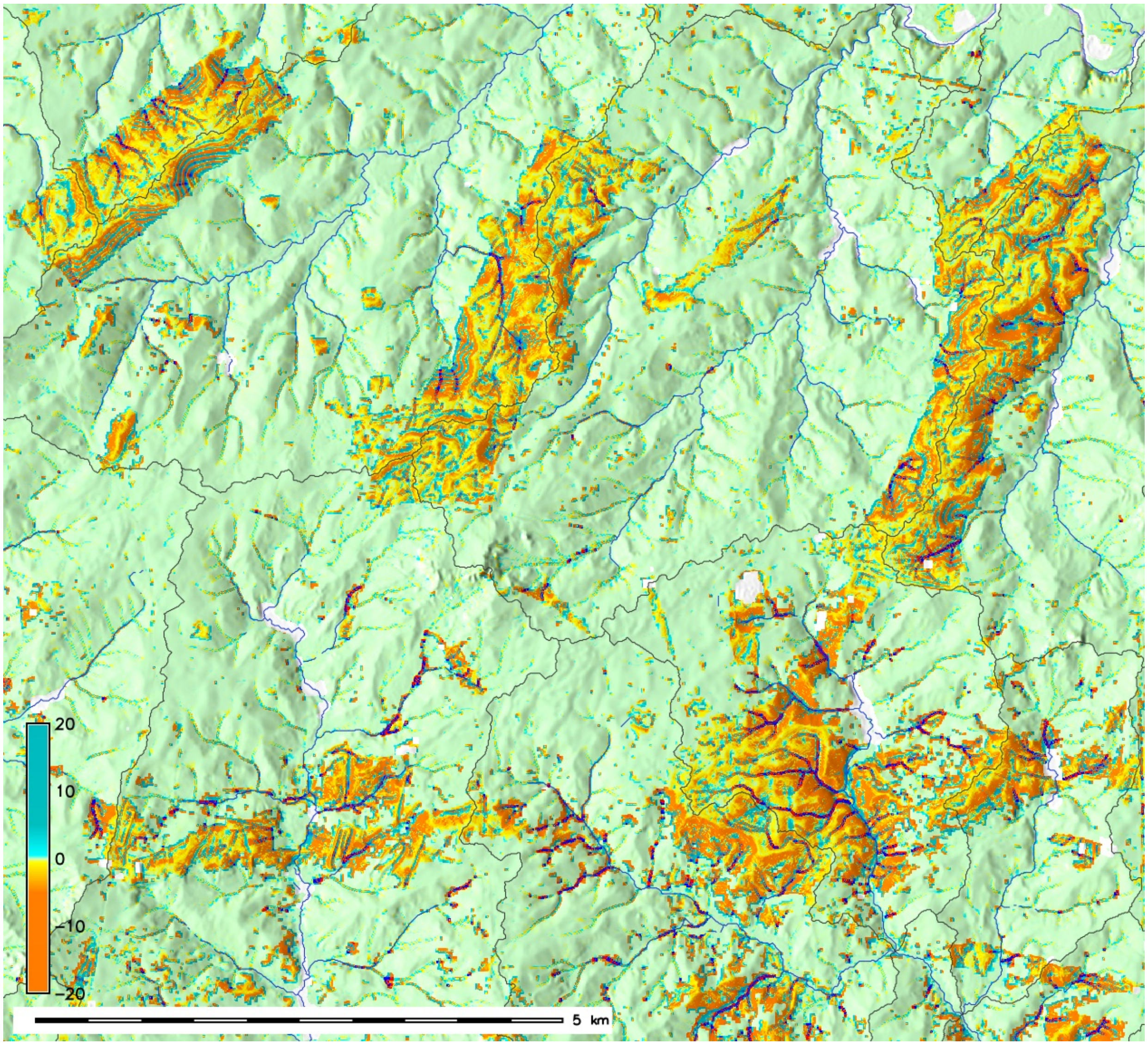

Figure 18. *The results of erosion and deposition modeling – zoom into the major landing zones and Black creek target area. The results show high potential for gullies in the Black creek and Patterson branch watersheds and in some of the landing zones. Although the erosion and deposition along some of the berms is very well represented, the 9m resolution model output may be overestimating the potential for gullies along the landing zones with berms.*

High resolution overland flow and sediment transport modeling – High resolution modeling was performed at the lower section of the Sicily drop zone and at the Patterson branch sub-watershed (see Fig 13. for location of these two areas) to analyze the impact of small scale topographic features, such as man-made berms, impact craters or naturally developed gullies on sediment transport to neighboring streams. The Sicily drop zone study site drains into the Jumping Run creek upstream from one of the sampling site (Figure 19) so the focus of the modeling was on understanding of sediment transport in this contributing area with significantly modified landscape. Surface water flow simulation demonstrates the functioning of berms as surface water traps, reducing the velocity and volume of water flow during simulated storm event (Figure 20). Post rainfall imagery confirms the water accumulation behind berm in the modeled location as well as ponding of water on the service road, also predicted by the model – providing valuable information not only for environmental applications but also mobility. Erosion and deposition modeling was performed for moderate and large events (Figure 21). The results indicate that a significant portion of sediment trapped along the berms is sediment from the berm slopes and the sediment is transported over very short distances during moderate events. However, an extreme event may cause break down of berms and creation of concentrated flows capable of carrying significant amount of sediment (Figure 21, right).

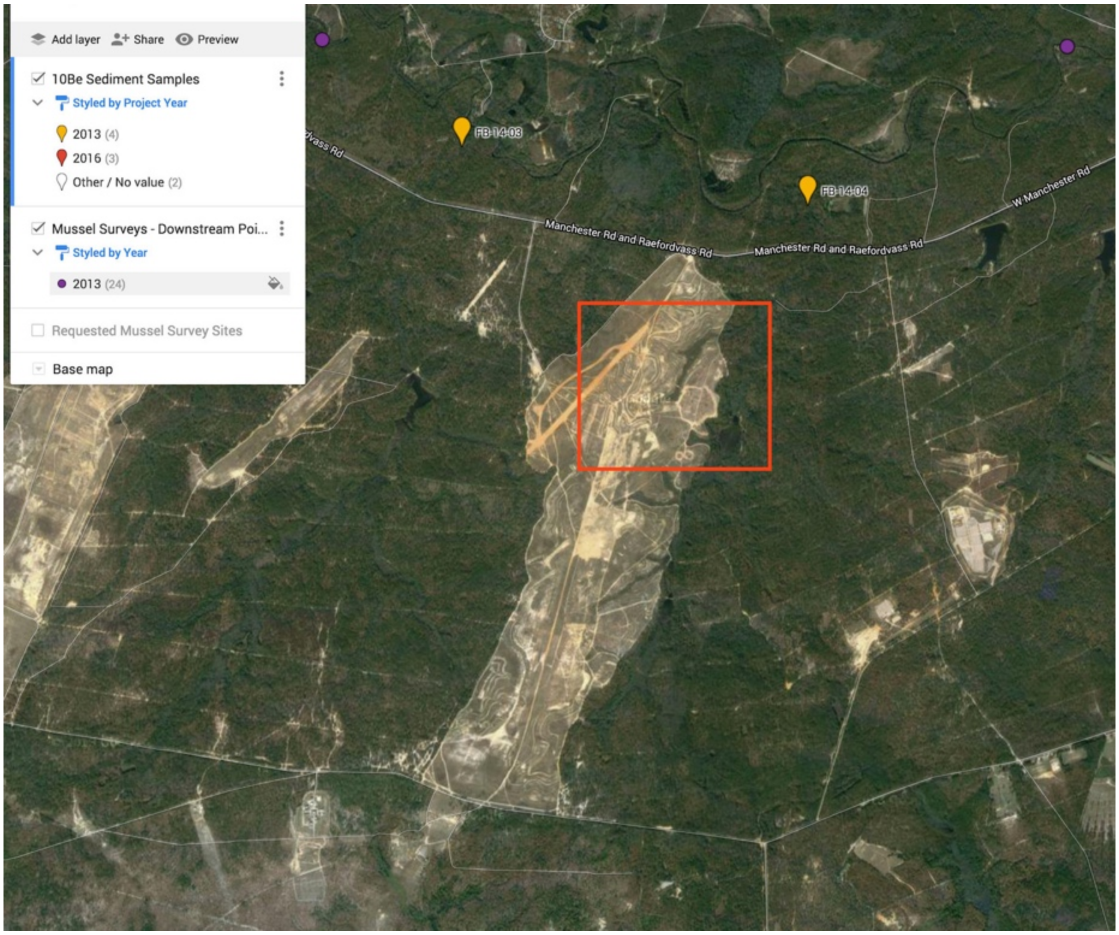

Figure 19. *Jumping Run creek and Sicily drop zone study site (red) and locations of sediment sampling sites from the previous study.*

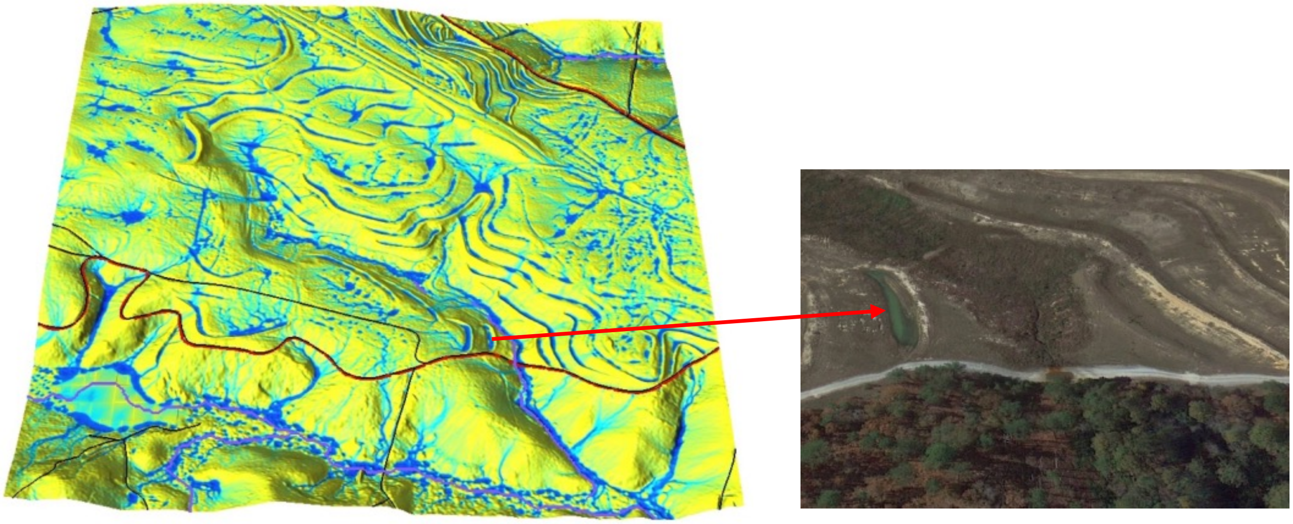

Figure 20. *Spatial distribution of surface water depth during a simulated rainfall event shows water accumulation in depressions along berms. Aerial photo (Google Earth) shows accumulated water behind the berm and along the road (red line in the model, grey in the google image) as predicted by the simulation.*

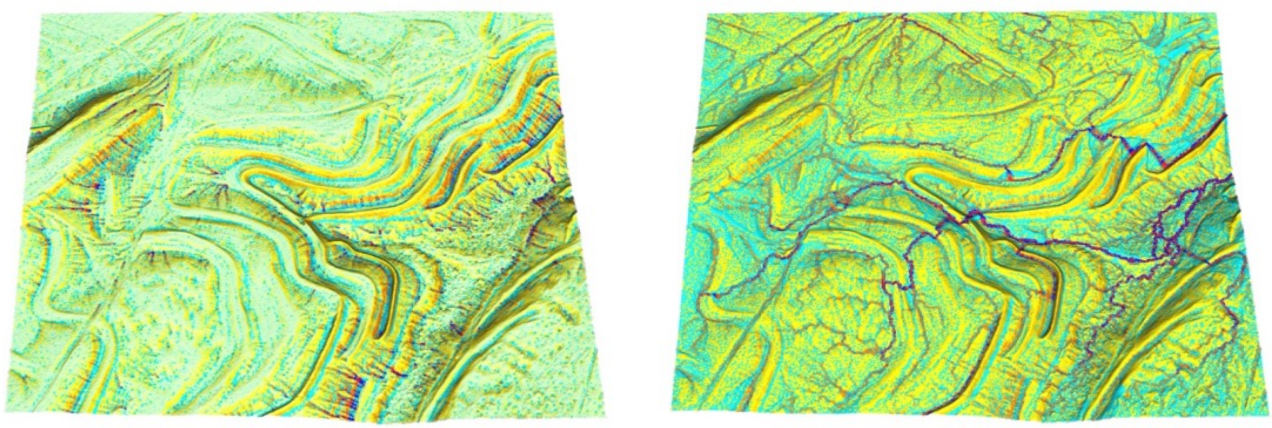

Figure 21. *Simulated net erosion and deposition for moderate (left) and extreme (right) rainfall events. The color legend is the same as in the Figure 18.*

The Patterson branch study site does not drain into sampled areas but it was selected because of its visible active erosion and topography substantially modified by large number of impact craters (Fig. 22). The craters significantly impact surface hydrology by trapping surface water (Fig. 23) and reducing overland flow and its sediment transport capacity. On the other hand, reduced land cover leads to extensive channelized overland flow in areas without craters with high potential for gully formation and sediment transport to the Patterson branch (Fig. 24). High resolution watershed and flow accumulation analysis was performed also for the Tank creek site (Fig. 13). Most of the contributing area for the Tank creek is in the developed area (Fig. 14) with limited sediment sources. Therefore, storm water runoff has greater impact on the stream than sediment transport from upland areas and effective control of storm water flow from the developed areas and through the channel along the airfield would be needed for long term, sustainable Tank creek restoration.

Figure 22. *Patterson Branch test area with visible erosion and deposition land forms*

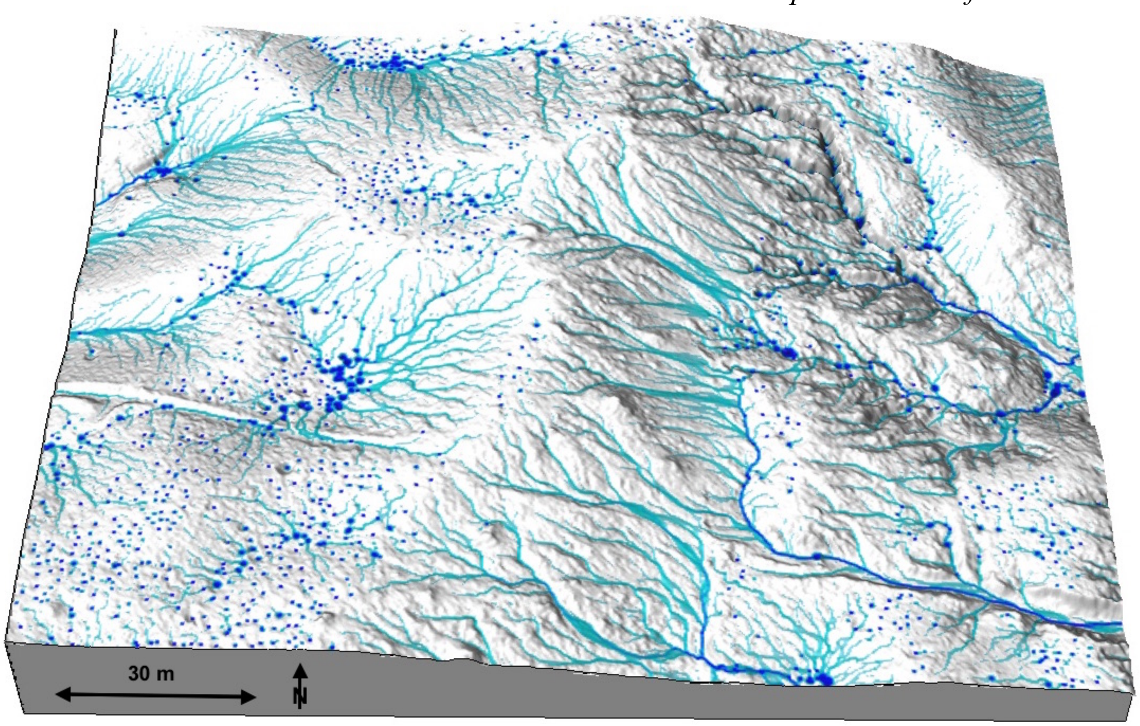

Figure 23. *Simulated surface water flow pattern is influenced by numerous impact craters trapping rainfall and reducing overland flow in Patterson Branch area.*

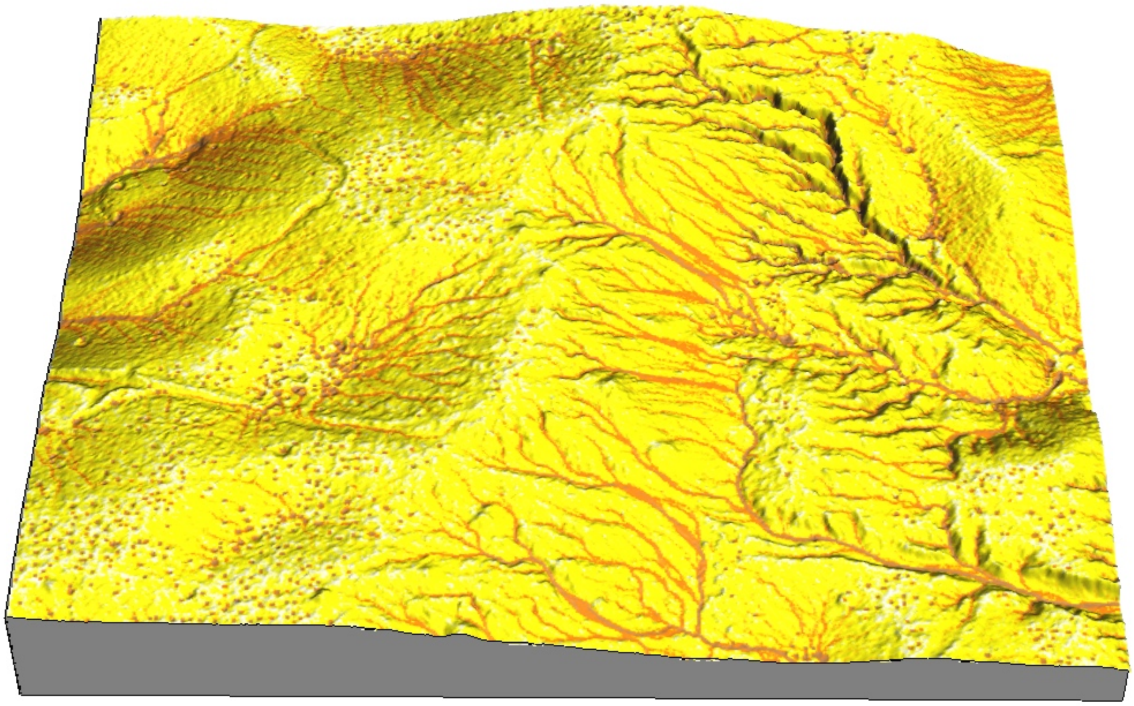

Figure 24. *Sediment transport capacity derived from flow accumulation and slope.*

Upland erosion estimates from lidar DEM differencing – We computed elevation change between 2012 and 2015 in effort to estimate short term upland erosion rates from lidar surveys. Analysis of the DEM differencing results revealed banding artifacts in one of the lidar surveys (usually due to error in recorded airplane pitch value) (Fig. 25) making it impossible to correctly detect elevation differences. However, locations of the largest changes in elevation were captured, indicating that with higher quality lidar data or even with a low cost Unmanned Aerial System, short term erosion rates can be measured at high resolution for the most critically impacted watersheds and to evaluate effectiveness of erosion control measures. The DEM differences during 2010 and 2015 captured the major elevation changes due to gully erosion at Patterson branch study site (Fig. 14), but the accuracy and resolution is not sufficient for providing reliable erosion estimates.

It is important to note that the modeling is based on limited vegetation, soil and rainfall data using uncalibrated models. Especially for the installation wide modeling at 9m resolution the results can be overestimated because the DEMs at this resolution do not fully capture erosion control berms and other measures. Although the results are in-line with expectations and highlight the importance of maintaining robust of erosion control measures at the installation, the GIS modeling should be considered preliminary. It provides valuable information about the high risk areas that can be used to guide future research work with the aim of providing knowledge and tools for cost effective, sustainable sediment and erosion control. With low cost, higher accuracy elevation surveys using UAS, the DEM differencing could provide valuable data for calibrating the erosion models and reducing uncertainty in sediment transport estimates.

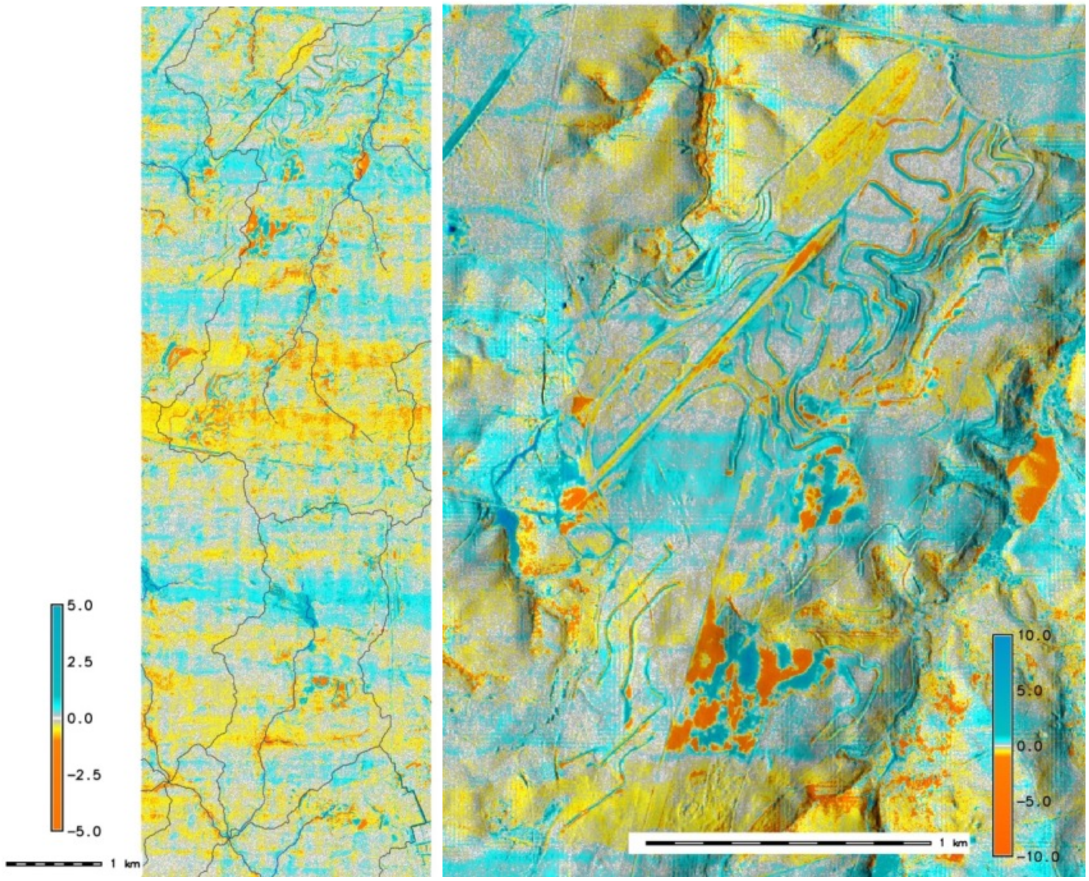

Figure 25. *Difference map between two lidar-based DEMs shows artificial banding of negative and positive values. Although major changes in topography are represented in the zoomed-in image (right), the actual values are not reliable enough to be used for upland erosion estimates.*

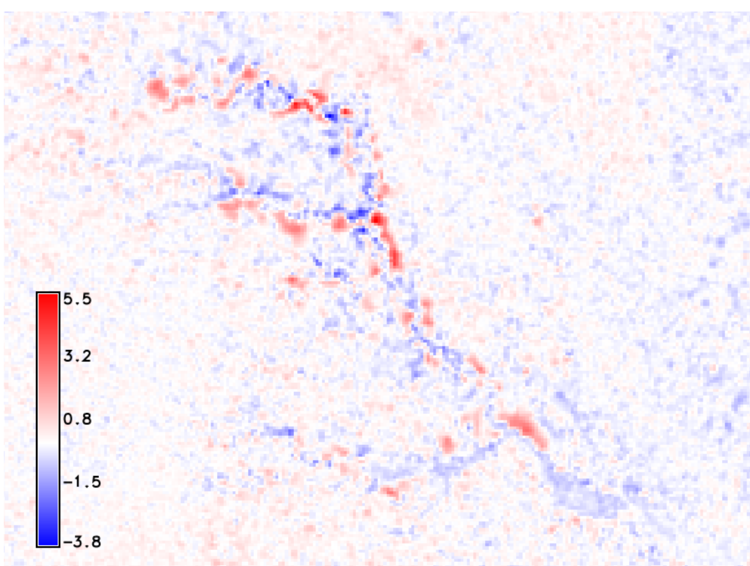

Figure 26. *Difference between an older, lower resolution (10m) DEM and the most recent lidar-based DEM captures major erosion and deposition features in the Patterson Branch creek area (see red rectangle in Fig. 22), but the accuracy and resolution is not sufficient for providing reliable erosion estimates.*

Objective 7) Develop a demonstration of a Tangible Landscape system as a collaborative environment for communication of spatial patterns and sediment transport.

Tangible Landscape is a projection-augmented sandbox powered by a GIS for real- time geospatial analysis and simulation (Petrasova et al., 2015). It was designed to intuitively 3D sketch landscapes — to rapidly explore ideas or test hypotheses with real-time computational feedback. The tangible system allows users to rapidly generate alternative land management scenarios with feedback on the sediment transport impact. Conceptually, Tangible Landscape couples a physical model with a digital model in a real-time feedback cycle of 3D scanning, geospatial modeling and simulation, and projection and 3D rendering. For example, by sculpting the terrain of the physical model, users can see how the changes affect processes like the flow of water, flooding, erosion, or solar irradiation. And since many users can interact with the physical model at once, Tangible Landscape encourages collaboration and interdisciplinary exchange.

Results and Discussion

Several new modes of interaction were developed in addition to changing topography (Fig. 27). Users can now define polygons using laser pointer or colored patches of felt or sand to design areas targeted for planting vegetation broadening the capabilities for designing storm water control and erosion control measures. The system was combined with Immersive virtual environment allowing users to explore realistic renderings of modified landscape (Fig. 28) and experience it from the ground, human perspective. Figure 29 illustrates the water flow modeling feedback projected along with an orthophoto, projected erosion-deposition modeling result for the initial state of landscape, modification of land cover using colored felt pieces representing construction of access road and planting of swale and tree buffer zone with project feedback on reduced concentrated flow erosion.

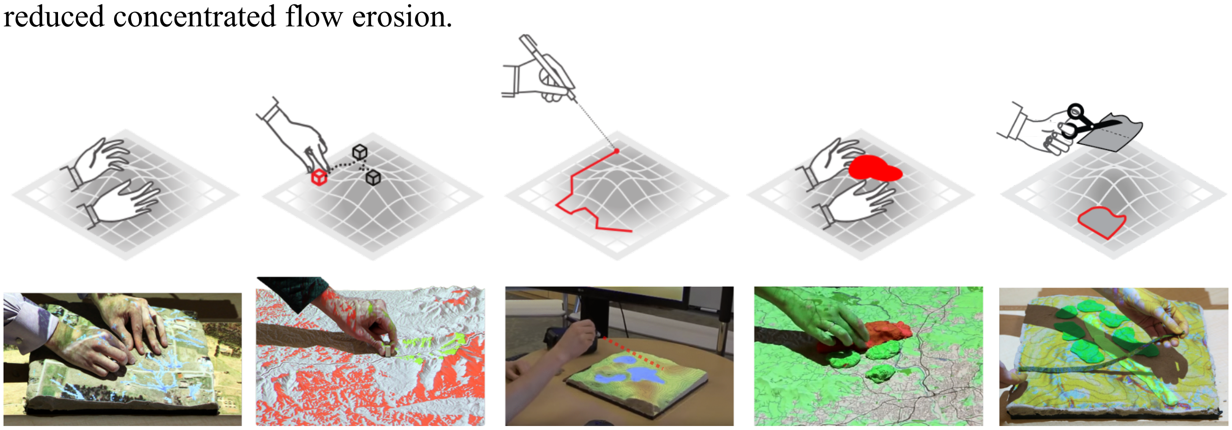

Figure 27. *New modes of interaction were developed to support both change in topography as well as landscape properties.*

We have used Tangible Landscape to visualize and explore our study area in Sicily drop zone. We digitally fabricated a physical model of this study area from high density foam using computer numerical control (CNC) routing and projected GIS layer over the model to highlight the relations between the topographic parameters, land cover and infrastructure. We then coupled the model with overland flow, ponding and erosion modeling feedback and explored various alternatives for surface runoff and erosion control (Fig. 29). As an interesting note – many years ago people from Ft Bragg environmental division came to try out our previous tangible modeling system. Their design is rendered in Fig. 31. Apparently they redesigned our test landscape in the way they did the sediment control for their drop zones, with the erosion-control berms following elevation contours.

Figure 28. *Designing conservation measures using colored felt with 3D rendering of the plantings.*

Figure 29. *Working with the Tangible Landscape application for Jumping Run creek near Sicily drop zone study area, exploring various options for reducing runoff into the stream and alternative erosion control measures with feedback on water flow and erosion/deposition.*

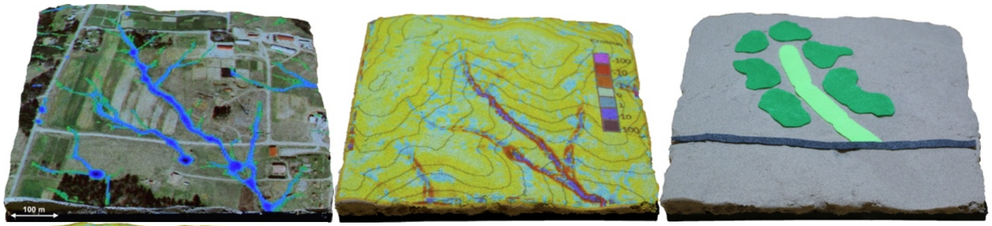
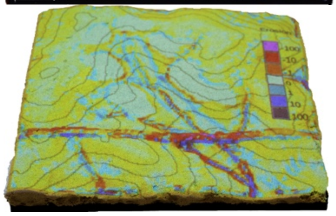

Figure 30. *Evaluating prevention of gully formation by installing vegetated swale and tree buffer with real-time feedback on resulting erosion and deposition rates.*

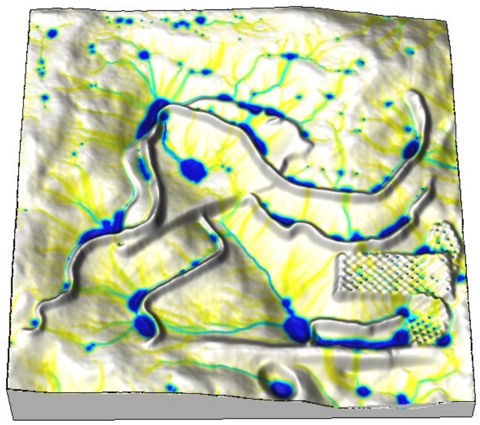

Figure 31. *Early version of a tangible landscape model for one of the Fort Bragg drop zones.*

Conclusions and Implications for Future Research/Implementation

1. Conduct bi-annual spring freshwater mussel surveys.
   Based on the two survey projects conducted to assess the diversity and abundance of freshwater mussels on Fort Bragg freshwater routine mussel surveys should be conducted. Little change was observed during the two series of studies and bi-annual surveys should be sufficient to provide a representative assessment of freshwater mussel populations on Fort Bragg. If population augmentation is attempted after stream restoration then a more frequent schedule of freshwater mussel surveys should be implemented in the restored stream reaches. Since freshwater mussel reproduction is tied to the presence of fish species that can serve as fish-hosts, routine fish surveys should be conducted to ensure the needed fish species are present in Fort Bragg streams.
2. The low pH observed in the Little River and tributaries on the base may be incompatible with freshwater mussel shell development. Although the threshold values for shell development need further study, a study to determine the reasons for the pH reduction on Fort Bragg is warranted. The low pH may be derived from base flow from areas with vegetation producing tannins or direct deposition of tannins. A study should be conducted to identify factors contributing to the marked change in freshwater mussel diversity and abundance at the confluence of James creek and the Little River.

3. Propagate *Villosa delumbis* and Release into Restored Streams. The Eastern Creekshell,

Villosa delumbis is listed as state endangered. During our previous project we also identified the species on the post. *Villosa delumbis* is a species that can be propagated in captivity and then released back into streams. However, releasing captive reared animals into degraded habit is of little conservation value. If stream restoration is undertaken adult *V. delumbis* can be collected upriver of Fort Bragg, propagated in the laboratory and then released back into restored streams.

4. Establish Groundwater Monitoring Wells to Determine if Low Stream pH is Associated with Low pH base-flow or Vegetation. There is a drop in stream pH as tributaries enter Fort Bragg. The origin of the low stream pH that could potential limit freshwater mussel shell development and limit freshwater mussel population could be derived from riparian vegetation releasing tannins into streams or base flow from areas with tannin releasing vegetation. A series of groundwater monitoring wells would need to be established and the pH of groundwater monitored to identify the origin of the low pH problem.
5. Conduct a Collaborative Exploration of Alternative Stream Ecosystem Recovery Design Scenarios for Fort Bragg Streams. A comprehensive study of military bases was conducted by another institution to identify streams on military property that could be and should be restored. We suggest accessing this study, when available, and then using the tangible landscape technology refined during the course of this study to develop a comprehensive plan for stream restoration on Fort Bragg. Restoration efforts should be paired with efforts to mitigate continued erosion and sand deposition into Fort Bragg streams.

6. Study Suitability of Jumping Run Creek Restoration and Mitigation of Erosion and Sand Loading from Landing Zones and Implement Erosion Control Measures to Minimize Sand Loading into Streams. Jumping Run Creek was identified as a degraded stream that could potentially be restored if steps are taken to mitigate erosion and sand sedimentation into the stream.

7. Study Suitability of Tank Creek Restoration by physical reworking of the channel. Tank Creek is completely contained within Fort Bragg. It is species depauperate lacking both freshwater macroinvertebrate and vertebrate diversity and abundance. It has been severely degraded by military activity and is a relatively straight channel with limited riparian vegetative buffer protection. Restoration efforts should include an effort to create a restored stream channel with meandering flow and include efforts to mitigate erosion and sand deposition in the stream.
8. Establish Vegetative Landcover Over Berms Adjacent to Landing Zones. Landing zones adjacent to Fort Bragg stream include soil berms that are not protected with vegetation from erosion. If feasible, without disrupting troop training, vegetative cover should be established to mitigate erosion and deposition of sand into adjacent streams.

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Addendum

Opportunities for training and professional development the project provided

The project supported the training of undergraduate and graduate students. Training in erosion model development and applications was provided to one graduate student. Training in calculating long-term basin average erosion rate estimates using in-situ cosmogenic nuclide geochronology with ^{10}Be was also provided to a graduate student. Training in stream geomorphology characterization was provided to one undergraduate student.

Dissemination to communities of interest

Tangible Landscape application was included into several demonstrations for professionals and students at the Center for Geospatial analytics and at conferences. The results will also be presented to and discussed with members of the Fort Bragg Endangered Species Branch.

Products

Tangible system's components were incorporated into relevant chapters of the book: Petrasova, A., Harmon, B., Petras, V., Tabrizian, P., Mitasova, H., 2018, Tangible Modeling with Open Source GIS, Springer International Publishing, p.202, in production.

Input data, including lidar-based DEMs and DSMs and results of watershed analysis and erosion modeling were integrated into an open source geospatial data-base.

The first long-term (10^4 years) basin average erosion rate estimates for the Little River catchment that will be reported in a peer-reviewed journal article to be submitted summer of 2018.

Website(s) or other Internet site(s): None

With additional resources the information generated could be included on the following site.

http://ncsu-geoforall-lab.github.io/erosion-modeling-tutorial/index.html

Technologies or techniques

A prototype integrated soil erosion modeling and landscape evolution simulations module was developed and implemented in open source GIS.

Module for design of erosion control and conservation measures was developed for Tangible Landscape system and incorporated into Tangible Landscape applications software stack.

Both of the above are available in public github repositories

Inventions, patent applications, and/or licenses: Nothing to report

Other products

Input data, including lidar-based DEMs and DSMs and results of watershed analysis and erosion modeling were integrated into an open source geospatial data base.

Participants & Other Collaborating Organizations:

INSTRUCTIONS - Participants & Other Collaborating Organizations
Provide the following information on participants:

Jay Levine (Co-PI) - overall project oversight, guidance of freshwater mussel studies, report preparation budget distribution and monitoring.

Christopher Eads (Field coordinator) - coordinated surveys of streams above and on Fort Bragg. Collected, identified and measured mussels and took ambient water quality data.

Samantha Peart (Field Assistant) - Assisted with freshwater mussel surveys.

Nicholas Oberle (Field Assistant) – Assisted with freshwater mussel surveys.

Mike Walter (Field Assistant) – Assisted with freshwater mussel surveys.

Helena Mitasova (co-PI) – advising student, coordinating erosion modeling and Tangible Landscape component, performing erosion modeling, generating visualization outputs, and writing relevant sections in the report

Brendan Harmon (grad student) – extensive processing of geospatial data and building of GIS database, developing integrated erosion modeling and landscape evolution simulation tools, generating visualization outputs, computing 3D modeling for CNC routing of the physical model, creating TL application set up.

Karl Wegmann (co-PI) – advising graduate and undergraduate student, and temporary research scientist, field data collection, geospatial analysis, laboratory analysis for sediment grain size and quartz purification, sediment transport modeling and ^{10}Be basin-average erosion rate calculations.

Nathan Lyons (PhD Student & Research Scientist) – Little River sediment size and basin-average erosion rate field surveys and modeling

Chanelle McCarther (Undergraduate Student) – Assisted with field and laboratory Little River sediment size modelling project.

Additional assistance was also provided by the Center for Geospatial Analytics students and personnel

No foreign country collaboration was involved in this project

What other organizations have been involved as partners? Nothing to report.

Have other collaborators or contacts been involved? No

Impact of the project on the principle disciplines of the project.

1-Assessed the suitability of streams above Fort Bragg to determine their suitability as habitat for freshwater mussels.

2- Documented the presence and distribution of freshwater mussels in selected streams.

3- Identified a reduction in stream pH as stream enter Fort Bragg.

4- The surface runoff and erosion modeling at high resolutions revealed specific spatial patterns of water flow and sediment transport in highly anthropogenic landscapes impacted by military training and extensive erosion control alteration of natural topography.

5- First estimates of long-term (10^4 yrs) basin average erosion rates (4 to 12 m / Ma) for the Little River basin, a component of the Sand Hills sub-region of the Coastal Plain physiographic province.

6- Field determination and geospatial modeling of the spatial location of the gravel-to-sand stream substrate transition along the mainstem of the Little River, an important variable for the distribution of freshwater mussels.

7- Further developed tangible landscape model

Impact on other disciplines

The workflow for processing lidar data inputs has provided insights into anomalies in lidar data, contributing to the geospatial analytics field.

Impact on the development of human resources?

Provided opportunities for graduate and undergraduate students to work with field and geospatial data representing unique natural and anthropogenic landscapes and their landforms and the opportunity to learn about how variations in soil exposure and vegetation cover impact Earth surface processes.

Impact on physical, institutional, and information resources that form infrastructure?

One 3D physical landscape model set up was added to the Tangible landscape portfolio of applications.

What is the impact on technology transfer?

Furthered the development of the tangible landscape model and identified potential value for assessing stream morphology on Fort Bragg.

What is the impact on society beyond science and technology?

The conducted studies could inform future efforts to minimize erosion and related sedimentation within streams on Fort Bragg. In addition, they may serve as an initial step toward restoring streams on the military post.

Dollar amount of the award's budget is being spent in foreign country(ies)? None

Changes that have a significant impact on expenditures: All the funds allocated to purchase back-pack sensors were not spent.

Significant changes in use or care of animals, human subjects, and/or biohazards: Nothing to report.

Change of primary performance site location from that originally proposed: Nothing to report.