ORGANIC CARBON STORAGE WITHIN IN-CHANNEL DEPOSITS,

TALLADEGA CREEK, ALABAMA

by

KELLEY COKER

LISA DAVIS, COMMITTEE CHAIR
JUSTIN HART
JENNIFER EDMONDS

A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Geography
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2012

ABSTRACT

River systems play an important role in carbon cycling and geomorphic processes influence rates of carbon storage and export within fluvial systems. Ecological studies have identified the importance of organic carbon (OC) as a food source for aquatic communities and geomorphological studies have identified floodplains as significant carbon sinks. However, information on in-channel OC storage dynamics is lacking. In this study, in-channel depositional landforms within Talladega Creek, located in the Southern Piedmont region of Alabama, were analyzed for OC content and total organic carbon (TOC) loads were estimated for in-channel sediment storage features and extrapolated to the reach scale. Additionally, relationships between OC storage and particle size were explored using Spearman's Rho tests. TOC loads were compared between two in-channel landform types, benches and bars using Mann Whitney U tests. On average, benches were found to have a higher OC content within sediments, and higher TOC loads than bars; however, large in-channel bars stored significant amounts of OC as well. OC content and clay content within benches were positively correlated, while OC content within bars was positively correlated with silt content. Reach-scale TOC was estimated for in-channel deposits to be 16,867 kgC. Overall TOC for all sampled features (14 in total) had a combined total of 143,310 kgC, with 91% of OC sequestered within bench deposits. Comparisons with floodplain data from other studies suggests that in-channel depositional features may be a significant carbon sink within fluvial systems and their TOC loads should be more explicitly incorporated in carbon budgets and carbon cycle models.

LIST OF ABBREVIATIONS

1. Organic carbon (OC)

2. Organic matter (OM)

3. Coarse woody debris (CWD)

4. Dissolved organic matter (DOC)

5. Fine particulate organic matter (FPOM)

6. Coarse particulate organic matter (CPOM)

7. Particulate organic carbon (POC)

8. Total organic carbon (TOC)

9. Cubic feet per second (cfs)

10. Above sea level (asl)

11. Loss on ignition (LOI)

12. Carbon correction factor (cf)

13. Gravel correction factor (gc)

14. Volume of fine sediment (Vf)

15. Total volume of sediment sample (Vs)

16. Organic content of subsample (OCsub)

17. Volume of surface sediment (Vss)

18. Volume of subsample (Vsub)

19. Surface area of deposit (SA)

20. Area of sample quadrat (Aq)

ACKNOWLEDGEMENTS

I would like to thank Dr. Greg Starr for the use of his electric mill for preparing samples. I also thank Sam Breadner for his help with sample collections, Kari Servold for her contributions in the lab, and Bryce Zimmermann for his assistance and insight in nearly all aspects of this project. I especially thank Lisa Davis, Justin Hart, and Jennifer Edmonds for their service on my thesis committee and their continued assistance and support throughout this process.

TABLE OF CONTENTS

ABSTRACT	ii
LIST OF ABBREVIATIONS	iii
ACKNOWLEDGEMENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
1.0 INTRODUCTION	1
1.1 RESEARCH OBJECTIVES	2
1.2 FLUVIAL SYSTEMS AND CARBON CYCLING	2
1.3 IN-CHANNEL SEDIMENT STORAGE	7
2.0 SITE DESCRIPTION	12
2.1 SITE HYDROLOGY AND GEOMORPHOLOGY	12
2.2 CLIMATE	13
2.3 ANTHROPOGENIC HISTORY AND LAND USE	13
2.4 STUDY REACHES	14
3.0 METHODS	19
3.1 ORGANIC MATTER CHARACTERIZATION	19
3.2 PARTICLE SIZE ANALYSIS	22
3.3 ORGANIC CARBON DETERMINATIONS	23
3.4 STATISTICAL ANALYSIS	23

4.0 RESULTS 25

4.1 ORGANIC CARBON WITHIN BENCHES 25

4.2 ORGANIC CARBON WITHIN BARS 28

4.3 REACH SCALE ORGANIC CARBON TOTALS 31

4.4 PARTICLE SIZE AND ORGANIC CARBON CONCENTRATIONS 32

5.0 DISCUSSION 39

5.1 DISTRIBUTION OF ORGANIC CARBON WITHIN IN-CHANNEL FEATURES 39

5.2 PARTICLE SIZE AND ORGANIC CARBON 44

5.3 REACH SCALE ORGANIC CARBON STORAGE 47

6.0 CONCLUSIONS 50

7.0 REFERENCES 53

LIST OF TABLES

1. Summary of in-channel features and their major characteristics 17

2. OC determination calculations and equations 27

3. Statistically significant results 29

4. Individual OC loads for each feature 36

LIST OF FIGURES

1. Bar classifications based on form and position in channel 8

2. Bench classifications 11

3. Site and feature location within Talladega Creek, Alabama 12

4. Images of study reaches 18

5. Sampling locations for OM 20

6. Sampling quadrat and pit sampling image 21

7. Average OM % for benches and bars 26

8.OC content (gC/m^3) for benches and bars 30

9.Surface OC loads (gC/m^2) for all features 31

10. TOC (kgC) for benches and bars 32

11.Particle size distributions of benches and bars 33

12. OM concentrations within the upstream portion of Site 5 37

13. OM concentrations within the downstream portion of Site 5 38

14. Clay content and OM relationships for bench sediment 34

15. OM, silt, and clay contents within benches 34

16. Silt content and OM relationship for bar sediment 35

17. OM and silt contents within bars 35

18.TOC load class model 46

1.0 Introduction

The carbon cycle is an exchange of carbon between various components of Earth systems, including the biosphere, lithosphere, hydrosphere, and the atmosphere. This flux occurs on a variety of spatial and temporal scales and results in large concentrations of carbon in certain locations of the earth. These locations are known as carbon "sinks" or "stores", and carbon cycle models assume the largest of these occur within oceans and terrestrial forests (Cole et al. 2007; Bolin 1981; Battin et al. 2009). Previous research indicates that river systems are highly involved in transporting and storing carbon and their role in carbon cycling is important to understanding the carbon cycle and climate change (Gislason et al. 2006; Sheldon and Thoms 2006; Batten et al. 2009). Additionally, organic carbon (OC) within rivers serves as an important food source for aquatic communities, and the availability of OC greatly impacts a freshwater ecosystem's structure and function (Vannote et al. 1980). River systems are often referred to as the "circulatory system of the Earth" because they serve as a conduit for water and denuded Earth materials, including carbon, to travel to the oceans. While in transit within streams, carbon may become stored within fluvial deposits and/or be released from the fluvial system via respiration (Cole et al. 2007). Certain aspects of carbon cycling in rivers has been well documented, such as floodplain storage and dissolved OC transport, but studies addressing the role that geomorphic features and processes play in carbon cycling are few. Ecological studies have explored this topic with emphasis on coarse woody debris concentrations and nutrient spiraling (Daniels 2005; Hadwen et al. 2009; Thomas 2005). From a geomorphological standpoint, some research exists on OC storage within floodplains with an emphasis on accumulation rates and broad scale OC budgets (Noe and Hupp 2010, Craft and Casey 2000); however, little is known about amounts of

OC stored within other deposits, particularly in-channel deposits such as alluvial benches and bars. This research aims to address these needs and in so doing, improve the understanding of the role that geomorphic processes have in OC cycling within river systems.

1.1 Research Objectives

The purpose of this study is to examine OC storage in in-channel landforms within a fluvial system. Specific research questions include: 1) How much OC is stored within and upon in-channel features; 2) How is OC distributed within individual features and within the watershed; 3) Is spatial variability of OC concentrations explained by changes in sediment particle size; and 4) How do OC storage potentials of in-channel features compare to one another and to those in other depositional environments, such as floodplains? OC storage within fluvial channel environments can take many forms and alter with changes in channel morphology and/or geomorphic processes operating within a reach. Characterizing in-channel stores of OC should help identify geomorphic processes that are important to in-channel storage and cycling of OC.

1.2 Fluvial Systems and Carbon Cycling

Carbon cycle modeling continues to be an important tool in climate change research; however, carbon cycle models are limited in that they consider terrestrial and inland water regions collectively. These models heavily focus on biotic systems, assuming that the most significant sinks lie within terrestrial forests and that cycling of OC is primarily a result of biological processes (Batten et al. 2009). Previously, rivers were considered to be a simple conduit or “pipeline” for the transportation of terrestrial carbon to the oceans; however, estimates based on this assumption resulted in large discrepancies between carbon imports to and from river systems, which demonstrated that rivers are active in carbon cycling (Battin, 2009, Cole et al, 2007; Cole et al. 2007). Research has shown that of the 1.9 $PgCy^{-1}$ that is imported to river systems annually, approximately one half of that carbon reaches the oceans. While much of the remaining carbon is released into the atmosphere during transport, approximately 0.2 - 0.6 Pg C y^{-1} is stored in aquatic sediments (Cole et al. 2007; Battin et al. 2009). These estimates suggest that approximately 20% of OC previously assumed to be buried in terrestrial areas may actually be accounted for within fluvial sediments (Battin et al. 2009). To date, most studies have focused on OC storage in floodplain units and coarse woody debris (CWD). As a result, the quantification of OC storage in other fluvial storage components remains relatively unknown.

Sources of riverine carbon include imports of soil carbon from terrestrial areas and primary production occurring within the system. Because of this terrestrial input, rates of carbon storage, respiration, and export in rivers often exceed that of primary production, making carbon cycling in fluvial systems unique from terrestrial systems (Cole et al. 2007). Large terrestrial soil inputs, resulting from widespread agricultural practices and increased erosion rates, provide an opportunity for increased amounts of soil carbon to enter rivers. Carbon content of soil inputs are influenced by the type of erosional process that displaced soil particles, and the intensity and duration of rainfall events (Wang et al. 2010). Sedimentary carbon has been shown to accumulate in aquatic systems over thousands of years, and in extremely stable environments, it has the capability of becoming part of the lithosphere over time (Batten et al. 2009; Thoms and Olley 2004). It is not known whether OC storage in inland waters indicates a net increase or a redistribution of terrestrial carbon (Batten et al. 2009) and further research is necessary to quantify carbon fluxes, especially within in-channel deposits.

Geomorphologists have studied in-channel OC storage within large, dryland rivers with regulated flow regimes. Large rivers tend to have a lack of retentive features and increased discharge, and as a result, have been thought to contain little organic matter. (Wallace et al. 1982; Sheldon and Thoms 2006). However, this concept ignores the role of large deposits of suspended sediment loads, often rich in particulate OC. In contrast to prior hypotheses, recent research suggests that these deposits, particularly alluvial benches, contain large amounts of organic matter, and contribute to channel roughness, which can further increase OM retention (Sheldon and Thoms 2006; Woodyer 1978). Organic matter within benches tends to increase towards the surface, likely because of the presence of established trees, which not only produces and contributes organic matter, but also traps particulate organic carbon (POC) that encounters the bench surface during flood events (Chanxing 1998). Additionally, organic-rich 'mud-drapes' have been reported on top of benches, particularly concave benches and those associated with reverse flows (Woodyer 1978). Other factors influencing OC storage potentials within bench sediments include the amount of OC inputs upstream, overall sedimentation rates, and the decomposition rates of the OM present within the deposit (Changxing 1998). Studies indicate that benches have the ability to persist for decades or longer, and therefore may represent long-term carbon sinks (Royall et al. 2010; Kilpatrick and Barnes 1964). Benches within the Southern Piedmont of the U.S. have remained within the channel for upwards of 50 years, while those in the Barwon Darling River of Australia have persisted for up to 2200 years, with portions of sediment being reworked at various intervals (Royall et al. 2010; Thoms and Olley 2004). OC storage within these systems has been shown to decrease as geomorphic complexity, or channel roughness, decreases. A decrease in complexity may be a result of flow regulation and anthropogenic disturbance, or simply a result of regional climate change and decreased flow variability (Sheldon and Thoms 2006).

The bulk of geomorphological research pertaining to carbon cycling within fluvial systems has focused on storage in floodplains and suggests that floodplains are likely a significant carbon storage sink (Battin et al. 2009; Noe and Hupp 2010; Craft and Casey 2000; Cole et al. 2007). Channels and their floodplains experience “lateral exchanges” during which sediment and nutrients, including OC, are moved from one component to the other. This exchange occurs during over-bank flood events, results in spatial and temporal variations in sediment and OC accumulations within floodplains and other alluvial landforms (Bechtold 2009). In systems where channels are decoupled from floodplains, as is the case in deeply incised channels, sedimentation and OC deposition is lessened in floodplains (Noe and Hupp 2005). While floodplains sedimentation rates widely vary, those with high historical or contemporary accumulation rates likely contain large amounts of OC (Bechtold 2009). Additionally, floodplains have been shown to contain large amounts of POC in the form of surface leaf litter. This litter then can be converted into dissolved organic carbon (DOC) during inundation and/or undergo *in-situ* decomposition by bacteria (Robertson et al. 1999). Floodplain studies have yet to address the time scales or processes involved in lateral exchanges of OC with in-channel environments.

Organic carbon is often considered in studies focusing on aquatic ecosystems and stream ecology. Particular emphasis has been on longitudinal trends of DOC and POC, and the ways in which these nutrient pools are processed by aquatic communities. DOC has been found to increase downstream while POC storage tends to decline downstream with increased discharge

(Battin et al. 2008; Hadwen et al. 2009). Oxidation of carbon within fluvial systems depends on microorganisms' response to the levels of OC in their environment, which is influenced by fluvial transportation and storage processes (Battin et al, 2008). The amounts of POC within an aquatic ecosystem is partially controlled by erosion rates and denudation processes, as sediments that are eroded and transferred to aquatic ecosystems are known to be carbon enriched due to preferential erosion of enriched clays (Wang et al. 2010). The longitudinal trends in OC concentrations and the type of OC available in an ecosystem is important, because it influences the structure of macroinvertebrate communities, and therefore nutrient spiraling dynamics (Vannote et al 1980).

Another type of OC storage commonly addressed in ecological literature is coarse woody debris (CWD) concentrations. CWD is also termed "large woody debris" (LWD) and when found in large concentrations within stream systems it may be referred to as a "debris dam." CWD is an important source of coarse carbon in streams, and through leaching and microbial processes, CWD becomes a source of POM and DOC over time (Lamberti 1989; Wallace and Benke 1984). In addition, the presence of CWD increases a stream's OM retention capabilities. Ehrman and Lamberti (1992) identified debris dams as a key factor in retention and found that OM transport distances in their study site decreased dramatically with the presence of debris dams. In low-gradient, meandering streams, patterns of OC storage within stream bends have been shown to depend on the presence and mobility of CWD (Daniels 2006). This study suggested that CWD in these types of systems may be more mobile than that of high-gradient streams, which results temporal pulses of OC, dependent on CWD transport downstream (Daniels 2006). In addition to CWD, in-channel sedimentation features have been shown to increase stream retention as well and also serve as habitation zones for aquatic species. Research suggests that in low-gradient streams, in-channel point bars and concave benches are equally important as CWD in providing habitats for fish, particularly during periods of bankfull flows (Schwartz and Herricks 2005).

1.3 In-Channel Sediment Storage

Sedimentation processes within fluvial systems are highly dynamic and result in a variety of in-channel storage landform types. The formation of these landform types are a function of sediment supply and hydrologic conditions within the river system. Depositional landform types vary in their residence times and stability, with in-channel bars being considered ephemeral, while floodplains are considered more permanent sediment sinks (Fryirs 2007). In idealized river models, residence times of sedimentation features increases downstream; however, residence times are controlled by many complex factors, including sediment particle size, distance from channel, vegetation cover and stream connectivity (the ability of a stream to transfer energy and sediment downstream) (Brown 1987; Friyers 2007). Common landform types present within Southern Piedmont streams include alluvial benches and bars. Both of these landforms types can be further divided into distinct subtypes. Additionally, sediment accumulates on the channel bed, either temporarily during low-flow periods or as a result of channel bed aggradation and prolonged deposition.

In-channel bars are most commonly found in meandering and braided channels and they exist in a variety of forms (Hooke and Yorke 2011). Rice et al. (2009) identified formative processes for bars, describing a rapid development in thickness and length until equilibrium is reached, after which lateral accretion then continues. Bars are particularly common in meandering and braided channels and they exist in a variety of forms (Hooke and Yorke 2011).

Zones of low velocity, and in-turn deposition, occur throughout a stream due to secondary flow patterns which create bars of differing shape, thickness, and sediment particle sizes (Burge and Smith 1999).

Many classification systems exist for these different types of in-channel bars (Smith 1974; Hooke and York 2011). The classification system described by Hooke and York (2011) is best suited to describe the types of bars present in Talladega Creek, which include mid-channel, point, and attached bars (Fig.1). "Mid-channel" bars are unattached from the stream bank and form in the middle of the channel. They most often form in straight reaches of a stream and are free to migrate throughout the channel. The occurrence of mid-channel bars may indicate a shift from a meandering stream channel to a braided channel (Hooke 2010). These bars are often diamond shaped and are initially small in size but accrete sediment over time. "Point" bars are the most common type of bar found in meandering channels. Point bars are bank-attached deposits formed on the inner bends of stream meanders, and they do not migrate within the channel. Finally, "attached" bars can evolve from mid-channel bars and become attached to the bank on one side. They differ from point bars in that they are not positioned within channel bends (Hooke and York 2011).

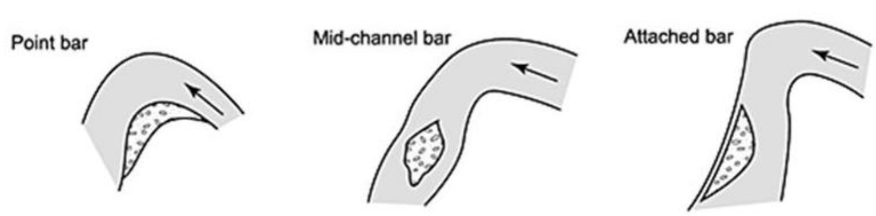


Fig.1. Bar classifications based on form and position in channel. Figure adapted from Hooke and Yorke 2010.

Another type of in-channel sedimentation feature, alluvial benches, are especially prevalent throughout the Southern Piedmont of the U.S.; particularly in small watershed streams (Kilpatrick and Barnes 1964; Royall et al. 2010). Alluvial benches are described as narrow, horizontal sediment deposits occurring at various elevations between the channel bed and the adjacent floodplain (Thoms and Olley 2004; Vietz et al. 2006). These features (or very similar features) may also be referred to by other terms including berms (Dunne and Leopold 1978; Schumm 2005), incipient floodplains (Warner 1987), and shelfs or innerberms, which Osterkamp and Hupp (1984) associate with mean annual discharge. In addition to the Southern Piedmont, alluvial benches have been reported in a variety of riverine settings, including large dry-land rivers of Australia (Sheldon and Thoms 2006; Thoms and Olley 2004; Vietz et al. 2006, Woodyer et al. 1978), and lowland section of the River Dee, North Wales, U.K. (Changxing et al. 1998). Three basic types of benches (Fig. 2) have been identified based on bench shape, formation, and position within the channel. These include: 1) point benches occurring on the inside of channel bends; 2) parallel benches or 'marginal' benches occurring along straight reaches; and 3) concave benches formed by reverse flow associated with hairpin bends in the stream channel (Woodyer et al. 1978; Erskin and Livingstone 1999; Royall et al. 2010).

The formation of alluvial benches is not completely understood and formation theories vary. However, previous research indicates that the dominant processes involved are lateral and vertical accretion of fine suspended-load sediment during low magnitude flood events (Thoms and Olley 2004; Changxing et al. 1998; Vietz et al. 2006). The formation of the three different bench types is partially caused by their height above the channel bed. Concave benches are thought to be a result of slackwater or eddy-water flows occurring directly downstream of a sharp bend in the channel. Point benches occur at the insides of bends due to deposition of the suspended-load sediment, and marginal (or parallel) benches are thought to be formed by sediment deposition in areas near the banks with increased tree establishment (Woodyer 1978). Other formation theories link mean annual discharge with bench formation, though the reason for this association is not discussed, and consider these features active parts of incipient floodplains (Harman 2000; Osterkamp and Hupp 1984). The stability of benches is debated and their longevity seems to vary based on fluvial settings. Woodyer (1978) described the benches of the Barwon-Darling River in Australia as remaining stable over long periods of time, likely because it is a low energy river system, with finely laminated sediments, and few erosional surfaces. In contrast, other studies have shown significant channel morphological changes in large rivers within the last century, which support the idea that benches are unstable and often reworked within the system (Thoms & Sheldon 1997, Sheldon and Thoms 2006; Changxing et al. 1998). Thoms and Sheldon (1997) describe the contemporary instability of benches within the Barwon-Darling River, stating that while benches at higher elevations within the channel are relatively stable, mid and lower benches are partially and completely reworked during large flood events, and reconstructed by intermittent low magnitude floods occurring thereafter. Bench formation requires conditions in which sediment transport is limited due to increased sediment availability, decreased discharge, or hydrologic changes within the channel (Changxing et al. 1999). These conditions may occur naturally due to climate change and drought periods (Royall et al. 2010), but may also be linked to anthropogenic factors including land-use change, flow regulation, and dam construction (Changxing et al. 1999).

The sedimentation and stratigraphy of alluvial benches has been examined in several studies, elucidating certain stratigraphic properties that are distinct among bench features. Most benches are dominated by fine silt and clay but some fine to medium sands have been reported in benches within the Barwon-Darling River (Woodyer 1978). Although stratigraphy has been shown to vary between settings and bench types, in general benches tend to exhibit an upward fining of sediments with rapid accretion rates (Thoms and Olley 2004; Woodyer 1978). Accretion rates tend to be highest in benches at low elevations within the channel, and decrease at higher elevations above the channel bed (Woodyer 1978). The rapid accretion of large amounts of suspended-load sediments contradicts the long-standing assumption that in-channel deposits are dominated by bed-load sediments, while overbank depositions are dominated by suspended-load sediments (Woodyer 1978). The stratigraphy of benches has been categorized by Erskine and Livingstone (1999) into three basic types: 1) well-stratified, “stratic” sediments consisting of thinly bedded silts and sands; 2) “massive” sediments composed of thick uniform beds; and 3) “cumulic” sediments consisting of thick, finer grained, relatively organic rich deposits found mainly on higher benches.

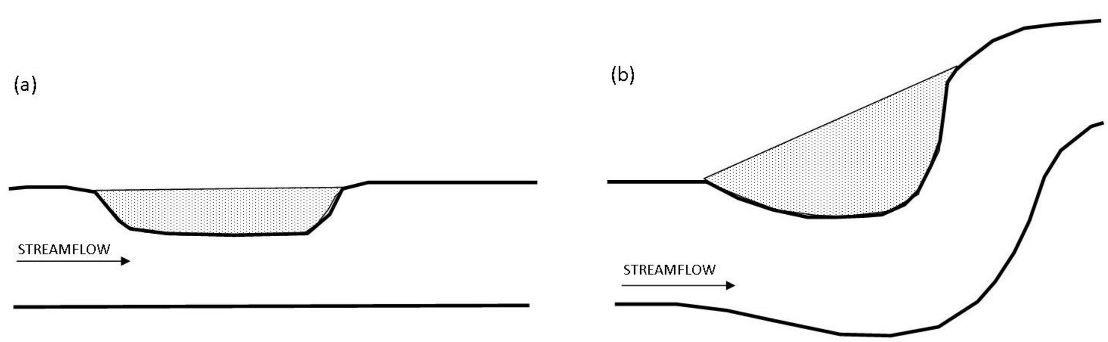


Fig. 2. Bench classifications. (a) “Marginal” or “parallel” bench formed along straight reaches. (b) “Point” bench formed on the insides of channel bends.

2.0 Site Description

This research was conducted at Talladega Creek, a stream located south of the city of Talladega, in northeastern Alabama. This site was chosen because previous studies (Kilpatrick and Barnes 1964; Royall et al. 2010) have documented the existence of in-channel sedimentation features, particularly alluvial benches, within Talladega Creek. This type of channel complexity was necessary for examining in-channel OC storage, which was the goal of this study.

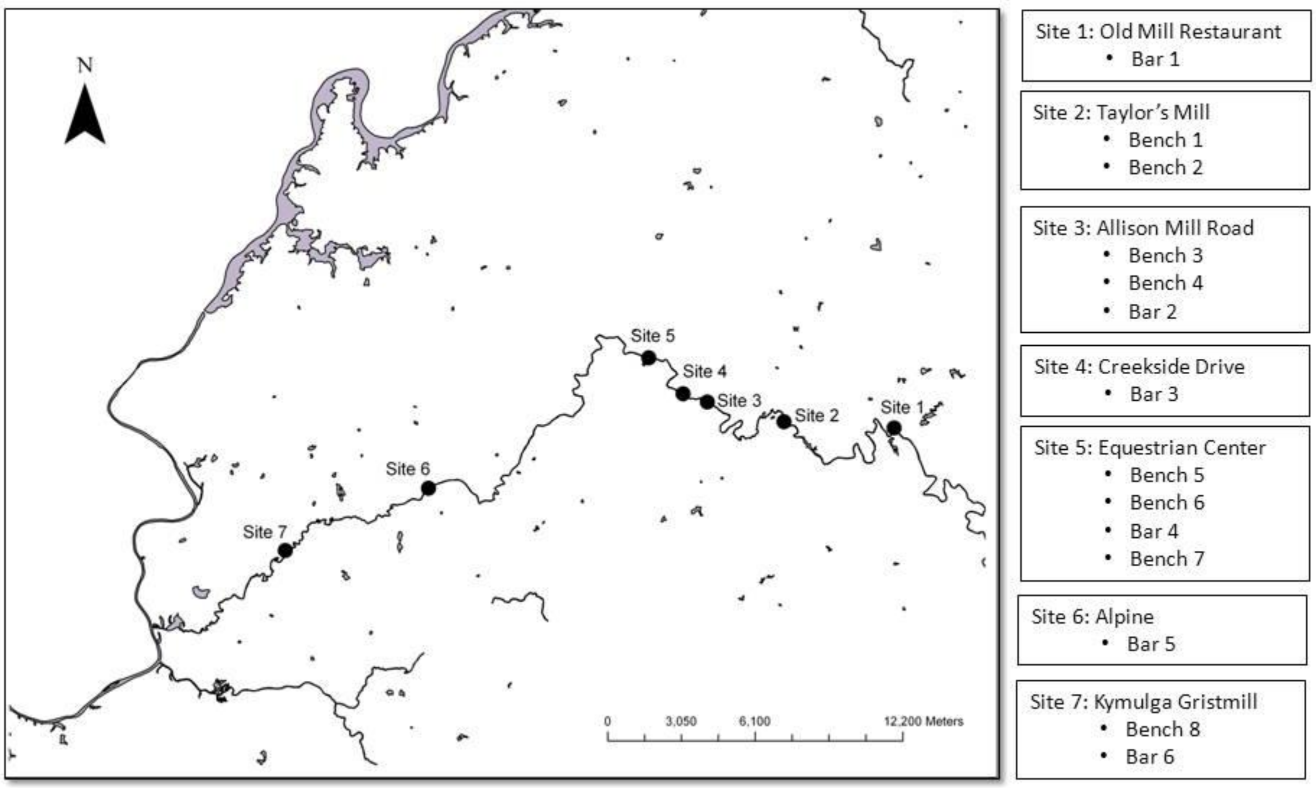


Fig. 3. Site and feature locations within Talladega Creek, Alabama.

2.1 Site Hydrology and Geomorphology

Talladega Creek lies within the Middle Coosa watershed, located in the Piedmont Physiographic Region of Alabama. The creek is approximately 50 km long and has a drainage area of 389 km^2. It is an alluvial stream with a high degree of channel complexity, i.e. in-channel sedimentation features. Elevations in the area range from 0.12 – 0.59 km above sea level (asl) and the elevation of the stream at the USGS gage station in Alpine, Alabama is 0.13 km asl. Hydrologic records at this site date back to 1901; over which time the average mean monthly discharge has ranged from 2.89 to 14.05 m^3/second. During the 2011 water year, the maximum discharge was recorded in March with a discharge of 185.19 m^3/second (USGS Waterdata Report 2012). The natural hydrograph for this stream displays a series of flood events of varying magnitudes distributed throughout the year; however, discharge tends to be highest in the winter and spring months and lowest during summer and fall months.

2.2 Climate

The climate in this region is classified as temperate or humid subtropical. It experiences an average annual precipitation of 133 cm that is relatively evenly distributed throughout the year; although precipitation in the winter and spring is often slightly higher than the rest of the year. The region experiences characteristically long, hot summers and variable temperatures in the fall and spring. Winter temperatures reflect both mild, maritime air and cold, dry, sub-tropical air masses that move into the region.

2.3 Anthropogenic History and Land Use

The majority of land in Talladega County is classified as forest land, which includes approximately 18616 ha of the Talladega National Forest. A large portion of land is also used as farmland (livestock and agriculture). Talladega Creek originates near the Talladega National Forest and flows south of town through agriculturally-dominated areas. Historically, agriculture has been a widespread practice in the region, and while it is still prevalent today, a shift has occurred from small, individual farms to larger farming operations. In addition, mill dams, which are used for processing agricultural crops, are prevalent in the area. Some mills and dams currently exist in the region, which are remnants of mills built in the 19th century. It is likely that many mill dams existed on Talladega Creek in the past.

2.4 Study Reaches

Site 1: Old Mill Restaurant

This reach is located the furthest upstream and is adjacent to the Talladega National Forest. This section of the stream is relatively straight and contains a large, mid-channel bar (Bar 1). Qualitative observations reveal that this bar is moderately vegetated. Currently, this site is occupied by a restaurant. However, historically this reach contained a mill dam approximately 0.4 km upstream of the bar deposit.

Site 2: Taylor's Mill

This section of Talladega Creek is regulated by a dam and contains several benches, two of which were sampled for this study (Benches 1 and 2). These benches occupy the same bank at different heights within the channel. Bench one is positioned low in the channel, is small in size compared to bench 2, and located immediately downstream of the dam. It is moderately vegetated with compact soils, likely due to walking trails and human traffic. Bench 2 is positioned higher in the channel, very large, and extended from the dam to an overpass downstream. Bench 2 is highly vegetated with decreased compaction. The bank opposite these benches is highly confined by exposed bedrock and valley walls.

Site 3: Allison Mill Road

This site was located on private property adjacent to an agricultural field. While no mill or dam was present, the name of the road suggests that a mill dam may have existed in the past. Two benches were sampled at this site (Benches 3 and 4). They occupied the same side of the bank while the opposite bank had a steep bank of exposed bedrock. Bench 3 was situated high in the channel and was densely vegetated. In contrast, bench 4 was lower in the channel and sparsely vegetated. This reach also contained a large attached bar (Bar 2) that was sparsely vegetated and located immediately upstream of a low, man-made cobblestone dam.

Site 4: Creekside Dr.

This section of Talladega Creek flows through agricultural fields just south of residential areas of Talladega. This site was located immediately adjacent to an agricultural field and the riparian areas were densely vegetated with Chinese Privet, a highly invasive species. This reach was very straight and contained one mid-channel bar (Bar 3), which had no established vegetation and was located immediately downstream of a small debris dam.

Site 5: Equestrian Center

This reach runs along pasture land owned by the Alabama School for the Deaf. This section of the stream includes three benches (Benches 5, 6, and 7) and one point bar (Bar 4). The reach, determined by changes in channel morphology, had a total length of 290.17 meters, and an average width of 24.21 meters. Both banks at the upstream portion of this reach had some degree of exposed bedrock. Bench 5 was located furthest upstream in a straight section of channel. The bench was discontinuous and consisted of two separate surfaces, distinguishable as the same feature based on the height above the channel bed. Several debris dams exist along the near-channel edge of these surfaces and the bench is moderately vegetated. Bench 6 was a concave bench located immediately downstream of Bench 5. It was small in size and sparsely vegetated. On the opposite side of the stream was Bar 4, which was large in size and sparsely vegetated, with the only established vegetation occurring in the back (near-bank) side of the bar. Bench 7 is a very small, marginal bench with moderate vegetation density. As the stream continues downstream of Bench 7, morphological changes occur. The stream becomes confined by steep bedrock banks and lacks depositional features and sinuosity, indicating a shift between a depositional zone to a transportation zone that lacks sediment deposits.

Site 6: Alpine

This site is located about one quarter of a mile downstream of the USGS gage station in Alpine, Alabama. It is adjacent to a contemporary agricultural field and included one attached bar (Bar 5) which was located within a straight, shallow section of the stream. The bar was small in size and sparsely vegetated on the near bank portion of the feature.

Site 7: Kymulga Gristmill Park

This section of the stream was within the Kymulga Gristmill Park, a functioning gristmill and tourist attraction. This site included one bench (Bench 8) and one mid-channel bar (Bar 6). Bench 8 was very large in size with very few established trees. However, the site was landscaped and the entire bench surface was covered in planted grass. This bench was located immediately upstream of the gristmill dam, while Bar 6 was located immediately downstream of the dam. This bar was small in size and had no established vegetation on its surface.

Table 1. Summary of in-channel features and their major characteristics. Height above channel bed is relative to other features within the reach. Vegetation density is a qualitative observation.

Site	*Feature and Number*	*Feature Type*	*Size (m^3)*	*Vegetation Density*	*Height above Channel Bed*
1	Bar 1	Mid-channel	201	Moderate	low
2	Bench 1	Marginal	133	moderate	low
	Bench 2	Marginal	1,078	high	high
3	Bench 3	Marginal	62	high	high
	Bench 4	Marginal	58	low	low
	Bar 2	Attached	899	low	low
4	Bar 3	Mid-channel	139	none	low
5	Bench 5	Marginal	490	moderate	high
	Bench 6	Point	81	low	high
	Bar 4	Point	1,021	low	low
	Bench 7	Marginal	42	moderate	med
6	Bar 5	Mid-Channel	221	low	low
7	Bench 8	Marginal	1044	high	high
	Bar 6	Mid-Channel	43	none	low

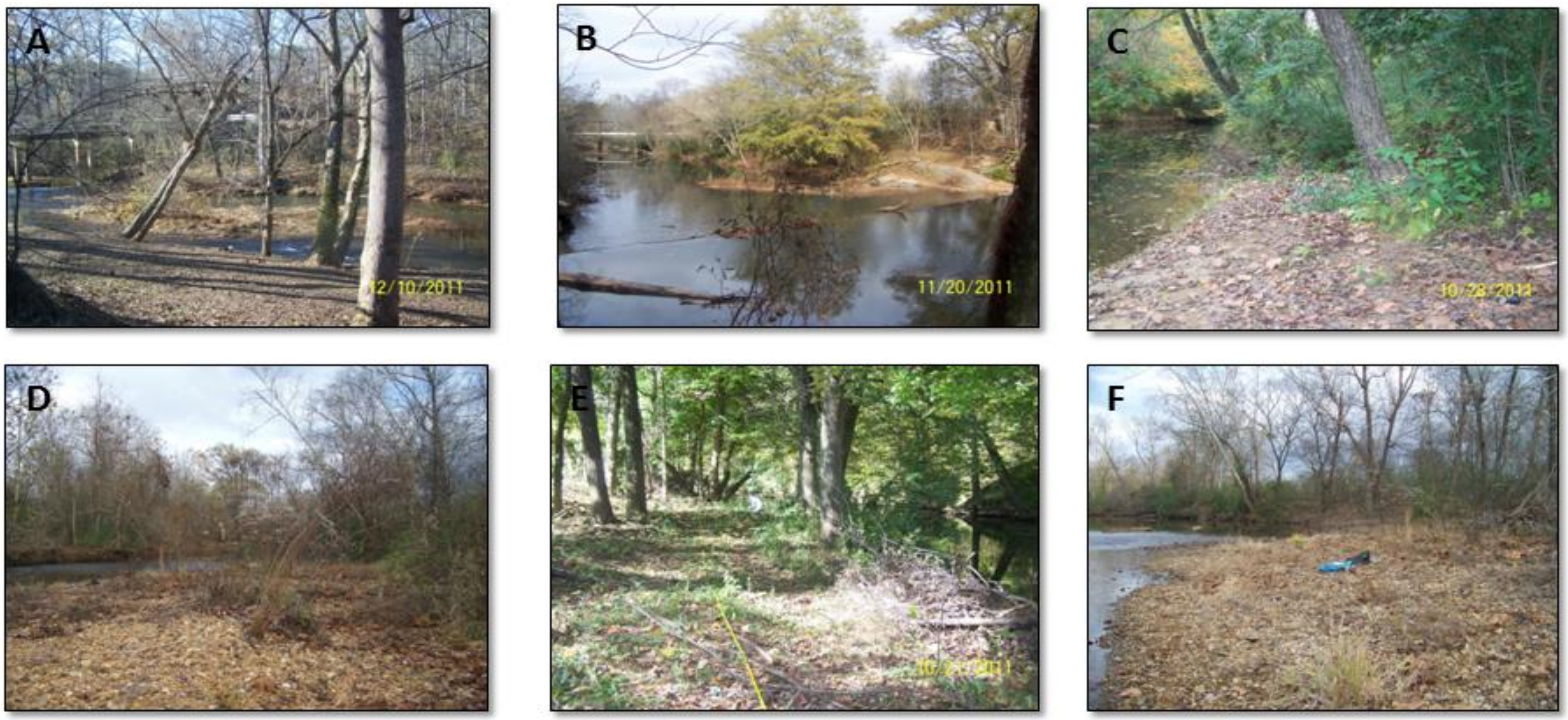


Fig. 4. (A) Site 1, Old Mill Restaurant. (B) Site 2, Taylor's Mill. (C) Site 3, Allison Mill Road. (D) Site 4, Creekside Drive. (E) Site 5, Equestrian Center. (F) Site 6, Alpine. (G) Site 7, Kymulga Grist Mill

3.0 Methods

The following methods were used to address the research objectives of this study, which included determinations of in-channel OC quantities and distributions, how concentrations differed between different types of deposits, and whether a relationship exists between particle size and OC concentrations. These methods were adapted from those used in a previous study (Sheldon and Thoms 2006) which examined alluvial bench deposits and OC concentrations in the Barwon-Darling River.

3.1 Organic Carbon Characterization

To examine the total organic carbon (TOC) associated with in-channel deposits, leaf litter and coarse organic samples were taken from the surface of each depositional feature. Six surface samples were collected per feature using a replicate 0.01 m^2 quadrat. Each feature was divided into 6 areas for sampling; upstream front, upstream back, middle front, middle back, downstream front, downstream back and sampling occurred in the center of each area (Fig.5). All non-living organic matter within the quadrat boundaries was collected and analyzed in the lab to determine the dry mass of each size fraction of OC within the sample, including 1) litter > 2cm in diameter, 2) coarse particulate organic matter (CPOM) between 125 μm and 2 cm in diameter, and 3) fine particulate organic matter (FPOM) < 125 μm in diameter. In instances in which a tree occupied the center of a sampling area, samples were collected immediately beside the tree. In one instance, a large debris dam was located within the sampling area. This organic matter was collected from the quadrat to a depth of 5 cm, which was then extrapolated to the measured depth of the debris dam. In the lab, samples were air dried and sieved to separate into the three size fractions (litter, CPOM, and FPOM). Each size fraction was then dried in a drying oven at 70 ° C for a minimum of two days, and weighed after drying. The dry mass of OC of the 6 surface sampling locations from each feature were averaged to determine the dry mass TOC load for the entire feature.

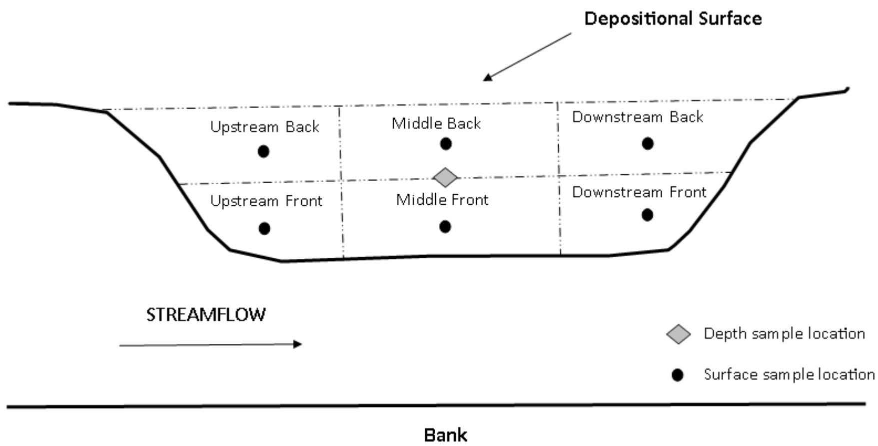


Fig.5. Sampling locations for surface OM, surface sediment, and depth sediment.

To examine the OC stored within deposits, sediment samples were taken in two ways from each feature. After taking surface OM samples from each quadrat, surface sediment samples (0 – 5 cm) were collected from the same location (Fig 6a), resulting in 6 surface sediment samples per feature (Fig 5). Sediment at depth was sampled at the center of each feature by digging a pit 30 cm deep and sampling at a 10 cm interval for a total of 3 depth samples per feature (Fig 5 and 6b). Sampling methods were consistent across landform feature, but bar deposits with armoring required the removal of large particles prior to sampling. Cobbles and boulders larger than 10cm in either length or width were removed and samples were collected beneath the armored layer. In the lab, bar and bench sediment samples underwent identical procedures to analyze OC using loss on ignition (LOI) procedures (Dean 1974). To prepare each sample for LOI analysis, coarse organic matter > 5 mm was removed, dried at 70°C, and finely ground using an electric mill. Gravel >2 mm was removed from the sample using a sieve. Ground organic matter was returned to the sediment sample, and the sample was manually homogenized. These steps were taken to ensure a representative subsample for LOI. A random subsample was then taken and dried at 105°C for a minimum of 24 hours. Dried subsamples were weighed prior to LOI analysis, then combusted in a muffle furnace at 450°C for 8 hours. They were then cooled in a desiccator for 30 minutes and re-weighed to determine the mass of OM lost during combustion. Volumes of each sample and subsample were determined using a graduated cylinder and used for extrapolations. The temperature and duration of combustion were chosen because studies have shown these conditions to be most effective parameters for optimal OC combustion while still limiting inorganic carbon combustion. LOI procedures that implement higher temperatures for a shorter duration can result in overestimations of OC due to inorganic carbon combustion (Heiri et al. 2001; Santisteban et al. 2004).

Fig.6. (a) Sampling quadrat for surface OC and surface sedimentary OC. (b) Pit sampling for sediment at depth.

To estimate the TOC loads at the reach scale, Site 5 was chosen as a representative reach, and all in-channel depositional features were analyzed in this reach, including bars, benches, and active channel sediment. The length of the reach sampled (290.17m) was defined based on continuous stream morphology and channel characteristics, including presence of in-channel sediment features, degree of bedrock confinement, channel geometry, and sinuosity. All in-channel depositional features (n = 4) within the reach were sampled using the methods previously described. Additionally, four samples were taken from the active channel bed at approximately 50m intervals along the length of the reach to determine the OC content within active channel sediments.

3.2 Particle Size Analysis

Following LOI combustion, the particle sizes of each subsample were determined by hydrometer method using modified USDA procedures (Gee and Bauder 1979; Bouyoucos 1962). Samples were soaked overnight in a 5% sodium hexametaphosphate solution. The following day, each sample was mechanically mixed for 5 minutes using an immersion blender and underwent 1 minute of hand stirring immediately prior to beginning the experiment. Hydrometer readings, and corresponding temperature readings, were taken at 40 seconds and 24 hours. Insulation sleeves were applied to each sedimentation cylinder to control temperature fluctuations throughout the duration of the test. Hydrometers were calibrated using a sample “blank” to account for water and dispersant solution densities. Hydrometer readings were corrected for temperature variations and “blank” calibration readings.

3.3 Organic Carbon Determinations

OC content within sediments was calculated for the surface and at depth and then extrapolated for entire features (gC/depositional feature) and per unit volume (gC/m^3). OC stored on the surface of depositional features was calculated and extrapolated for the entire feature (gC/ depositional feature) and per unit volume (gC/m^3). TOC estimates represent both of these types of OC storage. OM content was converted to OC (gC) using the EPA standard method (adapted from Nelson and Sommers 1996). OC content was also corrected to account for coarse particles (>2 mm) that were not included in LOI procedures using a "gravel correction factor." This correction factor was determined for each sample based on the ratio of fine sediment included in LOI to coarse sediment excluded from LOI. This correction is necessary because large inorganic particles occupy volume within the deposit area that must be considered when extrapolating the OC data. No correction for inorganic carbon was used in this study. Research suggests that combustion temperatures less than 500 ° C are appropriate for combustion of OM only, and that inorganic carbon combustion from these methods are negligible (Heiri et al. 2001; Santisteban et al. 2004). Table 2 summarizes operations and equations used to calculate OC loads.

3.4 Statistical Analysis

Differences in OC storage (at depth and on surfaces) between features were analyzed using a series of Kruskal Wallis tests. Data normality was tested using a Kilmolgorov- Smirnov test, which revealed that the data were not normal. Additionally, small sample sizes required the use of nonparametric tests. To determine longitudinal trends in OC storage, Spearman's Rho correlation tests were used and features were ranked based on their position within the watershed (with a rank of 1 being furthest upstream and 14 being furthest downstream). Differences in OC (both at depth and on surfaces) between sampling locations located within single features were examined using a series of Kruskal-Wallis tests. Significant differences in these distributions were further tested using a Spearman's Rho test. Particle size and OC relationships were examined using Pearson's Correlation tests. For this test, sample sizes were $n = 72$ for benches and $n = 54$ for a bars, and data normality was achieved by log transformation (natural log), permitting use of parametric tests. Mann-Whitney U tests were used to compare OC loads (OM%, gC/m^3; TOC kgC) between benches and bars because data for OM percent were not normal, and data for OC loads/feature resulted in small sample sizes (benches $n=8$; bars $n=6$); therefore, nonparametric tests were necessary for these comparisons.

4.0 Results

4.1 Organic Carbon within Benches

Average percent OM of sediments within the eight benches (Fig. 7a) sampled ranged from 2.0% to 15.9% with an overall average of 7.4%. Benches l and 2 (Site 2) displayed the highest percentage of OM with averages of 12.0% and 15.9%, respectively. Bench 4 (Site 3) displayed the lowest OM content of the benches sampled- 2.0%, while bench 3 (also at Site 3) had an OM content of 6.7%. Benches sampled at Site 5 (benches 5 - 7) had average OM contens that range between 4.2% to 5.8%. However, individual samples within benches 6 and 7 displayed high spatial variability of OM, with contents ranging from 0.02 to 12.0%. Bench OC loads per unit area (Fig 8a) ranged from 10,725gC/m³ for bench 4 (Site 3) to 58,579gC/m³ for bench 2 (Site 2). The average OC load for benches was 29,512 gC/m³.

OC loads on bench surfaces averaged 704 gC/m³. OC loads (fig. 9) ranged from 136 gC/m² on top of bench 8 (Site 7), to 1,881 gC/m² on top of bench 5 (Site 5). The highest contributing fraction of OM on top of benches was litter (> 2cm), comprising an average of 60.2% of the OC load. CPOM comprised 37.8% of the OC load, and FPOM comprised 2.0% of the OC load. Bench 5 contained a notable amount of litter with a contribution of 78.9%. Total OC loads for benches 794 kgC for bench 7 (Site 5) to 63,193 kgC for bench 2 (Site 2). Benches had an average OC load of 16,300 kgC. Bench 8 also contained a high OC load, with 43,287 kgC.

Organic carbon content within bench sediments differed between all sites ($p<0.001$). Total surface OM, surface litter, CPOM and FPOM were all significantly different ($p = 0.001$, 0.002, 0.001, and 0.010, respectively) between sites. Total surface organic matter, CPOM and FPOM were significantly correlated with longitudinal position within the watershed, but had low r^2 values (0.091, 0.056, and 0.131, respectively).

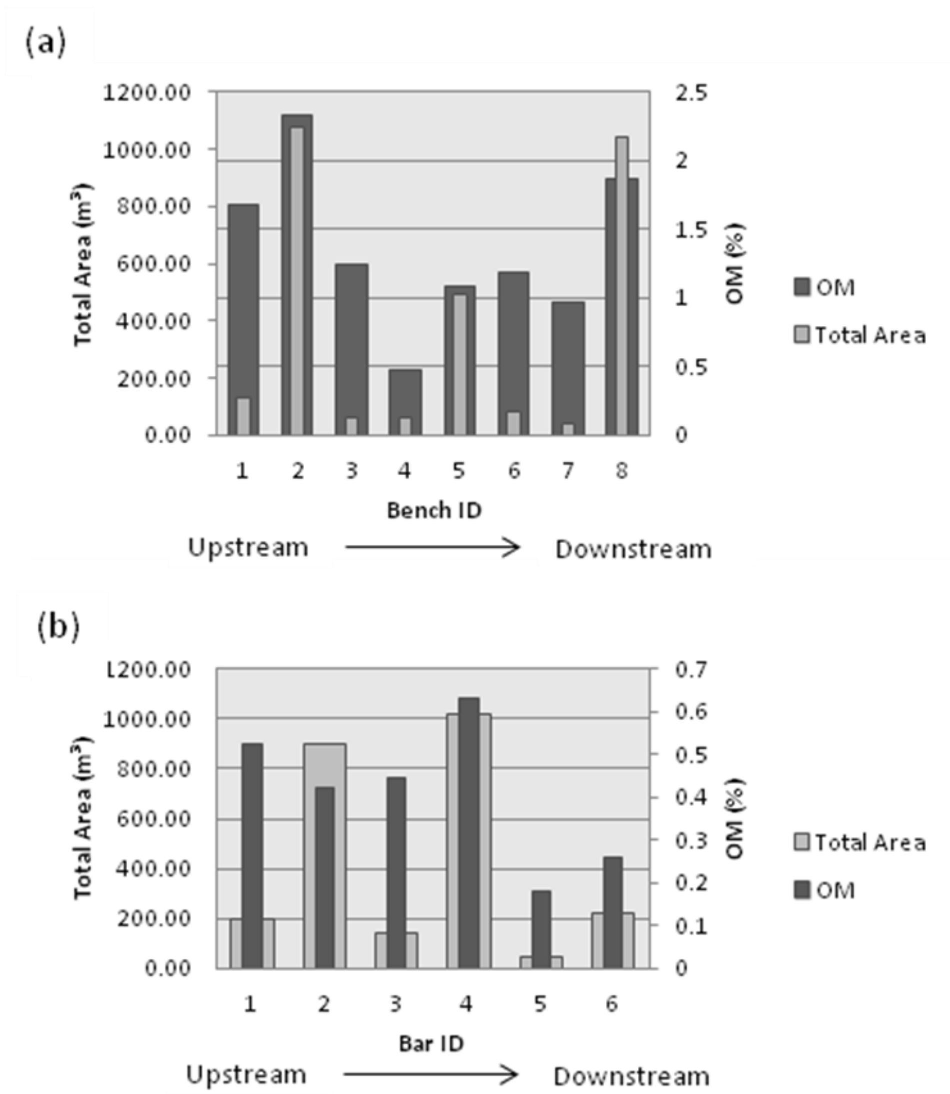


Fig. 7 (a) Average OM content (%) within bench sediment and bench surface area. (b) Average OM content (%) within bar sediment and bar surface area.

Table 2. OC determination calculations and equations; includes variable definitions.

Use of Calculation	Equation	Definition of Variables
Organic Carbon Conversion	*OC = OM x cf*	cf = Carbon Correction Factor, 1.724 OC = Organic Carbon OM = Organic Matter
Gravel Correction Factor	*gc = Vf / Vs*	gc = Gravel Correction factor Vf= Volume of fine sediment < 2mm Vs= Total volume of sediment sample
Sedimentary OC Extrapolations	*OC Surface Sediment = (OCsub x Vss / Vsub) gc* *OC Depth Sediment = (OCsub x Vds/ Vsub) gc*	OCsub = Organic Content of Subsample Vss= Volume of Surface Sediment in Deposit Vsub = Volume of Subsample gc = Gravel Correction Factor Vds= Volume Depth Sediment in Deposit
Sedimentary OC Loads per Feature	*Sedimentary OC Load = (Surface Sediment OC + Depth Sed.ment OC)*	OC = Organic Carbon
Surface OC Loads per Feature:	*Surface OC = (OCsub x SA/ Aq)*	OCsub = Organic Content of Subsample SA = Surface Area of Deposit Aq = Area of Sample Quadrat
Total OC Loads per Feature:	*TOC = Sedimentary OC + Surface OC*	TOC = Total Organic Carbon OC = Organic Carbon
Reach Scale TOC:	*TOC Site 5 = TOC Benches + TOC Bars + TOC Active Channel Sediment*	TOC = Total Organic Carbon

4.2 Organic Carbon within Bars

Results from LOI analysis revealed OM contents within bar sediment (Fig 7b) that ranged from 0.6% to 2.0%, with an overall average of 1.4%. Bar 1 (Site 1) and bar 4 (Site 5) contained the highest average amounts of OM, both of which contained 2.0% OM. Bars 5 (Site 6) and 6 (Site 7) contained the least OM within bar deposits, with OM contents of 0.6% and 0.7%, respectively. When extrapolated per unit volume, OC loads for bar deposits (Fig 8b) ranged from 2,521 gC/m^3 for bar 4 (Site 5), to 8,861 gC/m^3 for bar 2 (Site 3). The average OC load for all bar deposits was 4,025 gC/m^3.

OC loads on bar surfaces (Fig. 9) averaged 356 gC/m^2. OC loads ranged from 156 gC/m^2 on top of bar 6 (Site 7) to 698 gC/m^2 on top of bar 5 (Site 6). On average, litter comprised 56.7% of the total OC on top of bars, CPOM comprised 42.5%, and FPOM comprised 0.8%. Bar 5 (Site 6) exhibited the highest storage of CPOM at 66.1%, while bar 1 (Site 1) displayed the largest contribution of litter, with 71.4%. TOC loads for bars (Fig. 10b; table 3) ranges from 150kgC to 8,011 kgC for bars 6 (Site 7) and 2 (Site 3), respectively. Bar 4 (Site 5) also displayed a relatively high TOC load compared to other bars, with a TOC load of 2,791 kgC. The average TOC load for bars was 2,152kgC.

OC content within bar sediments differed between all sites ($p < 0.001$) and correlated with longitudinal position with an $r^2 = 0.252$. OC was significantly different between samples from the front of bars versus samples from the near bank area of bars ($p = 0.011$). Total OC on top of bars was significantly ($p = 0.011$) different between upstream and downstream sampling locations. Mann-Whitney U test results showed that benches and bars differ in their sedimentary

OM content ($p = 0.006$) and their OC content per cubic meter ($p = 0.002$). A comparison between TOC for all benches and bars was nearly significant ($p = 0.070$). Average area of benches and bars were not significantly different.

Table 3 (a). Statistically significant results for comparison of bench OC between all sites. (b). Statistically significant correlations between size fractions of bench OC and longitudinal position. (c) Statistically significant results for comparison of bar OC between all sites and sampling locations. (d) Statistically significant correlations between forms of bar OC and longitudinal position.

(a)

OC Variable	**P- Value**
Sedimentary OC	0.001
Total Surface OM	0.001
Surface Litter	0.002
CPOM	0.001
FPOM	0.010

(b)

OC Variables	$\mathbf{r^2}$
Total Surface OM	0.091
CPOM	0.056
FPOM	0.131

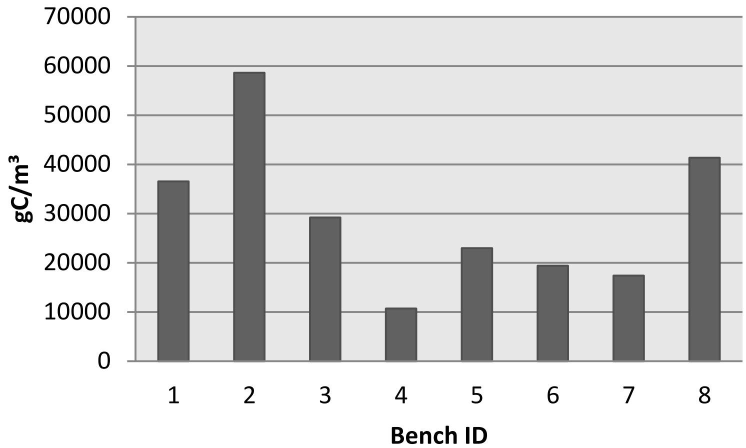
(c)

OC Variables	**P- Value**
Sedimentary OC	0.001
Sedimentary OC between sample location (front/back)	0.011
Total Surface OM between sample location (upstream/downstream)	0.011

(d)

OC Variables	$\mathbf{r^2}$
Sedimentary OC	0.252

(a)



(b)

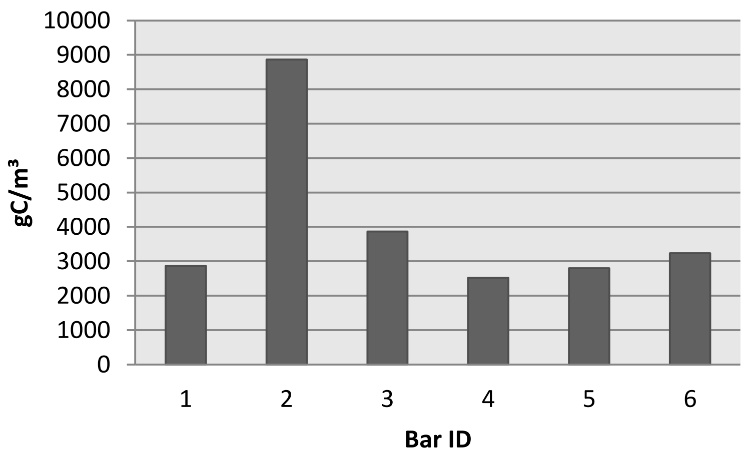


Fig. 8 (a) OC content (gC/m³) of bench sediment. (b) OC content (g/Cm³) of bar sediment.

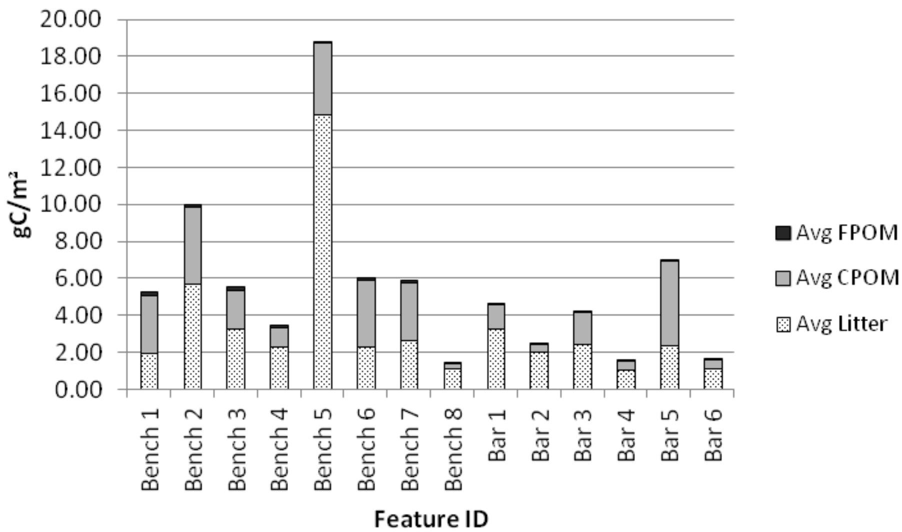


Fig. 9. Surface OC loads (gC/m²) for all features, including contributions from three size fractions; Litter, CPOM, and FPOM.

4.3 Reach Scale Organic Carbon Totals

OC loads for benches of the reach totaled 6,438 kgC, with 5,443 kgC stored within sediments and the remainder within surface OC. The bar contained a total of 2,731 kgC, with 2,573 kgC stored within sediments. Sediment within the active channel contributed 8,340 kgC.

The overall TOC for the reach was 16,867 kgC, with 16,356 kgC stored within sediments. The majority of OC within the reach was stored in benches, contributing a total of 56% of OC within the reach. Benches 5, 6, and 7 contributed 46%, 7%, and 3%, respectively. Active channel sediments store 33%, and the bar stored 11%.

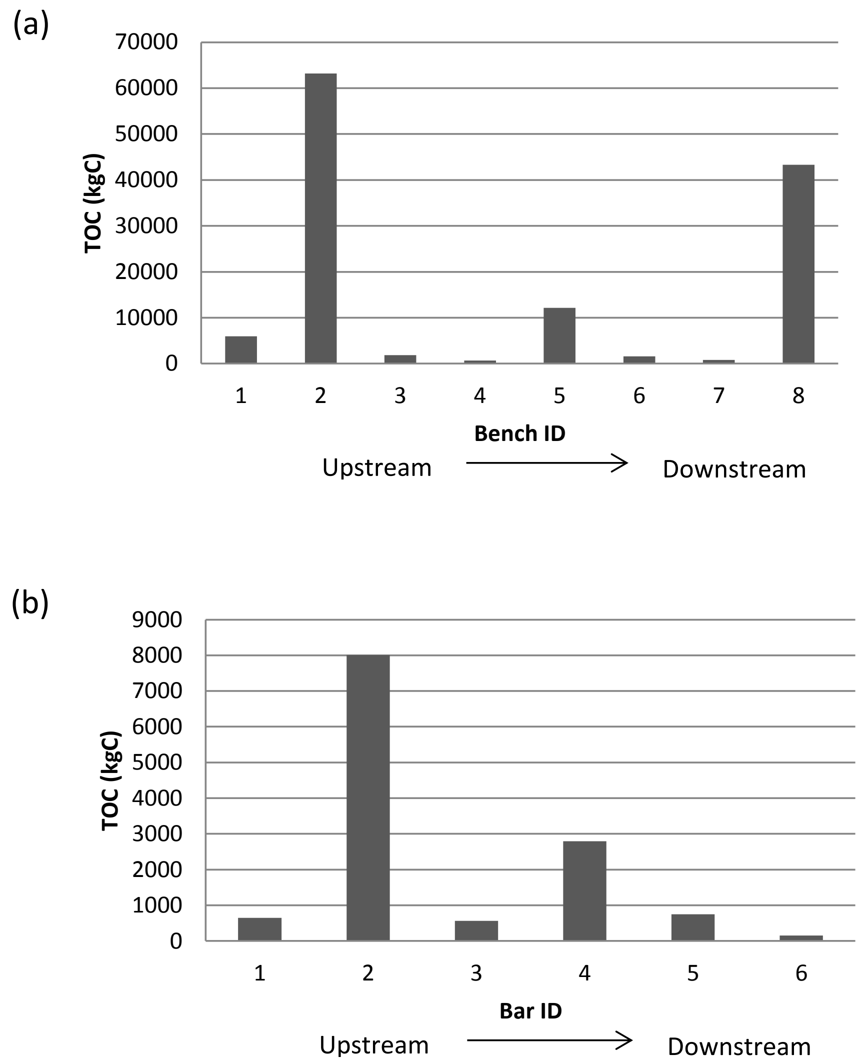


Fig. 10. (a) TOC (kgC) for benches, including sedimentary and surface OC. (b) TOC (kgC) for bars, including sedimentary and surface OC.

4.4 Particle Size and Organic Carbon Concentrations

Particle size analysis of benches revealed an overall dominance of fine particles (silt and clay) (Fig. 14a). Average particle size percentages for benches were 42% sand, 18% silt, and 40% clay. OC content was significantly (p<0.001) correlated with percent sand and percent clay.

Correlation with sand showed a negative relationship with an $r^2 = .384$. Bench OC content was significantly ($p<0.001$) correlated with percent clay content (Fig. 15; Fig. 16) with an $r^2 = 0.421$.

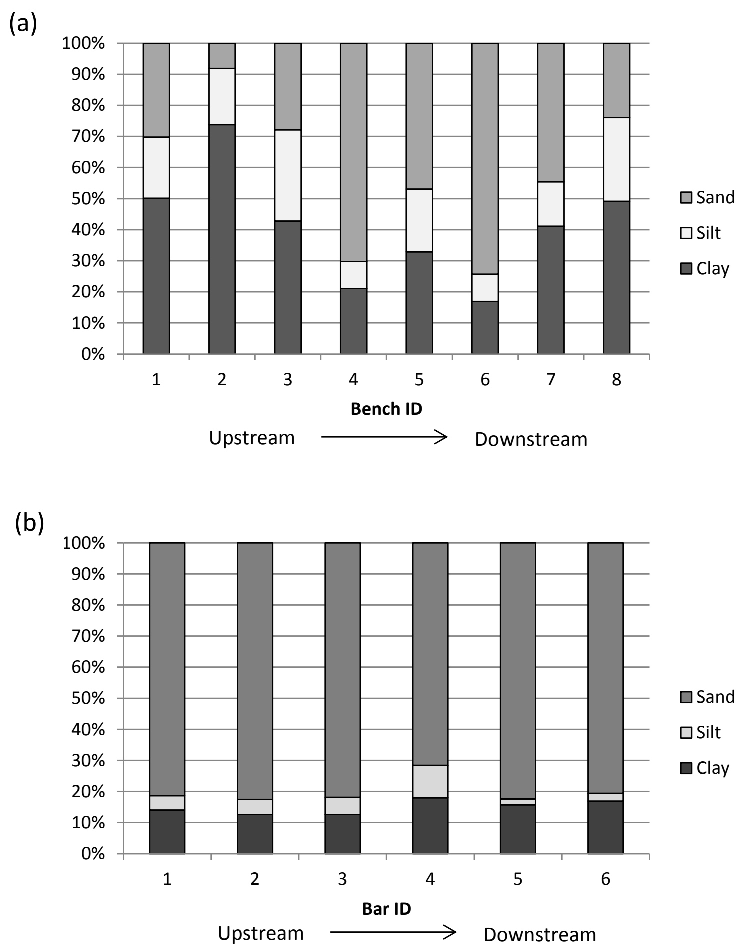


Fig. 11. (a) Particle size distributions of bench sediment. (b) Particle size distributions of bar sediment.

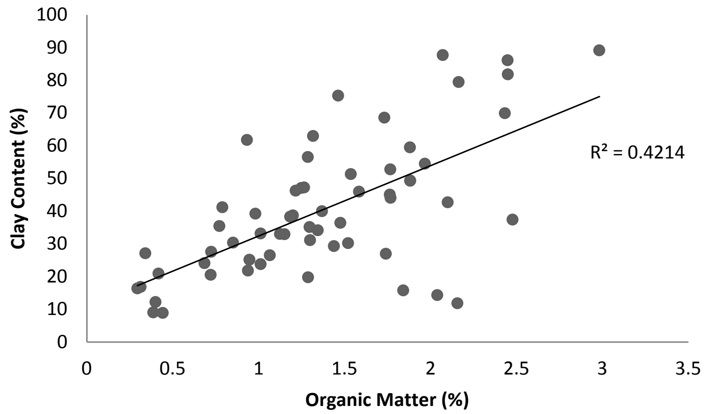


Fig. 14. Clay content (%) and OM content (%) relationship for bench sediment.

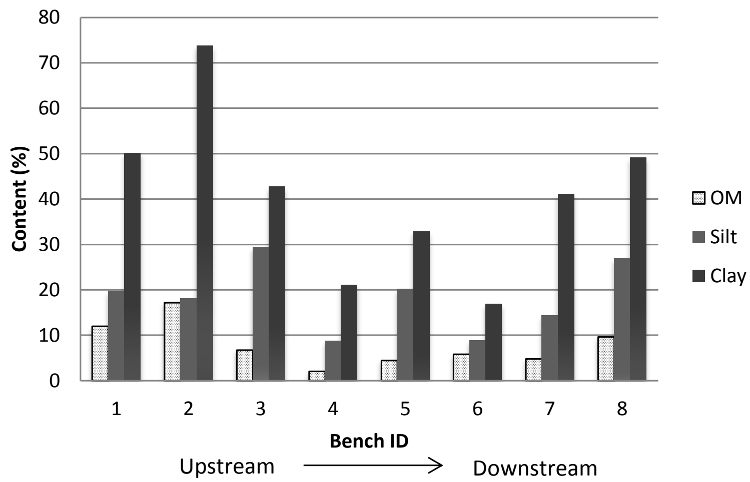


Fig. 15. Organic matter, silt, and clay contents within bench sediment.

Particle size analysis results for bars revealed that on average, bars predominantly consist of coarse particles relative to finer particles of silt and clay (Fig 14b). Average particle size contributions for bars were 80% sand, 5% silt, and 15% clay. Pearson's correlation test revealed correlations between OC content and all three particle size fractions. OC content was significantly (p<0.001) correlated with sand, with an r^2 = - 0.260. The correlation between OC content and silt (p<0.001) had the strongest correlation (Fig. 17; Fig. 18), with an r^2 = 0.430.

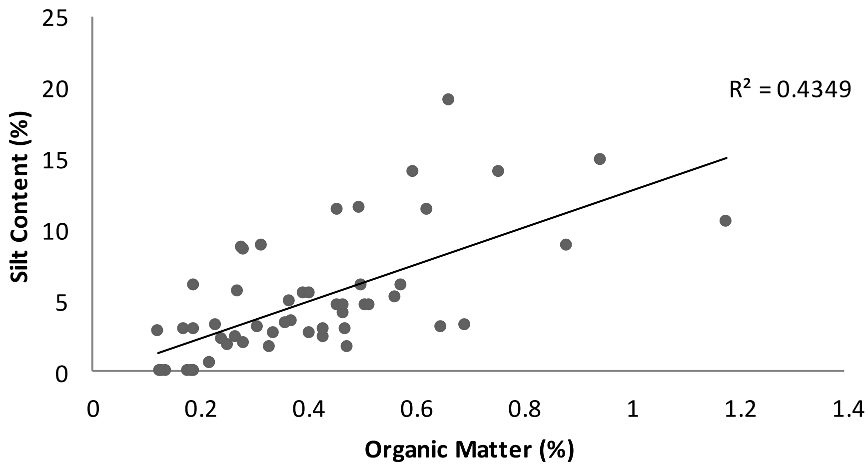


Fig. 16. Silt content (%) and OM content (%) relationship for bar sediment.

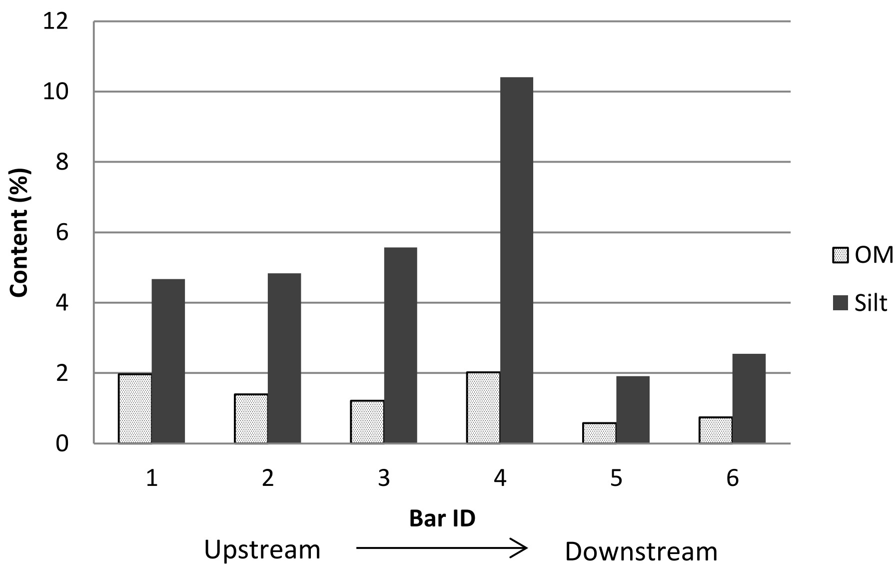


Fig. 17**.** Organic matter and silt contents within bar sediment.

Table 4. Individual OC loads for each feature listed in order of longitudinal location from upstream to downstream.

Site	Feature	Volume of Feature (m^3)	gC/m^3 (Sedimentary)	Total gC (Sedimentary)	gC/m^2 (Surface OM)	Total gC (Surface OM)	TOC Load (kgC)
1	**Bar 1**	2,865	2,865	576,197	457	69,711	646
2	**Bench 1**	36,537	36,537	4,853,884	525	1077,878	5,932
	Bench 2	58,579	58,579	63,158,584	1,000	34,188	63,193
3	**Bench 3**	29,187	29,187	1,796,224	556	19,947	1,816
	Bench 4	10,725	10,725	623,349	343	922,574	1,546
	Bar 2	8,861	8,861	7,961,950	242	48,637	8,011
4	**Bar 3**	3,866	3,866	537,266	424	24,709	562
5	**Bench 5**	22,955	22,955	11,255,736	1,881	922,573	12,178
	Bench 6	19,394	19,394	1,560,709	604	91,898	1,653
	Bar 4	2,521	2,521	2,572,863	155	217,873	2,791
	Bench 7	17,396	17,396	735,035	585	58,946	794
6	**Bench 8**	41,325	41,325	43,128,803	136	158,017	43,287
	Bar 5	2,801	3,239	715,283	156	34,528	750
7	**Bar 6**	3,239	2,801	120,352	698	30,010	150

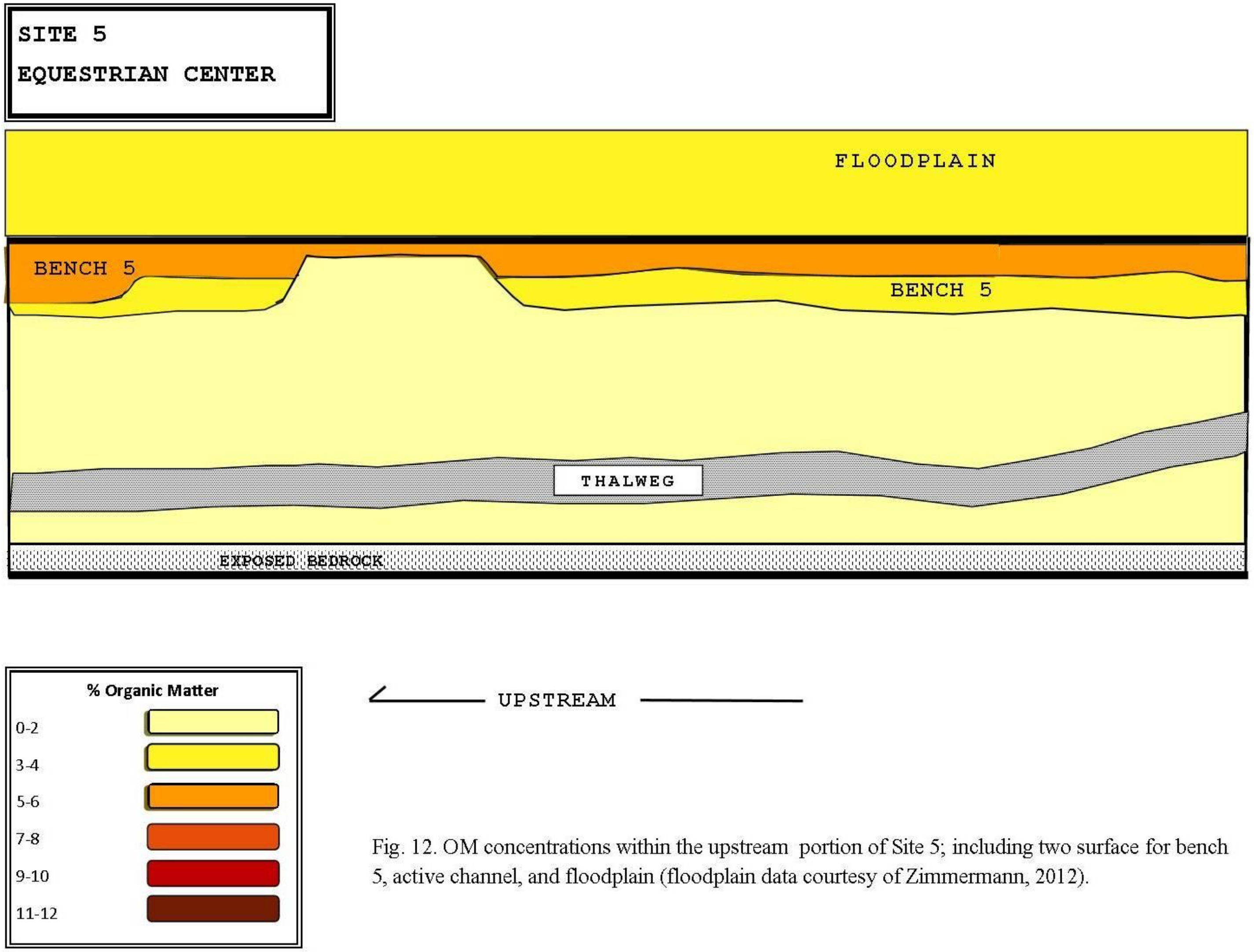
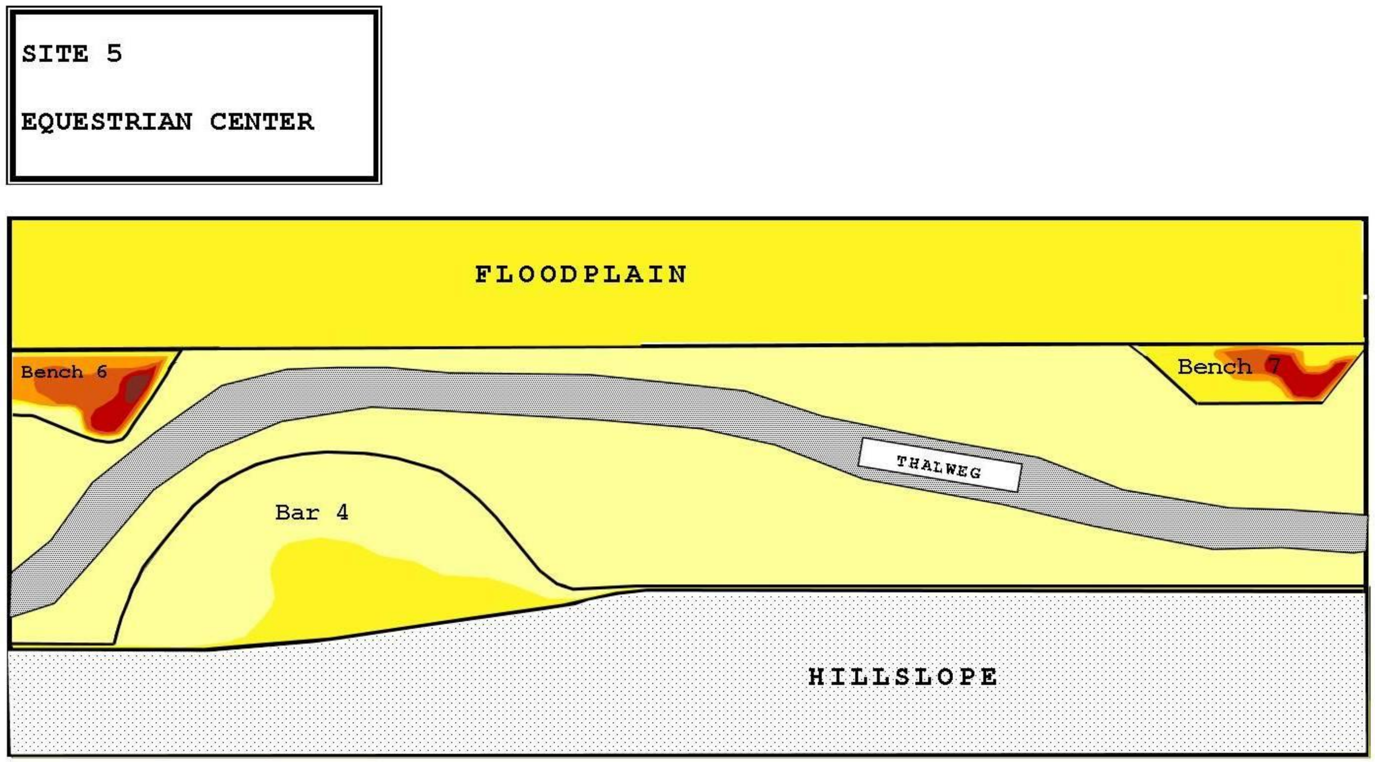
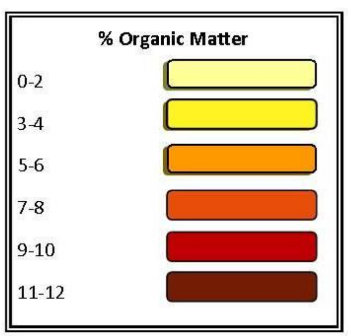


Fig. 12. OM concentrations within the upstream portion of Site 5; including two surface for bench 5, active channel, and floodplain (floodplain data courtesy of Zimmermann, 2012).





UPSTREAM

Fig. 13. OM concentraions within the downstream portion of Site 5; including bench 6, bar 4, bench 7, active channel, and floodplain (floodplain data courtesy of Zimmermann, 2012).

5.0 Discussion

5.1 Distribution of Organic Carbon within In-Channel Deposits

On average, OC percentages within bar sediment subsamples were consistently lower than bench sediments, and despite differences in site characteristics, such as hydrologic conditions and anthropogenic disturbance, bars displayed little variability in OC percentages between features. Bars likely have a lower OC content when compared to benches because the sediments are coarser, and their low in-channel position results in frequent inundation and short residence times. Especially low OC content were found at bar 5 (Site 6) and bar 6 (Site 7), which were located furthest downstream. Their longitudinal position may account for low OC content, due to decreased POC as discharge increases downstream. Interestingly, the OC percentages within the remaining bars (1,2,3, and 4) were relatively consistent despite differences in morphological form (mid-channel and point), levels of anthropogenic and hydrological disturbance, and vegetation densities. This may indicate that position in the channel and the particle size distributions have a greater influence on OC storage in bars than other site variables.

Benches displayed a greater variability in OM content across the eight benches sampled and within each feature. Benches 1 and 2 contained the greatest amounts of OM and were located at the same site (Site 2). Hydrologic conditions have been altered at this site due to a large dam that is in place. Bench 8 (Site 6), also displayed a high OM content and was associated with an area of the channel which has undergone hydrologic changes due to a mill-dam at Kymulga Gristmill. Additionally, both benches had high vegetation densities. Bench 8 was sparse in established trees, but it was heavily landscaped and planted sod covers the entire surface. Vegetation traps POC during inundation and helps to stabilize sediment, which may also help preserve this bench (Woodyer 1976). Additionally, OM production occurring on bench surfaces may be contributing large amounts of OC to the soils over time through decomposition. Results from site benches 3 and 4 (Site 2) support these findings, in which bench 4, a sparsely vegetated bench situated low in the channel contained the lowest amount of OC of all the benches sampled. Interestingly, bench 3, a highly vegetated bench situated high in the channel and immediately adjacent to bench 4, contained much greater OM content. Another possible explanation for this difference may have to do with the height of the feature above the channel. Bench 4 is likely reworked more often, and is constructed of coarse particles relative to bench 3, causing lower potential for OM accumulation.

While bench surfaces, on average, accumulated a greater amount of organic matter than bars, both types of in-channel deposits displayed potential for OM storage. Sources of this OM and the residence times within each feature may vary, suggesting that benches and bars may play distinctly different roles in surficial OM storage and processing. The greatest amount of surficial OM was located at bench 5 (Site 5). This was due to a debris dam located along the near-bank edge of the bench, which drastically increased the OC load of this bench. This created outlying data when compared to other surficial OM loads. All other features sampled consisted of leaf litter and particulate OM. No other debris dams were present. Sampling took place from late October to early December; therefore, data represents maximum inputs due to autumn shed leaves. While sites were not resampled later in the year, observations taken at site 5 during late winter, following the wet season, indicated that surficial OM on bars likely have a very short (seasonal) residence time, while benches may store OM shed in autumn for longer periods. The bar at site 5 was partially inundated while the three benches showed little sign of disturbance and large accumulations of leaf litter remained on the surfaces, as well as the debris dams on bench 5. Bars tend to be much less densely vegetated, but they accumulate all three size fractions of OM. The likely source of this OM is inputs from riparian zones upstream, making bars an important storage location for OM as it is transported downstream. This retention, while admittedly unimportant for long-term carbon budgets, is important to aquatic communities and nutrient cycling processes within aquatic systems. In contrast, benches in the Southern Piedmont have been shown to persist for decades (Royall et al. 2010) and field observations of multi-seasonal residence times for surface OM suggests that benches may represent long-term carbon sequestering sites with large inputs from in-situ biomass production. If transport of OM is limited on these landforms, autumn-shed leaves may be contributing greatly to soil OM contents.

While the distribution of sedimentary OC between benches in the watershed differ, there seems to be no relationship between longitudinal position and OC content. I hypothesize that this is due to other dominant controls of OC content, aside from longitudinal position. Differences in other variables, such as bench type (i.e. marginal, concave, point), vegetation density, height above the channel, reach hydrological characteristics and anthropogenic disturbances, likely muddle any possible relationship between longitudinal position and OC content. A variety of combinations of these variables were found within this study stream. Bench types differ in form due to secondary flow patterns, which in turn affect sediment particle size and OC content. Concave benches, for example, often contain relatively high OC contents compared to other bench types. Anthropogenic disturbance and flow regulations can alter these flowpaths and affect bench formation and OC storage. Additionally, the height of the feature above the channel influences the frequency of inundation, vegetation density, and particle size distributions, all of which may control OC concentrations within a deposit. Benches situated high above the channel bed are likely to be reworked infrequently, have increased vegetation densities, and fine particle size; all of which increase OC storage potential. Bench size becomes an important factor in OC storage potential when features are considered in their entirety. In-channel bars displayed less variety in form between features, which may indicate less complex formation, and explain the greater consistency in OC content within and between them. OC content within bars did tend to decrease with increased distance downstream, possibly due to decreased allocthanous OC inputs as hillslope/channel coupling decreasing downstream. Increased OC content at near-bank sampling locations may be due to increased vegetation density towards the back of bar surfaces, increasing *in-situ* OC contributions. Another explanation for the difference in distribution may have to do with flood frequency. Field observations from site 5 indicate that the near-bank portions of large point-bars may not be inundated as frequently as the near-channel portion; therefore allowing for fewer opportunities for OC accumulation and fine sediment. Contrary to previous research, this study did not find differences in OC content between surface and at depth samples. Other studies (Changxing et al. 1998) found increased OC due to buried organic matter “packs” and decreased OC otherwise. The sampling interval used in my study may not have been adequate for elucidating this relationship.

Distributions of surface organic matter on top of benches revealed a similar relationship with longitudinal position as was seen with OC and bars, indicating decreased surface litter, particularly FPOM, with distance downstream. Again, this may be due to decreased hillslope/channel coupling downstream. Sampling methods in this study for surface OM likely favored collection of coarse OM (i.e. autumn-shed leaves) and may have underrepresented

CPOM and FPOM where leaves were not present to collect finer OM fractions. These data are probably most reflective of the degree of vegetation establishment on benches. Therefore, surface organic data from this study, showed no differences between sampling locations, as vegetation densities were fairly uniform throughout each bench surface. In contrast, bar surfaces had low to moderate vegetation density, and autumn-shed leaf fall was not uniform. Surface OM data for bars may represent instances of established trees as well as accumulation zones of transported OM. Surface OM was greatest at the upstream ends of bars, where transported OM was accumulating due to velocity changes and flow obstruction. This OM storage is important for aquatic communities, and retention zones such as these are crucial for OC availability within the stream.

The dramatic difference in total OC loads between individual features is evident and is due to a number of variables controlling OC load potentials. These variables, as previously discussed, may include landform type, particle size, OM content, vegetation density, hydrologic characteristics, height above the channel, anthropogenic disturbance, and landform size. Each depositional feature sampled displayed a unique combination of these variables, which likely influences its OC loads. Many of these variables were not explicitly examined with these methods; however, their potential influence on OC storage potentials are likely important. The methods used for this study did, however, explicitly examine OM content in relation to landform type, and landform size. Both of these variables proved to be important in OC storage potentials.

Natural breaks in TOC data allows for discussion based on three TOC load classes; High: >13,000 kgC, Medium 5,000kgC- 13,000 kgC, and Low: < 5,000 kgC. Only two features had a TOC content higher than 13,000 kgC. These include bench 2 (Site 2) and bench 8 (Site 7). The cause of these elevated TOC loads is likely due to a few factors, including high OM content, very large surface areas, increased clay content and dense vegetation on the bench surface which further facilitated bench development. Exposed bedrock and channel confinement at site 2 may have enhanced bench deposition, resulting in the large surface area of bench 2. Additionally, dams are present at both of these reaches, influencing the flood frequencies, accumulation rates, and sediment texture available to these features. Features within the medium TOC loading class include benches 1(Site 2) and 5 (Site 5), as well as Bar 2 (Site 3). High TOC loads for bar 2 are due to the size of the feature, which was one of the largest features sampled. Aside from the size of the bench, bar 2 displays characteristics that would inhibit OC loading, including low OM content and a lack of established vegetation. The remainder of the bars sampled make up the low TOC loading class, along with benches 3,4,6, and 7. These benches have relatively low TOC loads compared to other benches for a number of reasons. Benches 3 and 7 display relatively high OM content; however, their extremely small area results in low TOC loads. Benches 4 and 6 were not only very small features, but also displayed low OM content as well as low silt and clay contents, causing low TOC loads on these features as well. Based on these data, a conceptual model can be utilized to describe TOC load classes and the feature characteristics influencing TOC loads (Fig. 19).

5.2 Sediment Particle Size and Organic Carbon

OC content within benches was correlated with fine particles, particularly clay. Previous research (Bechtold and Naiman 2009) has demonstrated this relationship, and the results from this study support these findings. The three benches with the greatest average OC content also contained the greatest percentages of clay and silt in comparison with sand. In considering the

OC differences between adjacent benches at Site 3 (benches 3 and 4), indeed particle size differences may offer an explanation. Bench 3 contained a much greater amount of clay and silt compared with the bench 4, which is situated immediately downstream and lower in the channel than bench 3. Interestingly, clay and silt content within bench 4 and bench 6 (a point bench at Site 5) are very similar, yet the OC content within bench 6 is slightly higher. It is possible that the different bench types and associated genetic processes are responsible for the differences in OC content, rather than strictly particle size. A much greater amount of sand particles within bar sediment results in a drastic decrease in OC content, when compared to benches. OC of bar sediment correlated with clay and silt, but the strongest relationship was detected with silt percentage, most likely because clay content in bars was very low. Bars 1-4 were located much further upstream than bars 5 and 6, and interestingly, particle size distributions between these sections of streams are very different. Bars 5 and 6 have much lower silt contents than the bars upstream, and thus have a lower OC contents as well.

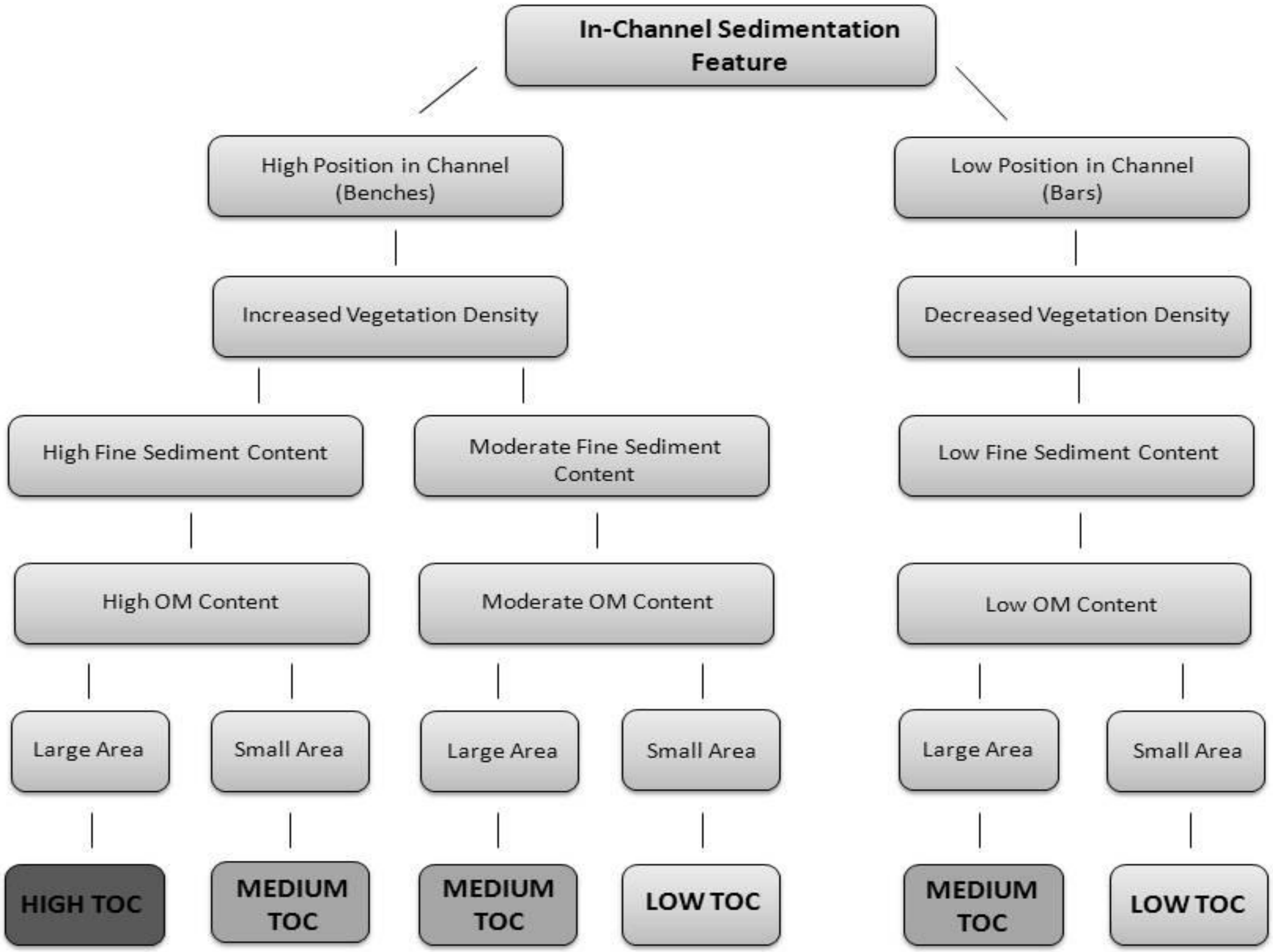


Fig.18. TOC load class model based on feature characteristics.

5.3 Reach-Scale Organic Carbon Storage

The reach at site five contained a large amount of OC, with the majority of storage taking place within in-channel deposits, benches in particular, in comparison to the active sediment within the channel bed. The features with the largest storage capacities were bench 5 and the active channel sediment. This is well-aligned with other findings of this study, that support the argument that accumulation rates and greater depositional area an important control on TOC storage potentials within in-channel deposits. However, bench 5 occupies a smaller area than the active channel bed, yet still has a slightly greater OC load when the two are compared. Similar to the active channel sediments, bar sediments within this reach had low OC contents, but bar 4 was a considerable size compared to the benches within the reach; therefore, bar 4 had a greater individual contribution than benches 6 and 7 combined. Benches 6 and 7 displayed the highest OC concentrations within sediments, but they are not large enough in size to contain OC loads similar to OC loads within large features. Interestingly, benches 6 and 7 displayed patterns of increased OC content similar to those reported in other studies. Both benches displayed increased OC content near the downstream section of the deposit. Hydrologic properties at this section of the reach may explain these concentrations. The thalweg meanders near these two benches, perhaps causing the downstream ends of these benches to be inundated more frequently. Bench 7 also contains a high percentage of clay particles, which also partially explains the increased OC content. A slight increase in OC content near the back of bar 4 may be explained by an increase in vegetation density in this area. Additionally, field observations in late winter revealed that the front portion of bar 4 was inundated, while the back portion appeared undisturbed. Site 5 proved to be an appropriate reach for estimating reach-scale TOC loads and represents complex sections of Talladega Creek well. This reach included both depositional landform types and it included benches with a variety of characteristics that may influence OC storage.

When considering only the 14 deposits sampled in this study, the TOC loads for these sections of Talladega Creek is approximately 143,310 kgC. Benches prove to be an important contribution in OC storages within this fluvial system. Using Site 5 TOC loads as an estimate for the entire stream, one could predict that Talladega Creek contains nearly 25,000,000 kgC within in-channel depositional features. This estimate assumes that the sections of Talladega Creek not sampled in this study exhibit similar channel complexity and in-channel sedimentation characteristics of sampled reaches.

Comparisons of these data to that of floodplain studies is problematic because of differing spatial and temporal scales as well as differing study objectives. Many studies that assess floodplain carbon cycling and sequestration loads do so at very large spatial scales and/or tend to examine accumulation rates rather than total OC loads. Hoffman (2007) found that the Rhine catchment in Germany, one of the largest in Europe, has sequestered 0.7 – 1.6 Gt of carbon with sequestering rates of 3.4 to 25.4g m^{-2}. Similar data exist for rivers within the Atlantic Coastal Plains, and identified a much greater accumulation rate of 61 – 212g m^{-2}, due to recent increased erosion (Noe and Hupp 2005). The best comparisons of floodplain and in-channel OC storage is accomplished by examining OC contents found in floodplain soils of these previous works. OC contents within soils within the Rhine catchment, Atlantic Rivers, and an additional study of the St. Lawrence River (Drouin et al. 2011) were 1.1 – 7.0%, 4.0 – 30.0%, and 0.05 – 3.16%, respectively. OC content within in-channel deposits of Talladega Creek ranged from 0.6 – 15.9%, with bench sediment containing an average of 7.4% OC. These values are comparable to those found in floodplains, and may indicate that TOC loads and OC sequestering rates for in-channel deposits are also significant. Additionally, a study conducted at four of the reaches examined in this research found that floodplain OC content tends to be lower than OC content of adjacent in-channel benches (Zimmermann, 2012). This further supports the idea that in-channel deposits are an important component of OC storage within river systems.

6.0 Conclusions

In-channel benches and bars within Talladega Creek differ in their OC storage potentials, but together these features sequester large amounts of OC and represent a significant OC sink, that in the case of benches can exist for decades. Analysis of sediment samples (<2mm) revealed that benches have a predisposition for increased OC storage when compared to sediments within bars. Benches are also inherently made up of these fine sediments, while the majority of volume within a bar consists of large, inorganic particles; therefore, when calculating organic content per cubic meter, the discrepancy between storage potentials of benches and bars becomes greater as we consider coarse particles (>2mm). This results in a much lower potential OC storage of bars per cubic meter when compared to in-channel benches. Both landform types stored significant amounts of surface OC; however, bars tend have less established vegetation, which suggests the source of OC on their surfaces is upstream inputs. These OC stores are likely short term, as bars are often positioned low in the channel and inundated often. Nonetheless, this OC retention is important for nutrient cycling and community structure of aquatic communities within the stream. Benches contained a greater amount of OC on their surfaces compared with bars, which may be attributed to increased vegetation densities. Benches are often situated higher in the channel and are inundated less frequently than bars, thus surficial OC loads on benches may have greater residence times and be important contributions to regional carbon budgets. OC storage within both landform types was found to be influenced by sediment particle size. An increase in fine sediment content; i.e. silt and clay, resulted in an increased OC content. Overall, bars tended to consist of coarse sand particles, while benches tended to have lower sand contents and increased fine sediment contents.

When extrapolating OC loads to determine TOC loads for entire features, feature size becomes an important factor and the differences in potential OC storage is somewhat diminished. On average, total area of benches and bars were similar and both landform types display a large range of depositional area. While benches had a greater OC storage capability per unit area, some very large bar deposits contained TOC loads comparable to those of small to medium benches, simply due to their size. It remains evident; however, that large benches have the greatest TOC storage potential. A lack of large concave and point benches within the stream suggests that marginal benches may be more likely to become very large in area, and therefor may have the greatest potential for OC storage, simply due to their size. The two largest benches sampled in the study were associated with dams, which may partially explain their increased size and/or OC content.

TOC load estimates for the features sampled within Talladega Creek reveals high TOC loads for in-channel deposits, with benches being particularly important OC storage features. A comparison of this data and floodplain studies suggests that in-channel OC content may be similar or higher than that of floodplains soils, and may represent another important OC sink within fluvial systems. Further research is necessary to determine broader scale in-channel TOC budgets; however these results demonstrate the importance of in-channel landforms and geomorphic processes in riverine OC cycling. An inclusion of in-channel OC loads in regional carbon budgets and carbon cycle models with increase model accuracy and predictions. In addition, the OM retention by in-channel landforms is important for the sustainability of aquatic communities and should be considered in river and land management practices.

7.0 References

Battin, T., Luyssaert, S., Kaplan, L., Aufdenkampe, A., Richter, A., Travnik, L. 2009. The Boundless Carbon Cycle. *Nature Geoscience* 2:598-600.

Bechtold, J., Naiman, R. 2009. A quantitative model of soil organic matter accumulation during floodplain primary succession. *Ecosystems* 12: 1352-1368.

Bouyoucos G.J. 1962. Hydrometer method improved for making particle size analysis of soil. *Journal of Agronomy* 54:464-465.

Brown, A.L. 1987. Freshwater Ecology. Heinimann Educational Books, London.

Burge, L.M, and Smith, D.G. 1999. Confined meandering river eddy accretions: sedimentology channel geometry, and depositional processes, *Fluvial Sedimentology VI*, Special Publication Number 28 of the International Association of Sedimentologists: Oxford, Blackwell Science, p. 113- 130.

Changxing, S., Petts, G., and Gurnell, A., 1999. Bench development along the regulated, lower River Dee, UK. *Earth Surface Processes and Landforms* 24:135-149.

Cole, J., Prairie, Y., Caraco, N., McDowel, W., Tranvik, L., Striegl, R., Duarte, C., Kortelainen, P., Downing, J., Middelburg, J., Melack, J. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* 10:171-184

Craft, B., Casey, W. 2000 Sediment ad nutrient accumulation in floodplain and depressional freshwater wetlands of Georgia, USA. *Wetlands* 20: 323-332.

Daniels, M. 2005. Distribution and dynamics of large woody debris and organic matter in a low-energy meandering stream. *Geomorphology* 77: 286-298.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44(1): 242-248.

Drouin, A., Saint-Laurent, D., Lavoie, L., and Ouellet, C. 2011. High-precision elevation model to evaluate the spatial distribution of soil organic carbon in active floodplains. *Wetlands* 31(6): 1151-1164.

Dunne, T. and Leopold, L.B., 1978. *Water in Environmental Planning*. Freeman, 818 p.

Ehrman, T., Lamberti, G .1992. Hydraulic and particulate matter retention in a 3rd order Indiana stream. *Journal of the North American Benthological Society* 4: 341-349.

Erskine, W. D., and Livingstone, E. A., 1999. In-channel benches: the role of floods in their formation and destruction on bedrock-confined rivers. Chapter 18 in: A.J. Miller and A. Gupta (Eds.), *Varieties of Fluvial Form*, p. 445-475

Fryirs, K.A., Brierley, G.J., Preston, N.J., and Kasai, M., 2007. The (dis)connectivity of catchment-scale sediment cascades. *Catena* 70: 49-67.

Gee, G.W., and J.W. Bauder. 1979. Particle size analysis by hydrometer: a simplified method for routine textural analysis and sensitivity test of measured parameters. *Soil Sci Scoc. Am. J.* 43:1004-1007.

Gislason, S., Oelker, E., Snorrason, A. 2006. The role of river-suspended material in the global carbon cycle. *Geology* 34:49-52.

Hadwen, W., Fellows, C., Westhorpe, D., Rees, G.,Mitrovic, S.,Taylor, B. 2009. Longitudinal trends in river functioning: Patterns of nutrient and carbon processing in three Australian rivers. *River Research and Applications* 26: 1129-1152.

Harman, W.A., 2000. Finding bankfull stage in North Carolina Streams. River Course Fact Sheet Number 3, North Carolina Stream Restoration Institute, North Carolina Cooperative Extension Service.

Heiri, O., Lotter, A., and Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25(1): 101-110.

Hooke, J.M. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology* 56 (1-2): 79- 84.

Hooke, J.M., Yorke, L. 2011. Channel bar dynamics on multi-decadal timescales in an active meandering river. *Earth Surface Processes and Landforms* 36: 1910-1928.

Kilpatrick, F.A., and Barnes, H.H. Jr., 1964. Channel Geometry of Piedmont Streams as Related to Frequency of Floods. Physiographic and Hydraulic Studies of Rivers, US Geological Survey Professional Paper 422-E.

Lamberti, G.A., Gregory, S.V., Ashkenas, L.R., Steinman, A.D., McIntire, C.D. 1989. Productive capacity of periphyton as aa determinant of plant-herbivore interationcs in streams. *Ecology* 70: 1840-1856.

Nelson, D.W., Sommers, L.E. 1982. Total carbon, organic carbon and organic matter. P. 539-580. In R. Lal et al. Page et al. (ed.) Methods of soil Analysis. Part2. 2nd ed. Madison, WI.

Noe, Gregory B., and Cliff R. Hupp. 2005. Carbon, Nitrogen, and Phosphorus accumulation in floodplains of Atlantic coastal plain rivers, USA. *Ecological Applications* 15:1178–1190.

National Resources Conservation Service, 1964. Soil survey of Talladega County, Alabama. U.S. Department of Agriculture.

Hupp, C.R. and Osterkamp, W.R., 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. *Ecology* 66(3): 670-681.

Rice, S. P., Church, M., Wooldridge, C.L., and Hickin, E.J. 2009. Morphology and evolution of bars in a wandering gravel-bed river; lower Fraser river, British Columbia, Canada. *Sedimentology* 56(3): 709-736

Robertson KM, Augspurger CK. 1999. Geomorphic processes and spatial patterns of primary forest succession on the Bogue Chitto Rier, USA. *Journal of Ecology* 87: 1052-63.

Royall, R., Davis, L., Kimbrow, D. 2010. In-channel benches in small watersheds; examples from the Southern Piedmont. *Southeastern Geographer* 50: 445-467

Santisteban, J.I., R. Mediavilla, E. Lopez-Pamo, C.J. Dabrio, M.B.R. Zapata, M.J.G. Garcia, S. Castano, and P.E. Martinez-Alfaro. 2004. Loss on ignition a qualitative or quantitative method for organic matter and carbonate mineral content in sediments? *Journal of Paleolimnology* 32: 287- 299.

Schwartz, J., Herricks, E. 2005. Fish use of stage-specific luvial habitats as refuge patches during a flood in a low-gradient Illinoise stream. *Canadian Journal of Fisheries and Aquatic Sciences* 62: 1540-1552.

Schumm, S.A. 2005. River Variability and Complexity. Cambridge University Press, New York.

Sheldon, F., Thoms, M.C. 2006. In-channel geomorphic complexity: The key to dynamics of organic matter in large dryland rivers? *Geomorphology* 77 (3-4): 270-285.

Thomas, S., Royer,T., Snyder, E., Davis, J. 2005. Organic carbon spiraling in an Idaho River. *Aquatic Science* 67: 424-433.

Thoms, M.C. and Olley, J.M. 2004. The stratigraphy, mode of deposition and age of inset flood plains on the Barwon-Darling River, Australia. International Association of Hydrological Sciences Publication 288.

U.S. Geological Survey. 2012. Water-resources data for the Unites States, Water Year 2011: U.S. Geological Survey Water Data Report WDR-US-2011, site 02406500, accessed at http://wdr.water.usgs.gov/wy2011/pdfs/02406500.pdf

Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 130-137

Vietz, G., Stewardson, M., Finlayson, B. 2006. Flows that form: the hydromorhphology of concave-bank bench formation in the Ovens River, Australia. *Sediment Dynamics and the Hydromorphology of Fluvial Systems* [Proceedings of a symposium].

Wallace J., and Benke, A. 1984. Quantification of wood habitat in subtropical coastal plain streams. *Canadian Journal of Fisheries and Aquatic Sciences* 41 (11): 1643-1652

Wang, Z., Govers, G., Steegan, A., Clymans, W., Putte, V., Langhans, C. 2010. Catchment-scale carbon redistribution and delivery by water erosion in an intensively cultivated area, *Geomorphology* 124 (1): 65-74

Warner, R.F. 1987. The impacts of alternating flood and drought-dominated regimes on channel morphology at Penrith, New South Wales, Australia. In: *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources*, IAHS Publication no. 168, pp. 327-338.

Woodyer, K., Taylor, G., Crook, K. 1979. Depositional processes along a very low-gradient, suspended-load stream: the Barwon River, New South Wales. *Sedimentary Geology* 22: 97-120.