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Anthropic signatures in alluvium of the Upper Little Tennessee River valley, Southern Blue Ridge Mountains, USA

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ABSTRACT

Human activities have become important influences on the fluvial systems of eastern North America since post-colonial settlement. This research identifies post-settlement anthropic signatures in alluvial sediments in the Upper Little Tennessee River, USA. Agricultural and mining activities were scattered and discontinuous in this relatively remote region of the Southern Blue Ridge Mountains. We compared physical and chemical characteristics of sediments in post-settlement and pre-settlement stratigraphic units at three separate sites. Chronologies were calculated using non-linear power functions based on radiocarbon and optically stimulated luminescence ages, as well as dates from ^{137}Cs and historical records. These chronologies suggest that sedimentation rates increased with time during the post-settlement period but decreased with time during the pre-settlement period. In addition, long-term average sedimentation rates are one order-of-magnitude higher in the post-settlement time than in the pre-settlement time. Sediment becomes finer upward through the pre-settlement unit but coarsens-upward in the post-settlement unit. Statistical analyses on adsorbed elemental concentrations suggest that three elements (Ca, Hg, Pb) clearly differentiate sediments between pre-settlement and post-settlement periods. The identified anthropic signatures thus include higher sedimentation rates, coarser sediment texture, and higher concentrations of the three elements in the post-settlement units. These characteristics likely reflect human activities such as commercial timber harvest and scattered gold mining in the late 19th and early 20th century, modern agricultural practices, and urbanization since the 1970s. Findings of this study demonstrate significant impact on fluvial systems in regions with very limited history of intense human activities. This history stands in stark contrast to other parts of the world, like Europe and Asia, that record thousands of years of anthropic impact.

1. Introduction

Climate change and human activities are the primary drivers of floodplain sedimentation in the late Holocene (Knighton, 1998; Charlton, 2008). Stratigraphic records of floodplain sedimentation provide important information about variations in climate and human impact on the landscape, and geomorphic processes (Gregory et al., 1995; Knighton, 1998; Knox, 1987, 2001, 2006; Macklin and Lewin, 2003; Lewin and Macklin, 2005). In many parts of the world such as Europe, Asia, and the Middle East, human activities have a long and continuous history so that anthropic signals appear early within the Holocene (Kalis et al., 2003; Xu, 2003; Jones et al., 2013; Leigh et al., 2015). In contrast, in North America, it is generally regarded that the most pronounced and significant human impacts on the fluvial system did not begin until after settlement by non-indigenous people (Trimble, 1974; Jacobson and Coleman, 1986; Knox, 1987; Ambers et al., 2006; James, 2011). We refer this time period as the post-settlement period. Although some have argued that Native Americans accelerated erosion and sedimentation in eastern North America from agricultural activities during the last 1000 years including the Mississippian and Cherokee cultural periods (Stinchcomb et al., 2011; Dotterweich et al., 2015), such effects may be spatially isolated and not necessarily transmitted to river floodplains. In fact, it has been demonstrated that such pre-settlement impacts are not apparent in the alluvium in the Upper Little Tennessee basin (Leigh, 2016).

It can be difficult to distinguish the anthropic signals in fluvial sediments from climate signals in regions where significant human activities started thousands of years earlier (Wolf et al., 2014), but in many places in North America, there are clear distinctions between floodplain sediments of the pre-settlement and post-

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settlement periods that signal human activity. Many studies have found significant differences of overbank sediments between the two periods in terms of sediment textures, sedimentology and sedimentation rates (Lecce, 1997; Knox, 2001, 2006; Benedetti, 2003; Leigh, 2016). Accelerated upland erosion and surface runoff, resulting from intensive human activities such as row-crop agriculture, timber harvest, and land clearing for construction during the post-settlement period (Glenn, 1911; Happ, 1945; Trimble, 1974; Leigh, 2007), has caused coarser sediments and greater sedimentation rates than those of pre-settlement time (Miller et al., 1993; Knox, 2001, 2006; Benedetti, 2003; Leigh, 2016). In addition to the physical characteristics, chemical characteristics vary significantly as well. For example, the lead and zinc content in overbank sediments increased greatly in the upper Mississippi valley during the 19th century due to mining activities (Knox, 1987, 2006). Mercury (Hg) and gold (Au) concentrations were distinctively higher in post-settlement sediments of Georgia and North Carolina because of past gold mining (Leigh, 1994, 1997; Lecce et al., 2008, 2011; Pavlowsky et al., 2010).

The signs of increased human activity in fluvial sediments are most apparent in regions where post-settlement agricultural and mining activities were long-lasting and pronounced. However, less study has been done in the more remote highlands of the Southern Blue Ridge Mountains, where historic subsistence agriculture was discontinuous and mining activities were low-intensity and scattered. Our research studies sedimentological and geochemical characteristics of overbank sediments in the Upper Little Tennessee River valley, a small catchment in these relatively remote highlands. Here we examine the differences between anthropic post-settlement and background pre-settlement periods and identify clear indicators of human impacts on fluvial sediments.

2. Study area

The Upper Little Tennessee River drains a 363 km^2 catchment above the United States Geological Survey (USGS) gaging station near Prentiss (USGS gage 03500000), with elevations ranging from 510 to 1600 m above sea level in northeast Georgia and western North Carolina (Fig. 1). The representative bedrock of the region is quartz dioritic gneiss and biotitic gneiss (Hatcher, 1988; Daniel and Payne, 1990; Robinson, 1992), which has been weathered to form a 1–30 m thick mantle of saprolite. The texture of saprolite ranges from sand to clay loam, providing abundant fine sediments to the drainage network (Price and Leigh, 2006; Leigh, 2010). Entisols and inceptisols are common soil orders on floodplains and the first terraces, which are derived from reworked saprolite, alluvium or colluvial deposits (Leigh, 2010). The Upper Little Tennessee River flows north and is fed predominantly by east- and west-flowing tributaries (Fig. 1). The morphology of the channel is characterized by meandering riffles and pools with coarse bed sediments of cobbles to coarse sand, and with finer overbank sediments of fine sand, silt and clay (Price and Leigh, 2006). The region lies in a humid temperate climate zone, with 30-year (1981–2010) average annual precipitation of 1752 mm and average annual temperature of 13 °C, as recorded at the low elevation climate station of the Coweeta hydrological laboratory.

Humans have been present in the region since the terminal Pleistocene but hunters and gathers of the early and middle Holocene were scattered in low density groups around the southeastern U.S. Permanent Native American settlements relying on maize and bean agriculture blossomed around 1000 years ago during the Mississippian cultural period (Delcourt et al., 1986). They were settled mainly on the floodplains with easy access to water and rich alluvial soils for agriculture practice (Swanton, 1946; Gragson and Bolstad, 2007). The indigenous

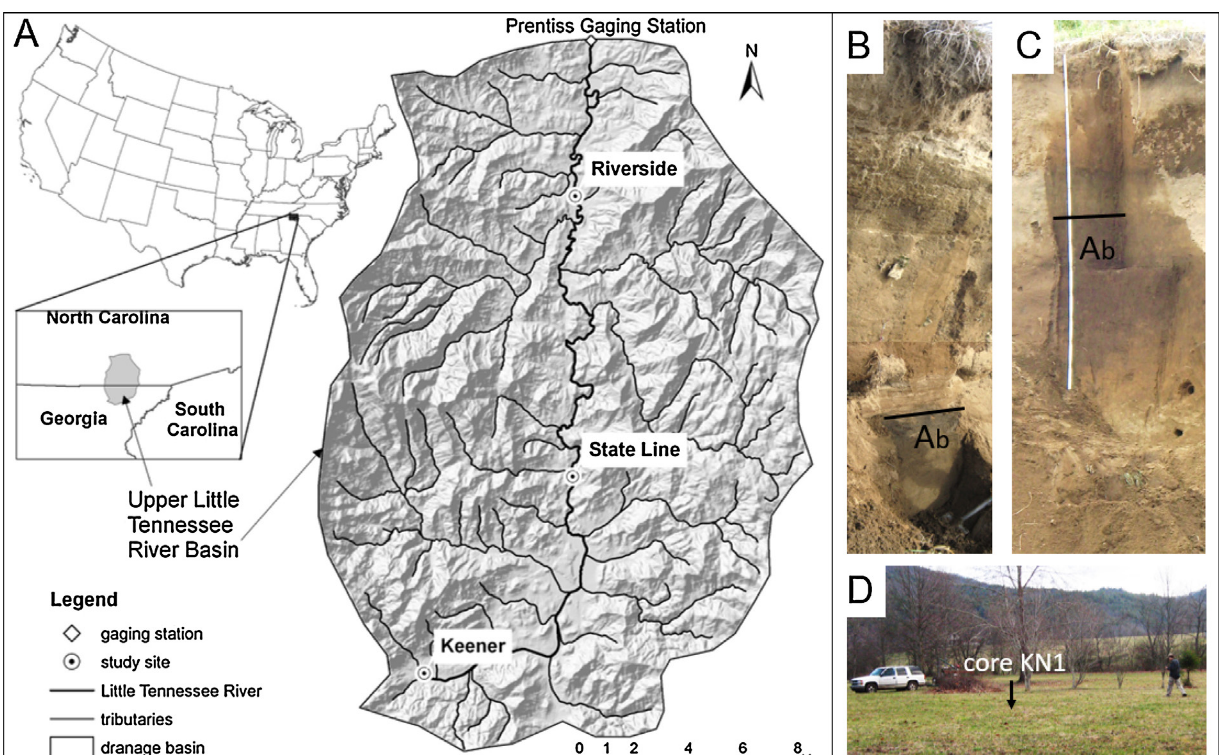

Fig. 1. A. Location of the Upper Little Tennessee River Valley and the three sites in this study (Wang and Leigh, 2012). B. Vertical profile of the State Line site; C. Vertical profile of the Riverside site; D. Landscape of the Keener site and the location of core KN1.

agriculture used simple tools and no mechanized methods and thus was minimally destructive to soil and slope stability (James, 2011). In fact, Leigh (2016) found no increases in floodplain sedimentation rates during the Mississippian and Cherokee agricultural periods based on chronologies from of six well-dated stratigraphic sections. In addition, there is no archeological or ethnographic evidence to suggest that Native Americans used mineral additives for agriculture nor any metal smelting techniques to generate pollutants (Swanton, 1946; Ethridge and Hudson, 2002). Therefore, with low population density, and limited forest clearance and subsistence crop cultivation, the indigenous people had comparatively little influence on the fluvial sediments in the mountainous environment (Leigh, 2016). Europeans first came to this highland region as traders, missionaries, and military personnel in the 18th century (Gragson and Bolstad, 2007), but the region's population stayed low until the late 19th century, when more European-Americans settled in the region. There was a significant increase in population, agriculture, logging, and mining activities circa. AD 1870 (Leigh, 2010, 2016), as commercial timber harvest moved into the region. A detailed land use history over the past centuries in the region is described by Yarnell (1998) and Harden (2004) with the most notable features being extensive and intensive timber harvest that peaked in the early 20th century, reforestation throughout the region since the 1940s, and vacation home development on hillslopes since the 1970s that has stimulated sustained erosional disturbance. Currently, the land cover classes within the catchment include, forest (79.5%), pasture-grasses-shrubs (11.9%), developed (7.9%), cultivated (0.4%), and others (0.3%), according to the latest (2011) land cover data set (Homer et al., 2015).

This research looked at three specific sites in the bottomland of the Upper Little Tennessee River valley, including the Keener (34.9352°N, 83.4220°W), State Line (34.9980°N, 83.3807°W), and Riverside (35.0910°N, 83.3821°W) sites situated in the upper, middle, and downstream portions of the Little Tennessee River, respectively (Fig. 1). All three sites currently are within pastures and have been the subjects of previous investigations (Price and Leigh, 2006; Leigh, 2007; Leigh, 2010; Wang, 2010; Wang and Leigh, 2012; Leigh, 2016). In this paper, we focus on comparison of post-settlement alluvium against the natural background of the immediate predecessor (previous 2000–3000 years) of late-Holocene pre-settlement alluvium at the three sites.

3. Methods

3.1. Field sampling

Sediment cores were taken with a trailer-mounted Giddings hydraulic soil probe at each site. Each core was wrapped with plastic and aluminum foil in the field and brought back to the laboratory. In addition to cores, monolith samples were obtained from the exposed vertical cutbanks at the State Line and Riverside sites by pounding PVC troughs into the profile and then meticulously excavating them out. The advantage of monoliths is that they are not compressed and preserve undisturbed layers in the best possible condition. Later in the laboratory, based on stratigraphic correlation and particle size analysis results, data from cores and monoliths were combined into a single profile to take advantage of the intact monolith samples. Samples for optically stimulated luminescence (OSL) dating were taken by pounding gray PVC tubes into sand strata and then sealing both ends with black duct tape. Charcoal and uncarbonized plant remains were collected from outcrops and cores for radiocarbon dating, including samples prior to our field work as cataloged by Leigh (2016).

3.2. Laboratory analyses

All cores and monoliths were cleaned, photographed and described according to the U.S. Department of Agriculture Soil Survey Manual (Soil Survey Division Staff, 1993). Samples were taken from each core and monolith in 3–14 cm increments to approximate 50-yr time intervals for pre-settlement sediments and 10-yr time intervals for post-settlement sediments, based on linear age models calculated from previous available dates from Price and Leigh (2006) and Leigh (2007). Abrupt and clear stratigraphic boundaries were more closely bracketed by smaller sampling intervals. Samples were oven dried at 55 °C and then sieved through 2 mm mesh. Particles larger than 2 mm were weighed and discarded, while particles smaller than 2 mm were retained for further analysis.

Approximately 0.5 g samples were taken for particle size measurements with an automatic laser particle size analyzer (*CILAS 1180*) in the Department of Geology and Environmental Geosciences at the College of Charleston. Samples were pretreated with 30% hydrogen peroxide (H_2O_2) to remove humus and then soaked in a sodium metaphosphate solution (50 g/L) to disperse clay aggregates before being introduced into *CILAS 1180*. The machine measures particles from 0.04 μm to 2500 μm and produces a continuous distribution of particle sizes. Traditional wet sieve and pipette methods were run on selected samples and the results were compared with the laser results, which showed a substantial underestimation of clay content by *CILAS* (Wang, 2010). This difference results from the non-sphericity of the particles, and is particularly significant for clay particles because of their platy form. Konert and Vandengerghe (1997) suggested a particle size of 8 μm by laser particle sizer is equivalent to <2 μm particle sizes by pipette method. According to this, when describing particle size data from *CILAS* using the program *GRADISTAT 4.0* (Blott and Pye, 2001), we treated the particles defined as fine and very fine silt in *GRADISTAT 4.0* as clay and actually used 8 μm as the boundary between silt and clay.

Samples of approximately 5 g were oven dried at 110 °C and then burned in a muffle furnace at 550 °C for four hours for loss on ignition (LOI) estimation. Weight loss from this process primarily comes from the combustion of organic matter (Dean, 1974; Heiri et al., 2001) but also includes dewatering of clay minerals and oxides (Beaudoin, 2003; Santisteban et al., 2004; Hoogsteen et al., 2015). Therefore, LOI values reflect variations imparted by organic matter, percent clay, and oxyhydroxides.

For chemical analysis, aqua regia (hot nitric:hydrochloric acid,1:3) was used to dissolve readily soluble matter and to remove extractable elements from the exterior of sediment grains that had been passed through a stainless steel mesh at 0.25 mm. Concentrations of 34 extractable elements were measured by inductively coupled plasma-atomic emission spectroscopy, and mercury (Hg) was analyzed by cold vapor atomic absorption spectrometry. The chemical analyses were conducted by a private commercial laboratory (ALS Chemex) with analytical precision certified to be within 10% of the detection limits.

Chronology of the three sediment profiles was based on ages obtained using four different techniques: OSL, radiocarbon, ^{137}Cs, and historic records. Three OSL samples were dated in the University of Georgia Luminescence Dating Laboratory. Samples were pretreated according to Srivastava et al. (2005) and paleodose was determined using single-aliquot regenerative-dose protocol (Murray and Wintle, 2000). Ages were calculated using the *ANALYST* program of Duller (1999).

Radiocarbon (^{14}C) samples were dated at the University of Georgia Center for Applied Isotope Studies using a National Electrostatics Corporation Model 1.5SDH-1500 kV Accelerator Mass Spectrometer. Calendar year calibrations were calculated using the program CLAM (Blaauw 2010) based on the IntCal-13 calibration

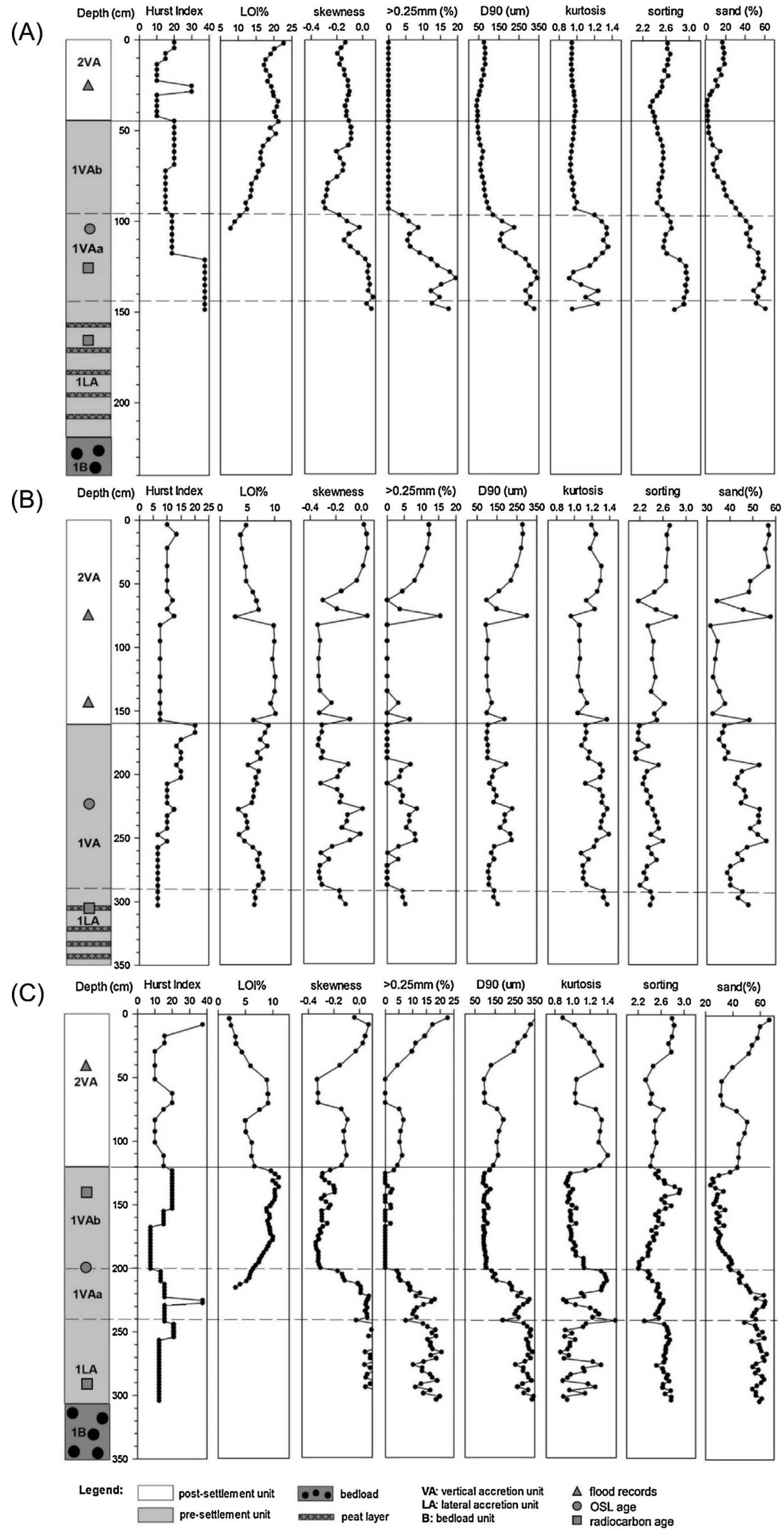

Fig. 2. Stratigraphic units and particle size characteristics of the cores from the three sites. (A) the Keener site; (B) the State Line site; (C) the Riverside site.

curve (Reimer et al., 2013) and the delta ^{13}C corrected ^{14}C ages. The estimates of calendar years before present (years BP) reference AD 1950 as present, and the single age assigned to each sample is the "best estimate" of the CLAM program according to the calibrated probability distributions and linear age-depth modeling as summarized by Leigh (2016). To be consistent with OSL ages, all calibrated radiocarbon dates were converted to years before AD 2009.

The radioactive isotope ^{137}Cs content of sediments was measured by gamma spectrometry with a high purity germanium crystal system coupled with an Ortec digital spectrometer in the University of Georgia Geomorphology Laboratory, with count times of 5000–10000 s to achieve analytical errors <10%. Samples at 2 cm intervals were measured to obtain a tightly constrained estimate of AD 1963 with ^{137}Cs. We adhere to the idea that maximum content of ^{137}Cs in the stratigraphic section represents the year AD 1963 (Ritchie and McHenry, 1990; Walling and He, 1997). However, at the Keener site the maximum ^{137}Cs content was blurred within the bioturbated and possibly plowed A horizon, so as an alternative we used the first distinct increase and peak in ^{137}Cs as AD 1958 (Ritchie and McHenry, 1990; Walling and He, 1997). Ages of certain sand layers in the post-settlement unit were estimated by correlating the sedimentological evidence of very large floods with USGS gaged flood records (i.e., the two largest floods on record in1902 and 1964) as explained by Leigh (2016).

3.3. Statistical analyses

Chemical elements adsorbed to the surface of sediments are strongly influenced by particle sizes and organic matter content. The negative charge possessed by organic colloids and relatively large surface area of finer particles make them adsorb more cations (Horowitz, 1991). Since our LOI values integrate clay, organic carbon, and oxyhydroxides (Hoogsteen et al., 2015) that adsorb cations, we normalized the original elemental concentrations by running linear regressions against LOI values, and used the residual values in the subsequent statistical analyses. Because Native Americans in the region did not exploit metals as in other parts of the world where metal smelting started thousands of years ago (Swanton, 1946; Ethridge and Hudson, 2002; Killick and Miller, 2014; Liu et al., 2015), we believe the geochemical data in the pre-settlement unit should reflect the natural variations under non-anthropic conditions. Therefore, linear regression of the elemental concentrations against LOI were generated using data from unit 1VAb and then the equations were used to generate residual values for both unit 1VAb and 2VA, separately for each site. In cases where LOI is not a significant predictor (p-values ≥ 0.05), the residuals were simply calculated by subtracting the mean of the 1VAb values. Such normalization is rather common in studies of trace metals on fluvial sediment (Miller and Miller, 2007; Pavlowsky et al., 2010; Lecce et al., 2011) and the analysis of residual values is a very standard approach in regression analysis (Draper and Smith, 1998).

After checking the data normality, a t-test or U-test was run on the descriptive statistics of particle sizes and chemical residuals to assess the differences of physical and chemical characteristics between the pre-settlement and post-settlement vertical accretion deposits. The most differentiating elements then were used as predictors in discriminant function analysis (DFA) to test their ability of predicting post-settlement or pre-settlement groups.

Table 1
Chronology and dating methods from the three study sites. The data is adjusted from Leigh (2016) (page 179–182).

Site	Lab #	sample depth (cm)	Unit & facies	Dating method	Material dated	^{14}C years BP	Calibrated ^{14}C age (cal. yr BP)	Non-^{14}C age estimate cal. yr	±1 SD	Age estimate (yr before AD 2009)
Keener	n.a.	0	2VA	GS[a]	Surface 2009	n.a.	n.a.	AD 2009	1	0
Keener	n.a.	13	2VA	Cs137	Flood sediment	n.a.	n.a.	AD 1958	10	51
Keener	n.a.	43	1/2VA	CORR[b]	Top of Ab horizon	n.a.	n.a.	AD 1870	10	139
Keener	UGA-09OSL-672	107	1VA	OSL	Aandy loam	n.a.	n.a.	1300[c]	50	1300
Keener	UGA-14484	125	1LA	C14	Charcoal	1620	1474	n.a.	40	1533
Keener	UGA-14485	143	1LA	C14	Acorn (uncarb.)	1630	1546	n.a.	40	1605
State Line	n.a.	0	2VA	CORR	Surface 2009	n.a.	n.a.	AD 2009	1	0
State Line	n.a.	73	2VA	Cs137	Flood sediment	n.a.	n.a.	AD 1964	10	45
State Line	n.a.	144	2VA	CORR	Flood sediment	n.a.	n.a.	AD 1902	10	107
State Line	n.a.	159	1/2VA	CORR	Top of Ab horizon	n.a.	n.a.	AD 1870	10	139
State Line	UGA-09OSL-670	225	1VA	OSL	Sandy loam sediment	n.a.	n.a.	1100[c]	50	1100
State Line	UGA-14480	290	1LA	C14	Leaf stem	1380	1301	n.a.	40	1360
Riverside	n.a.	0	2VA	GS	Surface 2009	n.a.	n.a.	AD 2009	1	0
Riverside	n.a.	42.5	2VA	Cs137	Flood sediment	n.a.	n.a.	AD 1964	10	45
Riverside	n.a.	122	1/2VA	CORR	top of Ab horizon	n.a.	n.a.	AD 1870	10	139
Riverside	UGAMS-10393	143.3	1VA	C14	<125 um sediment	1650	1552	n.a.	25	1611
Riverside	UGA-09OSL-669	200	1VA	OSL	Sandy loam sediment	n.a.	n.a.	2400[c]	150	2371
Riverside	UGA-9054	240	1LA	C14	Leaf	2530	2634	n.a.	23	2693

[a] Ground surface.
[b] Correlation with historic records.
[c] Cage is shown as calendar years before AD 2009.

Statistical analyses of t-test, U-test and DFA were run in the program language R (R Development Core Team, 2008).

4. Results

4.1. Stratigraphy

Buried A (Ab) horizons are prevalent in the stratigraphy of older floodplains or terraces in many places, containing more organic matter and appearing darker than the overlying post-settlement alluvium. The Ab horizons likely represent the land surface that existed prior to the time of initial European–American settlement (Happ, 1945; Trimble, 1974; Costa, 1975; Jacobson and Coleman, 1986; Knox, 1987, 2001, 2006; Leigh, 2010; Leigh, 2016). Age of the Ab horizon varies among studies depending on the specific settlement and land use history of a region. We used the upper boundary of the Ab horizon to divide the sedimentary profile into two major stratigraphic units (Fig. 2): the pre-settlement unit (unit 1) below the boundary and the post-settlement unit (unit 2) above the boundary. This boundary line was assigned a date of AD 1870, as determined by Leigh (2010, 2016).

The thickness, sediment color, and texture of each stratigraphic unit vary across the three sites. Visually, the Keener site has darker and finer sediments and a much thinner unit 2 than those of the State Line and the Riverside sites. However, all three sites show similar stratigraphic assemblages of facies. The pre-settlement unit 1 can be divided into three zones based on sediment structures and textures. The bottom zone contains sub-rounded to well-rounded gravels and coarse sand. The middle zone is composed primarily of medium and coarse sand with massive to weak blocky structure and redox features, and it commonly exhibits thin bedding of sand and uncarbonized organic material. The upper zone is characterized by a sandy fining-upward sequence in the initial lower portion that conformably grades upward into silty clay loam with pedogenic features (i.e., moderate fine to medium blocky structures). Although generally fine textured, several thin beds and laminae of fine sand are apparent in the upper zone, especially at the State Line and Riverside sites. Referring to the sediment texture and stratigraphic characters of typical floodplain deposits of meandering streams (Nichols, 1999; Boggs, 2006; Bridge, 2003), we designated the bottom zone as unit 1B, representing bedload deposits that were transported and deposited in a previous channel; the middle zone unit 1LA (lateral accretion), representing point bar deposits from lateral migration of the meandering channel; and the upper zone unit 1VA (vertical accretion), representing deposits that fell out of suspension during overbank floods. At the Keener and Riverside sites, unit 1VA was subdivided into 1VAa and 1VAb to separate the distinct fining-upward sequence of the lower part (1VAa) from the more homogenous upper part (1VAb). The post-settlement unit 2 is primarily composed of fine sand and silt loam, with several distinct light-colored medium and coarse sand layers. Overall, a coarsening-upward trend is shown in the upper part of unit 2 at all three sites (Fig. 2, sand% and D90). Pedogenic features of granular and blocky structures are present at the Keener site but not at the State Line and the Riverside sites, where sediments are massive with thin laminations. Roots and other evidence of bioturbation are common. Sediments in this unit are from overbank deposition after European-American settlement and thus the upper unit was designated as unit 2VA.

For this research, our focus is on the vertical accretion units 1VA and 2VA, as they represent comparable sedimentary environments. At the Keener and Riverside sites, only unit 1VAb was quantitatively compared with unit 2VA in terms of particle size and geochemistry, because 2VA does not have a distinct lower part with fining-upward sandy sediment like 1VAa.

4.2. Chronology and age vs. depth models

The age estimates from samples at the Keener, State Line, and Riverside sites are shown in Table 1. All the ages are within the last 2700 years and the Keener and State Line are younger than

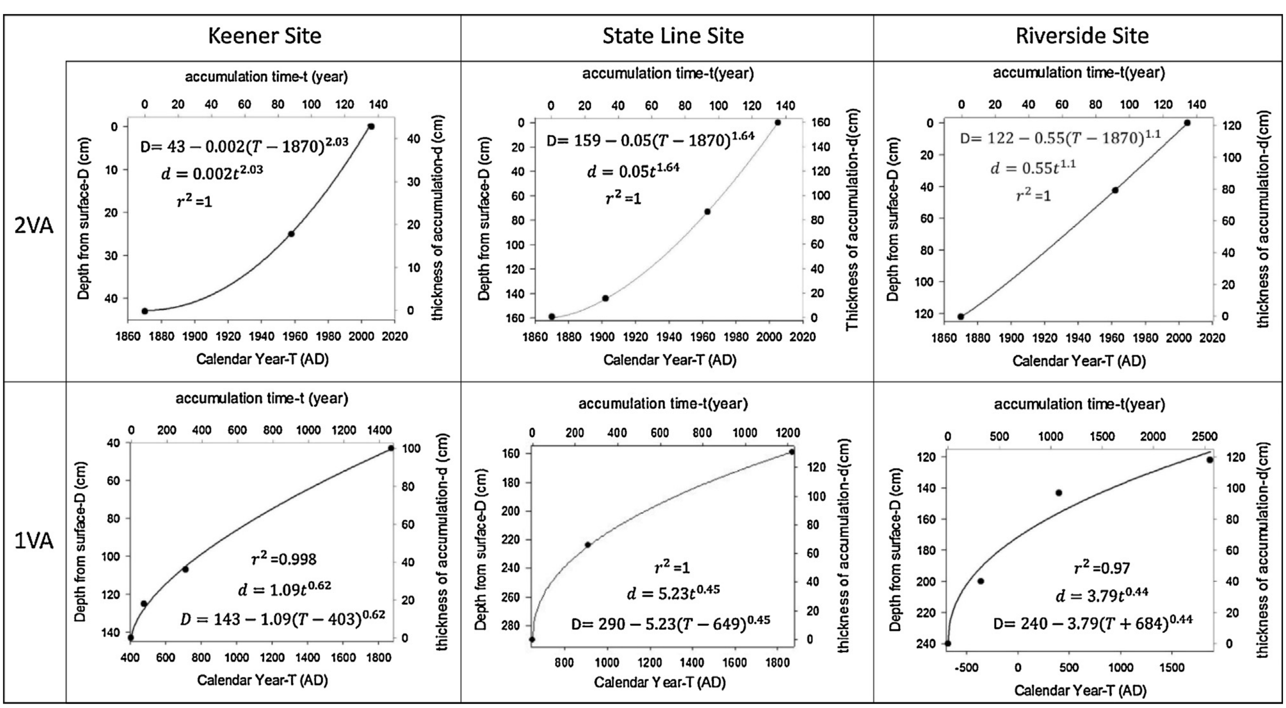

Fig. 3. Age-depth models for vertical accretions during post-settlement (unit 2VA) and pre-settlement (unit 1VA) at the three study sites. D (cm) refers to the depth from the surface in the core, T (AD) is the age in calendar years, d (cm) refers to the thickness of accumulation in the 1VA or 2VA units, t (yr) is the time of accumulation since the beginning of the 1VA or 2VA.

Table 2
Vertical sedimentation rates derived from depth-age model and average sedimentation rate for different periods. R = deposition rate (in cm/yr); t = deposition time (in year).

Site	Sedimentation rate model		Average sedimentation rate (mm/yr)			
	Post-settlement	Pre-settlement	Before 1870	After 1870	1870–1964	1964–2009
Keener	$R = 0.004\ t^{1.03}$	$R = 0.676\ t^{-0.38}$	0.68	3.18	2.05	5.32
State Line	$R = 0.082\ t^{0.64}$	$R = 2.35\ t^{-0.55}$	1.07	11.78	9.25	17.38
Riverside	$R = 0.605\ t^{0.1}$	$R = 1.67\ t^{-0.56}$	0.46	9.04	8.70	9.77

Table 3
Results of t-test or U-test on particle size parameters between unit 1VA and 2VA.

	Keener			State Line			Riverside		
	Mean or median			Mean or median			Mean or median		
	2VA	1VAb	p-value	2VA	1VA	p-value	2VA	1VAb	p-value
Mean (μm)	21.12	23.41	0.30	52.44	50.71	0.72	55.67	36.34	<0.001
D90 (μm)	62.98	65.96	0.62	148.69	130.20	0.68	165.18	94.48	<0.001
>0.25%	0.00	0.00	1.00	3.68	3.28	0.33	5.62	0.00	<0.001
Sand%	10.92	14.09	0.50	45.90	44.10	0.76	44.50	30.00	<0.001
Sorting	2.54	2.51	0.41	2.52	2.34	<0.001	2.57	2.55	0.62
Skewness	−0.13	−0.18	0.23	−0.19	−0.24	0.54	−0.12	−0.29	<0.001
Kurtosis	0.96	0.96	0.89	1.14	1.20	0.08	1.25	0.99	<0.001

1600 years. Ages of 1LA/1VA boundaries were assigned the same age as the underlying lateral accretion deposits, because lateral accretion typically occurs almost instantaneously during individual floods before being overlain by steady incremental additions of vertical accretion deposits. The surface of Ab horizon as 1VA/2VA boundary was assigned an age of AD 1870, when population, agriculture, logging and mining activities in the study area started to increase significantly (Leigh, 2010, 2016). Samples in the upper part of unit 2VA with a pronounced increase of >0.25 mm fraction and immediately above the AD 1963 peak of ^{137}Cs content were assigned an age of AD 1964 corresponding to the largest flood on record at the nearby Prentiss gage. At the State Line site, another sample with a pronounced increase of >0.25 mm fraction in lower 2VA was keyed to the AD 1902 large flood according to the deactivated gage downstream at Needmore. This AD 1902 age assignment was also established in another core at the same site, which contains railroad grade materials suggesting an age a few years earlier than the railway reached the State Line site in AD 1905 (Leigh, 2016). The surface of each site was assumed to be an age of AD 2009, the time when the cores were drilled.

In order to characterize overbank vertical accretion, Wolman and Leopold (1957) promoted a model (assuming natural conditions) wherein overbank sedimentation rates decrease with time as the floodplain surface accreted. Bridge (2003) expanded upon this by arguing that the deposition of overbank finning-upward sequence can be expressed by a general power function of $R = 10t^{-0.33}$ (R: sedimentation rate, in cm/yr; t: age of deposition, in year). If transferring to an age vs. depth ($d = f(t)$, d: thickness of accumulation, in cm; t: age of accumulation, in year) relationship, it would result in a power function with an exponent of 0.67. We applied this concept to unit 1VA and adjusted the constant and exponents for our data at the three sites, and all three age vs. depth power functions have exponents smaller than 1, and fitted 1VA ages very well ($r^2 \geq 0.97$) (Fig. 3). However, in stark contrast, Wolman and Leopold's and Bridge's conceptual models of decreasing accretion rates with time do not apply for the post-settlement period. Instead, we found that age vs. depth power functions with exponents larger than 1 best fit the 2VA ages ($r^2 = 1$), indicating increasing rates with time (Fig. 3).

4.3. Sedimentation rates and particle size

The sedimentation rates R (in cm/yr) derived from the age-depth models are shown in Table 2. All the age vs. rate power functions have negative exponents for the pre-settlement period and positive exponents for the post-settlement period, suggesting decreasing rates over time in the pre-settlement period and increasing rates over time in the post-settlement period. Table 2 also shows the long-term average sedimentation rates at different time intervals. The State Line site had the highest rates for both post-settlement (11.78 mm/yr) and pre-settlement (1.07 mm/yr) periods; the lowest post-settlement rate was at the Keener site (3.18 mm/yr); and the lowest pre-settlement rate was at the Riverside site (0.46 mm/yr). However, at all three sites, long-term average sedimentation rates during post-settlement time (AD 1870–2009) were about one order-of-magnitude greater than pre-settlement (before AD 1870) rates. Within the post-settlement period, rates after AD 1964 were nearly twice as high as those before AD 1964 (Table 2).

In contrast to the remarkably different sedimentation rates between post-settlement and pre-settlement periods, the t-test on particle size characteristics, including mean, D90, percentage of sand fractions larger than 0.25 μm, percentage of sand, sorting, kurtosis, and skewness, between 1VA and 2VA did not show significant differences at the 95% confidence level, except at the Riverside site (Table 3). However, as shown on Fig. 2, at all three sites, sediments exhibit a fining-upward trend in unit 1VAb but a coarsening-upward trend in 2VA.

4.4. Geochemistry

Of the analyzed 35 chemical elements, 15 of them do not have discrete concentration values (censored values below detection limits), so they were excluded from statistical analyses. For the remaining 20 elements, original concentrations (in ppm or%) were plotted against depth at each site (Fig. 4).

In most cases, LOI appears as a significant predictor (p-values < 0.05) of the elemental concentrations except for

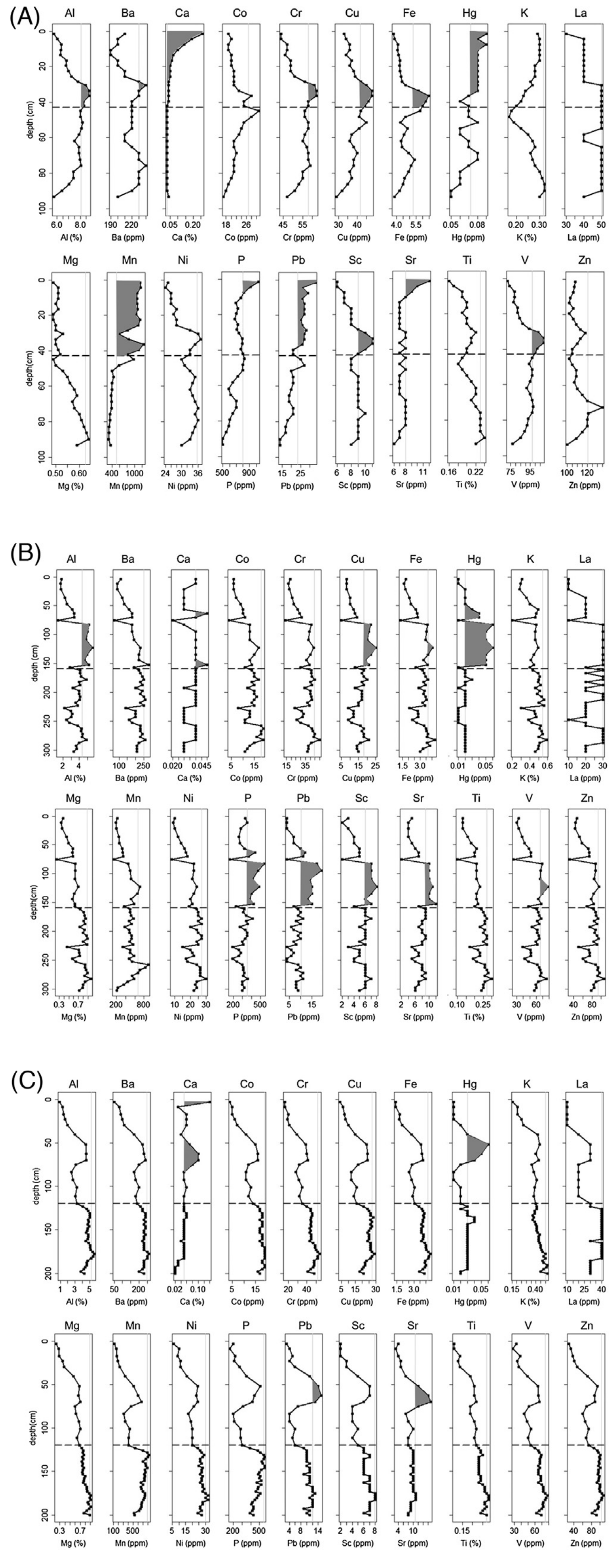

Fig. 4. Original elemental concentrations at the three sites. (A) Keener site; (B) State Line site; (C) Riverside site. On each figure, dashed horizontal line represents the 2VA/1VA boundary, the light gray vertical line represents the 90th percentile of data in unit 1VA, and the dark gray-shaded area shows where data in 2VA exceed 90th percentile of background values derived from unit 1VA.

Table 4
R-squared and *p*-values of linear regressions of original chemical concentrations on LOI using data in unit 1VAb. Data are shown in boldface when the linear regression is not significant, in which case the residuals were simply calculated by subtracting the original concentrations by the mean of concentrations in 1VAb.

		Al	Ba	Ca	Co	Cr	Cu	Fe	Hg	K	La
Keener	r^2	0.58	0.01	0.13	0.86	0.37	0.8	0.2	0.39	0.92	0.03
	p-value	<0.01	0.78	0.18	<0.01	0.015	<0.01	0.09	0.012	<0.01	0.55
State Line	r^2	0.85	0.6	0.49	0.47	0.82	0.86	0.64	0.7	0.37	0.48
	p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Riverside	r^2	0.35	0.13	0.77	0.004	0.0006	0.64	0.0001	0.28	0.53	0.55
	p-value	<0.01	0.04	<0.01	0.74	0.9	<0.01	0.94	0.002	<0.01	<0.01

		Mg	Mn	Ni	P	Pb	Sc	Sr	Ti	V	Zn
Keener	r^2	0.87	0.53	0.08	0.89	0.7	0.21	0.09	0.84	0.45	0.08
	p-value	<0.01	<0.01	0.3	<0.01	<0.01	0.09	0.28	<0.01	<0.01	0.3
State Line	r^2	0.54	0.04	0.7	0.71	0.72	0.74	0.65	0.6	0.76	0.68
	p-value	<0.01	0.29	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Riverside	r^2	0.24	0.58	0.03	0.57	0.006	0.05	0.43	0.15	0.0006	0.29
	p-value	0.004	<0.01	0.38	<0.01	0.67	0.22	<0.01	0.03	0.89	0.001

several elements (Table 4). The residuals, either from the linear regression (r) or relative to the background mean (m), were plotted against depth at each site to see the downcore trend (Fig. 5). We used the 90th percentile of 1VAb residuals to represent the “uppermost” background level, and shaded the area when residuals in 2VA are above this level. It is clear that the majority of elements in 2VA are considerably below the background level, and that some elements exhibit distinct shifts at the 1VA/2VA boundary but the direction of shifts was not consistent at all three sites (such as K, Mn, P, Ti), so they could not be logically related to anthropic drivers. Only Ca, Hg, and Pb have greater values at all three sites for multiple samples in 2VA when compared to the uppermost background level in 1VAb. The t-test or U-test of the residuals between unit 1VAb and 2VA indicate no single element has significantly ($p < 0.05$) higher values in 2VA than in 1VAb at all three sites (Table 5). In fact, Ca, Hg, and Pb are the only three elements that have significantly higher values in 2VA than 1VAb at two of the three sites (Table 5). Therefore, based on the downcore trend and *t*-test/*U*-test, elements Ca, Hg, and Pb were chosen as the best candidates for “signature elements” because the normalized data show consistently higher values in 2VA than in 1VAb at all three sites, and the differences are significant ($p < 0.05$) at least at two of the three sites.

Discriminant function analysis on the three elements’ residuals, percentages of sand, and LOI values shows that the five predictors performed well in predicting whether a sample belongs to the pre-settlement and post-settlement groups, with predictive accuracy greater than 89% (Table 6). The standard coefficient from the DFA also shows strong ability of these elements in differentiating the two units, particularly Hg and Ca (Table 6).

5. Discussion

5.1. Sedimentation and human activities

The negative exponents of sedimentation rate functions during the pre-settlement period indicate decreasing rates with time, while the positive exponents during the post-settlement period suggest increasing rates with time. Based on prevailing knowledge about natural process of floodplain development (Wolman and Leopold, 1957; Bridge, 2003), a decreasing rate with time should be expected. Thus, the increasing rates with time during post-settlement time are abnormal to the widely accepted process of vertical accretion sedimentation and might have been driven by human-induced changes in the system.

Our pre-settlement strata are confined to the last 2700 years, which includes early agricultural development by Native Americans. However, as mentioned earlier, their land use practices were limited to forest management (nut harvest and hunting) and subsistence crop cultivation that were patchy and dynamic (Munoz et al., 2014) with little influence on erosion and floodplain sedimentation in our study area (Van Doren, 1928; Swanton, 1946; Delcourt et al., 1986; Leigh, 2016). Impact on the landscape became significant and widespread only after the European-American settlement or during post-settlement time. Clear-cutting for timber harvest was intensive, and widespread row-crop agriculture also occurred in the late 19th and early 20th century (Yarnell, 1998; Harden, 2004), causing soil erosion on upland slopes and accelerated sedimentation in lower valleys, as noted by Glenn (1911). The federal acquisition of Appalachian land in 1911 and later established national forests and regulated logging activities (Yarnell, 1998; Harden, 2004), but human disturbance on private land persisted in the form of forest clearing, agriculture, urbanization, and road construction (Price and Leigh, 2006; Kirk et al., 2012). Especially since the 1970s, as more people migrated to this area, second-homes and roads have been built on sloping portions of the basin (Leigh, 2007, 2010; Kirk et al., 2012). Meanwhile, agricultural practices in lower valleys currently emphasize livestock over growing row crops (Harden, 2004). These human activities led to accelerated soil erosion and hillslope failures, which provided substantial amounts of sediments to floodplains (Leigh and Webb, 2006; Knox, 2006; Leigh, 2016), leading to the significant increases of our observed post-settlement sedimentation rates.

The coarsening-upward trend of in the upper part of unit 2VA could be affected by three factors. First, channel lateral migration and levee progradation can produce coarsening-upward overbank sediments. That is, sediments closer to the channel are generally coarser (Lecce, 1997; He and Walling, 1998), and with the lateral shift of the channel the cutbank is eroded and newer sediments on top of the cutbank are generally coarser than the underlying sediments because the deposition site is inherently closer to the channel. Second, source sediments could have become coarser. Sediments in the drainage basin came primarily from slope erosion in the upland soil (Glenn, 1911). During early post-settlement time, soil erosion first occurred in the relatively fine solum, but later, gully erosion cut deep into the underlying sandy saprolite (Glenn, 1911; Leigh and Webb, 2006), providing coarser sediments to the river channel. Third, land use changes can introduce coarser sediment to the channels via changes in hydrology that favor more energetic floods. Population growth and low density urban development in the region became rapid since the 1960s (Kirk et al., 2012). Land cover changes from forest to pasture and toward more urbanized land (including more roads and driveways) increased surface runoff and produced larger flood discharges that are able to transport and deposit coarser sediments during

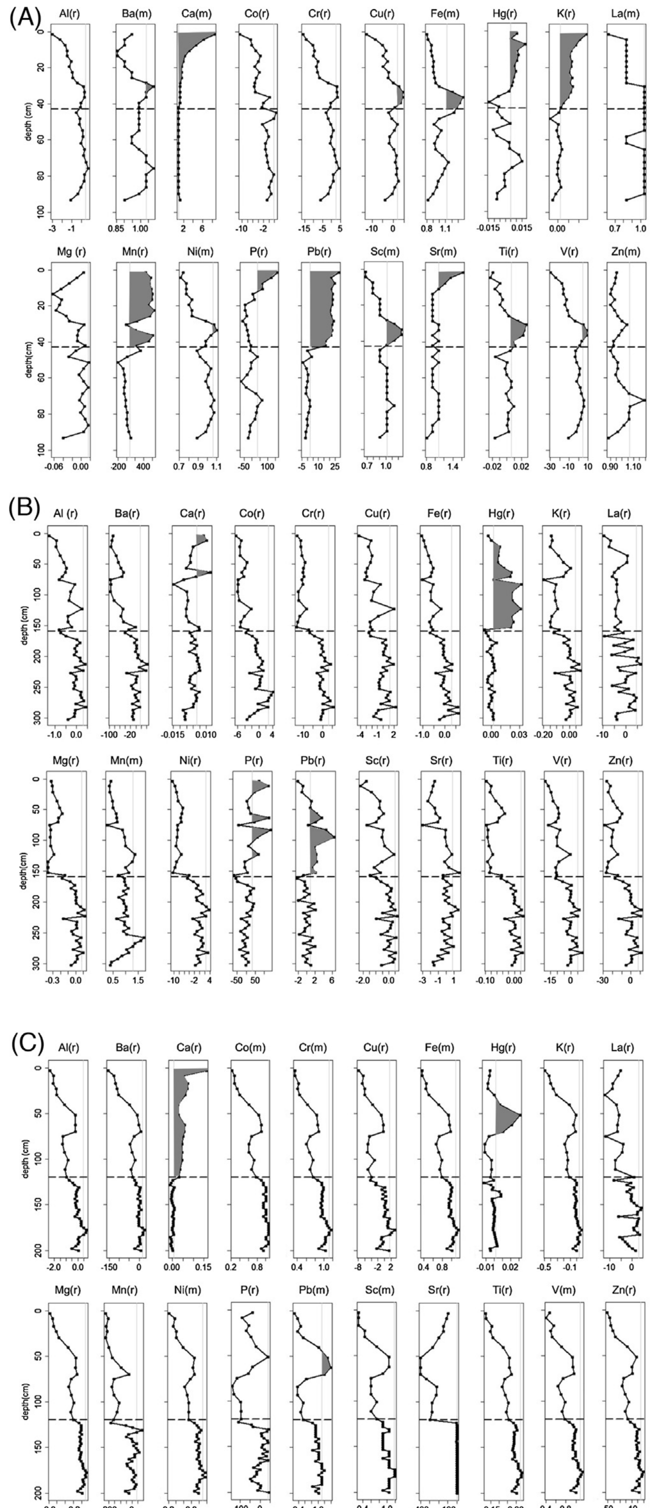

Fig 5. Residuals of chemical elements with depth at three sites. (a) Keener site; (b) State Line site; (c) Riverside site. The element is noted with (r) if residuals were derived from the linear regression on LOI, or with (m) if residuals were differences from the mean concentrations of unit 1VA. On each figure, the dashed horizontal line represents the 2VA/1VA boundary, the light gray vertical line represents the 90th percentile of data in unit 1VA, and gray-shaded area indicates where data in 2VA exceed the 90th percentile line of background values in unit 1VA.

overbank floods (Sutherland et al., 2002; Chin, 2006). All three factors may have caused the coarsening-upward trend in the late post-settlement vertical accretions. However, given that little lateral migration of the main stem of the Upper Little Tennessee River has occurred over the past century (Leigh, 2010), we argue that the first reason is less important. The other two reasons are more influential and both are related to increased human activities in the region.

Table 5
p-values of *t*-test or *U*-test on chemical residuals between unit 1VAb and 2VA. Data are shown in boldface when residuals in unit 2VA are significantly greater than in unit 1VAb.

	Al	Ba	Ca	Co	Cr	Cu	Fe	Hg	K	La
Keener	0.003	0.048	**0.01**	<0.001	0.005	0.13	0.98	**0.04**	<**0.001**	0.008
State Line	<0.001	<0.001	0.69	<0.001	<0.001	<0.001	<0.001	<**0.001**	<0.001	<0.001
Riverside	<0.001	<0.001	<**0.001**	<0.001	<0.001	<0.001	<0.001	0.89	0.0002	<0.001

	Mg	Mn	Ni	P	Pb	Sc	Sr	Ti	V	Zn
Keener	0.004	<**0.001**	0.004	0.65	<**0.001**	0.31	0.2	0.84	**0.02**	0.04
State Line	<0.001	0.01	<0.001	**0.02**	**0.01**	<0.001	0.02	<0.001	<0.001	<0.001
Riverside	<0.001	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001

5.2. Signature elements and human activities

Three chemical elements (Ca, Hg, Pb) were determined as anthropic signatures based on higher residual (or ratio to background mean) values in 2VA than the background level in 1VAb, and statistical test results with significant difference between the stratigraphic units at two of the three sites. Logically, the three elements are clearly related to human activities as Hg and Pb are obvious environmental contaminants and Ca is commonly used as an agricultural additive.

A gold-belt trends across the southeastern United States (Pardee and Park, 1948), including the Upper Little Tennessee watershed, and gold mining was quite active during the late 1800s and early 1900s (Lecce et al., 2011). Mercury (Hg) was used extensively in early gold mining to amalgamate and recover gold from sluices and stamp mills (Pardee and Park, 1948). This activity has significantly impacted the fluvial systems in that mercury was transported with sediments, reworked by fluvial process, and stored in overbank sediments (Leigh, 1994, 1997; Lecce et al., 2008). There were no major gold mining operations near the three study sites, but scattered prospecting occurred in the Upper Little Tennessee catchment during the early 1900s (Robinson, 1992). This probably is the primary reason for the significantly higher amounts of Hg in the post-settlement vertical accretions. Although gold mining stopped in the 1940s (Robinson, 1992), channel migration could have reworked the sediments and redistributed mercury in the watershed (e.g., Leigh, 1997). In addition, atmospheric fallout clearly is another possible source of mercury to the soils (Nriagu, 1994).

Lead (Pb) was a minor associate of the gold ore in the gold-belt, and lead mining was also active during the early post-settlement time (Eller, 1982; Robinson, 1992). Actually, the raw concentrations and residuals of the two elements are strongly correlated at all three sites. Therefore, the increase of Pb in post-settlement sediments may also be related to mining activities and atmospheric fallout. In addition, we think past use of leaded fuel is another source of Pb to the late post-settlement sediments. Lead was blended with gasoline between the early 1920s and 1990s and automobile exhaust has been an important source of lead pollution to the environment. Even though the United States Environmental Protection Agency began regulating lead content in gasoline in 1973, leaded fuel was still available until the Clean Air Act became effective in 1996. Even if the use of leaded gasoline has decreased since the 1970s, reworking of sediments and the redistribution of lead in the watershed may have maintained Pb at higher levels in the overbank sediments.

As a geochemically mobile element in soil solutions, Ca could be leached downward in the profile after deposition. The low residual values in unit 1VAb might be a result of intense leaching during pedogenesis, whereas the younger sediments in 2VA did not experience much leaching and would be expected to have higher values. At all three sites, the lower parts of unit 2VA also have notably depleted Ca residuals, suggesting leaching was possible in the 2VA unit. Therefore, the much higher values of Ca residuals toward the top of unit 2VA should be related to lime use as an agricultural supplement. Soils in the Southern Blue Ridge Mountains are generally acidic and application of lime is a common practice to reduce acidity in agricultural fields (Messick et al., 2001). However, the application of lime did not occur in the region until the 1930s and later, according to local agricultural records (Yarnell, 1998; Messick et al., 2001).

Although we argued in the previous section that sediment sources may have become coarser as upland erosion progressed down into the underlying sandy saprolite during late post-settlement time, this does not affect the geochemical results because we examined values normalized for particle size variation of the adsorbed chemical elements, rather than the whole-soil geochemistry. Indeed adsorbed elemental concentrations are greatly influenced by particle size via available surface area with finer sediments having higher concentrations (Horowitz, 1991; Miller and Miller, 2007; Pavlowsky et al., 2010; Lecce et al., 2011), but our linear regression and analysis of residual values intentionally masks the variation driven by particle size. Also, since we are focusing on adsorbed elements, rather than total chemical composition of the sediment samples, any primary mineral and chemical differences within the coarse sediment grains derived from soil versus saprolite are not included.

5.3. Justification of "anthropic signatures"

In spite of the geomorphic and sedimentologic variability among the three sites, physical and chemical characteristics of floodplain overbank sediments showed significant differences between post-settlement and pre-settlement periods. Therefore, in certain cases where identifying the Ab horizon is difficult due to coring disturbance or flood scouring (Happ, 1945), the sedimentation rates, sediment textures, and signature elements could be used to help differentiate post-settlement and pre-settlement sediments. The high predictive accuracy of these factors in DFA (Table 6) proved that they are quite effective in differentiating the two units.

These physical and chemical characteristics are designated here as "anthropic signatures" to reflect their connections with human activities. We are aware that sedimentation rates and sediment textures were not caused solely by human activities.

Table 6
Standard coefficient and predictive accuracy of discriminant function analysis. Prediction uses leave-one-out cross-validation method.

	Keener	State Line	Riverside
Hg	−48.30	201.69	121.43
Pb	0.52	−0.11	−0.31
Ca	−16.70	51.39	32.17
Sand%	0.08	−0.14	−0.05
LOI	0.25	0.03	−0.39
Predictive accuracy	100%	89%	96%

The autogenic process of floodplain development, such as natural levee progradation associated with channel lateral migration, was at least partly responsible for the increased sedimentation rates and the coarsening-upward trend in the upper post-settlement sediments. In addition, the frequency of high-magnitude floods increased in the past several decades according to the USGS Prentiss gage on the Little Tennessee River, and more frequent large floods could contribute to the increased sedimentation rates as well (Knox, 2006; Leigh and Webb, 2006). Although multiple factors acted on the fluvial system, given the close correlation between these substantial changes and human activities, we believe that direct human impacts overshadowed other factors during post-settlement time. Therefore, these "anthropic signatures" appear to be good indicators of human influence.

6. Conclusion

We compared the physical and chemical characteristics of floodplain vertical accretion deposits at three sites in the Upper Little Tennessee River valley of the Southern Blue Ridge Mountains, USA, a region where significant human impact on the landscape did not begin until after intensive and extensive settlement of European-Americans in the late 19th century. The comparison showed great differences between post-settlement (after AD 1870) and pre-settlement (Before AD 1870) periods. Post-settlement sedimentation rates increased with time while pre-settlement rates decreased with time, and the long-term average sedimentation rates during post-settlement time were about one order-of-magnitude greater than that during pre-settlement time. Sediments in pre-settlement vertical accretion deposits exhibit a fining-upward trend, but a coarsening-upward trend is apparent in post-settlement vertical accretion. The three "signature elements" (Ca, Hg, Pb) have significantly higher content in post-settlement sediments than in pre-settlement sediments. These substantial changes between the two periods are most likely related to human impacts, such as timber harvest and gold mining during early post-settlement time, lime use for agricultural practice, land clearing for urbanization after the 1970s, and even atmospheric influx of Hg and Pb. Even though the autogenic process of floodplain development and climate changes in the recent decades also accounted partly for these changes, we argue that such significant changes are more related to human activities. Thus the sedimentation rates, sediment texture and three elements (Ca, Hg, Pb) were identified as "anthropic signatures". This research demonstrates significant human impact on fluvial systems even in regions with only a centennial history of intense human activities as compared to other parts of the world where human impacts are apparent for millennia.

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