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Preliminary Assessment of Carbon and Nitrogen Sequestration Potential of Wildfire-Derived Sediments Stored by Erosion Control Structures in Forest Ecosystems, Southwest USA

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ABSTRACT: The role of pyrogenic carbon (PyC) in the global carbon cycle is still incompletely characterized. Much work has been done to characterize PyC on landforms and in soils where it originates or in "terminal" reservoirs such as marine sediments. Less is known about intermediate reservoirs such as streams and rivers, and few studies have characterized hillslope and in-stream erosion control structures (ECS) designed to capture soils and sediments destabilized by wildfire. In this preliminary study, organic carbon (OC), total nitrogen (N), and stable isotope parameters, $\delta^{13}C$ and $\delta^{15}N$, were compared to assess opportunities for carbon and nitrogen sequestration in postwildfire sediments (fluvents) deposited upgradient of ECS in ephemeral- and intermittent-stream channels. The variability of OC, N, $\delta^{13}C$, and $\delta^{15}N$ were analyzed in conjunction with fire history, age of captured sediments, topographic position, and land cover. Comparison of samples in 2 watersheds indicates higher OC and N in ECS with more recently captured sediments located downstream of areas with higher burn severity. This is likely a consequence of (1) higher burn severity causing greater runoff, erosion, and transport of OC (organic matter) to ECS and (2) greater cumulative loss of OC and N in older sediments stored behind older ECS. In addition, C/N, $\delta^{13}C$, and $\delta^{15}N$ results suggest that organic matter in sediments stored at older ECS are enriched in microbially processed biomass relative to those at newer ECS. We conservatively estimated the potential mean annual capture of OC by ECS, using values from the watershed with lower levels of OC, to be 3 to 4 metric tons, with a total potential storage of 293 to 368 metric tons in a watershed of 7.7 km^2 and total area of 2000 ECS estimated at 2.6 ha (203-255 metric tons/ha). We extrapolated the OC results to the regional level (southwest USA) to estimate the potential for carbon sequestration using these practices. We estimated a potential of 0.01 Pg, which is significant in terms of ecosystem services and regional efforts to promote carbon storage.

KEYWORDS: Watershed restoration, carbon sequestration, nitrogen sequestration, ephemeral and intermittent streams, wildfire, C/N, $\delta^{13}C$, $\delta^{15}N$, fluvents, mollisols, inceptisols

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Introduction

Globally, organic carbon (OC) and total nitrogen (N) stored in soil organic matter (SOM) have been depleted due to watershed degradation and agricultural management practices.[1-3] Wildfire also results in losses of SOM due to combustion at higher temperatures, and exposure and oxidation of soil aggregate-protected OC caused by lower temperature fires.[4] Losses are expected to continue, as climate change is predicted to increase fluxes of soil C to the atmosphere, mainly from peat, wetlands, and thawing permafrost. Such additions to the atmosphere could be partly offset by restoration of SOM. There is thus a need to investigate practices and techniques that enhance long-term organic matter (OM) storage. One technique that has a long history of being used both locally and globally to retain soil and water is installation of erosion control structures (ECS).[5,6] They have been used in watershed and riparian restoration, in agriculture for soil conservation, and after wildfires to stabilize slopes and capture sediments in stream channels.[6-11] They also have been shown to store SOM and OC[12,13] and have the potential to store pyrogenic carbon (PyC) from wildfires.

Pyrogenic carbon has been identified as a potentially significant sink in the context of the global carbon cycle, and a growing body of work has been done on understanding PyC stability, composition, fluxes, and storage in soils, lakes, and marine sediments.[14-16] Ash and char production and destabilization and erosion of hillslope soils lead to increases in delivery of nutrients and sediments to streams. This can negatively affect water quality and aquatic ecosystems[17,18] and lead to loss of carbon and nitrogen from watersheds. Consistent with recent experience, climate-change modeling predicts significant increases in wildfire frequency and extent, and postfire erosion rates in the coming decades in the western USA.[19,20] Before intensive logging in the late 1800s,[21,22] forests in the southwest USA were burned by frequent, low-severity, and widespread fires.[23] By the late 20th century, fuel accumulation and prolonged drought conditions were leading to wildfires of increased size and severity, a trend expected to increase as climate change leads to higher temperatures and increased evapotranspiration in the southwest USA.[24] Larger, hotter fires may be pushing mountain terrains toward geomorphic and ecosystem tipping points,[25,26] potentially leading to permanent loss of OM that accumulated over centuries to millennia.[27-34] It is thus timely to study and assess methods that can be applied after wildfires to retain carbon- and nitrogen-rich soil, wood, ash, and char.

This preliminary study considers possibilities for retention of wildfire-derived OM in sediments stored by ECS in forest ecosystems of the southwest United States. We hypothesize that ECS can be used to capture and sequester PyC and eroded SOM and that as surficial OM matures, some OC and N will be lost from the soil through leaching and/or diffusion. We use information on landcover, ECS characteristics (size, age, geomorphic setting), OC, total N, and stable isotopes to (1) evaluate the potential of ECS to retain and store OC and N in postwildfire transported sediments of the southwest USA and (2) discuss processes that may be affecting the amount and properties of retained OM over time.

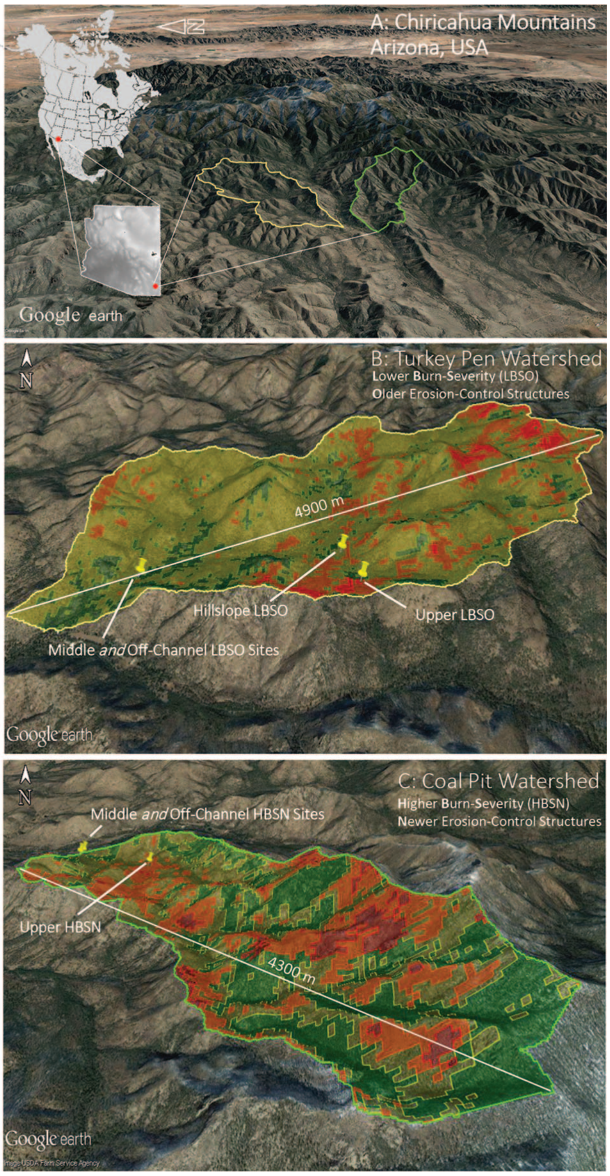

Figure 1. *(Continued)*

Figure 1. (A) Turkey Pen-LBSO (yellow) and Coal Pit-HBSN (green) watershed boundaries, and sampling locations, where LBSO stands for Lower Burn Severity Older ECS and HSBN stands for Higher Burn Severity Newer ECS. Inset map at left indicates location of study area in North America in the state of Arizona, USA. Parts (B) (Turkey Pen-LBSO) and (C) (Coal Pit-HBSN) with sampling locations and names (note some locations are too close together to distinguish at this scale). Burn severity[35,36] from the 2011 Horseshoe 2 Fire[37] is overlain on each watershed (red = high burn severity, orange = moderate burn severity, yellow = low burn severity, green = unburned).
ECS indicates erosion control structures; HBSN, higher burn severity newer; LBSO, lower burn severity older.

Background

Erosion control structures are one of many tools used to stabilize and restore degraded watersheds and mitigate impacts of fire-induced nutrient and sediment transport.[38-41] Check dams of varying permeability can be made from a variety of materials ranging from brush fill to natural stone, masonry, and packed earth.[6,42] Site selection and dam design depend on project objectives and factors such as channel shape and dimensions, access, slope, vegetation, soils, geology, proximity to erosion, dam type, cost, number of and distance between check dams, and flood frequency and magnitude. If ECS are improperly sited or constructed, negative impacts can range from neutral to catastrophic (for example, cascading failure in ECS networks during floods or debris flows[43]). When properly sited and installed, however, they can offer opportunities for capture and rapid burial of mobilized aboveground-biomass, SOM, and PyC.[44,45] Organic matter, OC, and N sequestration by ECS have been studied[12,44,46-49] especially where saturated or semisaturated conditions persist in the trapped sediments. This creates conditions similar to wetlands which have a well-documented OC sequestration potential.[50]

The study area was located in 2 forested watersheds in the Chiricahua Mountains of southeastern Arizona, USA (Figure 1). The watersheds are similar in elevation, vegetation assemblages, geology, and soils, but have different burn severity[51] and restoration histories. The Turkey Pen watershed (referred to as *L*ower *B*urn *S*everity *O*lder ECS or *LBSO*) has an area of about 7.7 km^2, with elevations ranging from 1760 to 2310 m. About 70% of LBSO has slopes greater than 30%. The Coal Pit watershed (referred to as *High*er *B*urn *S*everity *New*er ECS or *HBSN*) has an area of about 4.8 km^2 with elevations ranging from 1730 to 2500 m. Approximately 80% of the watershed has slopes greater than 30%. Bedrock in both watersheds consists of faulted intrusive and extrusive rhyolite and rhyodacite of late Paleogene age.[52,53] Precipitation increases with elevation and ranges between 385 and 660 mm per year with most of it arriving between July and mid-September via isolated convective storms.[54] Winter precipitation occurs from November to March and falls as snow at higher elevations. The dominant vegetation type in the lower reaches of the watersheds, and particularly in LBSO, is Madrean

Pinyon-Juniper-Oak Woodland which includes local patches of grasses and shrubs.[55] Common species include alligator juniper (*Juniperus deppeana*), oak (*Quercus* spp.), and pinyon pine (*Pinus edulis, Pinus cembroides*). Madrean Lower Montane Pine-Oak Forest and Woodland also occurs, favoring mesic slopes and valley bottoms in the upper reaches of the 2 watersheds. This forest type is dominated by Chihuahuan (*Pinus leiophylla*), Apache (*Pinus engelmannii*), and pinyon (*Pinus discolor*) pines and alligator juniper (*Juniperus deppeana*). Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) are locally abundant at higher elevations, and oak (*Quercus* spp.) at lower elevations.

Watershed restoration, primarily ECS installation, began in the LBSO in the first half of the 1980s[56] and in the HBSN in the 1990s (pers. comm. Valer Clark, 2016). Erosion control structures were installed in ephemeral and temporally and spatially intermittent streams. Globally, such streams present a widely available opportunity for OM storage as they make up more than half the combined length of rivers and streams.[57,58] The structures were primarily constructed of loose-rock, including 1-rock structures on hillslopes and in-channel structures (eg, check dams and gabions) to act as sediment traps (Figure 2). Once the network of ECS was installed, flood peaks were reduced, overall flow volume increased,[59] and few ECS failed even in larger floods (pers. comm. Valer Clark, 2016). Hillslope structures, about 90% of all ECS in the study area, typically consisted of dams 1-rock high and 1-rock thick placed at points of incipient erosion perpendicular to the direction of maximum slope. All ECS in the study area were permeable. Most ECS in LBSO and HBSN were filled to capacity with prefire sediment before the 2011 Horseshoe 2 Fire, which burned over 90 000 ha in the Chiricahua Mountains.[26] This included portions of the LBSO and HBSN watersheds, with high or moderate burn severity in 18% of LBSO and 28% of HBSN.[36,37,51] After the fire, previously installed and filled ECS were extended and repaired in HBSN but not LBSO, creating additional capacity for sediment capture HBSN. Rains following the fire caused flooding and debris flows.[26] There is no information on scour and fill history or OM delivery in the previously filled ECS in either watershed prior to the 2011 wildfire, but the newly expanded ECS in HBSN were filled with sediments rich in PyC including ash and charred wood (pers. comm. Valer Clark, 2016). In this study, we use both soil and sediment as terms for the material captured by ECS. Because the streams investigated are ephemeral and intermittent nd because of the ECS network, captured sediments that tend to be stable through time and only seasonally saturated throughout the profile. This creates a blend of terrestrial and fluvial conditions that allow soil forming processes to occur.

As this was a preliminary survey of OC and N, soil surveys were not carried out, but soil descriptions are available via lower (STATSGO2) and higher (SSURGO) resolution state-level

Figure 2. Examples of erosion control structures (ECS) used in the study. Location names: (A) Middle LBSO, (B) Hillslope LBSO, and (C) Middle HBSN.
ECS indicates erosion control structures; HBSN, higher burn severity newer; LBSO, lower burn severity older.

surveys.[60] The higher resolution surveys are available only for small portions of the study area near the watershed outlets. However, it is likely that the classifications are valid for nearby in- and near-channel soils and sediments on adjacent National Forest lands which constitute the bulk of the study area. In general, both watersheds consist of steep slopes with abundant rock outcrops, with in-channel sediments generally classified as Inceptisols and Entisols, and near-channel soils classified as Mollisols and Entisols.

Measurements of isotopic parameters $\delta^{13}C$ and $\delta^{15}N$ were critical to understanding the impacts of ECS in this study. Values of $\delta^{13}C$ can be used to distinguish OM from C_3 (predominantly woody cool-season species) or C_4 (predominantly warm-season herbaceous) plants.[61] It is probable that the majority of the grasses in the study area are C_4[62] The range of $\delta^{13}C$ in C_3 plants in arid ecosystems is about −25 to −27 ‰,[63] and globally the range of $\delta^{13}C$ in C_4 plants has been estimated to be −10 to −15 ‰.[64] Thus in soils, lower values of $\delta^{13}C$ could imply a greater proportion of C derived from C_3 plants.[65] Moreover, the preferential survival of biomass from woody C_3 plants in contrast to easily-decomposed herbaceous C_4 plants could lead to $\delta^{13}C$ of sediments being dominated by a C_3 isotopic signature.[66]

Values of $\delta^{13}C$ can increase with increasing soil depth and decreasing OC concentration[67] as well as with degree of decomposition and age.[64] Decay of coarse woody debris can lower the $\delta^{13}C$ of the remaining biomass, likely due to preferential loss of cellulose in which $\delta^{13}C$ is higher than more resistant lignin. Preston et al[68] summarized and confirmed the results of several studies, with lignin in selected evergreen species having $\delta^{13}C$ ranges 1.7 to 3.3 ‰ lower than whole wood and 3.0 to 4.4 ‰ lower than cellulose. A similar effect was noted in saltmarsh grass.[69] Microbial decomposition of OM may affect $\delta^{13}C$ by adding atmospheric and/or soil-gas CO_2 to SOM,[64] and fungal mycelia have been shown to incorporate CO_2 labeled with ^{14}C.[70] Such processes would result in an increase in $\delta^{13}C$ with age and degree of decomposition due to a combination of (1) microbial carboxylation of OM using ambient soil CO_2 (which is enriched in ^{13}C relative to the OM being decomposed), and (2) the "Suess effect," a decline in $\delta^{13}C$ in atmospheric CO_2 of about 1.5 ‰ since about 1960 to its current level of −8.5 ‰.[64,70-74]

Wildfire can affect $\delta^{13}C$ in OM, and the magnitude and direction of the effect depends on factors such as species, temperature, and duration of burning or charring. Some researchers have found little change in ash and charcoal from C_3 plants but shifts as large as 8 ‰ in $\delta^{13}C$ of burned C_4 OM.[75-77] Others[78] have found that low-temperature (150°C) charring causes $\delta^{13}C$ to increase in both softwood and hardwood (possibly due to volatilization of hydrocarbons), but higher temperatures, 340°C-480°C, lead to a decrease likely due to preservation of lignin and loss of cellulose. Another factor to consider is transport of PyC. It has been found that C_4-derived PyC is transported preferentially in watersheds, possibly due to small particle size relative to C_3 PyC.[79]

With respect to $\delta^{15}N$ in soils, several studies have found increases with depth and age related to microbial decomposition and/or effects of SOM-mineral association.[80-82] Ammonification and nitrification have the largest potential effects on $\delta^{15}N$, with nitrate, nitrite, and ammonia products being depleted in ^{15}N by as much as 20‰ relative to fresh OM. Removal of these products by leaching or denitrification would lead to an increase in $\delta^{15}N$ of the residual OM. Under conditions similar to wildfires, Pyle et al[83] found residual-biomass $\delta^{15}N$ increased with charring intensity. Processes other than wildfire can also affect $\delta^{15}N$, but not necessarily in predictable ways. For example, $\delta^{15}N$ in soils is likely to change during ecosystem disturbances such as grazing and during postdisturbance recovery, but the direction of change is inconsistent.[84]

Methods

Sampling site selection and description

A total of 22 sites were sampled at 7 locations (Figure 1; Table 1). Sampling locations were selected to represent geomorphic settings of interest: one ECS on a hillslope in LBSO, and in each watershed 2 ECS in stream channels and 1 terrestrial "off-channel" location (Figure 2). The off-channel locations were located to the side of each channel to investigate terrestrial conditions. They were situated on slopes that were normally unaffected by flooding and without ECS. In each watershed, one in-channel sampling location was located near the watershed outlet and one was located at an upstream location. A larger number of "in-channel" locations was assessed with the expectation that most OC and N would be stored in them, and therefore that understanding variability in these was a greater priority.

At each in-channel and hillslope location 4 sites (A-D) were sampled in the sediment upstream of each ECS to gain information on horizontal variability of measured parameters. Two depth intervals were sampled at each site to study vertical variability (0-10 cm and 20-30 cm below the mineral soil surface). During sampling, leaf litter and grass were removed to expose the mineral soil surface and in a few cases slight adjustments to the depth of the sample were necessary due to the presence of cobbles or bedrock. No information was available to assess whether the grasses were perennial or annual or of C_3 or C_4 types. However, it is likely they are C_4, given the predominance of C_4 grasses regionally.[62] All samples were assessed visually for color, texture, and roots, leaves, and charcoal. At each location, ECS dimensions were measured including height and width and an estimate of the upstream length of the sediment wedge (Figure 3). The volume of captured sediment was estimated using the equation for a half elliptical paraboloid (Table 2).[85]

In LBSO, 4 locations are represented: 2 in-channel ECS (with names: UPPER LBSO and MIDDLE LBSO (Figure 2A)), plus HILLSLOPE LBSO A to D (Figure 2B) and OFF-CHANNEL LBSO. The results and site information are found in Tables 1 and 2. They may also be found by following the highlighted link above to the USGS National Water Information System. The total number of sites in LBSO is 13: 3 locations with 4 sampling sites each (A thru D), and one with one sampling site (location name = Off-Channel LBSO). The channel at the Upper LBSO site was dry at the time of sampling with shallow gravelly sediment, high slope, and exposed fractured bedrock adjacent to the stream channel. The next site down gradient was Hillslope LBSO. This site and the adjoining area generally have low slope, covered with leaves and grass, and unknown depth to bedrock. The site furthest downstream, Middle LBSO, had a shallow water table at the time of sampling as evidenced by a pool of water downstream of the ECS. It is often flooded during the summer rainy season (Valer Clark, personal communication, 2016).

Three locations were sampled in HBSN: 2 in-channel sites (with names UPPER HBSN and MIDDLE HBSN (Figure 2C)), plus OFF-CHANNEL HBSN. The total number of sites in HBSN is 9: 2 locations with 4 sites each (A thru D), and 1 with 1 site (location name = Off-Channel HBSN). The Upper and Middle HBSN sites have soils in the upper 2 m that had been deposited at most 5 years before sampling and are commonly flooded in summer (Valer Clark, personal communication, 2016). At the Upper HBSN site, a sample was taken of the thick (about 15 cm) aerially extensive (about 30 m^2) in-channel cover of leaf litter. This consisted primarily of oak leaves but also of twigs and pine needles, all of which were presumed to originate from overhanging trees, upstream forest, and surrounding hillslopes.

Laboratory procedures

In the laboratory, standard procedures were followed. Samples were weighed, ground to break up aggregates, passed through a 2-mm sieve,[86] then oven dried at 60°C for at least 48 h until weight stabilized. Dried samples were ground to a uniform consistency, passed through a 0.25 mm sieve and weighed. Sieve ranges of 0.10 and 0.15 mm are common, but soils that pass through a 0.25-mm mesh do not give statistically different results.[87] Samples were analyzed for %OC, %N, $\delta^{13}C$, and $\delta^{15}N$ at the University of Arizona Environmental Isotope Laboratory using an elemental analyzer (Costech) coupled to a Finnigan Delta Plus XL continuous flow mass spectrometer. Carbonates were removed by addition of H_2SO_3. In the elemental analyzer, after dry combustion, OC and nitrogen fractions were determined by gas chromatography. A minimum of one acetanilide standard was run with every 10 samples. The acetanilide was calibrated against NBS-22 and USGS-24 for $\delta^{13}C$, and IAEA-N-1 and IAEA-N-2 for $\delta^{15}N$. Precision is better than ±0.08‰ for $\delta^{13}C$ and ±0.2‰ for $\delta^{15}N$ (1σ), based on repeated internal standards. Organic carbon and total N were reported as percent OC and total N in the <0.25-mm fraction. These values were converted to percentages of the total sample using the mass ratio of the <0.25-mm fraction to the total sample (Table 1). Monthly values of standards for the year prior to the measurements indicated acceptable instrument stability. Certain samples had mass of N below the range of standards. To remedy this, we prepared a set of standards to extend the range and used established approaches to determine method detection and quantitation limits.[88] We determined a method detection limit of 0.015 mg N, and a quantitation limit of 0.03 mg N. The data were reviewed according to USGS protocols and stored in the USGS National Water Information System.[89]

Modeling and statistical analysis

Procedures for comparing central tendencies were performed using NADA for *R*[88,90,91] and ProUCL.[92] For samples with uncensored data, either Wilcoxon Rank Sum[88] or Wilcoxon-Mann-Whitney[92] methods were used. The Wilcoxon Signed Rank test was used to compare paired (matched) samples collected at the same site at different depths.[88] Censored data were those values of N that fell between the limits of quantitation (0.03 mg N) and method detection (0.015 mg N). For censored data, all tests were carried out using the Gehan method.[92]

We calculated the potential mean annual capture of OC by combining information from the LBSO and HBSN including median OC of the hillslope and in-channel sites both depths, estimated sediment volumes (Table 2) and published modeling results of annual sediment accumulation rates for ECS in LBSO.[56] We use the full range of data available from both watersheds to make the results more widely applicable. In the previously published modeling work, it was estimated that ECS could retain about 178 to 242 metric tons of sediment per year. Using this range of values, their count of 2000 ECS with 90% on hillslopes, and the mean and median OC content from all in-channel samples (Table 1), we estimated the annual capture of OC in the group of 2000 ECS using equation (1)

$$Rate_{CC} = \left(Fx_{OC}\right)\left(Rate_{SC}\right)\left(Fx_{Sed}\right) \quad (1)$$

where $Rate_{CC}$ is the rate of carbon capture in metric tons per year, $Rate_{SC}$ is the rate of sediment capture in metric tons per year, and Fx_{OC} and Fx_{Sed} are, respectively, the fraction of total OC and fraction in each geomorphic setting of the total sediment captured by ECS (Table 3).

To calculate the total potential storage and storage per hectare in LBSO, the following equation was used with input data from Table 4

$$S_{TOT} = \left(Vol_{Sed}\right)\left(Fx_{OC}\right)(ECS)\left(\rho_b\right) \quad (2)$$

where for each geomorphic setting, Vol_{Sed} is the median volume of sediment, Fx_{OC} is the median fraction of total OC, *ECS* is the number of ECS, and ρ_b is bulk density in metric tons per cubic meter derived from the Rafter Soil Series.[60] Carbon storage per hectare is calculated by dividing S_{TOT} by the estimated total area of ECS in LBSO.

To illustrate the potential for ECS to store OC if they were implemented on a large scale, we carried out a modeling experiment by extrapolating the results of the study to the forests of the southwestern United States (Figure 4). Multiple sources of uncertainty exist (eg, not all sites are suitable for reasons of slope, geology, etc). The intention, however, is not to provide an exact estimate, but to begin a discussion of the possibilities for

Table 1. Sample site names, coordinates, sampling depth, and results of analysis for %C, %N, C/N, δ^{13}C, and δ^{15}N.

SITE NUMBER	WATERSHED NAME	GEOMORPHIC SETTING	SITE NAME[a]	SAMPLING DATE	LATITUDE	LONGITUDE
					DEG-MIN-SEC[h]	DEG-MIN-SEC[h]
315145109222101	Coal Pit	Stream channel	Upper HBSN A	12/8/2015	31 51 45.17	109 22 21.01
315145109222101	Coal Pit	Stream channel	Upper HBSN A	12/8/2015	31 51 45.17	109 22 21.01
315145109222101	Coal Pit	Stream channel	Upper HBSN A	12/8/2015	31 51 45.17	109 22 21.01
315145109222102	Coal Pit	Stream channel	Upper HBSN B	12/8/2015	31 51 45.17	109 22 21.01
315145109222102	Coal Pit	Stream channel	Upper HBSN B	12/8/2015	31 51 45.17	109 22 21.01
315145109222103	Coal Pit	Stream channel	Upper HBSN C	12/8/2015	31 51 45.17	109 22 21.01
315145109222103	Coal Pit	Stream channel	Upper HBSN C	12/8/2015	31 51 45.17	109 22 21.01
315145109222104	Coal Pit	Stream channel	Upper HBSN D	12/8/2015	31 51 45.17	109 22 21.01
315145109222104	Coal Pit	Stream channel	Upper HBSN D	12/8/2015	31 51 45.17	109 22 21.01
315152109224701	Coal Pit	Stream channel	Middle HBSN A	12/8/2015	31 51 52.10	109 22 47.21
315152109224701	Coal Pit	Stream channel	Middle HBSN A	12/8/2015	31 51 52.10	109 22 47.21
315152109224702	Coal Pit	Stream channel	Middle HBSN B	12/8/2015	31 51 52.10	109 22 47.21
315152109224702	Coal Pit	Stream channel	Middle HBSN B	12/8/2015	31 51 52.10	109 22 47.21
315152109224703	Coal Pit	Stream channel	Middle HBSN C	12/8/2015	31 51 52.10	109 22 47.21
315152109224703	Coal Pit	Stream channel	Middle HBSN C	12/8/2015	31 51 52.10	109 22 47.21
315152109224704	Coal Pit	Stream channel	Middle HBSN D	12/8/2015	31 51 52.10	109 22 47.21
315152109224704	Coal Pit	Stream channel	Middle HBSN D	12/8/2015	31 51 52.10	109 22 47.21
315153109224601	Coal Pit	Terrestrial	Off-Channel HBSN	12/8/2015	31 51 53.12	109 22 46.43
315153109224601	Coal Pit	Terrestrial	Off-Channel HBSN	12/8/2015	31 51 53.12	109 22 46.43
315222109210101	Turkey Pen	Stream channel	Upper LBSO A	12/7/2015	31 52 21.57	109 21 00.68
315222109210101	Turkey Pen	Stream channel	Upper LBSO A	12/7/2015	31 52 21.57	109 21 00.68
315222109210102	Turkey Pen	Stream channel	Upper LBSO B	12/7/2015	31 52 21.57	109 21 00.68
315222109210102	Turkey Pen	Stream channel	Upper LBSO B	12/7/2015	31 52 21.57	109 21 00.68
315222109210103	Turkey Pen	Stream channel	Upper LBSO C	12/7/2015	31 52 21.57	109 21 00.68
315222109210103	Turkey Pen	Stream channel	Upper LBSO C	12/7/2015	31 52 21.57	109 21 00.68
315222109210103	Turkey Pen	Stream channel	Upper LBSO C	12/7/2015	31 52 21.57	109 21 00.68
315222109210104	Turkey Pen	Stream channel	Upper LBSO D	12/7/2015	31 52 21.57	109 21 00.68
315222109210104	Turkey Pen	stream channel	Upper LBSO D	12/7/2015	31 52 21.57	109 21 00.68
315233109210501	Turkey Pen	Hillslope	Hillslope LBSO A	12/7/2015	31 52 32.98	109 21 05.43
315233109210501	Turkey Pen	Hillslope	Hillslope LBSO A	12/7/2015	31 52 32.98	109 21 05.43
315233109210502	Turkey Pen	Hillslope	Hillslope LBSO B	12/7/2015	31 52 32.98	109 21 05.43
315233109210502	Turkey Pen	Hillslope	Hillslope LBSO B	12/7/2015	31 52 32.98	109 21 05.43
315233109210503	Turkey Pen	Hillslope	Hillslope LBSO C	12/7/2015	31 52 32.98	109 21 05.43

DEPTH[b]	MASS OF SAMPLE	MASS OF FINES[c]	ORGANIC C FINES[c]	ORGANIC C WHOLE SAMPLE[d]	TOTAL N IN FINES[c,e]	TOTAL N IN WHOLE SAMPLE[d,e]	C/N	$\delta^{13}C^{c,f}$	$\delta^{15}N^{c,g}$
CENTIMETERS	GRAMS	GRAMS	%[i]	%[i]	%[i]	%[i]	GRAMS PER GRAM	‰	‰
Leaf litter[j]	–	3.684	16.8	–	0.59	–	28.7	−26.2	−1.1
10	–	6.328	1.3	–	0.06	–	21.8	−25.6	−0.4
30	5.513	5.164	5.0	4.7	0.15	0.14	32.7	−24.7	−2.0
10	1.738	1.498	4.1	3.6	0.15	0.13	27.6	−26.2	−0.3
30	6.858	6.429	2.1	2.0	0.08	0.08	25.1	−25.6	−1.2
10	3.127	2.953	7.3	6.9	0.28	0.26	26.3	−25.6	−1.3
20-25	3.055	2.712	3.1	2.7	0.11	0.09	29.1	−24.6	−1.2
10	3.588	3.193	9.3	8.3	0.28[k]	0.25[k]	33.2[k]	−25.9	−1.1
30	6.071	4.718	8.6	6.7	0.31	0.24	28.1	−25.5	−1.3
10	3.737	2.761	7.9	5.8	0.39	0.29	19.9	−25.3	−0.3
30	5.467	4.813	9.0	7.9	0.40	0.35	22.8	−25.1	−1.9
10	2.680	2.366	11.2	9.9	0.45	0.40	24.9	−25.7	−0.6
30	4.157	1.011	13.0	3.2	0.50	0.12	25.7	−24.9	−1.1
10	–	–	10.7	–	0.42	–	25.7	−25.8	−1.0
30	6.427	5.178	9.2	7.4	0.45	0.36	20.4	−25.2	−4.8
10	3.740	3.315	8.1	7.2	0.35	0.31	23.3	−25.6	−0.1
30	8.639	6.077	3.5	2.4	0.13	0.09	27.5	−25.6	−1.3
10	2.676	2.402	3.0	2.7	0.14	0.12	21.6	−25.3	0.3
30	4.456	3.916	0.4	0.4	0.03	0.02	17.3	−23.8	3.8
15	33.655	24.094	0.7	0.5	0.06	0.04	12.7	−24.2	2.1
30	17.119	13.217	1.0	0.8	0.07	0.05	15.7	−23.9	1.5
10	20.043	18.413	0.7	0.6	0.05	0.05	12.6	−25.2	1.9
30	19.327	15.456	1.3	1.0	0.08	0.06	16.2	−24.3	1.8
5	14.386	7.888	7.8	4.3	0.50	0.28	15.5	−24.4	1.3
10	18.326	15.963	0.4	0.4	0.03[k]	0.03[k]	12.4[k]	−24.5	1.5
30	9.301	8.626	1.1	1.0	0.07	0.07	15.0	−24.4	1.3
10	9.341	8.679	0.8	0.7	0.05	0.05	14.3	−24.3	2.3
30	9.343	8.482	2.0	1.8	0.13	0.11	15.7	−24.3	1.4
10	7.243	6.817	0.3	0.3	0.02[k]	0.02[k]	15.8[k]	−24.1	1.1
30	14.093	13.586	0.3	0.2	0.01[k]	0.01[k]	18.0[k]	−23.4	5.0
10	13.488	12.546	0.4	0.4	0.03[k]	0.03[k]	17.0[k]	−23.9	1.7
30	8.182	7.841	0.6	0.5	0.02	0.02	27.8	−24.8	3.3
10	7.502	7.281	0.5	0.5	0.03	0.03	19.1	−24.8	0.7

(Continued)

Table 1. (Continued)

SITE NUMBER	WATERSHED NAME	GEOMORPHIC SETTING	SITE NAME[a]	SAMPLING DATE	LATITUDE	LONGITUDE
					DEG-MIN-SEC[h]	DEG-MIN-SEC[h]
315233109210503	Turkey Pen	Hillslope	Hillslope LBSO C	12/7/2015	31 52 32.98	109 21 05.43
315233109210504	Turkey Pen	Hillslope	Hillslope LBSO D	12/7/2015	31 52 32.98	109 21 05.43
315233109210504	Turkey Pen	Hillslope	Hillslope LBSO D	12/7/2015	31 52 32.98	109 21 05.43
315228109220401	Turkey Pen	Stream channel	Middle LBSO A	12/7/2015	31 52 27.89	109 22 04.05
315228109220401	Turkey Pen	Stream channel	Middle LBSO A	12/7/2015	31 52 27.89	109 22 04.05
315228109220402	Turkey Pen	Stream channel	Middle LBSO B	12/7/2015	31 52 27.89	109 22 04.05
315228109220402	Turkey Pen	Stream channel	Middle LBSO B	12/7/2015	31 52 27.89	109 22 04.05
315228109220403	Turkey Pen	Stream channel	Middle LBSO C	12/7/2015	31 52 27.89	109 22 04.05
315228109220403	Turkey Pen	Stream channel	Middle LBSO C	12/7/2015	31 52 27.89	109 22 04.05
315228109220404	Turkey Pen	Stream channel	Middle LBSO D	12/7/2015	31 52 27.89	109 22 04.05
315228109220404	Turkey Pen	Stream channel	Middle LBSO D	12/7/2015	31 52 27.89	109 22 04.05
315228109220405	Turkey Pen	Terrestrial	Off-Channel LBSO	12/7/2015	31 52 27.74	109 22 03.93
315228109220405	Turkey Pen	Terrestrial	Off-Channel LBSO	12/7/2015	31 52 27.74	109 22 03.93

Abbreviations: HBSN, higher burn severity newer; LBSO, lower burn severity older; OC, organic carbon.
[a]To find the site name used in the USGS National Water Information System simply replace HBSN or LBSO with the Watershed Name.
[b]Measured from mineral soil surface.
[c]Reported laboratory value (measured on portion of sample sieved with 0.25 mm screen).
[d]C or N in whole sample = C or N content in Fines*Mass of Fines/Mass of Sample.
[e]Total N = nitrate + nitrite + ammonia + organic-N.
[f]$\delta^{13}C$ of organic C.
[g]$\delta^{15}N$ of total N.
[h]Datum NAD-83.
[i]Percentage of dry weight.
[j]Leaf litter sample was taken above the mineral soil.
[k]Mass of N in sample between quantification and method detection limits. See methods section for definitions.
[l]Mass of N in sample below method detection limit. See methods section for definition.

DEPTH[b]	MASS OF SAMPLE	MASS OF FINES[c]	ORGANIC C FINES[c]	ORGANIC C WHOLE SAMPLE[d]	TOTAL N IN FINES[c,e]	TOTAL N IN WHOLE SAMPLE[d,e]	C/N	$\delta^{13}C$[c,f]	$\delta^{15}N$[c,g]
CENTIMETERS	GRAMS	GRAMS	%[i]	%[i]	%[i]	%[i]	GRAMS PER GRAM	‰	‰
30	18.534	17.769	0.5	0.5	0.03[k]	0.03[k]	17.7[k]	−24.2	2.8
10	8.493	7.888	0.2	0.2	0.02[k]	0.02[k]	14.3[k]	−23.7	2.7
30	8.027	7.717	0.4	0.4	0.02	0.02	18.3	−23.4	4.7
10	10.233	8.162	0.6	0.5	0.04	0.03	13.5	−24.8	1.2
30	16.619	15.600	0.2	0.2	0.02	0.02	10.9	−24.4	2.7
10	8.944	8.399	0.5	0.4	0.04[k]	0.04[k]	13[k]	−24.8	1.4
30	8.449	7.775	1.0	0.9	0.07	0.07	13.5	−25.1	2.0
10	9.665	8.652	0.3	0.3	0.03	0.02	11.1	−24.2	2.1
25	11.287	10.256	0.7	0.6	0.05	0.05	13.2	−24.6	1.8
10	4.353	4.011	1.6	1.5	0.11	0.10	15.3	−24.1	0.6
30	14.739	13.426	0.3	0.2	0.02[k]	0.02[k]	12.7[k]	−24.7	2.8
10	29.886	14.358	1.3	0.6	0.09	0.04	15.4	−22.3	1.9
30	5.552	4.803	0.1	0.1	[l]	[l]	[l]	−22.4	6.3
Mean OC whole sample (all in-channel sites, both depths)				3.0					
Mean OCwhole Sample (Hillslope site, both depths)				0.4					
Median OC whole sample (all in-channel sites, both depths)				1.8					
Median OC whole sample (Hillslope site, both depths)				0.4					

ECS-induced OC sequestration over large areas using modeling as a virtual laboratory. To begin, we assumed that forested areas in the southwest USA have the potential for 2.6 ECS per hectare, which is the estimated spatial density of ECS in the LBSO watershed (Table 4). For a conservative estimate, we used the lower %OC values in LBSO, which will be shown below to represent longer-term storage of OC. The structures in this watershed are older (most are between 20 and 35 years old: Valer Clark, personal communication, 2016), sediments tend to be wetter, and as a result SOM is potentially closer to long-term values. Organic carbon is likely to be retained in cases where soils remain saturated and have low oxygen concentrations, conditions similar to wetland soils.[38,93-96]

The calculation of the potential total C sequestration requires estimates of volumes of sediment captured by ECS. The estimate was developed using the measured dimensions of the hillslope and in-channel sites (Table 2) and the equation for volume of a half elliptical paraboloid.[85] Total potential for C sequestration was then calculated by multiplying the estimated sediment capture volumes, ECS_{pot}, an estimate of soil bulk density (ρ_b), and the average weight-percent C found in hillslope (OC_{Hill}) and in-channel (OC_{Chan}) ECS (equation (3)). We estimated C_{Tot} and the uncertainty therein using a Monte Carlo approach that accounts for uncertainties in each of the input variables. We carried out a total of 5000 realizations. Input values and error terms for the following equation are summarized in Table 5

$$C_{Tot} = \left(FA + eFA\right)^* \left(e\rho_b + \rho_b\right)^* \left[\begin{pmatrix} 0.9^*(eECS_{pot} + ECS_{pot})^* \\ (eVol_{Hill} + Vol_{Hill})^* \\ (eC_{Hill} + C_{Hill}) \end{pmatrix} + \begin{pmatrix} 0.1^*(eECS_{pot} + ECS_{pot})^* \\ (eVol_{Chan} + Vol_{Chan})^* \\ (eC_{Chan} + C_{Chan}) \end{pmatrix} \right] \quad (3)$$

where C_{Tot} is the potential for C sequestration (mass C) stored behind ECS in southwest USA Forests, *FA* is the area of forest in the southwest USA extracted from the National Land Cover Database,[97] ρ_b is soil bulk density derived from the Rafter Soil Series,[60] *ECSpot* is the potential number of ECS per unit area.[56] Combining data from both LBSO and HBSN, Vol_{HILL} and Vol_{Chan} are the estimated volumes of sediment retained upstream of hillslope and channel ECS (Table 2), and C_{hill} and C_{chan} are the mean measured OC contents in samples of sediment retained upstream of hillslope and channel ECS expressed as a fraction by weight. Error terms "*e*" were estimated for each variable in the Monte Carlo simulation. The factors 0.1 and 0.9 in equation (1) were based on the assumption that approximately 10% of ECS were installed in channels and 90% on hillslopes. The 5000 realizations of C_{Tot} were log-transformed to more closely approximate a normal distribution.

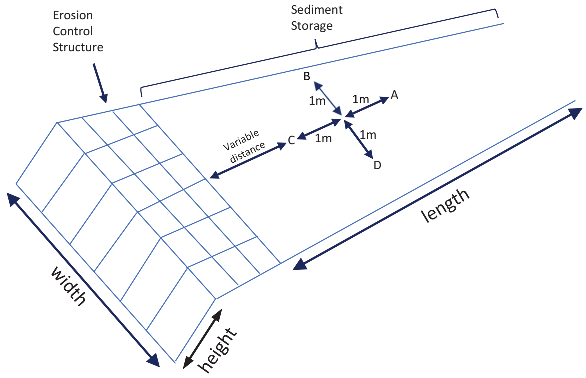

Figure 3. Geometry of sediment sampling sites relative to erosion control structures.

Results

Table 2. Dimensions of erosion control structures and estimated volume of captured sediments.

LOCATION NAME	WIDTH	HEIGHT	LENGTH	SEDIMENT AREA[a]	SEDIMENT VOLUME[b]
	METERS	METERS	METERS	SQUARE METERS	CUBIC METERS
Upper HSBN	10.0	2.0	24.0		
Middle HSBN	12.0	1.60	15.0		
Upper LBSO	4.05	1.40	4.00		
Middle LBSO	7.30	0.90	5.30		
Median dimensions	8.7	1.5	10.2	73[c]	52[c]
Hillslope LBSO	2.75	0.29	3.30	6	1

Abbreviations: HBSN, higher burn severity newer; LBSO, lower burn severity older.
[a]Area parabola = 2/3wl (median of sediment areas).
[b]volume elliptical paraboloid = π(w/2)–l/4 (using median dimensions).
[c]Estimated using median dimensions.

Table 3. Potential annual capture rate of organic carbon in ECS-captured sediments.

GEOMORPHIC SETTING	VOLUME OF SEDIMENT (VOL_{SED})[a]	NUMBER OF *ECS* OF EACH TYPE[b]	FRACTION OF TOTAL VOLUME OF SEDIMENT (FX_{SED})	FRACTION ORGANIC CARBON (FX_{OC})[c]	*LOW* ESTIMATE *SEDIMENT* CAPTURE RATE ($RATE_{SC}$)[b]	*LOW* ESTIMATE *CARBON* CAPTURE RATE ($RATE_{CC}$)[d]	*HIGH* ESTIMATE *SEDIMENT* CAPTURE RATE ($RATE_{SC}$)[b]	*HIGH* ESTIMATE *CARBON* CAPTURE RATE ($RATE_{CC}$)[d]
	CUBIC METERS			%	METRIC TONS PER YEAR	METRIC TONS PER YEAR	METRIC TONS PER YEAR	METRIC TONS PER YEAR
				MEAN				
Stream channel	52	200	0.85	3.0	178	5	242	6
Hillslope	1	1800	0.15	0.4	178	0.1	242	0.1
				MEDIAN				
Stream channel	52	200	0.85	1.8	178	3	242	4
Hillslope	1	1800	0.15	0.4	178	0.1	242	0.1

Abbreviations: ECS, erosion control structures.
[a]From Table 2.
[b]From Norman and Niraula.[56]
[c]From Table 1.
[d]Calculated using equation (1).

Table 4. Estimate of total potential storage of organic carbon and storage per unit area in ECS-captured sediments.

GEOMORPHIC SETTING	VOLUME OF SEDIMENT (VOL_{SED})[a]	MEDIAN FRACTION ORGANIC CARBON (FX_{OC})[b]	NUMBER OF *ECS* OF EACH TYPE[c]	*LOW* ESTIMATE TOTAL POTENTIAL CARBON STORAGE (S_{TOT})[d,e]	*HIGH* ESTIMATE TOTAL POTENTIAL CARBON STORAGE (S_{TOT})[d,f]	MEDIAN AREA OF ECS[a]	ESTIMATED TOTAL AREA OF ECS IN LBSO	*LOW* ESTIMATE CARBON STORAGE PER HECTARE[d,e]	*HIGH* ESTIMATE CARBON STORAGE PER HECTARE[d,f]
	CUBIC METERS	%		METRIC TONS	METRIC TONS	SQUARE METERS	HECTARES	METRIC TONS PER HECTARE	METRIC TONS PER HECTARE
Stream channel	52	1.8	200	282	353	73	1.5	193	242
Hillslope	1	0.4	1800	11	14	6	1.1	10	13
			Total →	293	368		2.6	203	255

Abbreviations: ECS, erosion control structures; LBSO, lower burn severity older.
[a]From Table 2.
[b]From Table 1.
[c]from Norman and Niraula.[56]
[d]Calculated using equation (2).
[e]Bulk density (ρ_b) low = 1.53 metric ton/m^3 (Rafter Soil Series [NRCS USDA Web Soil Series]: See Soil Survey Staff NRCS USDA.[60]
[f]Bulk density (ρ_b) high = 1.92 metric ton/m^3 (Rafter Soil Series [NRCS USDA Web Soil Series]: See Soil Survey Staff NRCS USDA.[60]

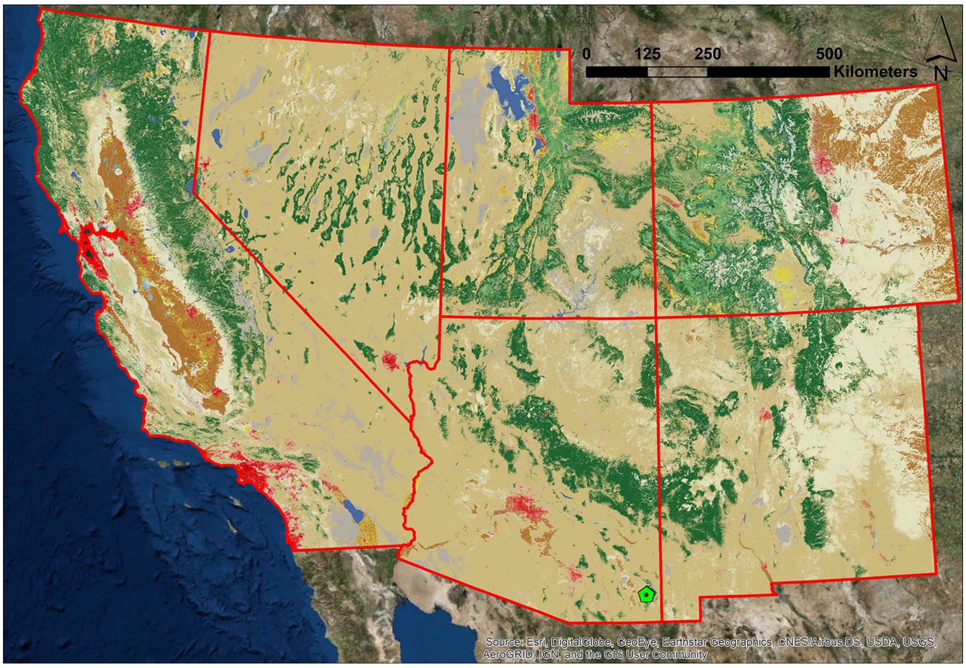

Figure 4. National Land Cover Database 2011 for the southwest USA.[97] Forests are indicated by areas in green. The green pentagon symbol indicates the location of the study area.

Soil, sediment, and leaf litter composition

The ranges of OC, N, and C/N of soils, sediments, and leaf litter were found to be within typical ranges for forest soils in the semiarid southwest USA[63] with OC ranging from 0.1% to 9.9% (median: 0.8%) and N from 0.01% to 0.6% (median: 0.1%). The range of $\delta^{13}C$ was −26.2 to −22.3 ‰ with a median of −24.7 ‰ which is slightly lower than the lower range for C_3 plants in arid ecosystems (Figure 5A).[63] Values of $\delta^{13}C$ at 30 cm were generally higher than at 10 cm. The range of $\delta^{15}N$ was −4.8 to +6.2 ‰, with a median of +1.3 ‰ (Figure 5B). The C/N (mass) ratio ranged from 11 to 33 with a median of 17.5. As expected, OC and N were linearly related, as soil N and C cycles are typically closely coupled and controlled by microbial communities.[98,99]

The two watersheds studied were significantly different with respect to all parameters measured. Values from HBSN samples were higher in OC, N, C/N, and lower in $\delta^{15}N$ and $\delta^{13}C$ than LBSO, and C/N plotted against $\delta^{13}C$ and $\delta^{15}N$ shows clear groupings for each watershed (Figure 5; Table 1). Depth was not generally a significant factor with the exception of $\delta^{13}C$ in HBSN (0.5 ‰ difference, 10 cm < 30 cm) and $\delta^{15}N$ in LBSO where, contrary to expectations,[80,81] they were significantly higher at 10 cm than at 30 cm depth. The single hillslope sample from LBSO had values of $\delta^{13}C$, $\delta^{15}N$, and C/N intermediate between those of in-channel sediments from LBSO and HBSN.

Leaf litter was primarily oak leaves though some pine needles and twigs were present. Leaf litter (and the ash derived from it) was of interest because it represents one of the possible sources of OC and N in captured sediments. The leaf litter was sampled at the Upper HBSN site. $\delta^{15}N$ of the leaf litter, −1.1 ‰, was near the median for HBSN sediment samples. It had the highest OC, 16.8%, and N, 0.6%, and the lowest $\delta^{13}C$, −26.2 ‰, which is near the middle of the typical range for C_3 plants in dry ecosystems.[63] The leaf litter had one of the highest C/N values in the study, 28.7, though this is lower than the average C/N, 68, for temperate oak leaf litter.[67] Three samples had C/N higher than 28.7, all at the Upper HBSN site.

Off-channel soils, in contrast to the ECS-associated sediments, represent soil profiles unaffected by frequent flooding, seasonal inundation, and accompanying erosion/deposition. In HBSN, the 10-cm depth off-channel sediment resembled in-channel sediments in $\delta^{13}C$, $\delta^{15}N$, and C/N, but the 30-cm depth had higher $\delta^{13}C$, −23.8 ‰, $\delta^{15}N$, +3.8 ‰, and lower C/N, 17.3 (Figure 5). In fact, the highest values of $\delta^{13}C$ and $\delta^{15}N$ and lowest C/N in that watershed were found off-channel at the 30-cm depth. At the HBSN off-channel site, OC was higher at both depths than the comparable sample in LBSO. In LBSO, 10-cm depth off-channel sediment resembled in-channel sediment except in $\delta^{13}C$, −22.3 ‰. Off-channel sediment at 30-cm depth was distinct from in-channel sediment in $\delta^{13}C$, −22.3 ‰ and $\delta^{15}N$, +6.3 ‰, but not in C/N.

Capture of OC and N by ECS

Both OC and N at the ECS in HBSN were higher (by a factor of 2 or more at 10 cm, and a factor of 10 or more at 30 cm) than in off-channel samples (Figure 5; Table 1). Values of N followed a similar pattern at LBSO. However, in-channel OC values in LBSO were not as readily distinguishable from off-channel values, especially at the 10-cm depth.

Table 5. Mean and error of variables used in equation (1) to calculate the potential for ECS-sequestered organic carbon in the Southwest USA. Estimated errors are standard deviations of a normal distribution.

	AREA OF FOREST IN THE SOUTHWEST USA (*FA*)	MEDIAN SOIL BULK DENSITY (ρ_B)[a]	POTENTIAL NUMBER OF ECS PER UNIT AREA (ECS_{POT})[b]	SEDIMENT VOLUME HILLSLOPE (VOL_{HILL})[c]	SEDIMENT VOLUME IN-CHANNEL (VOL_{CHAN})[c]	*MEDIAN OC WHOLE SAMPLE HILLSLOPE* (C_{HILL})[d]	*MEDIAN OC WHOLE SAMPLE IN-CHANNEL* (C_{CHAN})[d]
	HECTARES	KILOGRAMS PER CUBIC METER	ECS PER HECTARE	CUBIC METERS	CUBIC METERS	FRACTION BY WEIGHT	FRACTION BY WEIGHT
Estimate	35952308	1710	2.6	1.0	52	0.004	0.03
Error	1000	210	1.3	0.5	25	0.0013	0.03

Abbreviations: ECS, erosion control structures; OC, organic carbon.
[a]From Rafter Soil Series (NRCS USDA Web Soil Series): See Soil Survey Staff NRCS USDA.[60]
[b]From Norman and Niraula.[56]
[c]From Table 2.
[d]From Table 1.

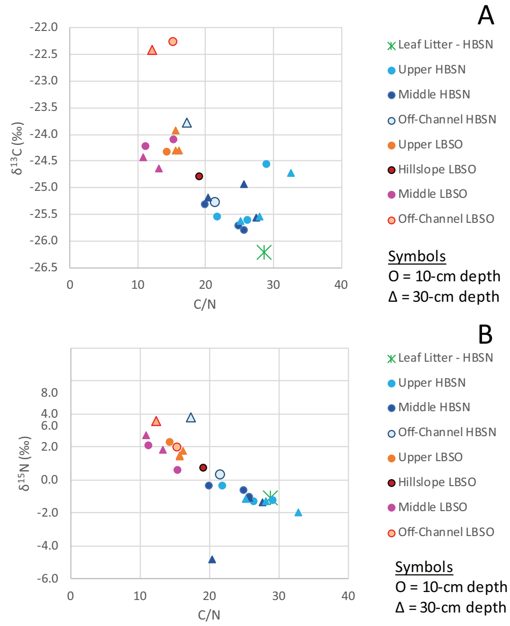

Figure 5. C/N plotted against (A) δ[13]C and (B) δ[15]N. Values of samples from LBSO are shown in shades of red or orange. Those from HBSN are blue or green. Samples taken from the 10-cm depth are indicated by circles and 30-cm depths by triangles. Censored data are not shown except for the off-channel LBSO 30-cm sample. Its C/N is imprecise because of a below-method-detection-limit N measurement, but it is plotted to show the magnitude of δ[13]C and δ[15]N relative to other samples. HBSN indicates higher burn severity newer; LBSO, lower burn severity older.

A previous study of the LBSO watershed using coupled rainfall-runoff and sediment transport modeling found that the ECS in that watershed can retain about 178 to 242 metric tons of sediment per year (although we expect that this rate would decline as ECS fill over time).[56] Using this range of values and equation (1), we estimated the mean *potential annual capture of OC* in LBSO to be 5 to 6 metric tons, and the median to be 3 to 4 tons (Table 3). The difference between mean and median is caused by data outliers that skew the mean. We also calculated the range of *total potential storage* in LBSO using our estimated range of ECS storage volumes, OC content, and estimates of bulk density.[60] The range of total potential OC storage was about 293 to 368 metric tons, corresponding to a range of 203 to 255 metric tons per hectare of ECS (Table 4). Although filling these structures via the simulated annual rate would take many decades, most of the filling would likely occur during a few postwildfire floods. The modeling for the entire region yielded a conservative *regional estimate of total sequestration potential* of 0.0109 Pg of OC with a 95% confidence interval of 0.0104 to 0.0114 Pg (Table 3).

Discussion

Watershed comparison

The differences between the 2 watersheds are notable, given their similar size and location. In HBSN, ECS extended or constructed after the 2011 Horseshoe 2 fire filled with black flood-transported postfire debris (Valer Clark, personal communication, 2016). Thus, the higher OC and N in HBSN likely reflect the higher burn severity and more recent filling of new ECS. Values of $\delta^{13}C$ and $\delta^{15}N$ in LBSO are generally higher than in HBSN and C/N lower. Hypotheses to explain the general increase of $\delta^{13}C$ and $\delta^{15}N$ as C/N decreases (Figure 5) include (1) progressive decomposition decreases C/N and increases $\delta^{13}C$ as original SOM is replaced by increasing amounts of microbially processed OM over time; (2) C_4 grass growing on ECS-captured sediments and greater proportion of C_4 plants in LBSO watershed contributing C_4-rich OM to sediment; and (3) higher burn severity in HBSN, leading to PyC-rich sediments containing proportionally more lignin than LBSO (lignin having lower $\delta^{13}C$ than whole wood).[68,100] Hypothesis 2 can be rejected because grass is present at all sites in both watersheds and grass straw and its combustion products have high C/N.[101] Thus, increasing the amount of C_4 OM would not be expected to lead to the observed trend of increasing $\delta^{13}C$ with decreasing C/N. Hypothesis 3 can also be rejected because lignin has high C/N. Two arguments favor hypothesis 1. First, hypothesis 1 is consistent with the ages of ECS sediment: upper layers of HBSN sediment are younger than those in LBSO. Second, HBSN leaf litter (representing a source of OM in ECS) that is unaffected by burning is among the samples with lowest $\delta^{13}C$ and highest C/N.

Off-channel soils

Off-channel soils, in contrast to the ECS-associated samples, represent soil profiles unaffected by frequent flooding, seasonal inundation, and accompanying erosion/deposition. At the HBSN off-channel site, OC was higher at both depths than in the comparable sample in LBSO (Figure 5), consistent with the higher proportion of C_3 plants (having greater lignin content) observed in HBSN, possibly due to greater proportion of OM derived from C_4 plants. In HBSN, the highest values of $\delta^{13}C$ and $\delta^{15}N$ and lowest C/N in that watershed were found off-channel at 30 cm depth. A possible explanation for the high $\delta^{13}C$ may be greater incorporation of $\delta^{13}C$-enriched soil CO_2 in older more microbially processed SOM at depth,[64,102] With respect to $\delta^{15}N$, an accompanying increase with depth and age[82,103,104] is consistent with a combination of 1) removal of soluble and gaseous N species with low $\delta^{15}N$, such as ammonia and nitrate, which are readily transported away leaving behind ^{15}N-enriched OM[105,106] and (2) progressive stabilization by mineral particles as this ^{15}N-enriched OM is transported downward.[81] Similar explanations can be used to understand differences in $\delta^{13}C$, $\delta^{15}N$, and C/N between the 10- and 30-cm depths at the off-channel sites with the potential addition of the Suess effect decreasing $\delta^{13}C$ in younger, shallower SOM and/or increasing prevalence of C_4 plants over time.[64,74]

Sequestration potential

The high OC and N contents of young (< 5 years) in-channel sediment relative to off-channel sediment at HSBN demonstrates the potential for sequestration of SOM, at least in the short term, of postwildfire sediment capture by ECS. However, older (up to 35 years) in-channel sediment at LBSO was not as readily distinguishable from off-channel sediment, suggesting that, over the long-term, sequestered OC in frequently-unsaturated surficial channel sediments that are well oxygenated may come to resemble levels in nearby soils. The amounts stored under these conditions are lower, but long-term storage may still be significant, given that OM and especially PyC have mean residence times in soil on the order of decades to millennia.[16] In addition, deeper sediments upstream of ECS are more likely to remain saturated. Moreover, when ECS are distributed at sufficiently high density across the landscape, they seldom fail even after heavy rainfall, and significant scour and redeposition events are unlikely to occur (Valer Clark, personal communication, 2016). With this combination of physical stability, chemical recalcitrance, and low oxygen environment, deeper PyC-rich sediments behind ECS may come to resemble wetland soils over time, and ultimately sequester larger amounts of OC than unsaturated soils.

Carbon capture rate, storage, and regionalization

The *mean* potential annual capture of OC estimated by combining information from the 2 study watersheds was 5 to 6 metric tons (equation (1), Table 2). The *median* was estimated to be 3 to 4 tons. The difference in the 2 is caused by outliers which underscores the spatial variability of OC. This is likely due to differences in composition of deposited sediment caused by differences in flood magnitude and watershed and burn characteristics. We also calculated the potential OC storage per hectare with a range of about 200 to 250 metric tons per hectare. This is similar to the range of OC stored in some wetlands.

Given the potential for OC storage by ECS suggested by these results and the projection that the Southwest United States will undergo more than a doubling in post fire sedimentation in the coming decades,[20] estimating sequestration potential is timely. Although small compared to estimates of OC in global fire emissions ($2.2\,Pg\,yr^{-1}$)[107] and storage in soils, the potential OC sequestration for the southwest USA is substantial in terms of ecosystem services and regional efforts to promote storage and reduce losses of carbon. If ECS are installed at a density that stabilizes a watershed, and sediments become saturated or semisaturated at depth, buried SOM may become effectively sequestered. The captured OM is transformed over time by microbial processes, reflected in lower C/N and increases in $\delta^{13}C$ and $\delta^{15}N$. This stored OM could aid in the restoration of ecosystem services,[108] especially hydrologic functioning.

Water holding capacity is improved, supporting slow release of water downstream.[38,59,95,109] We suggest that maintenance of the OC stored by ECS is dependent on quantity of recalcitrant OM such as lignin, persistence of low-O_2 saturated or semisaturated conditions in deep ECS sediments, and the areal density of ECS. To the extent that these conditions are not met, long-term storage of OC may be less than estimated.

Conclusions and Future Research

Measurements of OC and N in 2 watersheds with ephemeral and intermittent streams indicated that ECS retain OC within ephemeral channels at levels that are comparable to off-channel terrestrial soils or even higher in young (<5 years) captured wildfire-derived sediments. The construction of ECS can therefore potentially reduce transport and loss of OC and N from wildfire-affected watersheds by capturing PyC and other OM. In the combined data set for both watersheds, measurements of $\delta^{13}C$ and $\delta^{15}N$ generally increase as C/N decreases. This observation is best explained by progressive decomposition as original SOM is replaced by increasing amounts of microbially processed OM.

With respect to capture and sequestration of OC, total potential storage of OC was calculated to range from about 200 to 250 metric tons per hectare of ECS-stored sediments, similar to the amount stored in some wetlands. The modeled value of potential sequestration of OC in ECS over the southwestern USA lies within a 95% confidence interval of 0.0104 to 0.0114 Pg, similar in magnitude to the annual increase in OC in U.S. soils.[110]

Suggestions for future work include duplication of this work at sites in different ecosystems and in perennial streams. Given that sediments behind larger ECS can be 10-m thick or more, using classical and geostatistical design to select number of samples and horizontal and vertical locations would improve evaluation of the magnitude and spatial variability of measured parameters. In addition, there is a need to improve understanding of the effects of water content, redox potential, and microbial processes on timing and extent of OC and N transformations in ephemeral- and intermittent-stream channels. Detailed data from precipitation, sediment sampling, and stream-gage networks and knowledge of the prefire distribution of C_3 to C_4 plants would aid in understanding inputs to ECS. Future work may also address the effects of adding char and compostable material/green waste to ECS to promote ecosystem services and sequestration of C and N from other sources.[111] It has been found that wood and leaves from different species and with differing weathering status are transported and degraded differently.[112,113] Moreover some types of wood, depending on physical and biochemical conditions, can persist for hundreds to thousands of years when buried.[114,115] It would thus be useful to investigate the effect of vegetation type, soil properties, burial depth, elevation, and climate on OC storage in terms of quantity, biogeochemical processing, and persistence.

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Author Contributions

JBC: experiment and system conceptualization, experimentdesign and implementation, results' technical interpretation, and text writing. LNM: experiment and system conceptualization, implementation, text writing. CJE: development of system conceptual model, implementation, results' technical interpretation, and text writing. JBS: development of system conceptual model and numerical modeling, AY: development of system conceptual model.

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