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Abstract
The international conference SOIL *CARBON SEQUESTRATION for climate, food security and ecosystem services* – linking science, policy and action (SCS2013) took place in Reykjavik Iceland on 27. – 29. May 2013. The conference was organized by the Soil Conservation Service of Iceland, the Agricultural University of Iceland and the Joint Research Centre of the European Commission (Collaboration Agreement No 31059) in partnership with a group of international and UN agencies, universities and non-governmental organizations. The scientific soil community acknowledges that there is an urgent need to communicate better the value of soil carbon to a broader public. The message so far has not actively reached the media, the public and policy makers. The SCS2013 conference brought together a broad spectrum of soil carbon experts, in order to link science, policy and action on soil carbon sequestration issues. Approximately 200 people from 40 countries from all continents attended the conference: young and high level scientists; present and future leaders in restoration and land management; administrators and policymakers. The conference received extensive media coverage, both in Iceland and globally. Despite coming from different countries and backgrounds, with varied scientific interests and convictions, the overall message was that soil and soil management, specifically soil carbon, needs be a substantial part of the solution in mitigating climate change, ensuring food security and providing ecosystem services. Furthermore soil conservation, preservation and restoration could be considered as "win-win" processes for meeting other goals. The SCS2013 conference represented an excellent example of bridge between scientists, land managers and policy makers. The EC was actively involved in the conference and is still willing to bridge the communication gap between science and policy and to continue to act as interface. The conference proceedings aim to present how the potential role of soil carbon sequestration has been discussed along different sessions (forest/ cropland/ revegetation/ desertification/ wetland/ rangeland/ verification) and from different perspectives.

Monitoring soil organic carbon loss from erosion using stable isotopes

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Introduction

This manuscript examines the great potential for carbon management scope in urban lands using scientifically valid and statistically sound methods through integration of contributions from scientists and engineers from different backgrounds. The main objective is to complement the current Natural Resources Conservation Service (NRCS) initiatives to update the soil carbon stock inventory of the United States. The traditional research approaches in the US help solve local carbon sequestration issues on a watershed but fail to address the spatial and temporal impact of such local management decisions under uncertain hydrologic pulses (e.g. episodic rainfall) on the soil erosion rate distribution and the resulting soil organic carbon loss. The contribution of soil organic matter (SOM), originating from soils with different compositions, to suspended sediments in runoff, can be derived using soil organic carbon (SOC) erosion rates and stable isotope ratio (δ13C, δ15N) measurements (Boutton and Yamasaki, 1996). Traditional soil erosion budget models and numerical erosion prediction models are based on empirical relationships between estimates of the average SOC content and that of suspended organic carbon derived from river discharges (Fox and Papanicolaou, 2008). However, they do not provide information on the nature and the origin of eroded SOC and its further evolution in the hydrographic network which could provide a holistic approach to monitoring soil loss and quantify the actual sequestration. Refinements in SOC identification is achieved using δ13C measurements and its geospatial variability (Ahmed et. al., 2013).

The methods used to apply the novel isotope science include: i) Rainfall-runoff relationship, ii) Assessment of episodic nature of rainfall, iii) Land use fingerprinting, iv) Integration framework, and v) Decision Support System (DSS) development. The project began in January 2013 and has gone through phase one which received focus on items (i) and (ii) leading to item (iii) this summer of 2013. The integration framework will lead to the DSS supported by GIS and visual software tools. The three-year project is expected to end in the year 2015, and lead to a scientifically and statistically valid decision support unit to monitor soil carbon loss, and allow a basis for correlation with soil carbon sequestration in urban lands.

1. Project location, watershed physical characteristics and rainfall pattern

Under a three-year Federal grant from the US Department of Agriculture (USDA), a three institution team of scientists from Prairie View A&M University (Lead), Texas A&M University and University of Houston is currently studying soil organic nutrient distribution within the highly urbanized Buffalo Bayou Watershed in Houston, Texas. In tune with current NRCS efforts to update the national carbon stock inventory, the study is timely and sets the groundwork for future scientists interested in a region that has never been studied in this context. The watershed is characterized by low to moderate slope topography and is part of the coastal prairie lands of

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South Texas. Though the watershed is known for flooding, it drains well. This leads to soil loss from surficial erosion processes under episodic rainfall that tend to have a Poisson distribution (Irvin-Smith *et al.*, 2012).

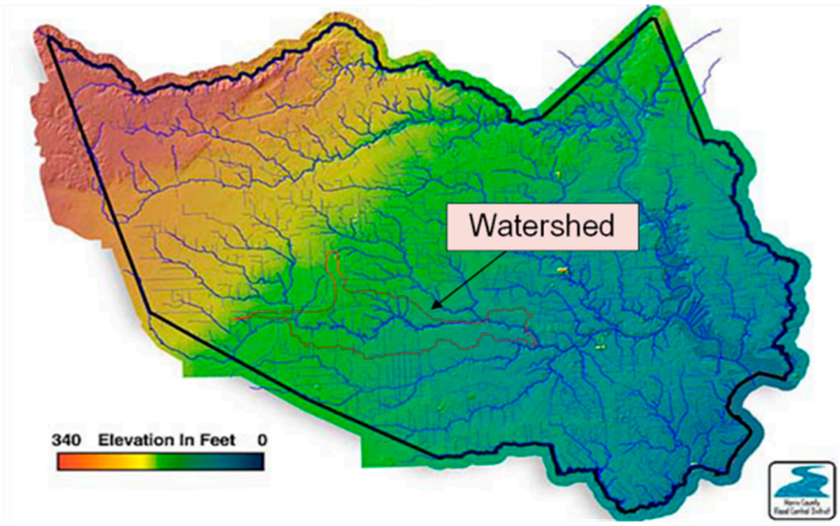

Figure 1. Study watershed within the greater Harris County watershed in Texas

Local vegetation varies from grass to century old oak trees within the urban and man-made reservoir areas of the watershed managed by the US Army Corps of Engineers. The Buffalo Bayou Watershed encompasses 150 square kilometer area within the greater Harris County watershed (Fig. 1), Texas. It is the innermost watershed in the County and therefore, the Buffalo Bayou receives a heavy load of eroded sediment from the upper parts of the watershed. The land use fingerprinting method, briefly discussed in the latter part of this paper, benefits from the inner-most location of the water-shed within Harris County. The LiDAR map in Fig. 1 shows a maximum ground elevation of approximately 104 meter (340 feet) above sea level. GIS layers from the government source were only available U.S. unit system.

1.1. Rainfall pattern and climate model for eroded soil yield estimation

Rainfall occurrence of different months of a year for up to 22 years of rain gage data were averaged and plotted by stations so that both spatial and temporal dimensions of rainfall fluctuations could be determined and assessed. Rainfall distribution over a typical year shows no discernible pattern (or trend) in the time series. Such variation in the annual rainfall pattern is noted at all rain gage stations. The plots rarely suggest any regular pattern in the occurrence of rainfall for the selected stations but rather indicate episodic (sometimes erratic) nature of rainfall incidence. This local scale erratic pattern of rainfall may be influenced by continental scale physical and climatic processes. Annual average rainfall for the study gages compared favourably (Table 1). However, as seen in Table 1 and in Chart 1 below, the highest and the lowest deviations of rainfall from the respective annual averages are significant. This indicates that rainfall variability is equally important component that deserve consideration (along with the mean values) in the assessment of climatic conditions/change, and consequently, the susceptibility of soil erosion under variable runoffs. Fig. 2 shows the rain gage locations in the watershed.

The Water Erosion Prediction Project (WEEP) software of the USDA is used to predict watershed-wide relationship between eroded soil yield and contributing sub-watershed (response units)

Table 1. Average annual rainfall with highest deviation from average

Gage (data years)	Annual Average Rainfall (mm)	Highest Deviation from Average + mm (year)	Lowest Deviation from Average - mm (year)
Beltway-8 (1990-2011)	1143	+ 711 (1992)	- 660 (1996)
San Felipe (1990-2011)	1168	+ 965 (1992)	- 686 (2011)
Shepherd (2000-2011)	1194	+ 635 (2007)	- 635 (2011)
Milam	1168	+ 965 (2007)	- 711 (1996)

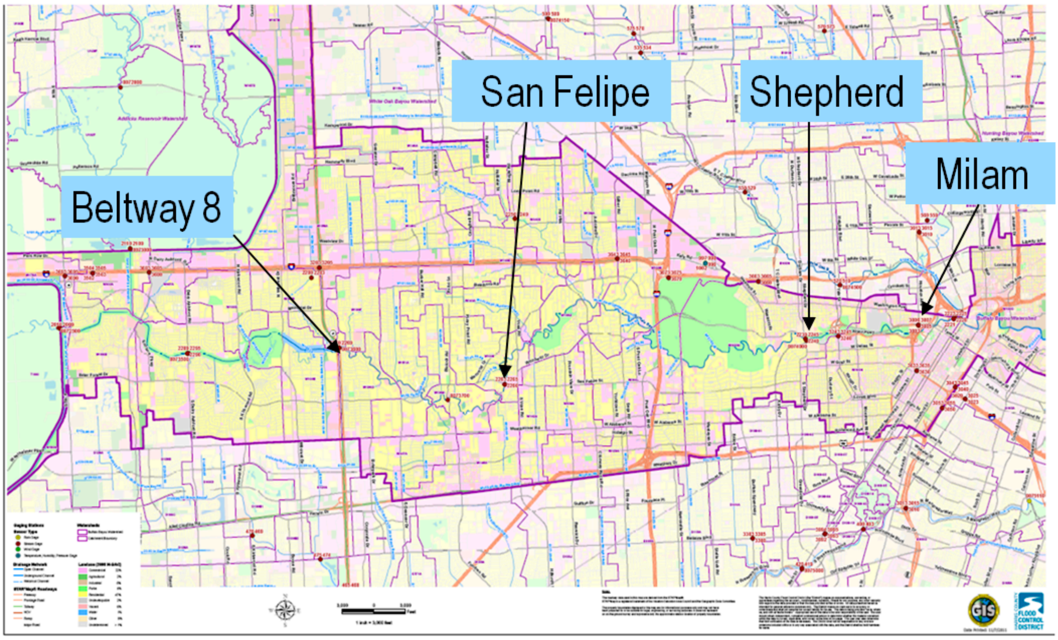

Figure 3. Buffalo Bayou watershed with rain gages along the fringes of the Bayou

slopes. The original 26 sub-watersheds of the Buffalo Bayou watershed were further divided into smaller sub-watersheds to capture the widely varying land slopes. The four basic input files for WEPP runs were climate, soils, slope, and management files. The management file consists of percent vegetation cover which play significant role in the amount of soil yield. The soil parameters selection was supported by USDA/NRCS Soils Database and Texas A&M University Soil Characterization Laboratory Database of the Texas Agricultural Research Station (TAES), and are discussed in a latter section of this paper. The climate model in WEPP is based on CLIGEN weather generator (Nicks *et. al.*, 1995). CLIGEN is a stochastic weather generator that produces daily time series estimates of precipitation in Markov Chain framework, temperature, dew point, wind, and solar radiation, based on average monthly measurements for the period of climatic record, like means and standard deviations. To generate rainfall from WEPP, a random number is selected, and inverse transform of probability distribution is found. When analytic inverse transform is not possible, numerical integration is necessary.

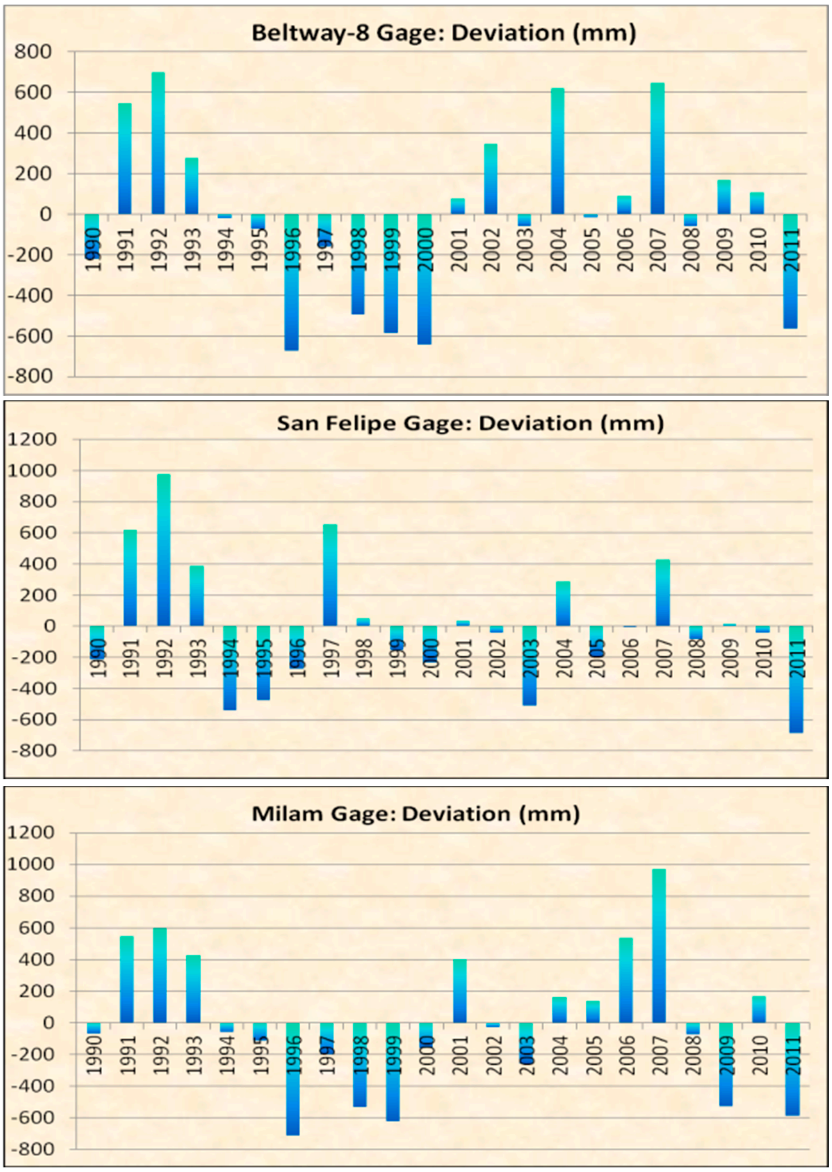

Chart 1. Annual average rainfall deviations at lowes three rainfall gages with 22 years of data.

In CLIGEN, skewed normal distribution is used to find daily precipitation amount, and it is assumed that there is an exponential relation between storm events and mean monthly duration (USDA, 1995; Nicks *et. al*., 1995).

1.2. Soil physical and chemical characteristics in the study area

The soil physical properties supported by WEPP include initial saturation level, inter-rill erodibility, rill erodibility, critical shear, effective hydraulic conductivity, layer depth, percent sand, clay, organic matter, and Rock, and cation exchange capacity. Solar albedo is used to estimate the net radiation reaching the soil surface, which is then used to estimate evapotranspiration within the WEPP water balance routines (USDA, 1995). The TAES soil series represented in Harris County is *Addicks Variant* which falls in the soil family named and characterized by Typic Argiaquoll; coarse-loamy, siliceous, active, and thermic. Fig. 3 shows dominant soil orders in Texas and Houston area soil is predominantly Vertisols. Uderts (dominant suborder) are the Vertisols of humid areas like Houston. They have cracks that open and close, depending on the amount of precipitation. In some years the cracks may not open completely.

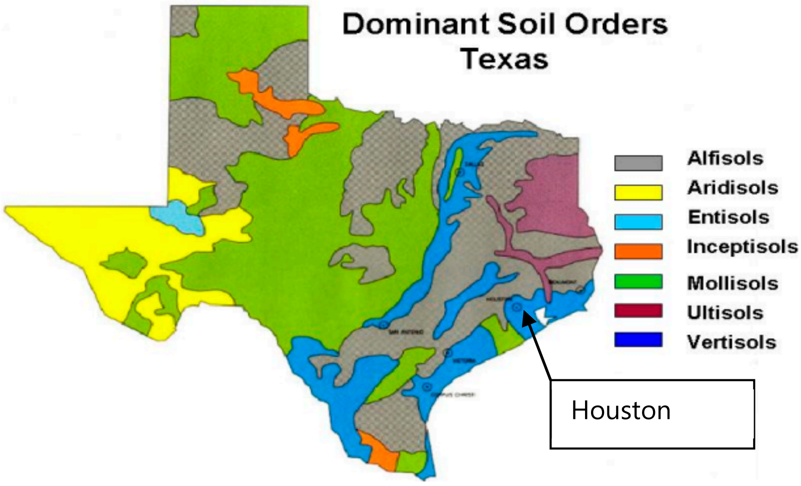

Figure 3. Soil order distribution in Texas

These soils are natives of Texas, the lower Mississippi River Valley, and Alabama. At one time many of these soils supported grass and widely spaced trees, although some supported hardwood forest vegetation. Uderts are used mostly as pasture, cropland, or forest. Because the saturated hydraulic conductivity of these soils is very low, a surface drainage system is commonly used to remove excess water from cropland. Rice is grown on some Uderts that have a thermic or warmer temperature regime (USDA, 1995). The project area used to support rice paddies at the time Houston was prone to flooding and before the US Army Corps of Engineers (USACE) built two dams that currently regulate flow in the Buffalo Bayou.

Soil bulk density and pH were measured and their histograms show reasonable spread for both (Fig. 4). In most of the natural ecosystems the research team at TAMU worked in, bulk density tends to be closer to 0.9-1.0. However, the soils under study are likely to be impacted by human activities that compress soil and increase bulk density. The large range of pH values from 5 to 8 is surprising, but this is a fairly large geographic area needing future geostatistical analysis of varying soil properties. Values of pH in the *basic* range (> 6.5) lead to unstable $\delta^{13}C$ tracer values in the lab due to presence of carbonate. Acid test was necessary to eliminate the presence of carbonate.

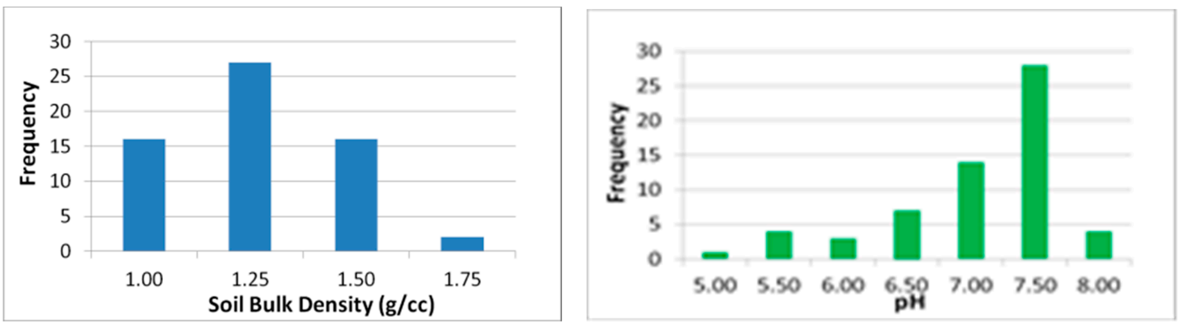

Figure 4. Physical properties of soil

Elemental and isotopic analyses of carbon (C) and nitrogen (N) in soils were conducted in the Stable Isotopes for Biosphere Sciences Laboratory at Texas A&M University at TAMU. Aliquots of each dried, ground soil sample were weighed with a microbalance (± 1 μg) into tin capsules and combusted in an oxygen atmosphere at 1020°C in a Carlo Erba EA-1108 elemental analyzer interfaced with a Finnigan Delta Plus gas isotope ratio mass spectrometer running in continuous flow mode (Fig. 5). Soil samples containing $CaCO_3$ were pre-treated with HCl vapour to volatilize the inorganic carbon prior to the combustion process (Harris *et. al*, 2001). This system was configured to derive $\delta^{13}C$, $\delta^{15}N$, and concentrations of C and N from the combustion of each soil sample. Isotope results are presented in δ-notation that expresses the relative difference between the stable isotope ratios of a sample and a standard as:

$$\delta^{13}C \text{ or } \delta^{15}N\ (‰) = [(R_{sample} - R_{standard}) / R_{standard}] \times 10^3 \quad (1)$$

where R = mass 45/44 ratio for $\delta^{13}C$, or mass 29/28 for $\delta^{15}N$. $\delta^{13}C$ values are expressed in ‰ relative to the V-PDB standard (Coplen 1995), while the $\delta^{15}N$ values are expressed in ‰ relative to the atmospheric N_2 standard (Mariotti 1983). Precision was < 0.1‰ for $\delta^{13}C$ and < 0.2 ‰ for $\delta^{15}N$ (Boutton, 2012). Preliminary elemental and isotopic results for 180 soil samples from the Buffalo Bayou watershed vary notably in range. The $\delta^{13}C$ values (‰ vs. the V-PDB standard) ranged from -27.42 ‰ to -11.05 ‰. These values span nearly the entire range of values reported previously for terrestrial and aquatic organic matter derived from natural or anthropogenic sources (Boutton, 2012). The $\delta^{15}N$ values (‰ vs. the AIR standard) of soil and sediment samples ranged from 2.54 ‰ to 11.22 ‰. As with the carbon isotopes, these $\delta^{15}N$ values span almost the entire known range for environmental $\delta^{15}N$ values in terrestrial and aquatic systems. Collectively, the large range

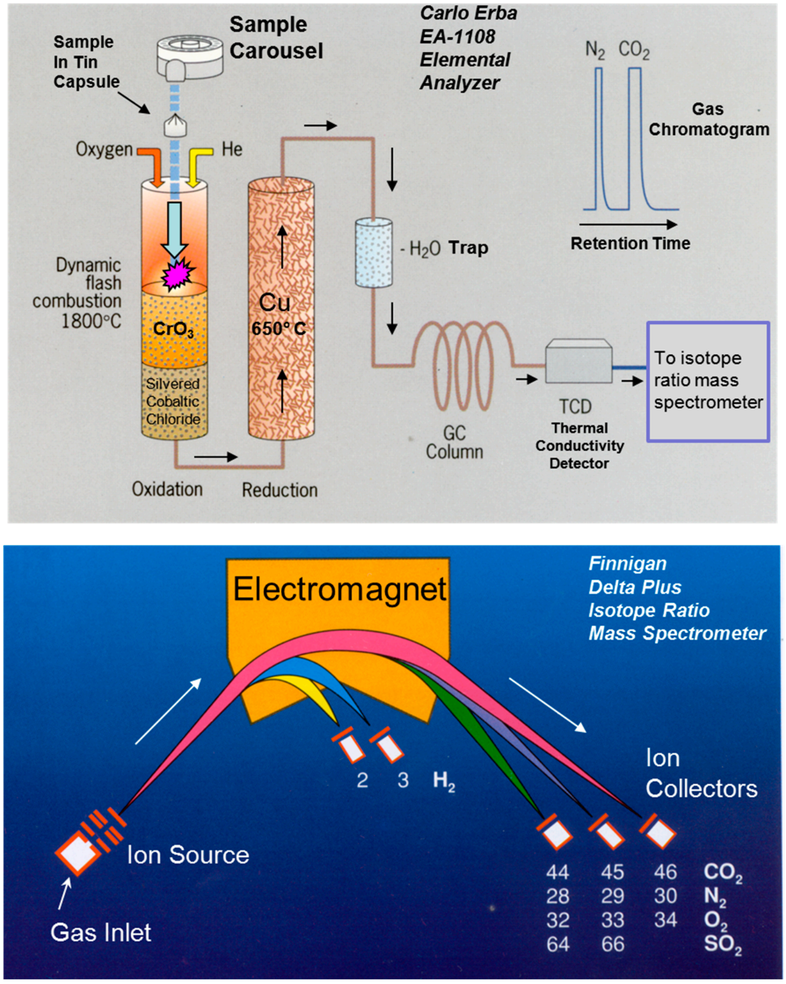

Figure 5. Soil processing chart

of values for both $\delta^{13}C$ and $\delta^{15}N$ values for our soils and sediments indicate that there are many isotopically distinct potential sources of organic matter in this watershed. Therefore, these preliminary results give us great confidence that it should be feasible to use isotopic fingerprinting of soils and sediments to identify the specific sources that contribute carbon and nitrogen to the Buffalo Bayou watershed (Boutton, 2012).

Soil organic carbon concentrations ranged from 0.29% C to 23.97% C, and soil total nitrogen concentrations ranged from 0.02% N to 0.81% N. As described above for the isotopes, these values span nearly the entire range of C and N concentrations previously reported for surface soils around the world (Boutton, 2012). Because soil organic carbon and soil total nitrogen concentrations tend to be relatively more constant within a given biogeographic region, these extremely large ranges for soil C and N concentrations suggest that the land cover and land use changes that characterize urban watersheds have dramatic impacts on these soil properties (Pickett and Cadenasso 2009). The large range of values indicates that some portions of the landscape have clearly lost large quantities of soil C and N through erosional processes, while other portions of the landscape appear to be depositional environments for nutrient rich surface soils that have been transported from elsewhere. These results are consistent with soil C and N patterns described in other urban environments (Pouyat *et. al.* 2006).

2. Land use fingerprinting using Bayesian Markov Chain Monte Carlo (B-MCMC) Simulation

B-MCMC simulation of land use fingerprinting has recently received greater attention (Fox and Papanicolaou, 2008). Typically, two kinds of tracer data ($\delta^{13}C$ and $\delta^{15}N$) are used including those from land use sources, *x*, and those from eroded-soil, *z*. The contribution of eroded soil from each source is estimated using an un-mixing model. Thus, the mass balance equation for the un-mixing model takes the form (Fox and Papanicolaou, 2008):

$$z^T = \sum_k (x_k^T \times p_k) \quad (2)$$

$$\sum_k p_k = 1 \quad (3)$$

where *p* is the fraction of eroded-soil originating from each *k* land use source. *T* is the number of tracer data. The mass balance matrix is over-determined due to the use of multiple tracers, and includes a multivariate distribution for *x* and *z*. Fox and Papanicolaou (2008) show that B-MCMC has the ability to efficiently solve the over-determined mass balance matrix, even with the consideration of multiple erosion processes. The tracer distribution of soil eroded from each land use source depends on the sampling duration because soil erosion does not necessarily occur at the same rate over a watershed. The Buffalo Bayou Watershed is urbanized and is prone rill/inter-rill erosion. The tracer data value, *j* the index of soil erosion process (e.g., rill/inter-rill is one type of soil erosion process), and *k* is land use type:

$$x_{jk}^{i} \sim MVN_T[\mu_{jk}, COV_{T\times T}(x_{jk})]$$

In the Bayesian statistical paradigm, the mean μ and *COV(x)* will have distribution of their own which can be multivariate normal (MVN) and Wishart distributions (Ntzoufras, 2009) to facilitate MCMC simulation using Gibbs sampling in WinBUGS:

$$\mu_{jk} \sim MVN(\theta, \tau)$$

$$COV(x_{jk}) \sim Wishart(\omega, \rho)$$

Here, θ, τ, ω and ρ can be specified as non-informative priors. Similarly, the tracer data at all bayou-tributary confluences can also be represented by multivariate normal parameterization and thus, *uncertainty* is included in measurement error:

$$z_{mixture} \sim MVN_T(\varphi, \Gamma)$$

with z being a vector of soil mixture tracer values, and Γ ~ Wishart(Λ,ς). The parameter φ is specified in the *deterministic* equation for the mass balance inversion as follows (Fox and Papanicolaou, 2008):

$$\varphi = \sum_k v_k \, p_k \quad (4)$$

with P_k having a Dirichlet distribution with parameter λ_k , and v_k is a soil erosion type identifier which can be related to sediment yield and slopes of sub-watersheds (response units) from WEPP runs in the case of a single predominant erosion type (rill/inter-rill) as in the current study. Given the single type of soil erosion process in the greater study watershed, the erosion type identifier is best correlated with sub-watershed slopes appear to control erosion based on WEPP results. Thus, for sites with predominantly residential plots, *k* may correspond to land slope as opposed to land use source. Work is in progress to formulate such modification for this study. Finally, Bayesian MCMC (Bolstad, 2010; Ntzoufras, 2009) with Gibbs sampling (simplified form of the Blockwise Metropolis-Hastings Sampling Method) can be applied to determine probabilistic solution to the un-mixing equations for all parameters in the model. The posterior distribution of all model parameters based on data is given by Bayes theorem:

P (All model Parameters | x_{jk}, v_k, z*) = P (All model parameters) x P (*x_{jk}, v_k, z *| All model parameters)* (5)

The solutions to this model are the percentages of soils eroded from different land use types or sources.

Conclusions

The task at hand is challenging and yet a driving force for integrated management of soil carbon in urban environment. The objective of this paper was to present a computational statistical method to identify soil organic carbon sources that is dependent on accurate determination of soil chemical characteristics, justified by the soil physical characteristics as allowed by the existing watershed conditions. Integration of knowledge from different fields of background of the authors is essential to accomplish research tasks in quantifying hydrologic influences on soil organic carbon loss monitoring using stable isotopes. Integration of biogeochemistry with hydrology, erosion prediction, sediment engineering, and geospatial statistical analyses may lead to robust soil carbon management decisions. Collaborative efforts are needed to support field based technology to validate numerical models. Bayesian-MCMC has shown to lead to accuracy with increased number of parameter sampling even if raw data is non-normal. However, the role of information is critical. The current work will look into tackling the model uncertainties.

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References

Ahmed, I., T.W. Boutton, K.B. Strom, A. Karim and N. Irvin-Smith, 2013. "Soil carbon distribution and loss monitoring in the urbanized Buffalo Bayou watershed, Houston, Texas "*Proceedings of 4th Annual All Investigators Meeting of the North American Carbon Program (NACP)*, February 4-7, Albuquerque, NM.

Bolstad, W.M., 2010. *Understanding Computational Bayesian Statistics*. Series in Computational Statistics, Wiley, NY.

Boutton, T.W., 2012. "USDA-CBG grant annual report to Prairie View A&M University" College Station, TX.

Boutton, T.W. and S.I. Yamasaki, 1996. *Mass Spectroscopy of Soils*, Marcel Dekker, NY.

Coplen, T. B., 1996. "New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data" *Geochimica et Cosmochimica Acta*, 60: 3359-3360.

Fox, J.F. and A.N. Papanicolaou, 2008. "An un-mixing model to study watershed erosion processes," *Advances in Water Resources*, 31: 96-108.

Harris, D., W.R. Horwath, and C. van Kessel, 2001. "Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis" *Soil Science Society of America Journal*, 65: 1853 1856.

Irvin-Smith, N., T. Chatman and I. Ahmed, 2012. "Rainfall trend assessment for the Buffalo Bayou Watershed" *Proceedings of 10th Texas A&M University System (TAMUS) Pathways Symposium*, Galveston, TX.

Mariotti, A., 1983. "Atmospheric nitrogen is a reliable standard for natural ^{15}N abundance measurements" *Nature*, 303: 685-687

Nicks, A.D., L.J. Lane and G.A. Gandor, 1995. "Chapter 2: Weather Generator" in *Water Erosion Prediction Project (WEPP): Hillslope profile and watershed model documentation*, NSERL Report No. 10, West Lafayette, IN.

Ntzoufras, I., 2009. *Bayesian Modeling Using WinBUGS*. Series in Computational Statistics, Wiley, NY.

Pickett, S. and M. Cadenasso, 2009. "Altered resources, disturbance, and heterogeneity: A framework for comparing urban and non-urban soils" *Urban Ecosystems*, 12: 23-44.

Pouyat, R., I. Yesilonis and D. Nowak, 2006. "Carbon storage by urban soils in the United States" *Journal of Environmental Quality*, 35: 1566-1575.

USDA-ARS, 1995. "Water Erosion Prediction Project (WEPP): Hillslope profile and watershed model documentation" NSERL Report No. 10, West Lafayette, IN.