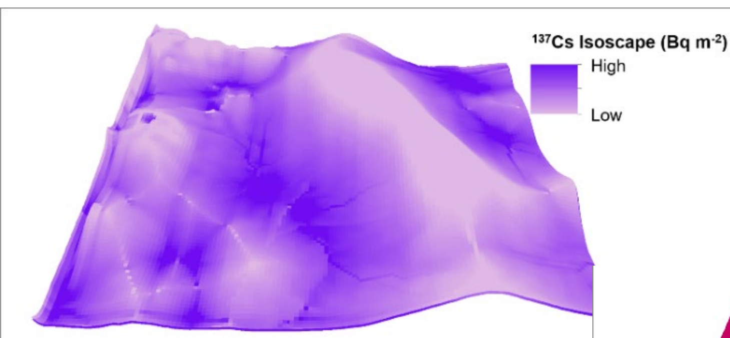
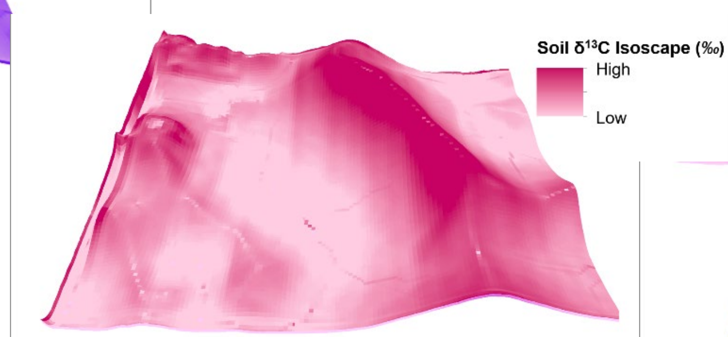
Soil Organic Carbon Distribution and Isotope Composition Response to Erosion in Cropland under Soybean/Maize Production

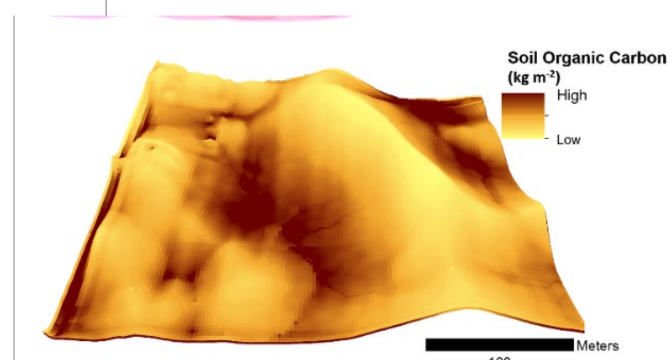
Greg McCarty and Xia Li

USDA Hydrology & Remote Sensing Laboratory

Beltsville Maryland USA







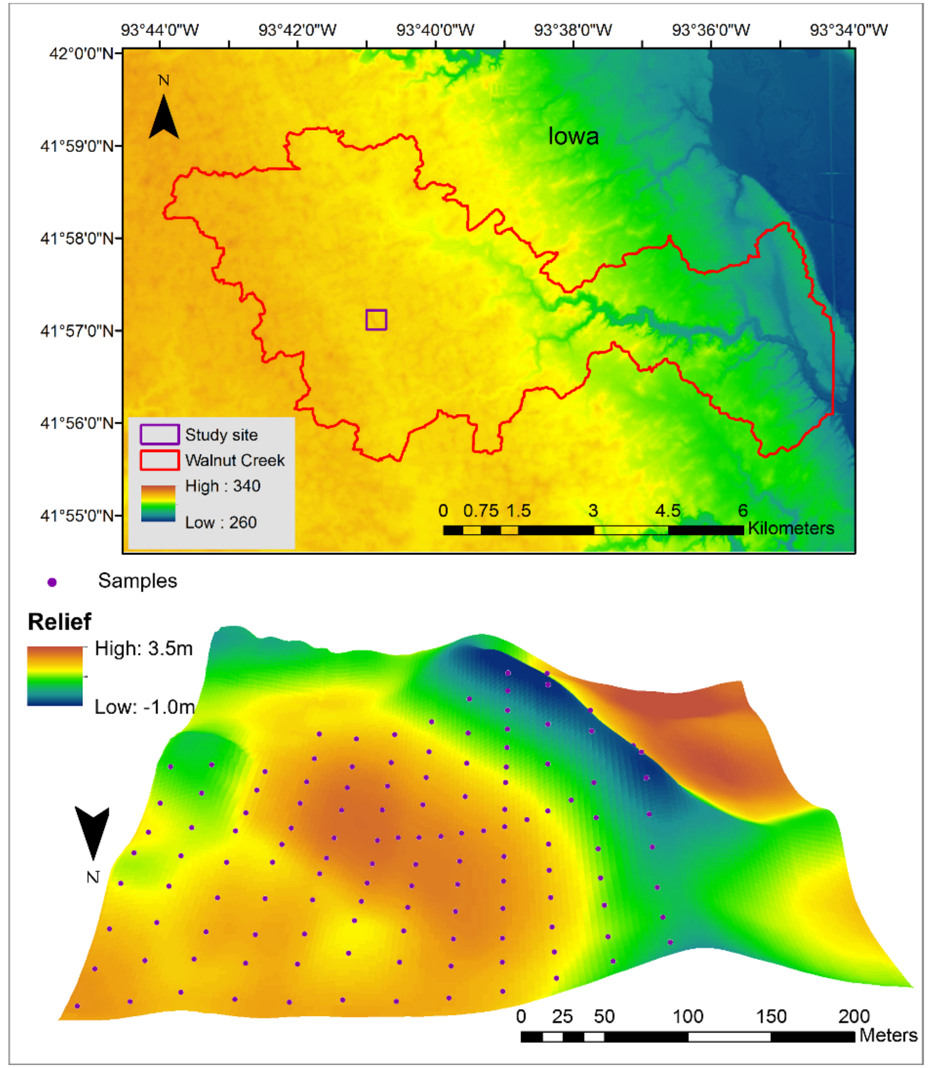
Study area in Iowa, USA

Cropland field under cultivation for corn and soybean

Field was sampled to 30 cm depth using a 25 m grid sampling pattern

Samples were analyses for organic soil carbon, ^{13}C and ^{137}Cs contents as well as soil texture

Maps of soil properties isotope tracers were developed from lidar DEMs using topographic principal component regression (TPCR).



Various soil maps were generated using topographic regression or kriging models

Metrics used to construct topographic models

Variables	Definition	Significance
Slope (radian)	An angle between a tangent and a horizontal planes at a given point	Runoff velocity, soil water content (Afshar et al., 2010; Li et al., 2014)
Profile Curvature (m^{-1})	Curvature of the surface in the direction of the steepest slope	Flow acceleration, soil erosion, deposition rate (Troch et al., 2002; Ritchie et al., 2007)
Plan Curvature (m^{-1})	Curvature in a horizontal plane	Flow convergence and divergence, soil water content (Troch et al., 2002)
General Curvature (m^{-1})	Curvature of the surface itself	Runoff velocity , soil erosion, deposition (Li et al., 2014)
Flow Accumulation	Upslope number of grid cells	Soil water content, runoff volume (Gessler et al., 2000)
Topographic Relief (m)	Difference between the highest point over an area (h_{max}) and a given location (h_i)	Landscape drainage characteristics, runoff velocity and acceleration (Tucker and Bras, 1998; Montgomery and Brandon, 2002)
Positive Openness	An angular measure of the relation between surface relief and horizontal distance	Landscape drainage characteristics , soil water content (Seijmonsbergen et al., 2011)
Upslope Slope (m)	Mean slope of upslope area	Runoff velocity (Moore et al., 1991; Kirkby, 2014)
Flow Path Length (m)	Maximum distance of water flow to a point in the catchment	Sediment yield, erosion rate (Sharpley and Kleinman, 2003)
Downslope Index (radian)	Head differences along flow path	Soil water content (Hjerdt, 2004)
Catchment Area (m^2)	Area draining to catchment outlet	Runoff velocity and volume (Moore et al., 1991; Kasai et al., 2001)
Topographic Wetness Index	Frequencies and duration of saturated conditions	Soil moisture distribution (Afshar et al., 2010; Lang et al., 2013)
Stream Power Index	Erosive power of overland flow	Soil erosion, Convergence of flow (Conforti et al., 2011)

Advantage of using Principal Component Regression

- Large collinearities often exist between these topographic metrics (Table 1) for a given landscape with two main causes for the correlations;
  - One being these metrics quantify the properties of a self-organized landscape whose properties would be expected to be correlated;
  - Another being that various metrics are derived from mathematical equations containing common elements which induce correlations between the resulting metrics;
- Principal Component Analysis (PCA) is a common approach to generate sets of orthogonal factors from correlated metrics and thereby reduce the dimension of parameters;
- These PCA factors, in turn, can be used as a set of orthogonal parameters in prediction models;
- This is the approach we have used in developing more robust topographic models using information contained within 13 topographic metrics with reduced dimensionality.

First four principal components used in prediction models

	TPC1(38%)	TPC2(24%)	TPC3(14%)	TPC4(7%)
Slope	-0.267	0.378	0.041	-0.137
P_Cur	-0.259	-0.248	0.365	0.253
Pl_Cur	-0.269	-0.032	-0.403	0.360
G_Cur	-0.286	-0.276	0.264	0.320
FA	0.238	0.012	0.467	-0.048
LsRe	0.395	0.040	-0.222	0.182
SsRe	-0.031	0.487	-0.004	-0.120
POP	-0.364	-0.054	0.175	-0.058
Upsl	-0.066	0.482	0.029	0.154
FPL	0.295	0.030	0.081	0.515
DI	0.232	-0.193	0.079	-0.493
CA	0.238	0.011	0.463	0.013
TWI	0.367	-0.198	-0.210	0.162
SPI	0.156	0.408	0.250	0.270

TPCs 1–4 were highly associated with runoff velocity, flow acceleration, runoff volume, flow convergence and divergence, and

Topographic Principal Component Regression (TPCR) models for map generation

	Model	R^2_{adj}	NSE	RSR
$^{137}C_s$	2447.251-342.099TPC1+303.280TPC5†	0.622	0.628	0.609
$\delta^{13}C$	-20.399+0.683TPC1+0.286TPC3+0.140TPC2-0.305TPC6	0.591	0.603	0.630
logSOC	2.946-0.063TPC1-0.018TPC3+0.012TPC2+ 0.030TPC5+0.020TPC4	0.692	0.704	0.544

† The order of TPCs is based on the stepwise selection steps

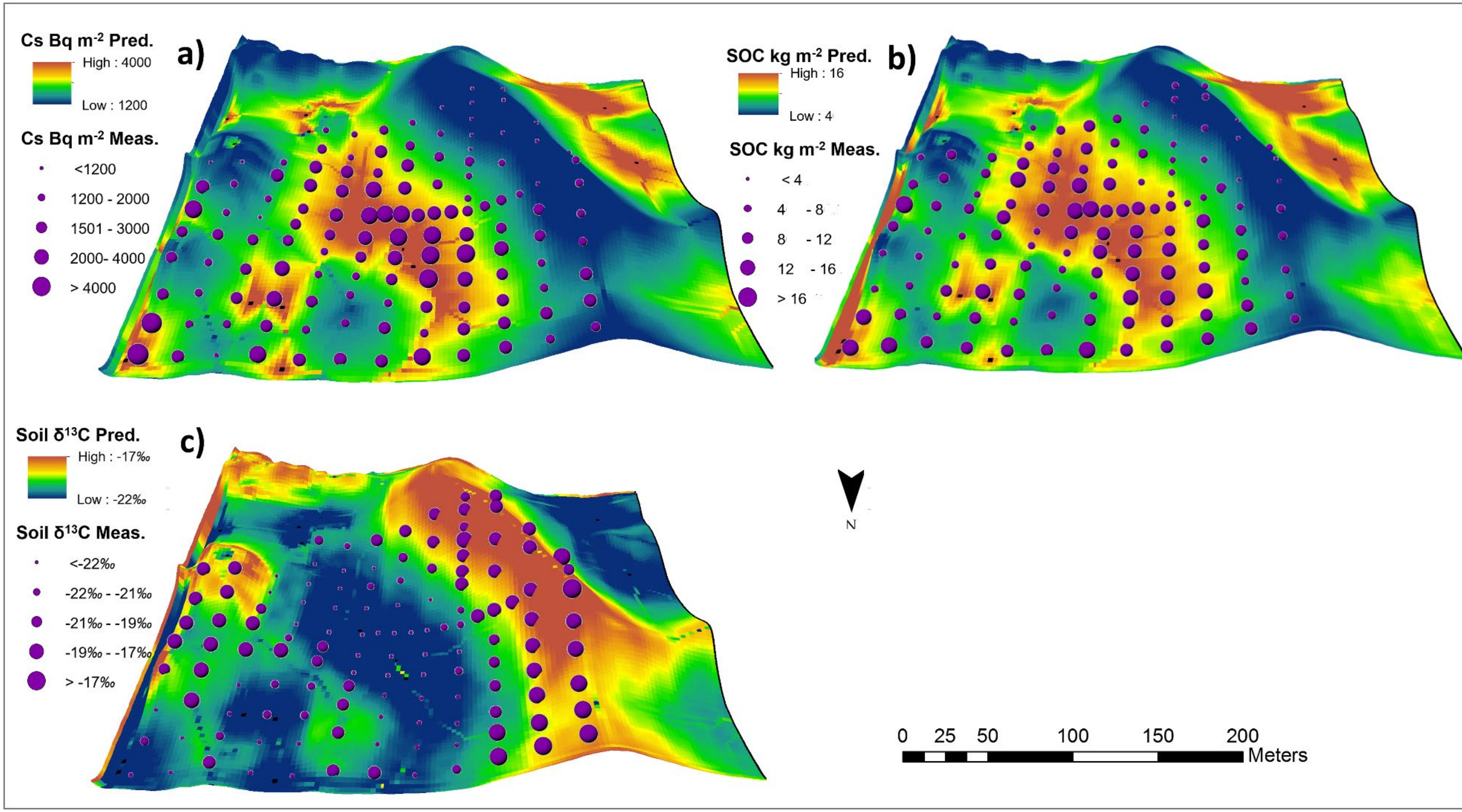
R^2_{adj} is adjusted coefficient of determination; NSE is Nash-Sutcliffe efficiency; RSR is ratio of the root mean square error (RMSE) to the standard deviation of measured data.

Measured cesium (^{137}Cs) inventory, soil redistribution (SR) rate, soil organic carbon (SOC) density, and isotopic ratio of $\delta^{13}C$ in the study area.

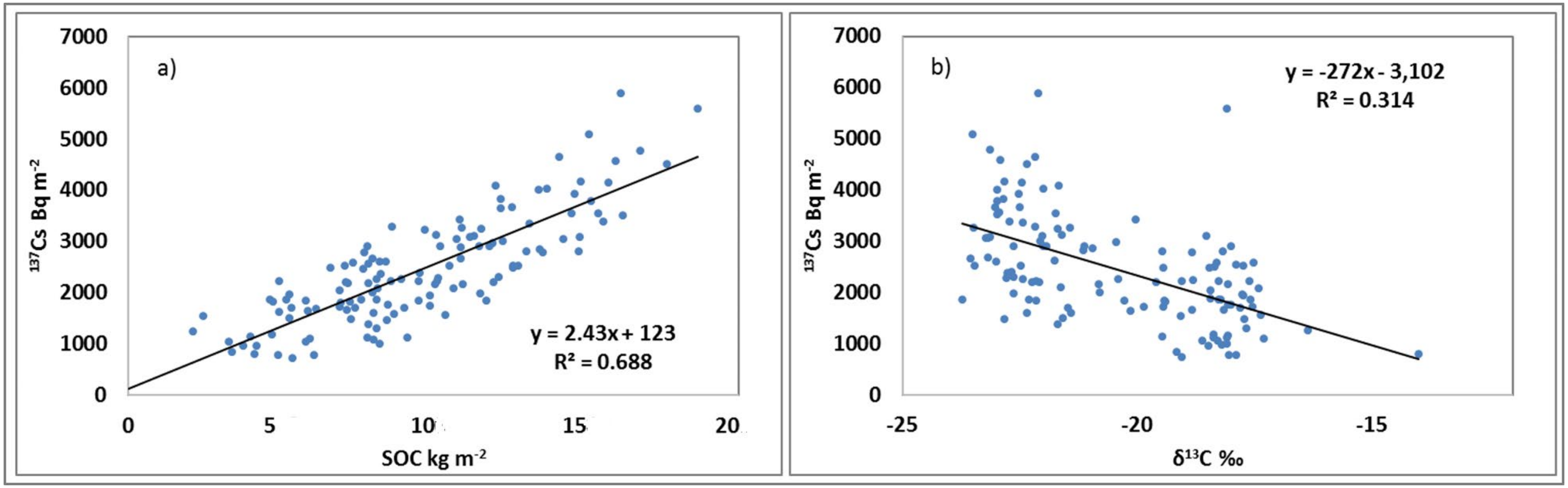
	N	^{137}Cs (Bq m^{-2})	SR rate (kg m^{-2} yr^{-1})	SOC (kg m^{-2})	$\delta^{13}C$ (‰)
Erosion	81	1791 (531.7)^{b†}	-1.719 (1.383)^{b}	759.3 (245.8)^{b}	-19.55 (2.05)^{a}
Deposition	47	3547 (768.7)^{a}	1.571 (1.324)^{a}	1292 (258.6)^{a}	-21.85 (1.52)^{b}
All	128	2435 (1056)	-0.511 (2.091)	956.4 (357.7)	-20.40 (2.16)

† Mean and standard deviation (in parentheses); Letters estimate based on Duncan's multiple range tests. There are no significant ($P < 0.05$) differences for a parameter with the same letter.

Prediction maps for ^{137}Cs, SOC and $\delta^{13}C$

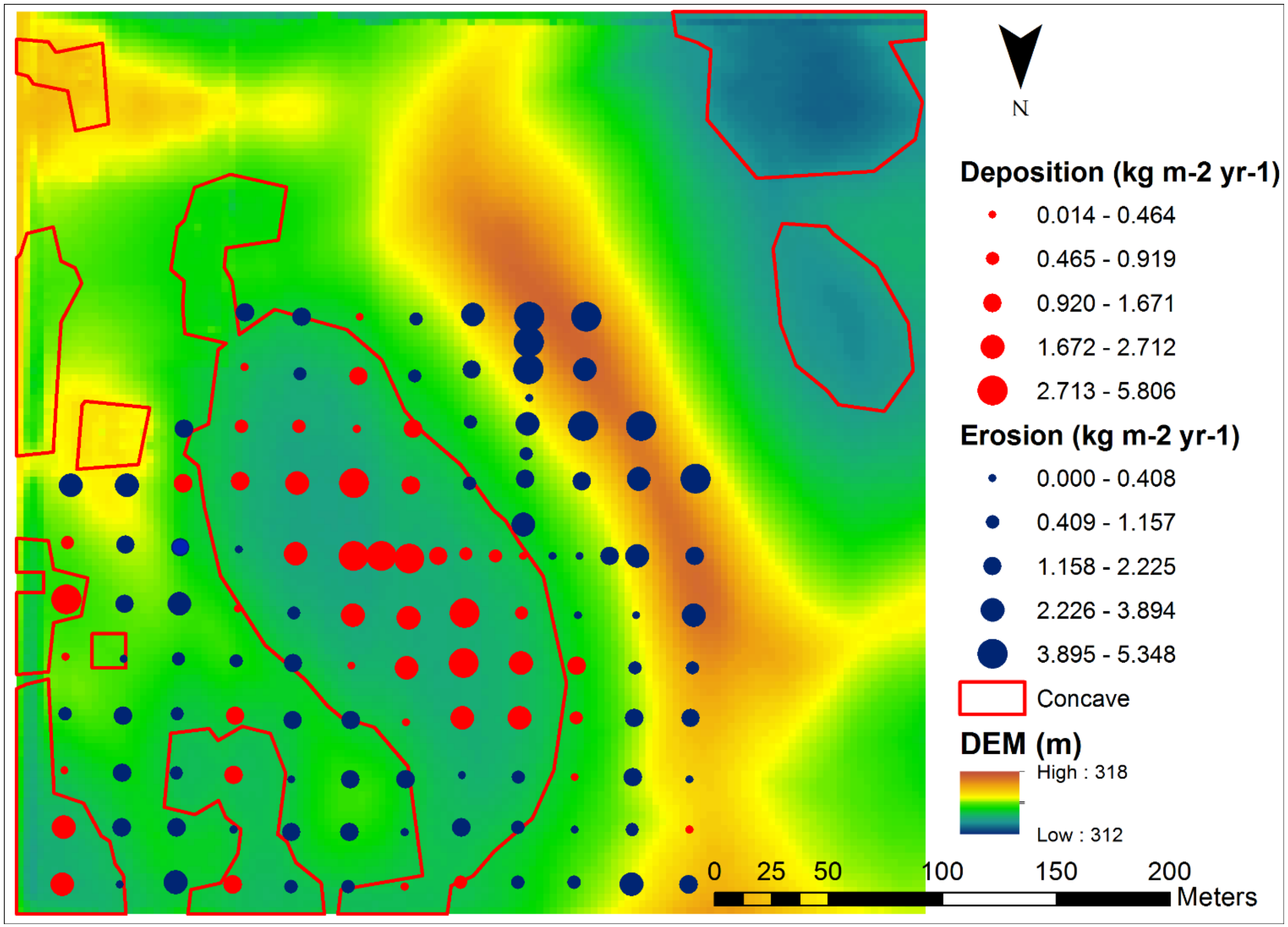


Relationship between SOC and $\delta^{13}C$ densities versus ^{137}Cs inventory



^{137}Cs was positively correlated to SOC and negatively correlated to $\delta^{13}C$ indicating that soil erosion redistributed SOC with a strong C3 signature.

Modeled soil erosion and deposition based on ^{137}Cs inventories



Soil texture associations with erosional and depositional sites

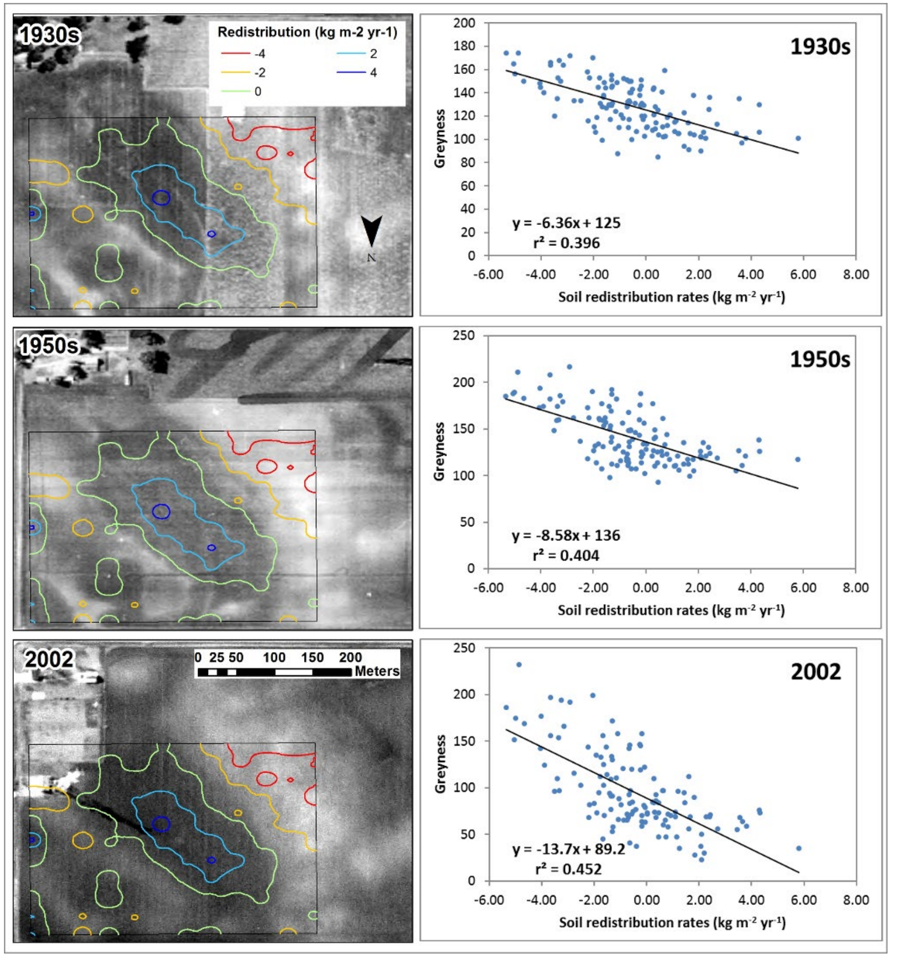
	Number of Sample	Fractional sand content (g g^{-1})	Fractional silt content (g g^{-1})	Fractional clay content (g g^{-1})
Erosion	81	0.480 (0.084)a†	0.297 (0.054)b	0.223 (0.070)b
Deposition	47	0.391 (0.101)b	0.356 (0.059)a	0.252 (0.066)a
All	128	0.447 (0.100)	0.319 (0.063)	0.233 (0.070)

† Mean values and standard deviation (in parentheses)

- The relative enrichments of silt and clay likely increases stability of SOC at sites of deposition.
- These findings are consistent with preferential movement of silt and clay by erosional processes.

Anthropogenic erosion as a soil forming process

- The mollic soils in Iowa have been subject to enhanced redistribution processes (erosion) since the prairie sod was broken after 1860's.
- The black mollic epipedon was redistributed from upslopes which is readily apparent as early as the 1930's bare soil image.
- Remarkably the patterns of redistribution after the event of early 1960's ^{137}Cs fallout and subsequently measured in 2003 (depicted in isolines) is very similar to the pattern of mollic epipedon redistribution.
- This substantiates the influence of soil distribution in current soil classification.
- The mollic epideden is more depleted of ^{13}C which is indicative of prairie vegetation with C3 signature.

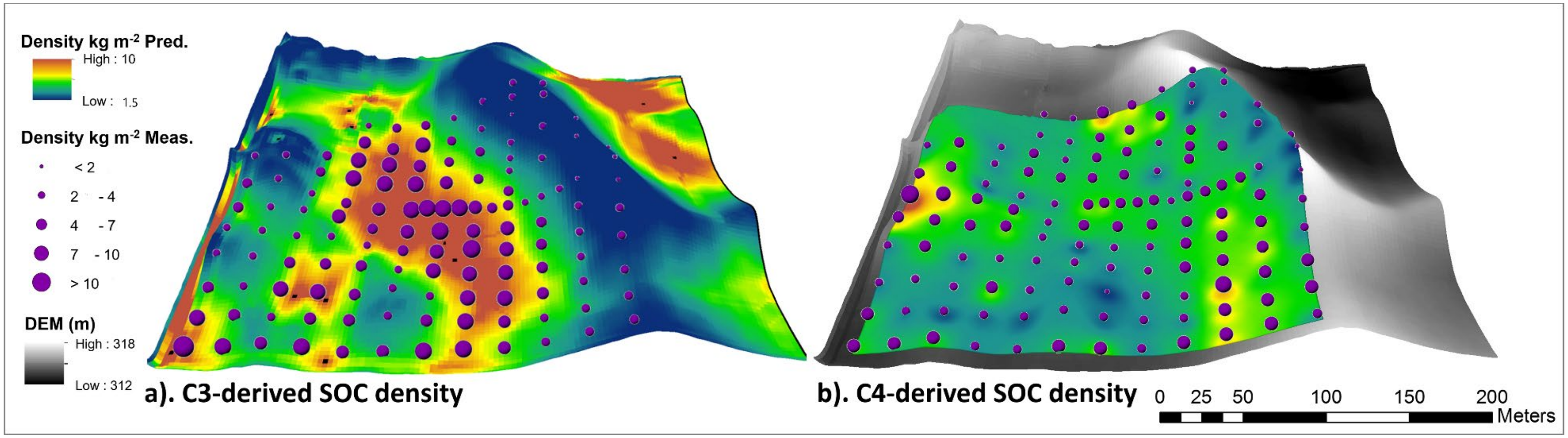


Topographic Principal Component Regression (TPCR) models for C3 and C4 map generation

	Model	R^2_{adj}	NSE	RSR
Average value combination				
C3 (27‰)	564.985-109.143TPC1+63.381TPC5+30.207TPC4+29.345TPC6	0.733	0.741	0.509
logC4 (12‰)	2.565+0.021TPC2-0.016TPC1+0.029TPC5	0.134	0.154	0.920
Combination scenario 1				
C3 (-27‰)	630.222-111.082TPC1+67.068TPC5+31.479TPC4	0.735	0.741	0.509
logC4 (-9‰)	2.486+0.021TPC2-0.016TPC1+0.029TPC5	0.134	0.154	0.919
Combination scenario 2				
C3 (-32‰)	493.217-86.934TPC1+52.488TPC5+24.636TPC4	0.735	0.741	0.509
logC4 (-9‰)	2.641-0.037TPC1+0.017TPC2+0.029TPC5+0.017TPC4	0.340	0.409	0.769
Combination scenario 3				
C3 (-32‰)	364.554-77.532TPC1+43.317TPC5+20.968TPC4+23.963TPC6	0.722	0.731	0.518
logC4 (-13‰)	2.748-0.037TPC1+0.017TPC2+0.029TPC5+0.017TPC4	0.390	0.409	0.769

Different ranges in isotope discrimination for C3 and C4 photosynthesis were used to test uncertainty

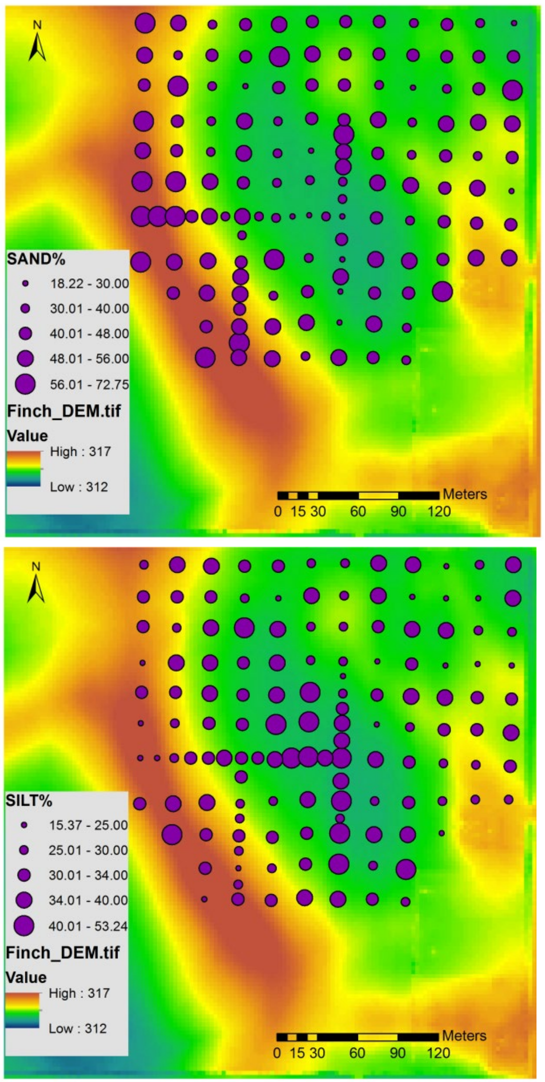
Maps of C3 and C4 carbon pools based on 27‰ and 12‰ discrimination respectively.



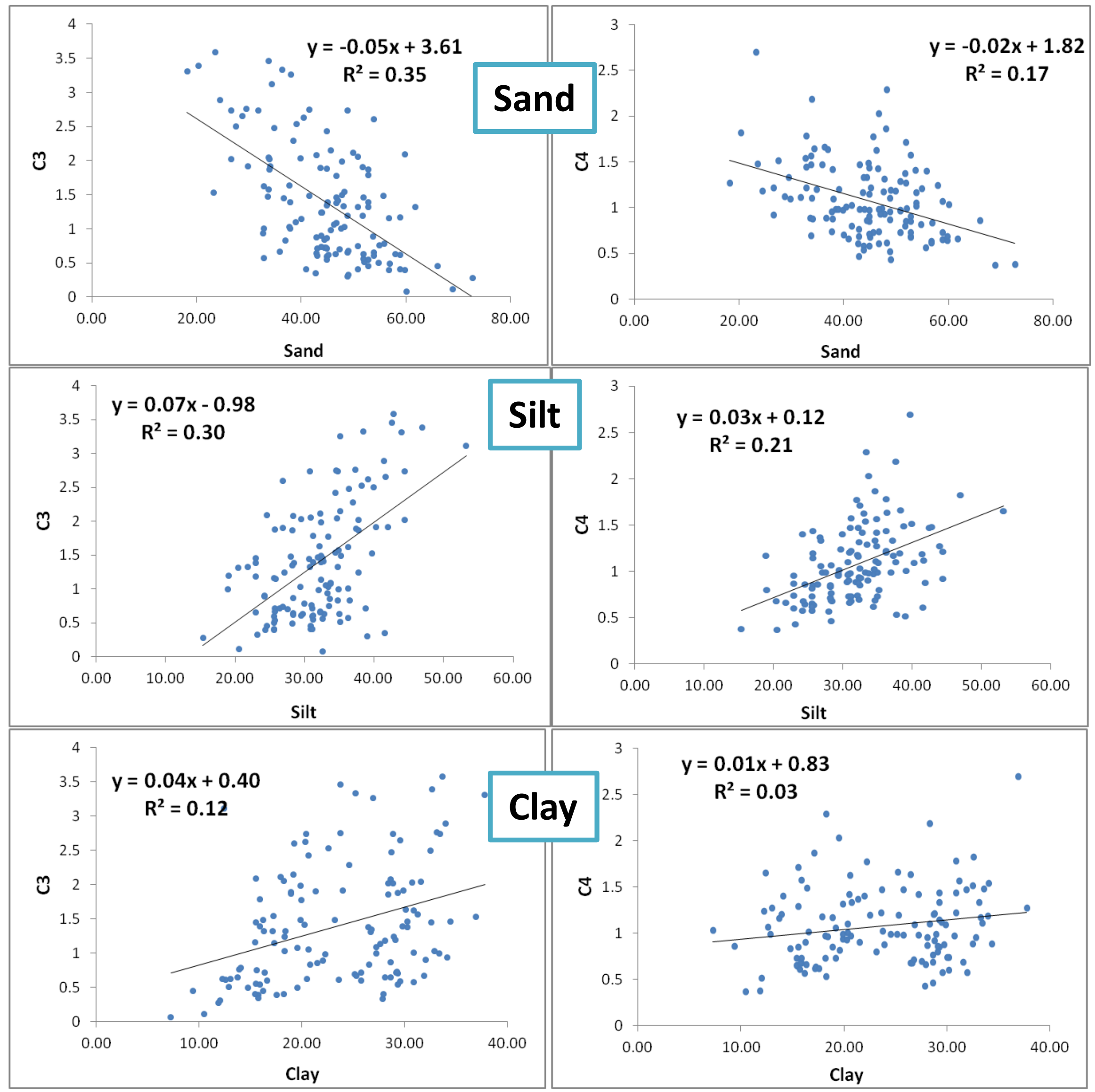
- Stronger topographic influence on spatial variation of C3- than C4-derived SOC
  - Photosynthetic discrimination;
  - Relative chemical stability in 13C-depleted compounds with C3 signature;
  - Preferential sorption of 13C-depleted compounds.

- Midslope accumulation in C4-derived SOC
  - Preferential decomposition;
  - Preferential movement.

Soil texture association with C3 and C4 densities



Soil texture along with elevation



Discussion of Results

- More detailed information on the mollic epipedon distribution relative to soil redistribution is needed for a better understanding of soil movement;

- There can be wide variation within the $\delta^{13}C_{C3}$ and $\delta^{13}C_{C4}$ values, resulting in variability in the estimates C3- and C4-derived SOC density;

- The studies on soil redistribution and SOC dynamics could benefit from combining topography and transport processes of C3- and C4-derived SOC with process-based soil erosion models.

Conclusions

- Topographic heterogeneity significantly impact the spatial variability in soil redistribution and SOC dynamics;
- Topographic models are feasible to simulate soil properties and processes and advanced in large-scale soil variable prediction;
- Mollic epipedon distribution can be a tracer for larger scale soil redistribution studies;
- Use of C isotopes exemplified how differences in the distribution of native and recently sequestered SOC occurred in response to erosion.