Quantifying Soil Profile Change Caused by Land Use in Central Missouri Loess Hillslopes

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Three major challenges are present when studying anthropogenic impacts on soil profile properties: (i) site selection; (ii) sampling and modeling native and cultivated soil–landscape relationships; and (iii) graphically and statistically comparing native and cultivated sites to model soil profile changes. This study addressed those challenges by measuring and modeling selected soil profile properties of paired (native) forest and analogous nonnative (cultivated) loess hillslopes in central Missouri. The paired hillslopes in Saline County were mapped as Mollic Hapludalfs and the paired hillslopes in Boone County were mapped as Typic Hapludalfs. Horizonation and depth distribution of Hapludalf soil properties provide markers when measuring land use impacts on soil profile properties. Summit pedons on the four sites verified the mapping and classification. Transect data revealed soil profile variation by slope position and by site. Regression analysis identified relationships at the $p < 0.007$ level between depth to clay maximum (adjusted $R^2 = 0.74$), thickness of the A horizon (adjusted $R^2 = 0.32$), thickness of the subsurface horizon (adjusted $R^2 = 0.69$), depth to the top of the B horizon (adjusted $R^2 = 0.69$), clay content of the surface horizon ($R^2 = 0.76$), organic C content of the surface horizon (adjusted $R^2 = 0.56$), and depth to ≤ 7.5 g kg^{-1} organic C (adjusted $R^2 = 0.59$) and slope position and site characteristics. A different response surface for each site for each soil characteristic supported the hypothesis that vegetative history and land use significantly affected the distribution of these soil properties.

Abbreviations: DDF, depth distribution function; EMB, empirical model building; OC, organic carbon; $OC_{7.5}$, depth to ≤ 7.5 g kg^{-1} organic carbon; RA, regression analysis; RSM, response surface methodology.

Determining the effects of land use on the soil resource remains one of the foremost challenges facing soil scientists and agronomists (Tugel et al., 2005; Lin, 2011). Of particular importance is the difficulty in assessing the true impact of land use on native soil properties and productivity. Establishing a proper baseline of soil properties is critical when the impacts of land use on the soil are determined (Kiss et al., 1986; Soil Survey Staff, 1993; Olson, 2010; Stolt et al., 2010; Olson et al., 2013). For quantifying the effects of cultivation, the proper baseline soils are those that have formed under the same parent materials, climate, and native vegetation but have not been cultivated (Ruhe and Daniels,1965; Ruhe et al., 1967; Daniels et al., 1987); because soil properties are also affected by slope position, the proper baseline on sloping landscapes requires an understanding of soil-landscape relationships by slope position (Lee et al., 2001; Wilson et al., 2010; Kabrick et al., 2011) and a quantification of those relationships (Thompson et al., 2001, 2006; Thompson and Kolka, 2005). Native and cultivated landscapes must be compared to provide an accurate measure of soil change resulting from land use, cultivation, and accelerated erosion (Ruhe and Daniels,1965; Ruhe et al., 1967; Daniels et al., 1987), and depth distribution functions (DDFs) depict changes in soil properties with

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depth. Typically, the *y* axis of a graph is the profile depth, and the *x* axis is the numerical representation of a soil property (e.g., clay percentage) or the depth to a soil property (e.g., clay maximum) or a description of a soil horizon (e.g., A horizon thickness). The DDFs are soil property "signatures" that can be used to better understand the soil development that occurs during periods of relative landscape stability (Butler, 1959). They have been used to study the relationships between soil-landscape positions and depth distributions of clay (Norton and Smith, 1930; Ruhe, 1969; Molina, 2009; Wilson et al., 2010), organic C (Aandahl, 1949; Kleiss, 1970; Nizeyimana and Olson, 1988; Thompson and Kolka, 2005; Thompson et al., 2006; Molina, 2009), and P (Runge and Riecken, 1966; Smeck and Runge, 1971; Day et al., 1987; Cassagne et al., 2000; Wang et al., 2008; Molina, 2009).

Depth distribution functions have also been applied to study the effects of cultivation and accelerated erosion (periods of relative landscape instability) on the soil profile. Researchers have studied the depth distributions of clay (Stone et al., 1985; Kreznor et al., 1989; Olson et al., 1994; Jankauskas and Fullen, 2002), organic C (Kreznor et al., 1989; Olson et al., 1994, 2002; Jankauskas and Fullen, 2002), and P (Sharpley and Smith, 1983; Jankauskas and Fullen, 2002). This body of research suggests that the downward migration of the boundary between the surface soil and subsoil might be traced by studying and comparing the clay, organic C, and P DDFs for native forest and corresponding cultivated soil profiles:

The final challenge is the modeling of these complex native and cultivated soil-landscape systems to make statistical and graphical comparisons to determine land use impacts. Many researchers (Kleiss, 1970; Ruhe, 1969; Ruhe and Walker, 1968; Walker and Ruhe, 1968; Thompson et al., 2001, 2006) have shown that regression analysis (RA) is well suited for the study of the relationships between terrain attributes as the independent variables (such as slope percentage, distance from summit, slope length, and slope shape) and surface layer and subsoil features as the dependent variables.

These previous studies have outlined three major challenges and approaches in measuring soil–landscape relationships and soil change: (i) locating similar native and cultivated landscapes for comparison; (ii) modeling soil–landscape relationships on both native and cultivated sites using DDFs as a basis for comparison; and (iii) statistically comparing the DDFs of native and cultivated sites across soil landscapes to quantify soil change. This study addressed those challenges by careful selection of native baseline sites and analogous cultivated sites, by systematic soil profile description and site sampling by topographic position to highlight soil-landscape relationships and impacts of slope position on soil properties, which facilitates comparison of native and cultivated soil properties by slope position, and by applying the statistical methods of RA when a predictor variable or variables is used for predicting a variable of interest (Neter et al., 1990). To increase the utility of the statistical analysis, included within the RA used in this study were empirical model building (EMB) and response surface methodology (RSM). Box and Draper, (1987) described RSM as a group of statistical techniques for EMB and model exploitation. They explained that by careful design and analysis of experiments, RSM seeks to relate a response (*Y*) or output variable to the levels of predictor or input variables (*X*) that affect it. Researchers have successfully applied EMB and RSM to soils research (e.g., Thoma et al., 2006; Tranter et al., 2007), and it has been shown to be a useful approach in modeling land use and land cover change (e.g., Verburg, 2006). The EMB and RSM approaches emphasize an iterative approach of investigation and provide tools that are highly suited to increase our knowledge of soil–landscape relationships and land use impacts on these relationships.

The objectives of this study were to sample and model the depth distributions of clay and organic C and the horizonation of native (forested) and nonnative (cultivated) loess soil landscapes and to determine the effects of land use on these loess hillslope soils in central Missouri. Our hypotheses were that (i) native and cultivated sites needed to be paired by location and by slope position to control for differences in parent materials, native vegetation, and soil development patterns, (ii) DDFs would differ among slope positions because of differential soil development patterns mediated by topography, and (iii) that RA, EMB, and RSM could be used to model changes in DDFs so that soil properties at native vs. cultivated sites could be compared across soil landscapes.

MATERIALS AND METHODS

Study Site Selection

Locating native baseline sites presented the greatest challenge in this study. In the humid Midwest, most areas that have soils and landscapes suited for agriculture or forestry have been logged, cultivated, or both. Final selections of the two native study sites were based on historical documents, historical aerial photography, topographic quadrangles, on-site investigation of vegetation, parent material, landscape, soil maps, soil profile descriptions, and site accessibility for sampling. Sloping loess landscapes along the Missouri River provided the widest choice of sites that met the criteria for the study and also soils that were formed in one parent material. Sites with the least amount of anthropogenic disturbance were selected. Selections of the two cultivated sites proved to be much easier, and they were selected using the same criteria used for the native site selection. Four study sites were selected: paired native and cultivated sites in Saline County, Missouri, and paired native and cultivated sites in Boone County, Missouri (Fig. 1; Table 1). The selected sites were at similar distances from the loess source and were similar in soils, elevation, aspect, and gradient (Table 1). The sites were labeled with the name of the dominant soil series and land use at each location. The dominant soil series was Knox (Soil Survey Staff, 2013) at the Saline County sites, and the sites were labeled as Knox–native and Knox–cultivated. The dominant soil series was Menfro (Soil Survey Staff, 2013) at the Boone County sites, and the sites were labeled Menfro–native and Menfro–cultivated. Detailed site and soil series information is presented below.

Environmental Settings

The Saline County sites occur in Major Land Resource Area 107B, the Missouri and Iowa Deep Loess Hills, and the Boone County sites occur in Major Land Resource Area 115B, the

Central Mississippi Valley Wooded Hillslopes (NRCS, 2006). All sites are on the deep loess bluffs adjacent to the Missouri River. Krusekopf and Scrivner (1962) reported that loess along the Missouri River was deposited during two or more glacial episodes and is >9 m thick adjacent to the source. Loveland Silt (loess) is the lower deposit, and Peoria Loess is the upper deposit. The Loveland Silt accumulated during the Illinoian glacial episode approximately 125,000 yr BCE (Norton et al., 1988). The Peoria Loess accumulated during the late Wisconsinan glacial episode, from 29,000 to 14,000 yr BCE (Ruhe, 1969). Most of the loess that forms the contemporary land surface along the Missouri River is considered to be Peoria. Specific stratigraphic and geomorphic control was not established for these sites, but in general the nearly level portion of these loess interfluves probably has been stable since loess deposition and weathering for approximately 14,000 yr (Ruhe and Daniels, 1965; Ruhe et al., 1967). The less stable valley slopes are generally younger than the interfluves (Ruhe and Daniels, 1965; Ruhe et al., 1967; Huddleston et al., 1975). The age differences between interfluves and valley slopes emphasize the need to take into consideration slope position when selecting and comparing sites.

The Saline County native site (Knox–native) was forested when sampled (Table 2) but had a history of prairie vegetation according to Volumes 43 and 44 of the field notes to the original land survey of Saline County from 1817, now located in the Missouri State Archives (Carr and Belden, 1905). The Saline County cultivated site (Knox–cultivated) had been cultivated or in native prairie pasture since the early or mid-1800s and has been intensively cultivated since the late 1800s or early 1900s (Carr and Belden, 1905; Schroeder, 1981). The two Saline County sites were mapped as a phase of the Knox series (fine-silty, mixed, superactive, mesic Mollic Hapludalfs) in the modern soil survey (Baker, 1993; Soil Survey Staff, 2010b) at a scale of 1:24,000.

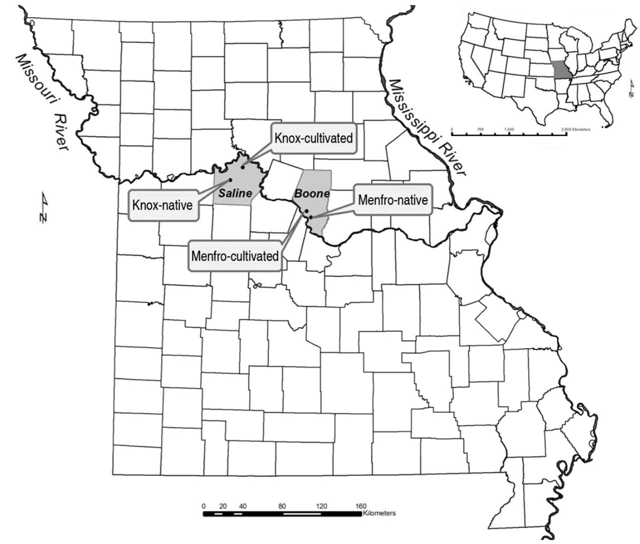

Fig. 1. Location of the paired study sites in Saline and Boone counties, Missouri.

The Boone County native site (Menfro–native) supports native deciduous forest (Table 2) and is considered a relict of the forests that once covered the steep loess hills along the Missouri River (Walters, 1981). The Boone County cultivated site (Menfro–cultivated) has been cultivated or in pasture since the mid- to late 1800s and has been intensively cultivated since the early 1900s with the advent mechanized agriculture (Woodruff, 1990; C.M. Woodruff, personal communication, 1990). Both Boone County sites were mapped as a phase of the Menfro series (fine-silty, mixed, superactive, mesic Typic Hapludalfs) (Krusekopf and Scrivner, 1962; Young et al., 2003; Soil Survey Staff, 2010a) at a scale of 1:24,000.

Soil descriptions (Schoeneberger et al., 2012) were made from reference soil pits that were excavated near the summits of

Table 1. Information on the four study sites in Saline and Boone counties, Missouri.

County	Dominant soil series†	Site name	Location	Summit elevation	Slope aspect	Gradient range
				m		%
Saline	Knox	Knox–native	Section 24, Township 52 N, Range 22 W	256	S–SE	0.0–35.5
Saline	Knox	Knox–cultivated	Section 26, Township 53 N, Range 21 W	224	S–SW	0.5– 17.0
Boone	Menfro	Menfro–native	Section 7, Township 47 N, Range 14 W	231	S–SE	0.5–34.5
Boone	Menfro	Menfro–cultivated	Section 6, Township 47 N, Range 13 W	219	S–SE	0.5–20.0

† Knox: fine-silty, mixed, superactive, mesic Mollic Hapludalfs; Menfro: fine-silty, mixed, superactive, mesic Typic Hapludalfs.

Table 2. Tree species basal area for the Saline County and Boone County native sites.

Knox–native site		Menfro–native site	
Species	Basal area	Species	Basal area
	m^2 ha^{-1}		m^2 ha^{-1}
Burr oak (*Quercus macrocarpa* Michx.)	9.1	Sugar maple (*Acer saccharum* Marshall)	12.2
Basswood (*Tilia americana* L.)	6.5	Black oak (*Quercus velutina* Lam.)	9.0
Honey locust (*Gleditsia triacanthos* L.)	6.2	White oak (*Quercus alba* L.)	5.1
Northern red oak (*Quercus rubra* L.)	4.3	Shagbark hickory [*Carya ovata* (Mill.) K. Koch]	4.7
White ash (*Fraxinus Americana* L.)	4.3	Northern red oak (*Quercus rubra*)	1.4
American elm (*Ulmus Americana* L.)	1.5	Chinkapin oak (*Quercus muehlenbergii* Engelm.)	0.1
Sassafras [*Sassafras albidum* (Nutt.) Nees]	1.4		
Box-elder (*Acer negundo* L.)	0.8		
Shagbark hickory (*Carya ovata*)	0.8		
Hackberry (*Celtis occidentalis* L.)	0.2		
Total	35.0		32.5

Table 3. Description of representative soils taken near the summits of the Knox–native, Knox–cultivated, Menfro–native, and Menfro–cultivated sites.

Horizon	Depth	Matrix color	Texture†	Clay	Organic C
	cm			%	g kg^{-1}
Knox–native site (Knox silt loam)					
Oi	2–0				
A1	0–5	10YR 2/1	sil	18.8	47
A2	5–13	10YR 3/2	sil	17.7	25
A/E	13–22	10YR 3/2	sil	18.4	12
B	22–43	10YR 3/3	sil	18.7	10
Bt1	43–64	10YR 4/6	sil	24.2	8
Bt2	64–87	10YR 4/6	sil	23.2	6
Bt3	87–118	10YR 4/6	sil	21.9	3
BC1	118–147	10YR 4/6	sil	17.1	2
BC2	147–192	10YR 5/6	sil	15.1	2
Knox–cultivated site (Knox silt loam)					
Ap	0–11	10YR 3/4	sil	23.0	16
BE	11–22	10YR 4/4	sil	23.4	7
Bt1	22–62	10YR 4/6	sil	28.4	5
Bt2	62–87	10YR 4/6	sil	24.5	3
Bt3	87–109	10YR 4/4	sil	23.3	2
Bt4	109–145	10YR 4/5	sil	21.3	2
2BC	145–180	10YR 4/6	sil	22.6	2
Menfro–native site (Menfro silt loam)					
Oi	1–0				
A1	0–5	10YR 2/1	sil	13.8	37
A2	5–10	10YR 3/2	sil	11.1	19
AE	10–16	10YR 3/3	sil	11.4	12
E1	16–23	10YR 5/3	si	8.3	7
E2	23–31	10YR 5/3	sil	9.9	4
EB	31–39	10YR 3/4	sil	19.1	4
Bt1	39–56	10YR 4/6	sicl	31.7	3
Bt2	56–79	7.5YR 4/4	sicl	30.1	3
Bt3	79–105	7.5YR 4/4	sicl	27.5	2
2Bt4	105–136	7.5YR 4/4	sil	25.7	2
2Bt5	136–171	10YR 4/4	sil	24.2	2
2Bt6	171–185	10YR 5/4	sil	21.4	2
2BC	185–200	10YR4/6	sil	20.1	2
Menfro–cultivated site (Menfro silt loam)					
Ap1	0–9	10YR 3/3	sil	12.5	20
Ap2	9–23	10YR 4/3	sil	13.6	13
EB	23–30	10YR 5/4	sil	16.0	7
Bt1	30–37	10YR 5/4	sil	23.3	5
Bt2	37–50	10YR 5/4	sicl	29.6	4
Bt3	50–84	10YR 5/4	sicl	33.9	4
Bt4	84–110	10YR 5/4	sicl	30.9	3
Bt5	110–150	10YR 5/4	sicl	27.9	2
Bt6	150–180	10YR 5/4	sicl	27.5	2

† sil, silt loam; si, silt; sicl, silty clay loam.

all four sites, and samples were collected for laboratory analysis (Soil Survey Laboratory Staff, 2004). All four reference pedons fit within the classification of the dominant soil series mapped at each site (Table 3). All four reference pedons classified as Hapludalfs and thus are high-base-status soils with argillic horizons (Buol et al., 2011). The Mollic Hapludalf pedons of the Saline County sites (Knox–native and Knox–cultivated) are like the Typic Hapludalfs of the Boone County sites (Menfro–native and Menfro–cultivated), but they have a surface horizon that meets all of the requirements for a mollic epipedon except thickness (Soil Survey Staff, 2010c). Both the Typic and Mollic Hapludalfs exhibit contrasting soil horizons, which are typically, but not exclusively, O, A, E, and Bt, and provide distinct depth distribution signatures of morphological, physical, and chemical properties. The variations of these signatures with slope position and land use are presented in the representative DDF cross-sections and graphs.

Topographic Mapping

The 1:24,000 scale of soil mapping, landform and landscape parameters, and land use guided the site sampling scheme and intensity. At each site, a grid consisting of four transects 10 m apart was established from the summit to the lower part of the backslope. The transects were typically 68 m in length and were oriented downslope, perpendicular to the contour. Elevation was measured at 1-m intervals along each transect established, using a cloth tape for measuring horizontal distances and a transit for measuring changes in elevation. The topographic maps were used to delineate the summit, shoulder, and backslope positions.

Distance from the slope summit was determined by measuring from the slope summit to the sampling point with a cloth tape. Slope percentage was calculated from the elevation data for each sampling point by taking the difference between the elevations 1 m above and 1 m below the sampling point, dividing the difference by 2, and then multiplying by 100. Slope positions were assigned following the nomenclature of Ruhe (1969) using slope percentage, slope shape, and onsite observation.

Transect Soil Profile Description and Transect Soil Sampling

Cores were collected to a depth of approximately 120 cm at 6-m intervals down the four transects at each site beginning with the second point from the slope summit. The native site cores were taken with a hand probe with a 3.0-cm-diameter soil tube. On the cultivated sites, soils were cored with a trailer-mounted hydraulic probe with a 4.0-cm-diameter soil tube. At each site, the parts of the hillslope sampled included the summit, shoulder, and backslope.

The sola were described using standard descriptive nomenclature (Schoeneberger et al., 2012), with the following modifications: (i) an A horizon for forested sites is a mineral horizon that formed at the surface and is characterized by an accumulation of organic matter intimately mixed with the mineral fraction and not dominated by characteristics of E or B horizons; (ii) an A horizon on cultivated sites (designated as Ap) is a mineral horizon that formed at the surface and has properties resulting from cultivation; (iii) a plowed mineral horizon, even though previously an E or B horizon, is designated as an Ap; (iv) an E horizon is a mineral horizon in which the dominant pedogenic process is loss of silicate clay; and (v) an argillic B horizon is characterized by an illuvial concentration of clay.

For the purposes of this study, an A horizon at the native sites and an Ap horizon at the cultivated sites were designated as surface horizons. A subsurface horizon was an E and/or a transitional AB, EB, or BE horizon dominated by the characteristics of A, E, or B horizons, where the first letter designates the horizon most characteristic of the subsurface horizon. An argillic B horizon was designated as subsoil.

Cores were segmented and sampled by horizon to the top of the B horizon; the remainder of the core was segmented and sampled in 10-cm increments to the bottom of the core. The samples were then placed in polyethylene bags and taken to the laboratory for analyses. Forty-eight cores were taken at the Knox–native, Menfro–native, and Menfro–cultivated sites, and 44 cores were taken at the Knox–cultivated site for a total of 188 observations of each soil property.

Laboratory Procedures

The transect soil samples were air dried and crushed to pass a 2-mm sieve. Clay percentage was determined by the Follmer procedure (Indorante et al., 1990). Organic C was determined by dry combustion (Soil Survey Laboratory Staff, 2004) using a Leco CR-12 C analyzer. Organic C (OC) was reported as grams per kilogram to facilitate the depth distribution graphical comparison of OC with clay percentage.

Depth Distribution Functions

In this study, we used DDFs of OC (g kg^{-1}) and clay content (%) in conjunction with the soil descriptions to provide information on surface horizons (A or Ap), the location of the Ap horizon in the soil profile in relation to subsurface horizons (AB, E, EB, or BE), and subsoil horizons (B) for selected hillslope transects. One of the four transects at each site was selected for DDF cross-sectional representation. This information included the thickness of the A or Ap horizon (surface horizon), the thickness of the subsurface horizon, depth to the top of the B horizon, depth to $\leq$7.5 g kg^{-1} OC ($OC_{7.5}$), and depth to the clay maximum.

Statistical Model Building

To meet the objectives of the study and to specifically test Hypothesis (iii) of the study, RA, EMB, and RSM were used to model changes in DDFs by slope position and by land use (native vs. cultivated sites).

Empirical model building is based on the regression fit (i.e., RA) of one or more variables (predictors) known to be related to the response variable(s) of interest (Neter et al., 1990). With two or more predictors, the resulting fit is a response surface relating the response variable to the predictor. The EMB process allows a sequence of models that can account for linear, curve, and interaction relations among variables. In addition, the modeling process allows easy testing of interactions and of terms indicating linear or curvilinear fit. The present study incorporated RA (Neter et al., 1990) and EMB (Box and Draper, 1987) to first determine the relationships among landscape features, slope position as measured by distance from summit, and soil properties in the upper part of the soil profile and then to determine the effects of land use on these soil profile properties.

Distance from the slope summit (as a measure of slope position) was chosen as one of the predictor variables because previous studies (Kleiss, 1970; Ruhe, 1969; Ruhe and Walker, 1968; Walker and Ruhe, 1968) documented its influence on soil properties and soil variability on sloping landscapes. The distance from the summit of the slope was designated as X_1. The four sites were labeled as qualitative independent variables as outlined by Neter et al. (1990) and were designated as X_2 through X_4 and appropriately coded as 0 or 1:

Site	X_2	X_3	X_4
Knox–native	1	0	0
Knox–cultivated	0	1	0
Menfro–native	0	0	1
Menfro–cultivated	0	0	0

Figure 2 summarizes the model-building steps and regression analysis. Multiple regression analysis was performed with Minitab 16 statistical software (Minitab Inc.). All four sites were included for analysis. The selected soil profile properties (Y) were depth to clay maximum, thickness of the A horizon, thickness of the subsurface horizon, depth to the top of the B horizon, clay content of the surface horizon, OC content of the surface horizon, and depth to $\leq$7.5 g kg^{-1} OC ($OC_{7.5}$). The predictor variables for the selected soil profile properties (Y) were X_1, distance from the summit of the slope (m), and the four sites designated as X_2 through X_4 with the proper coding.

The models were labeled with Roman numerals and were built and tested in the following order:

Model I had X_1 as a single predictor variable.

Model II had X_1 and $X_1{}^2$ as the predictor variables.

Model III added site (X_2–X_4) to the X_1 and $X_1{}^2$ predictor variables.

Model IV added site (X_2–X_4) to the X_1 and $X_1{}^2$ predictor variables and the interaction of site with the X_1 predictor variable.

Model V added site (X_2–X_4) to the X_1 and $X_1{}^2$ predictor variables and the interactions of site with the X_1 predictor variable and the $X_1{}^2$ predictor variable with site.

The model(s) with the best fit were selected based on model significance and highest adjusted R^2. The use of the adjusted R^2 was desirable in this study because the adjusted R^2 increases (i.e., improves the model fit) only if the added independent variable improves the model more than would be expected by chance. The response surfaces (also referred to as regression functions or regression surfaces) were plotted using statistically significant model(s) with the highest adjusted R^2. The plotted points were distance from summit X_1 values with the appropriate site coding (coded X_2–X_4). The model equations and the corresponding response surfaces represent the influence of the independent variables (X_1) of slope position and site (X_2–X_4) on the selected soil properties (Y).

RESULTS AND DISCUSSION

Knox–Native vs. Menfro–Native Depth Distribution Function Cross-Sections

The surface, subsurface, and subsoil layers were present at all slope positions at the Knox–native site (Fig. 3a) and, with the exception of a point 14 m from the slope summit, they were present at all slope positions at the Menfro–native site (Fig. 3b).

The horizonation and the expression and shape of the representative and clay DDFs for the Knox–native (Fig. 3a) and Menfro–native (Fig. 3b) sites are typical in this region for Hapludalfs formed in loess. The representative OC DDF graphs for the three slope positions show a maximum in the surface horizon, ranging from 15 to >40 g kg^{-1} in the surface horizon for the Knox–native site and ranging from 5 to slightly >30 g kg^{-1} for the Menfro–native site. The $OC_{7.5}$ ranges from slightly more than 20 to approximately 40 cm for the Knox–native site representative DDFs and ranges from 20 to 25 cm for the Menfro–native site representative DDFs. Beneath the $OC_{7.5}$, the OC content for both sites is similar in OC content and distribution, with OC content ranging from approximately 5 to 7 g kg^{-1}.

The representative clay DDFs show distinct zones of eluviation and illuviation at all three slope positions for both sites. The surface and subsurface clay contents for the Knox–native sites range from 10 to 15% and from 5 to 15% for the Menfro–native site. There is a distinct clay increase at the 40-cm depth for the Knox–native site and at the 20- to 25-cm depth for the Menfro–native site. The clay maximum percentage for the Knox–native site occurs at 59 cm at the summit and increases to a depth of 70 cm on the shoulder and to almost 80 cm on the backslope, with the clay maximum ranging from 20 to 25%. For the Menfro–native site, the clay maximum occurs at 60 cm at the summit and at approximately 50 cm on the shoulder and backslope. The clay maximum is 30% for all three slope positions.

The expression and shape of the OC and clay DDFs reflect the Knox–native site's history of prairie vegetation according to the original land survey from 1817 (Carr and Belden, 1905) and its classification as a Mollic Hapludalf compared with the Menfro–native site's history of forest vegetation (Walters, 1981) and classification as a Typic Hapludalf. It is critical to note that the Knox–native and Menfro–native site DDF cross-sections show variation by site (i.e., because of differing pedogenesis) and by slope position, emphasizing the importance of considering these two variables when studying land use impacts on the soil landscape and the need for selecting appropriate baseline sites for studying the impacts of land use as emphasized by Daniels et al. (1987) and Olson (2010).

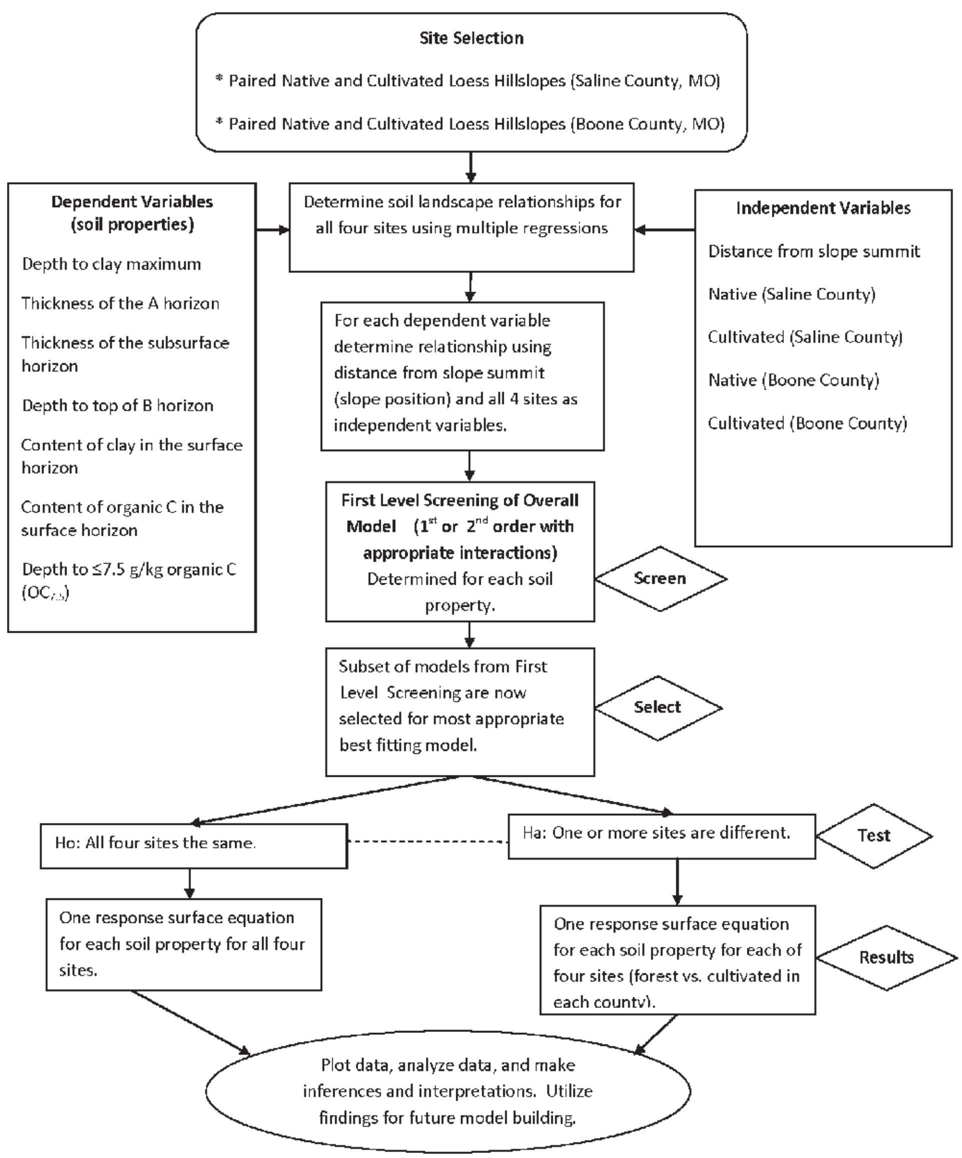

Fig. 2. Flow chart for empirical model building and response surface representation of soil-landscape relationships in native and cultivated sites in Missouri.

Knox–Native vs. Knox–Cultivated and Menfro–Native vs. Menfro–Cultivated Depth Distribution Function Cross-Sections

Using the Knox–native site (Fig. 3a) as a baseline, comparisons could now be made to the Knox–cultivated site (Fig. 3c) to determine the impacts of cultivation and accelerated erosion. The surface, subsurface, and subsoil layers are present at the summit position of the Knox–cultivated site.

Moving downslope on the Knox–cultivated site to the shoulder and backslope, the subsurface horizon thins and eventually disappears. The representative DDFs for the Knox–cultivated site document the shallower depth to the top of the B horizon, the shallower depth to clay maximum, lower surface OC contents, and shallower $OC_{7.5}$. Comparison of Knox–native and Knox–cultivated DDF cross-sections and representative DDF graphs shows distinct soil profile changes related to slope position and land use. The more sloping positions (shoulder and backslope) are more susceptible to accelerated erosion, and the consequent mixing by cultivation blends A, E, and B horizons, creating an A

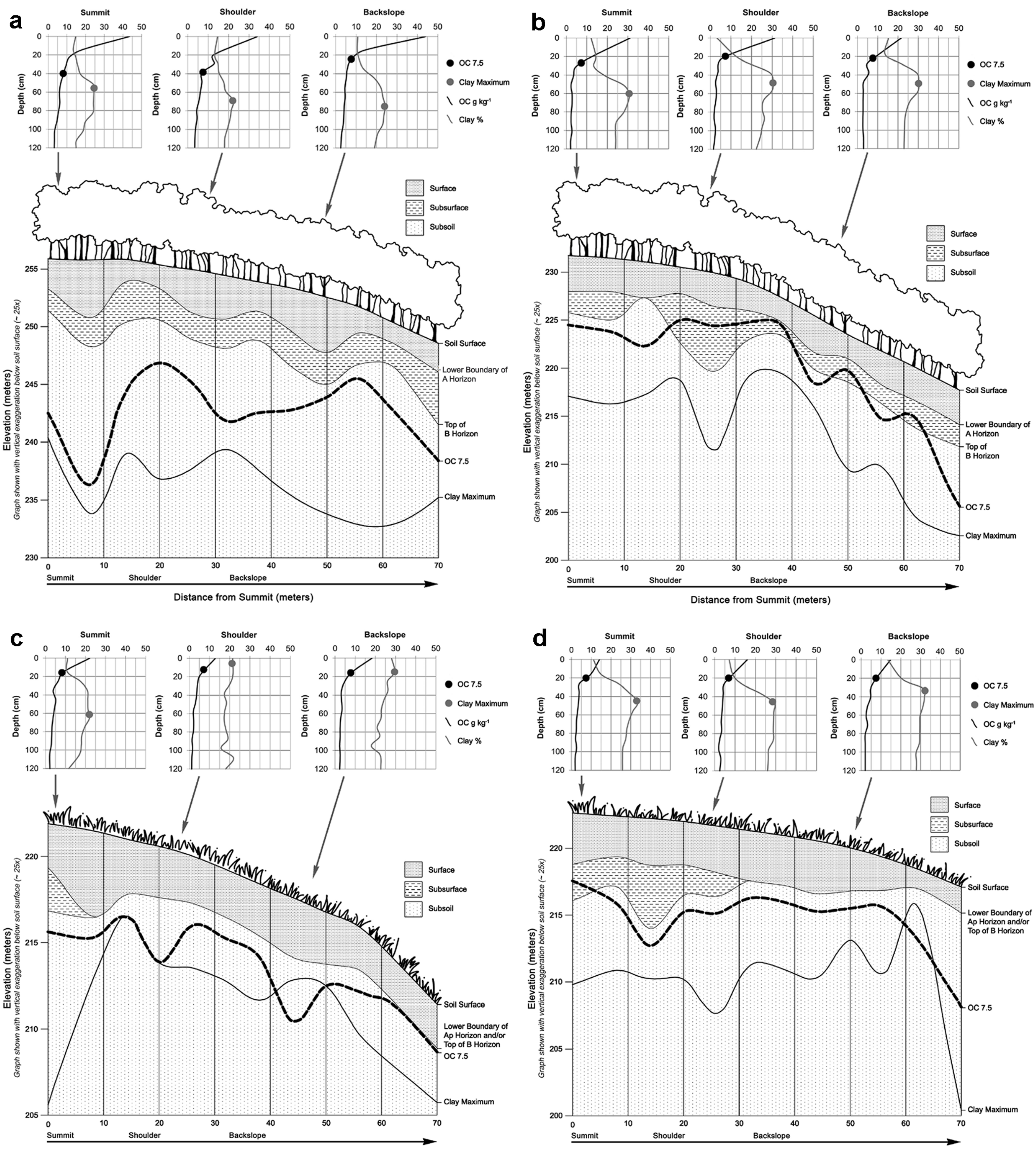

Fig. 3. Depth distribution of selected soil properties for the (a) Knox–native site, (b) Menfro–native site, (c) Knox–cultivated site, and (d) Menfro–cultivated site. Twelve points were sampled along the downslope transect and are represented in the cross-section. A representative depth distribution function for organic C and clay is presented for each of the three slope positions (summit, shoulder, and backslope) sampled.

horizon that is now labeled Ap, and indicates a disturbance of the surface layer by mechanical means (Soil Survey Staff, 1993).

With the exception of a point 14 m from the summit, the surface, subsurface, and subsoil layers are present at the shoulder position of the Menfro–native site (Fig. 3b). The Menfro–cultivated site (Fig. 3d) shows a similar downslope horizonation pattern to the Knox–cultivated site. Moving from the shoulder down through the backslope, the subsurface horizon thins and eventually disappears and the depth to the top of the B horizon and the depth to clay maximum become shallower. Comparison of Menfro–native and Menfro–cultivated DDF cross-sections and representative DDF graphs shows distinct soil profile changes related to slope position and land use. The results of this comparison are similar to the results of the Knox–native, Knox–cultivated comparison and show that the more sloping positions (shoulder and backslope) are more susceptible to accelerated erosion and the consequent truncation and admixing of soil horizons due in large part to cultivation.

Summary of Depth Distribution Function Cross-Section and Representative Depth Distribution Function Results

The DDF cross-sections and representative DDFs by slope position support our hypotheses that (i) native and cultivated sites needed to be paired by slope to control for differences in parent materials, native vegetation, and soil development patterns; and (ii) DDFs would differ among slope positions because of differential soil development patterns mediated by topography. These results lead us to the testing of Hypothesis (iii) that RA, EMB, and RSM could be used to model changes in DDFs so that soil properties in native vs. cultivated sites could be compared across soil landscapes.

Site Response Surfaces

The flowchart for the EMB is presented in Fig. 2. The first-level screening revealed five models with the greatest potential for modeling the relationships between the selected soil profile properties and slope position and site (Table 4). All of the models were significant at the $P < 0.007$ level with the exception of Model I (distance from summit) and Model II (distance from summit and distance from summit squared) for surface horizon OC content, which have $P < 0.80$. Adding the site variables (Model III) greatly increased the adjusted R^2 for all response variables except for the A horizon thickness. Adding terms that accounted for site interactions increased the adjusted R^2 (Models IV and V), and Model V (Table 4) was selected as the most appropriate model for all measured soil properties. For each soil property, Model V was significant at $P < 0.007$ and had the greatest adjusted R^2 values. The high level of significance and high adjusted R^2 led us to conclude that RSM could be used to model changes in DDFs so that soil properties in native vs. cultivated sites could be compared across soil landscapes (Hypothesis iii).

Using Model V in Table 4 and the response surface equation parameters for the seven soil properties at the four sites (Table 5), response surfaces (Fig. 4) were generated by substituting a distance from summit X_1 in meters and incorporating the indicator variables X_2 to X_4 to change the coefficients associated with the differences for each site. The X_1 values ranged from 2 to 62 m from the summit with 3 m between each point for a total of 21 X_1 values. Distance from the summit X_1 for each site represented actual points on the summit, shoulder, and backslope.

Knox–Native vs. Menfro–NativeResponse Surfaces

As shown in Fig. 4, the primary response surface comparisons were between the Knox–native and the Knox–cultivated sites and between the Menfro–native and the Menfro–cultivated sites, but a brief discussion to compare the Knox–native and the Menfro–native sites is necessary to stress the importance of native-site differences when selecting baseline sites for study.

Table 4. Results of overall multiple regression analysis by soil property (Y). The predictor variables are distance from summit of slope (m), X_1; site indicator variables are X_2 though X_4. For Knox–native: $X_2 = 1$, $X_3 = 0$, $X_4 = 0$. For Knox–cultivated: $X_2 = 0$, $X_3 = 1$, $X_4 = 0$. For Menfro–native: $X_2 = 0$, $X_3 = 0$, $X_4 = 1$. For Menfro–cultivated: $X_2 = 0$, $X_3 = 0$, $X_4 = 0$. Model I has X_1 as a single predictor variable. Model II adds X_1^2 as a predictor variable. Model III adds site as a predictor variable. Model IV adds the interaction of site with the X_1 predictor variable. Model V then adds the interaction of the X_1^2 predictor variable with site. The adjusted R^2 values indicate the overall "appropriateness" of the model, including any differences in site.

Model	Adjusted R^2						
	A horizon thickness	Surface horizon organic C content	Surface horizon clay content	Subsurface horizon thickness	Depth to clay maximum	Depth to top of B horizon	$OC_{7.5}$‡
I: $y = \beta_0 + \beta_1 X_1$	0.19	0.0†	0.09	0.06	0.04	0.16	0.05
II: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2$	0.21	0.0†	0.10	0.07	0.05	0.15	0.04
III: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_2 + \beta_4 X_3 + \beta_5 X_4$	0.22	0.55	0.51	0.59	0.69	0.59	0.44
IV: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_2 + \beta_4 X_3 + \beta_5 X_4 + \beta_6 X_1 X_2 + \beta_7 X_1 X_3 + \beta_8 X_1 X_4$	0.26	0.56	0.69	0.67	0.73	0.68	0.58
V: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_2 + \beta_4 X_3 + \beta_5 X_4 + \beta_6 X_1 X_2 + \beta_7 X_1 X_3 + \beta_8 X_1 X_4 + \beta_9 X_1^2 X_2 + \beta_{10} X_1^2 X_3 + \beta_{11} X_1^2 X_4$	0.32	0.56	0.76	0.69	0.74	0.69	0.59

† Model has $P < 0.80$; all other models have $P < 0.007$.

‡ Depth to ≤ 7.5 g kg^{-1} organic C.

The soil property response surfaces varied by slope position (Fig. 4) for the Knox–native and Menfro–native sites differed in shape (e.g., linear, concave, or convex), slope, and magnitude. Also, the interacting independent variables, distance from the slope summit (e.g., slope position), and site in Model V show that the impacts of slope vary with site and that both variables need to be accounted for when interpreting the results of the predictive equations.

The common factors for both sites were the Peoria Loess parent material, the summit shoulder and backslope landscape positions, and the humid continental macroclimate. The primary difference between the two sites was vegetative history. The Knox–native site was forested when sampled (Table 2) but had a history of prairie vegetation according to the original land survey from 1817 (Carr and Belden, 1905), and the area is presently mapped as Knox silt loam, which is a Mollic Hapludalf. The forest of the Menfro–native site is considered a relict of the forests (see Table 2) that once covered the steep loess hills along the Missouri River (Walters, 1981); the area is presently mapped as Menfro silt loam, which is a Typic Hapludalf. The thickness of the A horizon was similar in all three slope positions for both the Knox–native and Menfro–native sites, but the OC content in the surface horizon, and $OC_{7.5}$ were greater at the Knox–native site. This difference is a reflection of the prairie influence on the site and is indicated by the mollic subgroup of the Knox series mapped at the site.

Knox–Native vs. Knox–Cultivated and Menfro–Native vs. Menfro–Cultivated Response Surfaces

The response surfaces of the Knox–native site vs. Knox–cultivated site and the Menfro–native site vs. Menfro–cultivated site are presented in Fig. 4. The thickness of the A horizon (Fig. 4) was similar for the Knox–native and Knox–cultivated sites at all three slope positions and for the Menfro–native and Menfro–cultivated sites at all three slope positions. This similarity can be explained by looking at the standard nomenclature that is used to

Table 5. Response surface equation parameters for seven soil properties (*Y*) at four sites; X_1 = distance from summit. Equations are from Model V in Table 4. These equations incorporate the indicator variables to change the coefficients associated with the site differences. For Knox–native: $X_2 = 1, X_3 = 0, X_4 = 0$. For Knox–cultivated: $X_2 = 0, X_3 = 1, X_4 = 0$. For Menfro–native: $X_2 = 0, X_3 = 0, X_4 = 1$. For Menfro–cultivated: $X_2 = 0, X_3 = 0, X_4 = 0$.

Soil property	Model V parameters					
			Knox–native site equations			
	β_0	β_1	β_2	β_3	β_6	β_9
Depth to clay maximum	53.74	−0.08	−0.004	4.95	0.5	−0.0004
Subsurface horizon thickness	14.1	−0.41	0.0028	−7.27	0.58	−0.0049
Depth to top of B horizon	27.07	−0.23	−0.0011	−7.02	0.39	−0.0017
A horizon thickness	13.01	0.18	−0.0039	−0.57	−0.12	0.0024
Surface horizon clay content	9.53	−0.07	0.0054	5.71	0.03	−0.0058
$OC_{7.5}$†	27.34	−0.25	0.0028	25.78	−0.02	−0.0055
Surface horizon organic C content	1.66	−0.01	0.0002	2.01	0.02	−0.0006
			Knox–cultivated site equations			
	β_0	β_1	β_2	β_4	β_7	β_{10}
Depth to clay maximum	53.74	−0.08	−0.0049	−13.41	−0.79	0.0115
Subsurface horizon thickness	14.07	−0.41	0.0028	−8.00	0.05	0.0017
Depth to top of B horizon	27.07	−0.23	−0.0011	−7.27	−0.07	0.0033
A horizon thickness	13.01	0.18	−0.0039	0.73	−0.13	0.0016
Surface horizon clay content	9.53	−0.07	0.0053	4.86	0.64	−0.0117
$OC_{7.5}$	27.34	−0.25	0.0028	−6.10	0.53	−0.0076
Surface horizon organic C content	1.66	−0.01	0.0002	−0.12	0.01	−0.0001
			Menfro–native site equations			
	β_0	β_1	β_2	β_5	β_8	β_{11}
Depth to clay maximum	53.74	−0.08	−0.0049	9.04	−0.81	0.0148
Subsurface horizon thickness	14.07	−0.41	0.0028	1.67	0.23	−0.0011
Depth to top of B horizon	27.07	−0.23	−0.0011	3.53	−0.06	0.0041
A horizon thickness	13.01	0.18	−0.0039	1.86	−0.29	0.0051
Surface horizon clay content	9.53	−0.07	0.0053	−2.53	0.49	−0.0104
$OC_{7.5}$	27.34	−0.25	0.0028	−0.02	0.00	0.0014
Surface horizon organic C content	1.66	−0.01	0.0002	1.11	−0.01	0.0000
			Menfro–cultivated site equations			
	β_0	β_1	β_2			
Depth to clay maximum	53.74	−0.08	−0.0049			
Subsurface horizon thickness	14.07	−0.41	0.0028			
Depth to top of B horizon	27.07	−0.23	−0.0011			
A horizon thickness	13.01	0.18	−0.0039			
Surface horizon clay content	9.53	−0.07	0.0053			
$OC_{7.5}$	27.34	−0.25	0.0028			
Surface horizon organic C content	1.66	−0.01	0.0002			

† Depth to ≤ 7.5 g kg^{-1} organic C.

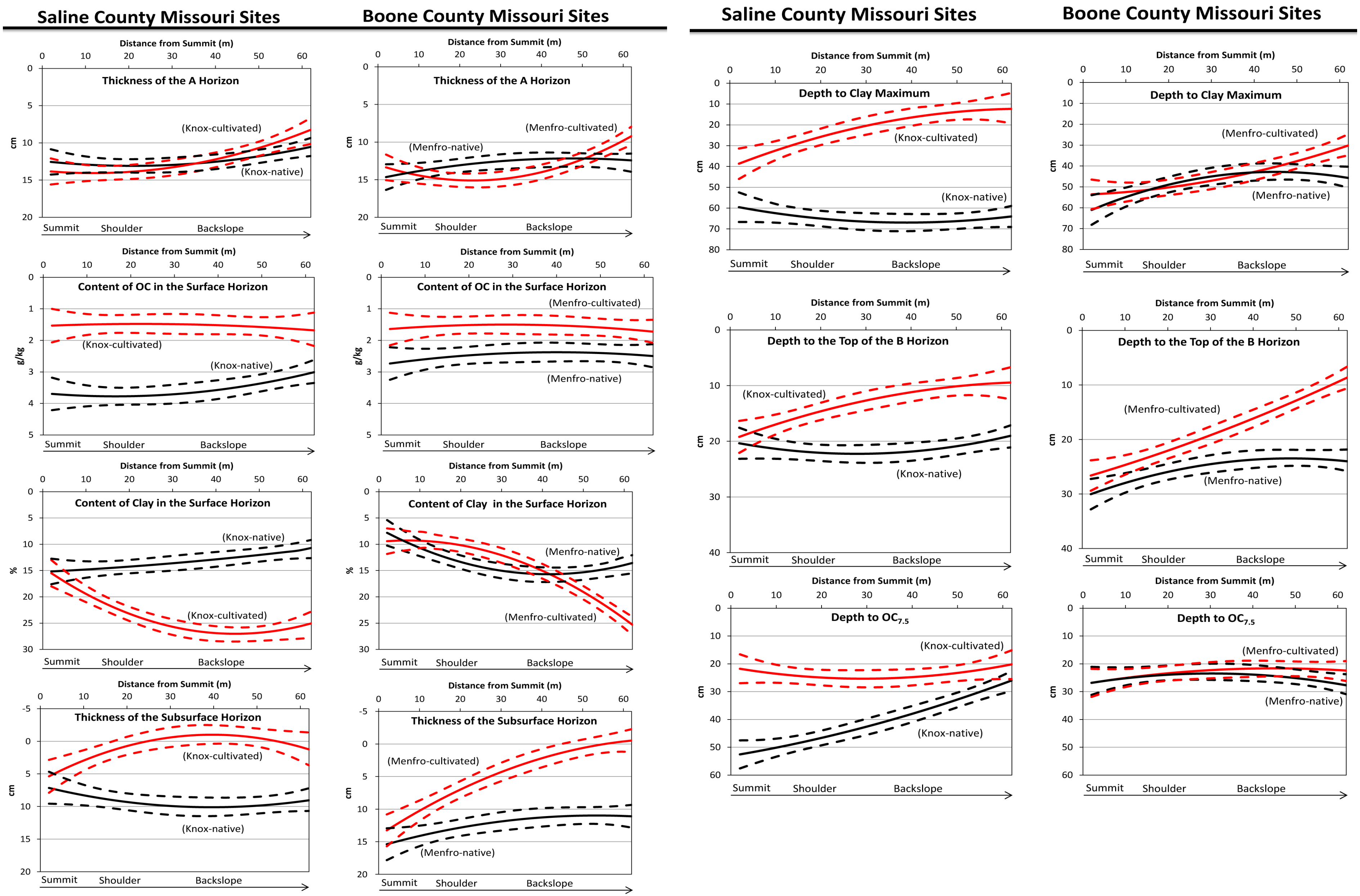

Fig. 4. Soil properties predicted from the response surface equations (see Table 5) for the Knox–native and Knox–cultivated sites and the Menfro–native and Menfro–cultivated sites. The response surfaces and error bars were generated by inserting distances from the summit in meters for actual points on the summit, shoulder, and backslope positions. The error bars represent the 0.95 confidence interval.

describe and label soil horizons (Schoeneberger et al., 2012). The A horizon is, by definition, a mineral horizon that has formed at the surface; the A horizon at cultivated sites is a mineral horizon that formed at the surface and has properties resulting from cultivation, designated as Ap (or "plow layer"). In this part of Missouri and on these landscapes, the thickness of the plow layer can range from a few to 50 cm, depending on the tillage practice. The definition of an Ap horizon does not consider the location of the horizon within the original or undisturbed soil profile (Soil Survey Staff, 1993).

Evidence supporting this fact included the surface horizon clay content, subsurface horizon thickness, depth to top of B horizon, and depth to clay maximum response surfaces (Fig. 4). Summits are the most stable part of these hillslopes and the least susceptible to erosion; as expected, the horizon sequences of the native and cultivated sites at the summits are similar in both counties. The shoulder and backslope positions are more susceptible to erosion, and, as shown by the response surfaces, an increase in surface horizon clay content and a decrease in subsurface horizon thickness, depth to the top of the B horizon, and depth to the clay maximum supported this observation. Also, the surface horizon OC content showed a distinct decrease from the Knox–native to the Knox–cultivated sites and from the Menfro–native to the Menfro–cultivated sites. This decrease was probably a result of the combined effects of accelerated erosion and the dilution of the OC amount by mixing with the deeper E and B horizons, which have a lower OC content.

Soil Profile Change

The cross-sectional DDF graphs, representative DDFs by slope position, and DDF response surfaces for each site highlight the distinct changes that occurred on these native loess hillslopes when the soils were cultivated. Model V indicated significance for the independent variable of X_1 and X_1^2 and the interactions of X_1 and X_1^2 with site. From Model V, we observed a curvilinear response and significant interactions of the independent variables of slope position, as measured by the distance from the slope summit (X_1 and X_1^2) and site (X_2, X_3 and X_4 coded appropriately as 0 or 1). We inferred that together landscape position and land use impact soil profile expression at all four sites and when comparing the Knox–native with the Knox–cultivated site and the Menfro–native with the Menfro–cultivated site, we measured and modeled anthropogenic soil profile change.

This anthropogenic soil profile change included a reduction of the surface horizon C, a decrease in the $OC_{7.5}$, a thinning or loss of subsurface horizons (E, AB, EB, or BE), a decreasing depth to the top of the B horizon, and a decreasing depth to the clay maximum. Taken together, these soil properties indicate how simultaneous cultivation and erosion resulted in both the truncation of the profile and the incorporation of material from the subsurface layer and subsoil into the plow layer.

These soil changes highlight the importance of having appropriate baseline sites (Daniels et al., 1987; Papiernik et al., 2007); understanding native soil variability and anthropogenic impacts on that variability (Daniels et al., 1987; Lobb, 2011; Olson et al., 2005); studying the whole soil profile (Kravchenko and Robertson, 2011; Stolt et al., 2010; Syswerda et al., 2011); studying soil-landscapes or catenas (De Alba et al., 2004; Arriaga and Lowery, 2005; Papiernik et al., 2007, 2009); having appropriate spatial units (e.g., hillslope components) (Ruhe, 1969; Pennock et al., 1994); and an appropriate experimental design and statistical analysis (Neter et al., 1990; Box and Draper, 1987) to model, include and integrate these pedological concepts.

Experimental Design to Study Soil Profile Change

Brown et al. (2004) emphasized the importance of linking an understanding of soil-landscape formation to predictive soil-landscape models. This study linked classic soil-landscape analysis and the RA, EMB, and RSM modeling techniques to understand native and cultivated soil-landscape formation and to build predictive models of these relationships. The results of our study suggested that anthropogenic soil profile change on these loess hillslopes could be successfully modeled and that slope position and site characteristics are major contributors to the change. The approach in this study adds a pedological dimension to the study of soil change by including both soil profile properties and the variation of the soil profile properties across these sloping landscapes.

Our experimental design presented three major challenges: (i) site selection; (ii) sampling and modeling native and cultivated soil–landscape relationships; and (iii) graphically and statistically comparing native and cultivated sites to model soil profile change.

Baseline sites are critical for this type of study (Ruhe and Daniels, 1965; Daniels et al., 1987; Papiernik et al., 2007; Olson, 2010; Lobb, 2011). The challenge of finding two native study baseline sites was difficult, but a review of historical documents, historical aerial photography, topographic quadrangles, onsite investigation of vegetation, parent material, landscape, soil maps, soil profile descriptions, and site accessibility for sampling guided us in the selection of sites suitable for the study.

The DDF cross-sections were revealing and comparisons could be made, but statistical and graphical models would be needed to analyze the large data set to make comparisons and inferences. To meet this challenge, we built on the descriptive hillslope models (Ruhe, 1969) and applied RA, EMB, and RSM statistical techniques (Box and Draper, 1987). Taking the classic application of RA (Neter et al., 1990) to soil-landscape studies (Ruhe and Walker, 1968; Walker and Ruhe, 1968) a step further, we used EMB (Box and Draper, 1987) to systematically build a model (Fig. 2) of soil–landscape relationships for all four sites, which then allowed testing of the differences between the native and cultivated sites to determine anthropogenic soil profile changes to these loess hillslopes. The response surfaces (Fig. 4) show statistically and graphically the DDF changes that occurred by slope position and by land use, and they also show the error involved in these types of measurements. The error does not lessen the usefulness of the models, but it does highlight future challenges when building soil-landscape models using RA, EMB, and RSM.

The significance and high adjusted R^2 for the final models suggests that the approach used in this study was an effective way to model soil profile change in these loess landscapes. This approach can also be applied to other soil-landscape studies. With proper site selection, application of soil-landscape concepts, and statistical model building, we gained a better understanding of soil-landscape formation and soil-landscape evolution to provide an improved predictive soil-landscape model for understanding baseline soil variability and how that variability is influenced by land use. This study reinforces the importance of soil-landscape modeling in our science, as outlined by Brown et al. (2004) and Brown (2005), and how soil-landscape modeling can improve our understanding of anthropogenic influences on those models.

CONCLUSIONS

Both DDFs and EMB were successfully applied to characterize the impact of land use on native loess soil landscapes in Missouri. Two native sites and two nonnative sites were carefully selected for comparison. Understanding native soil variability is critical as a basis for understanding changes in soil properties resulting from cultivation. Statistical and graphical comparisons revealed changes in soil properties by slope position within a site and changes resulting from cultivation. The EMB approach allowed other independent variables, such as slope shape and native vegetation type, to be added to the model and tested. Greater geomorphic and stratigraphic control at the study sites will increase our understanding of the impacts of geologic, modern, and accelerated erosion on these loess soil landscapes.

The results showed a distinct downward migration of the native A horizon into the subsurface layer and subsoil in the soils on cultivated hillslopes and highlights the importance of studying the complete soil solum when modeling and quantifying soil change. This downward migration of the Ap horizon occurred predominantly on the shoulder and backslope of the cultivated-site hillslopes, which are the most sloping and unstable parts of these landscapes and the most susceptible to accelerated erosion. Using baseline soil landscape sites and making soil profile comparisons by slope position allows soil scientists to more accurately map this downward migration in soil descriptions. The thickness of an Ap horizon gives little or no indication of the amount of accelerated erosion that has taken place. The location of the Ap horizon in relation to the location of the native A horizon is a much more accurate measurement of accelerated erosion. This downward migration of the Ap horizon during a short period of time shows that our soil resources are limited not only in area but also quantitatively and qualitatively in depth.

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REFERENCES

Aandahl, A.R. 1949. The characterization of slope positions and their influence on the total nitrogen content of a few virgin soils of western Iowa. Soil Sci. Soc. Am. Proc. 13:449–454. doi:10.2136/sssaj1949.036159950013000C0081x

Arriaga, F.J., and B. Lowery. 2005. Spatial distribution of carbon over an eroded landscape in southwest Wisconsin. Soil Tillage Res. 81:155–162. doi:10.1016/j.still.2004.09.004

Baker, J.L. 1993. Soil survey of Saline County, Missouri. U.S. Gov. Print. Office, Washington, DC.

Box, G.E.P., and N.R. Draper. 1987. Empirical model building and response surfaces. John Wiley & Sons, New York.

Brown, D.J. 2005. A historical perspective on soil-landscape modeling. In: S. Grunwald, editor, Environmental soil-landscape modeling: Geographic information technologies and pedometrics. CRC Press, Boca Raton, FL.

Brown, D.J., M.K. Clayton, and K. McSweeney. 2004. Potential terrain controls on soil color, texture contrast and grain size deposition for the original catena landscape in Uganda. Geoderma 122:51–72. doi:10.1016/j.geoderma.2003.12.004

Buol, S.W., R.J. Southard, R.C. Graham, and P.A. McDaniel. 2011. Soil genesis and classification. 6th ed. John Wiley & Sons, New York.

Butler, B.E. 1959. Periodic phenomena in landscapes as a basis for soil studies. Soil Publ. 14. CSIRO, Melbourne, VIC, Australia.

Carr, M.E., and H.L. Belden. 1905. Soil survey of Saline County, Missouri. In: Field operations of the Bureau of Soils, 1904. U.S. Gov. Print. Office, Washington, DC. p. 791–814.

Cassagne, N., T. Remaury, T. Gauquelin, and A. Fabre. 2000. Forms and profile distribution of soil phosphorus in alpine Inceptisols and Spodosols (Pyrenees, France). Geoderma 95:161–172. doi:10.1016/S0016-7061(99)00093-2

Daniels, R.B., J.W. Gilliam, D.K. Cassel, and L.A. Nelson. 1987. Quantifying the effects of past soil erosion on present soil productivity. J. Soil Water Conserv. 42:183–187.

Day, L.D., M.E. Collins, and N.E. Washer. 1987. Landscape position and particle-size effects on soil phosphorus distributions. Soil Sci. Soc. Am. J. 51:1547–1553. doi:10.2136/sssaj1987.03615995005100060026x

De Alba, S., M. Lindstrom, T.E. Schumacher, and D.D. Malo. 2004. Soil landscape evolution due to soil redistribution by tillage: A new conceptual model of soil catena evolution in agricultural landscapes. Catena 58:77–100. doi:10.1016/j.catena.2003.12.004

Huddleston, J.H., J.A. Walsh, D. Jowett, and F.F. Riecken. 1975. Local soil–landscape relationships in eastern Iowa: II. Quantification of geologic and pedologic effects. Soil Sci. Soc. Am. J. 39:908–913. doi:10.2136/sssaj1975.03615995003900050033x

Indorante, S.J., L.R. Follmer, R.D. Hammer, and P.G. Koenig. 1990. A modified pipette procedure for particle analysis. Soil Sci. Soc. Am. J. 54:560–563. doi:10.2136/sssaj1990.03615995005400020047x

Jankauskas, B., and M.A. Fullen. 2002. A pedological investigation of soil erosion severity on undulating land in Lithuania. Can. J. Soil Sci. 82:311–321. doi:10.4141/S01-058

Kabrick, J.M., K.W. Goyne, Z. Fan, and D. Meinert. 2011. Landscape determinants of exchangeable calcium and magnesium in Ozark Highland forest soils. Soil Sci. Soc. Am. J. 75:164–180. doi:10.2136/sssaj2009.0382

Kiss, J.J., E. De Jong, and H.P.W. Rostad. 1986. An assessment of soil erosion in west-central Saskatchewan using cesium-137. Can. J. Soil Sci. 66:591–600. doi:10.4141/cjss86-059

Kleiss, H.J. 1970. Hillslope sedimentation and soil formation in northeastern Iowa. Soil Sci. Soc. Am. Proc. 34:287–290. doi:10.2136/sssaj1970.03615995003400020030x

Kravchenko, A.N., and G.P. Robertson. 2011. Whole-profile soil carbon stocks: The danger of assuming too much from analyses of too little. Soil Sci. Soc. Am. J. 75:235–240. doi:10.2136/sssaj2010.0076

Kreznor, W.R., K.R. Olson, W.L. Banwart, and D.L. Johnson. 1989. Soil, landscape, and erosion relationships in a northwest Illinois watershed. Soil Sci. Soc. Am. J. 53:1763–1771. doi:10.2136/sssaj1989.03615995005300060026x

Krusekopf, H.H., and C.L. Scrivner. 1962. Soil survey of Boone County, Missouri. U.S. Gov. Print. Office, Washington, DC.

Lee, B.D., R.C. Graham, T.E. Laurent, C. Amrhein, and R.M. Creasy. 2001. Spatial distributions of soil chemical conditions in serpentinitic wetland and surrounding landscape. Soil Sci. Soc. Am. J. 65:1183–1196. doi:10.2136/sssaj2001.6541183x

Lin, H. 2011. Three principles of soil change and pedogenesis in time and space. Soil Sci. Soc. Am. J. 75:2049–2070. doi:10.2136/sssaj2011.0130

Lobb, D.A. 2011. Understanding and managing the causes of soil variability. J. Soil Water Conserv. 66:175A–170A. doi:10.2489/jswc.66.6.175A

Molina, N.C. 2009. Verification of conceptual models of phosphorus, clay, sand and organic matter distribution in ABt sola. Geoderma 150:396–403. doi:10.1016/j.geoderma.2009.02.019

Neter, J., W. Wasserman, and M.H. Kutner. 1990. Applied linear statistical models. 3rd ed. Richard D. Irwin, Homewood, IL.

Nizeyimana, E., and K.R. Olson. 1988. Chemical, mineralogical, and physical property differences between moderately and severely eroded Illinois soils. Soil Sci. Soc. Am. J. 52:1740–1748. doi:10.2136/sssaj1988.03615995005200060041x

Norton, E.A., and R.S. Smith. 1930. The influence of topography on soil profile character. J. Am. Soc. Agron. 22:251–262. doi:10.2134/agronj1930.0002 1962002200030006x

Norton, L.D., L.T. West, and K. McSweeney. 1988. Soil development and loess stratigraphy of the midcontinental USA. In: D.N. Eden and R.J. Furket, editors, Loess: Its distribution, geology and soils. A.A. Balkema Publ., Rotterdam, the Netherlands.

NRCS. 2006. Land resource regions and major land resource regions of the United States, the Carribbean, and the Pacific Basin. Agric. Handbk. 296. U.S. Gov. Print. Office, Washington, DC.

Olson, K.R. 2010. Impacts of tillage, slope, and erosion on soil organic carbon retention. Soil Sci. 175:562–567. doi:10.1097/SS.0b013e3181fa2837

Olson, K.R., A.N. Gennadiyev, R.L. Jones, and S. Chernyanskii. 2002. Erosion patterns on cultivated and reforested hillslopes in Moscow region, Russia. Soil Sci. Soc. Am. J. 66:193–201. doi:10.2136/sssaj2002.0193

Olson, K.R., A.N. Gennadiyev, A.P. Zhidkin, M.V. Markelov, V.N. Golosov, and J.M. Lang. 2013. Use of magnetic tracer and radio-cesium methods to determine past cropland soil erosion amounts and rates. Catena 104:103–110. doi:10.1016/j.catena.2012.10.015

Olson, K.R., J.M. Lang, and S.A. Ebelhar. 2005. Soil organic carbon changes after 12 years of no-tillage and tillage of Grantsburg soil in southern Illinois. Soil Tillage Res. 81:217–225.

Olson, K.R., S.R. Phillips, and B.K. Kitur. 1994. Identification of eroded phases of an Alfisol. Soil Sci. 157:108–115. doi:10.1097/00010694-199402000-00006

Papiernik, S.K., M.J. Lindstrom, T.E. Schumacher, J.A. Schumacher, D.D. Malo, and D.A. Lobb. 2007. Characterization of soil profiles in a landscape affected by long-term tillage. Soil Tillage Res. 93:335–345. doi:10.1016/j.still.2006.05.007

Papiernik, S.K., T.E. Schumacher, D.A. Lobb, M.J. Lindstrom, M.L. Lieser, A. Eynard, and J.A. Schumacher. 2009. Soil properties and productivity as affected by topsoil movement within an eroded landform. Soil Tillage Res. 102:67–77. doi:10.1016/j.still.2008.07.018

Pennock, D.J., D.W. Anderson, and E. de Jong. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma 64:1–19. doi:10.1016/0016-7061(94)90086-8

Ruhe, R.V. 1969. Quaternary landscapes in Iowa. Iowa State Univ. Press, Ames.

Ruhe, R.V., and R.B. Daniels. 1965. Landscape erosion: Geologic and historic. J. Soil Water Conserv. 20:52–57.

Ruhe, R.V., R.B. Daniels, and J.G. Cady. 1967. Landscape evolution and soil development in southwestern Iowa. USDA Tech. Bull. 1349. U.S. Gov. Print. Office, Washington, DC.

Ruhe, R.V., and P.W. Walker. 1968. Hillslope models and soil formation: I. Open systems. In: J.W. Holmes, editor, Transactions of the 9th International Congress of Soil Science, Adelaide. Australia. 6–16 Aug. 1968. Vol. 4. Elsevier, New York. p. 551–560.

Runge, E.C.A., and F.F. Riecken. 1966. Influence of natural drainage on the distribution and forms of phosphorus in some Iowa prairie soils. Soil Sci. Soc. Am. Proc. 30:624–630. doi:10.2136/sssaj1966.03615995003000050026x

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and Soil Survey Staff. 2012. Field book for describing and sampling soils. Version 3.0. Natl. Soil Surv. Ctr., Lincoln, NE.

Schroeder, W.A. 1981. Presettlement prairie of Missouri. Nat. History Ser. 2. Missouri Dep. of Conserv., Jefferson City.

Sharpley, A.N., and S.J. Smith. 1983. Distribution of phosphorus forms in virgin and cultivated soils and potential erosion losses. Soil Sci. Soc. Am. J. 47:581–586. doi:10.2136/sssaj1983.03615995004700030038x

Smeck, N.E., and E.C.A. Runge. 1971. Phosphorus availability and redistribution in relation to profile development in an Illinois landscape segment. Soil Sci. Soc. Am. Proc. 35:952–959. doi:10.2136/sssaj1971.03615995003500060030x

Soil Survey Laboratory Staff. 2004. Soil survey laboratory methods manual. Soil Surv. Invest. Rep. 42. Version 4.0. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1993. Soil survey manual. Agric. Handbk. 18. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 2010a. Soil survey of Boone County, Missouri. NRCS, Washington, DC. http://websoilsurvey.nrcs.usda.gov/ (accessed 7 Aug. 2010).

Soil Survey Staff. 2010b. Soil survey of Saline County, Missouri. NRCS, Washington, DC. http://websoilsurvey.nrcs.usda.gov/ (accessed 7 Aug. 2010).

Soil Survey Staff. 2010c. Keys to Soil Taxonomy. NRCS, Washington, DC.

Soil Survey Staff. 2013. Official soil series descriptions. NRCS, Washington, DC. http://soils.usda.gov/technical/classification/osd/index.html (accessed 1 Sept. 2013).

Stolt, M.H., P.J. Drohan, and M.J. Richardson. 2010. Insights and approaches for mapping soil organic carbon as a dynamic soil property. Soil Sci. Soc. Am. J. 74:1685–1689. doi:10.2136/sssaj2009.0326N

Stone, J.R., J.W. Gilliam, D.K. Cassel, R.B. Daniels, L.A. Nelson, and H.J. Kleiss. 1985. Effect of erosion and landscape position on the productivity of Piedmont soils. Soil Sci. Soc. Am. J. 49:987–991. doi:10.2136/sssaj1985.03615995004900040039x

Syswerda, S.P., A.T. Corbin, D.L. Mokema, A.N. Kravchenko, and G.P. Robertson. 2011. Agricultural management and soil carbon storage in surface vs. deep layers. Soil Sci. Soc. Am. J. 75:92–101. doi:10.2136/sssaj2009.0414

Thoma, D.P., M.S. Moran, R. Bryant, M. Rahman, C.D. Holifield-Collins, S. Skirvin, and E.E. Sano. 2006. Comparison of four models to determine surface soil moisture from C-band radar imagery in a sparsely vegetated semiarid landscape. Water Resour. Res. 42:W01418. doi:10.1029/2004WR003905

Thompson, J.A., J.C. Bell, and C.A. Butler. 2001. Digital elevation model resolution: Effects on terrain attribute calculation and quantitative soil-landscape modeling. Geoderma 100:67–89. doi:10.1016/S0016-7061(00)00081-1

Thompson, J.A., and R.K. Kolka. 2005. Soil carbon storage estimation in a forested watershed using quantitative soil-landscape modeling. Soil Sci. Soc. Am. J. 69:1086–1093. doi:10.2136/sssaj2004.0322

Thompson, J.A., E.M. Pena-Yewtukhiw, and J.H. Grove. 2006. Soil-landscape modeling across a physiographic region: Topographic patterns and model transportability. Geoderma 133:57–70. doi:10.1016/j.geoderma.2006.03.037

Tranter, G., B. Minasny, A.B. McBratney, B. Murphy, N.J. McKenzie, and D. Brough. 2007. Building and testing conceptual empirical models for predicting soil bulk density. Soil Use Manage. 23:437–443. doi:10.1111/j.1475-2743.2007.00092.x

Tugel, A.J., J.E. Herrick, J.R. Brown, M.J. Mausbach, W. Puckett, and K. Hipple. 2005. Soil change, soil survey, and natural resources decision making: A blueprint for action. Soil Sci. Soc. Am. J. 69:738–747. doi:10.2136/sssaj2004.0163

Verburg, P.H. 2006. Simulating feedbacks in land use and land cover change models. Landscape Ecol. 21:1171–1183. doi:10.1007/s10980-006-0029-4

Walker, P.H., and R.V. Ruhe. 1968. Hillslope models and soil formation: II. Closed systems. In: J.W. Holmes, editor, Transactions of the 9th International Congress of Soil Science, Adelaide. Australia. 6–16 Aug. 1968. Vol. 4. Elsevier, New York. p. 561–568.

Walters, M.A. 1981. Soil carbon and nitrogen trends with varied land use histories 1930–1980. M.S. thesis. Univ. of Missouri, Columbia.

Wang, G.-P., Z.-L. Zhai, J.-S. Liu, and J.-D. Wang. 2008. Forms and profile distribution of soil phosphorus in four wetlands across gradients of sand desertification in Northeast China. Geoderma 145:50–59. doi:10.1016/j.geoderma.2008.02.004

Wilson, M.A., S.J. Indorante, B.D. Lee, L.R. Follmer, D.R. Williams, B.C. Fitch, et al. 2010. Location and expression of fragic soil properties in a loess-covered landscape, southern Illinois, USA. Geoderma 154:529–543. doi:10.1016/j.geoderma.2009.03.003

Woodruff, C.M. 1990. A history of the Department of Soils and soil science at the University of Missouri. College of Agric., Univ. of Missouri, Columbia.

Young, F.J., C.A. Radatz, and C.A. Marshall. 2003. Soil survey of Saline County. U.S. Gov. Print. Office, Washington, DC.