# Developing models to predict soil bulk density in southern Wisconsin using soil chemical properties

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## ABSTRACT

There is an emerging need to estimate and verify soil carbon credits attributed to conservation tillage and prairie restoration in the Midwestern U.S. for the developing global carbon market. However, current soil sampling strategies may need to be augmented by empirical modeling to minimize costs while covering larger regions. Models were constructed relating soil bulk density (BD) to soil organic carbon (SOC) and total nitrogen (TN) concentrations using 146 sites in southern Wisconsin under varied land use to determine whether empirical models could reliably predict BD in an effort to support estimates of SOC sequestration for future carbon crediting programs. As expected, a significant exponential relationship resulted between %SOC and BD ($R^2$ = 0.90; $P < 0.0001$) across all sites. Exponential models were then constructed after categorizing data into undisturbed ecosystems, prairie restorations, and croplands, and showed that the correlation between observed and predicted BD values, along with model parameters, were quite different. Predicted values were most correlated to observed values for undisturbed sites ($R^2$ = 0.90), less correlated with prairie restorations ($R^2$ = 0.49), and the least correlated with croplands ($R^2$ = 0.25). This suggests that highly intensified crop management practices influence BD in a way that might make using %SOC or %TN as single predictor variables unreliable. It is suggested that models relating BD and soil chemical properties should consider the varied effects of land-use management over many different soil textures, particularly for the determination of carbon credits on agricultural land in temperate climate regions.


**Key words:** bulk density, carbon credits, modeling, soil carbon

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J. Integr. Biosci. 6(1):53-63.

## INTRODUCTION

As the need for verification of terrestrial carbon credits becomes more urgent with emerging carbon markets, development of cost-effective ways to estimate soil and plant carbon mass in a timely, reliable, and accurate fashion will become crucial (Metting et al., 2001; Post et al., 2001; Rosenberg and Izaurralde, 2001). In the agricultural Midwest, this is particularly relevant for conservation tillage and grassland restoration, two example land-use practices under which farmers can now enroll acres to receive compensation for sequestering carbon under the auspices of the Chicago Climate Exchange (CCX) and now administered by the National Farmers Union (CCX, 2007). The current CCX program allocates the same number of credits (e.g., 2.47 mT $CO_2$ ha$^{-1}$ for grassland restoration in Wisconsin, or 1 and 1.5 mT $CO_2$ ha$^{-1}$ for conservation tillage) to landowners over large (e.g., statewide and greater) geographic areas, regardless of soil texture and climate (CCX, 2007). Currently, site- or project-specific verification is time and cost prohibitive. A key step forward to implementing such a carbon-crediting program with confidence is to build reliable numerical models that relate soil properties, such as bulk density and soil carbon, to estimate carbon mass changes at individual project locations.

Across the U.S., there are numerous examples of field studies that have quantified rates and total amounts of soil carbon that have been sequestered through conservation tillage or prairie restoration (Burke et al., 1995; Bruce et al., 1999; Knops and Tilman, 2000; Post and Kwon, 2000; Baer et al., 2002; West and Post, 2002). Unfortunately, it is often hard to generalize the results from one particular region to another with a high level of confidence, especially when large variations in soil texture and climate make accuracy in assigning carbon credits associated with agricultural land management difficult to achieve. The forces driving variability in soil properties are largely dependent upon scale (Jenny, 1941). For example, within individual fields, properties such as soil carbon and bulk density are often highly correlated with landscape position and terrain (Jenny, 1941), reflecting the impacts of soil erosion and differences in vegetation productivity (Harden et al., 1999; Ritchie et al., 2007). At the scale of several fields that share similar climate and soil parent material, differences in land management are key factors driving variability in soil properties. Across larger scales, such as counties, states, or countries, the climate regime and soil parent material will be the key factors in determining differences in average soil properties between larger areas.

By taking advantage of soil data that have already been collected for varied land-use practices, it has been possible to estimate and track changes in grassland soil carbon at sub-regional scales, such as counties, in southern Wisconsin (Kucharik et al., 2003; Kucharik et al., 2006; Kucharik, 2007; Jelinski, 2007). In practice, however, this has required many years of intensive sampling, data analysis, time, and resources that would be unavailable for the determination of carbon credits due to land management at the level of the individual farm. Fortunately, in Wisconsin numerous soil samples are also collected independently every four years on dairy farms as part of nutrient management plans, which are often required to qualify for government programs designed to improve water quality (WDATCP, 2006; Powell et al., 2007). A new database of commonly measured soil chemical properties, such as soil organic carbon (SOC) and total nitrogen (TN) concentrations, from many different soil textures could be extremely valuable in quantifying carbon sequestration for many locations across the state. A critical barrier to using these data, however, is that bulk density (BD) is not commonly quantified as part of this large-scale effort and would be needed to convert soil carbon (%SOC) and total nitrogen (%TN) mass-per-mass concentrations to a mass-per-area basis. If reliable, numerical models relating soil chemical properties and bulk density were developed based on example ecosystem and land-management types, they could allow for more accurate and cost-effective estimation of SOC and TN changes attributed to land-management practices in locations where BD is not commonly measured.

Several easily measured soil chemical properties have been previously used to predict more difficult-to-measure soil properties in other studies and at various scales (Bouma, 1989; Vereecken et al., 1989; Webster, 1994; McBratney et al., 2000). Through the use of pedometric techniques and pedotransfer functions (Bouma et al., 1989; Cornelis et al., 2001), geostatistics and modern statistics have been used to predict hard-to-measure soil properties from more easily attainable quantities, and have gained increased popularity as computing power and resources have advanced since the 1980s (Webster, 1994; McBratney et al., 2000). For example, Vereecken et al. (1989) used soil carbon, bulk density, and textural characteristics to estimate soil moisture retention curves. Other studies have used the concentration of soil organic matter to predict porosity, carbon to nitrogen (C:N) ratio and BD (Saini, 1966; Prévost, 2004). Prévost (2004) developed models that related organic matter concentration and bulk density with high degrees of correlation, but these models were developed with data from only two sites, and thus cannot reasonably be extrapolated to other sites in different areas with the same level of accuracy. Saini (1966) based his models on the Ohio Soil Survey, a larger sampling area, but his analysis was conducted on three specific groupings of soils (humic-gley, imperfectly drained, and well-drained) that did not consider land use differences. A similar study by Calhoun et al. (2001), also based on a limited sampling population, in Ohio showed a moderate correlation ($R^2$=0.46) between soil organic carbon concentration and bulk density.

Heuscher et al. (2005) sampled soil from all 50 states and some territories of the United States, but obtained lower correlation than the studies based on smaller sampling areas. In the Heuscher et al. (2005) study, linear regression analysis of the relationship between %SOC ($R^2$=0.25), or the square root of %SOC ($R^2$=0.33), and BD demonstrated weak, but significant correlation. When data on more soil properties, such as particle-size distribution, water content, and depth, were used along with SOC content to predict bulk density for all samples in the study ($R^2$=0.45) and the data set was broken down into soil suborders and analyzed with the same soil properties ($R^2$=0.62), accuracy increased dramatically.

Although previous studies have provided useful information on the relationship between soil chemical properties and BD, the scales of these studies have either been too small (i.e., site specific) or too large (i.e., the entire U.S.) to be usefully applied to regional estimates in Wisconsin. The results of these studies suggest that successful models relating soil chemical concentrations to BD at the regional scale and larger must account for differences in management or soil texture in order for useful relationships to emerge. Additionally, it is hypothesized that, unless soil data are broken down by land-use type, the inclusion of currently used agricultural soils, which have bulk densities that change temporally and are highly impacted by recent activities, with fallow or unplowed soils may obscure relationships that would otherwise be significant.

Using a data set of soil chemical properties and bulk densities from 165 sites in southern Wisconsin, the effectiveness of models relating 0-10 cm BD and 0-10 cm %SOC and %TN for a subset of 146 sites was developed and evaluated. Samples were also categorized into specific land-use types of cropland (i.e., currently cropped soils), grassland restorations (i.e., prairie restorations and fallow fields), and undisturbed land (i.e., unplowed prairies, forests, and wetlands – including pastures).

The objectives of this study were to i) determine the effectiveness of models that predict BD from soil chemical properties based on a regional data set and ii) examine relationships of soil chemical properties to BD within land-use groupings to determine if BD could be more reasonably estimated for cropland, prairie restoration, or undisturbed land individually. It is these land-use-specific models that would be of most use for estimating real changes in soil carbon from chemical concentrations, particularly if soil sampling programs do not measure corresponding BD. The ultimate goal was to evaluate the robustness of these models for the determination of carbon credits when data on soil chemical properties is available.

## MATERIALS AND METHODS

*Study region*

A data set of soil samples from 165 sites throughout south-central Wisconsin located in the counties of Sauk, Iowa, Dane, Columbia, and Jefferson was compiled from several previous field studies (Kucharik et al., 2003; Kucharik et al., 2006; Kucharik, 2007; Jelinski, 2007). The land-management types sampled included the following: (1) land enrolled in the Conservation Reserve Program (CRP) and seeded to tallgrass prairie with ages varying between 4 and 16 years old, (2) cropland – typically managed as corn (*Zea mays*)-soybean (*Glycine max*) rotations with conventional tillage, (3) prairie restoration, where time elapsed since last disturbance was between 4 years to 75 years, and (4) remnant prairie. Also sampled were several wetlands, deciduous forests, and a few grazed pastures consisting of mixed grasses. Mean annual precipitation in the region is approximately 780 mm, with a mean annual minimum temperature of 1.5°C and mean annual maximum temperature of 13.1°C. The region lies to the south of an ecological tension zone that separates northern forest vegetation and associated soils from southern soils that developed under prairie and oak (*Quercus sps*.)-savanna vegetation (Curtis, 1959; Hole, 1976). The soils of the region are predominantly Alfisols, Mollisols, and Entisols, most often classified as Typic Hapludalfs, Lithic Hapludalfs, Typic Endoaquolls, Mollic Hapludalfs, Typic Argiudolls, and Lithic Hapludalfs (Kucharik, 2007).

*Soil chemical properties*

Sites were sampled using four to ten replicate plots from which 10-15 soil cores each were removed with a 2-cm-diameter, 25-cm long probe. At 146 sites, cores were then separated into three unique layers (i.e., 0-5 cm, 5-10 cm, and 10-25 cm) and combined to form one aggregate sample for each layer and plot. At the remaining 19 sites, the 25-cm soil cores were not separated into three depth increments before they were combined to form an aggregate sample. These sites were not used to build the models relating BD to soil chemical properties, but those data were used to summarize typical values observed across the region (Table 1). All soil samples for undisturbed sites and prairie restorations were collected from 1999 through 2006, typically during the months of May through August.

Soil sampling took place in a manner to form an overall average for each site (e.g., entire farm fields, remnant prairies, or prairie restoration areas), and to minimize the impacts of slope and aspect of each study site (Kucharik, 2007). Thus, in sites were topographic relief was significant (e.g., slope greater than 2%), replicate plots and soil cores were collected across toposequences rather than parallel to them. The soil probe was randomly positioned for each sample in each replicate plot and no preference was made to sample soils under vegetation or between plants in prairie sites. On cropped land, replicated plots were located in a systematic pattern so that all representative row-position locations that were influenced by varied management (e.g., within rows, between rows, wheel-tracked interrow, nonwheel-tracked interrow) contributed to the overall field average (Kucharik, 2007). This deliberate, systematic sampling pattern was necessary to minimize any chance that all cores were collected in similar positions with respect to row orientation. In the event that planting and tillage practices followed a similar tracking pattern in the long term across fields for several decades, systematic patterns of soil C and N storage could develop and could be correlated with row placement. All cropland samples were consistently collected in the mid-summer timeframe (e.g., late June through August) to minimize potential increases in bulk density that could occur following tillage during the spring (Franzluebbers et al., 1995).

According to field observations and official soil series descriptions of the United Stated Department of Agriculture Natural Resources Conservation Service (USDA-NRCS), the experimental design called for sampling of soils that extended below the Ap horizon (i.e., 12 to 23 cm depth) (USDA-NRCS, 2008). Soil samples were dried for 48 hours at 33ºC, after which all plant matter was removed from the sample. Samples were then mechanically ground to pass through a 2-mm sieve, visible plant roots and residue were removed, and then were re-ground with a mortar and pestle to pass through a 150-μm sieve. Soil organic carbon and TN concentrations were determined on soil subsamples (5 g) through high-temperature catalytic combustion using a Carlo-Erba Model NA 1500 C and N analyzer (Thermo Electron Corporation, Milan, Italy; Kucharik et al., 2003; Kucharik, 2007).

While many soils in the region are calcareous in origin, for the majority of sites no removal of inorganic soil carbon took place before

**Table 1.** Summary statistics for 0-10 cm soil bulk density (BD), 0-25 cm soil organic carbon (SOC) and total soil nitrogen (TN) concentrations, and 0-25 cm C:N ratio across the study area according to land use.

| | | BD (g cm$^{-3}$) | | | 0-25 cm SOC (%) | | | 0-25 cm TN (%) | | | 0-25 cm C:N | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Land use | n | Mean | Range | CV† (%) | Mean | Range | CV (%) | Mean | Range | CV (%) | Mean | Range | CV (%) |
| Remnant prairie / wetland | 30 | 0.75 | 0.08 - 1.70 | 63 | 15.3 | 0.56 - 44.1 | 80.6 | 1.29 | 0.04 - 4.08 | 80.9 | 12.51 | 8.88 - 23.03 | 24.0 |
| Prairie restoration | 79 | 1.36 | 0.71 - 1.65 | 12 | 2.50 | 0.60 - 12.8 | 83.2 | 0.23 | 0.05 - 1.11 | 82.9 | 11.29 | 7.50 - 26.47 | 20.9 |
| Forest | 4 | 1.27 | 1.20 - 1.33 | 5.2 | 1.63 | 1.02 - 2.46 | 38.4 | 0.13 | 0.06 - 0.19 | 47.7 | 13.45 | 10.4 - 16.6 | 19.4 |
| Pasture / grazing | 3 | 1.29 | 1.25 - 1.35 | 4.0 | 2.34 | 1.53 - 3.46 | 42.9 | 0.24 | 0.17 - 0.36 | 41.2 | 9.69 | 9.07 - 10.06 | 5.5 |
| Cropland | 49 | 1.39 | 0.88 - 1.82 | 6.9 | 2.07 | 0.98 - 5.38 | 50.8 | 0.18 | 0.09 - 0.56 | 48.6 | 11.28 | 8.88 - 20.29 | 20.6 |

† Coefficient of variation (CV)

SOC and TN were determined because free carbonates were not detected upon reaction with dilute hydrochloric acid (1 M HCl). On a small subset (10) of cropland and prairie sites located in a floodplain in Jefferson Co. (Jelinski, 2007), soil inorganic carbon values in addition to total carbon were determined for all soil samples due to the existence of calcareous shell fragments visible in the top 25 cm of soil. Soil organic carbon was determined as the difference between separate measures of total soil carbon (TC) and inorganic carbon at these sites (Jelinski, 2007). For this subset of samples, elemental concentrations were determined by high-temperature catalytic combustion using a Leco 2000 C and N analyzer (Leco Instruments, Inc., St. Joseph, MI). Total carbon was determined using a profile temperature of 1350 °C, which maximized the recovery of total carbon, while a second combustion profile of 925 °C minimized the decomposition of carbonate C and maximized the recovery of SOC. Soil inorganic carbon (SIC) was determined by the difference between TC and SOC values.

*Soil bulk density measurements*

A single 0-10 cm soil core sample and corresponding bulk density measurement was obtained for each replicate plot for a total of four to ten measurements at each of the 165 study sites using a gravity-driven hammer attachment (Elliott et al., 1999). The sampling methodology provided intact soil cores (4.8-cm inside diameter by 10 cm in length) that were subsequently dried for 48 hours at 33ºC and weighed to determine the oven-dry mass. This dry soil mass was then divided by the volume of the soil core (184 cm$^3$) to determine the bulk density (g cm$^{-3}$) of each sample.

*Statistical analyses*

As these study sites differed in the number of measurement plots created, and therefore the number of samples collected at each site, the average values of all plot replicates for each site were used as the point of comparison in this study. The average of the 0-5 cm and 5-10 cm SOC and soil TN concentration data (weighted equally) were calculated and compared to the corresponding 0-10 cm BD average site values for the development of all models in this study, as carbon crediting programs are most interested in the sequestration occurring in the upper layer of soil, which is most subject to changes in land management (Jelinski, 2007; Kucharik, 2007). All descriptive statistics including means, coefficients of variation (CV), and comparative analyses were performed using the JMP (v5.01a) software package (SAS Institute Inc., Cary, NC). All models and relationships were evaluated through regression analysis in the JMP statistical software package by fitting linear, logarithmic, second-order polynomial, power, and exponential lines of best fit. JMP was also used to calculate correlation coefficients for the models, *P* values, and perform all model diagnostics and analyses. In some cases, Box-Cox transformations were necessary to achieve normality of data.

In determining the goodness-of-prediction with the simple statistical models according to land-use category, the root mean squared error (RMSE) and a calculation of the prediction efficiency were used. A positive prediction efficiency is defined as the percentage reduction in mean squared error (MSE; sum of accuracy and precision) when using the predictive model compared to using a simpler approach that uses the average value (Mueller and Pierce, 2003). The prediction efficiency, defined by Mueller and Pierce (2003), was calculated as

$$\text{Prediction efficiency} = 100\% \times (MSE_{ave} - MSE_{prediction})\,(MSE_{ave})^{-1}.$$

As an example, if the prediction efficiency was 40% for a linear relationship relating soil organic carbon and bulk density, this indicates that the predictive model reduced the MSE by 40% over using just the average observed value for the study region.

## RESULTS

*Land-use effects on soil properties*

Table 1 was constructed to illustrate the typical range of soil chemical and physical properties that were observed throughout our study region in southern Wisconsin. The original data set of 165 sites had a range of %SOC in the top 25 cm of 0.56 to 44.1% and a range of %TN in the top 25 cm of between 0.04 to 4.1% (Table 1). Soil bulk density (0-10 cm) for all sites had an average value of 1.24 g $cm^{-3}$, ranging from a low of 0.08 g $cm^{-3}$ in 30 remnant prairie and wetland sites to 1.82 g $cm^{-3}$ in 49 cropland sites, which were dominated by corn-soybean rotations and conventional tillage practices. Remnant prairies generally exhibited the largest range in BD, %SOC, and %TN, presumably because these have never been disturbed, and are located on soils that span a larger gradient in average annual soil moisture conditions (e.g., extremely wet and seasonally flooded to much drier, upland locations) than is found across more managed sites (e.g., prairie restorations and cropland). Soil C:N ratio for the 0-25 cm layer ranged from an average of 9.7 for pastures to 13.5 for the four forested sites that were sampled (Table 1).

Averages for the land-use categories give some indication of the differences in soil chemical properties and bulk density that would be expected throughout the study region due to differing land cover and land-use practices. As expected, croplands generally had greater bulk densities and lower soil organic carbon and total soil nitrogen ($P < 0.05$) than undisturbed or restoration lands, however undisturbed and restoration lands most often had a larger range of values and variability (CV) than cropland, which was particularly true for soil bulk density. It was hypothesized that the common agricultural management practices (i.e., tillage, crop types grown, and crop rotations) in the region that have occurred for greater than 50 years have caused the inherent natural spatial heterogeneity of soil properties, particularly BD, to be minimized (Kucharik et al., 2006). The fact that remnant prairie ecosystems of the region have a considerably lower average bulk density than cropland and correspondingly greater SOC and TN suggest that many of these areas were not disturbed by the plow because they were too wet to be suitable for productive farming (Kucharik et al., 2006).

*Model development to predict soil bulk density from soil chemical properties*

A key objective of this study was to investigate whether statistical models relating soil chemical properties and soil BD could be constructed based on the extensive soil property database gathered for southern Wisconsin. Several independent studies (Prevost et al., 2004; Heuscher et al., 2005) previously determined that exponential models fit a BD – soil chemical property relationship the best. In this study, it was also determined that when using correlation coefficients to test for goodness of fit, exponential models indeed fit the BD – %SOC or %TN data better than linear, logarithmic, second-order polynomial, and power models. Therefore, the exponential model was used for all relationships in this study. For the 146 sites included in the composite model, %SOC and %TN in the 0-10 cm layer explained a large portion of the variation in 0-10 cm soil bulk density ($R^2$ = 0.90 and 0.89, respectively) and all of the relationships were highly significant ($P < 0.0001$) (Fig. 1a and 1b; Table 2).

It was also hypothesized that numerical relationships between soil chemical properties and bulk density would differ significantly due to land-use practices in the region. For sites categorized by

**Table 2.** Exponential model equations and summary statistics for models that predict 0-10 cm soil bulk density (g $cm^{-3}$) from soil organic carbon concentration (%SOC).

| Land use | n | Model | RMSE† | $R^2$ | *P*-value | RMSE‡ | Prediction efficiency (%) |
|---|---|---|---|---|---|---|---|
| All sites | 146 | $y = 1.599\ e^{-0.0767}$ | 0.158 | 0.896 | < 0.001 | 0.361 | 80.9 |
| Undisturbed | 27 | $y = 1.400\ e^{-0.0719}$ | 0.154 | 0.907 | < 0.001 | 0.465 | 89.1 |
| Restoration | 71 | $y = 1.639\ e^{-0.0857}$ | 0.141 | 0.498 | < 0.001 | 0.201 | 50.4 |
| Cropland | 48 | $y = 1.552\ e^{-0.0502}$ | 0.173 | 0.253 | < 0.001 | 0.200 | 25.3 |

†RMSE associated with predictive exponential model

‡RMSE associated with using land-use category average bulk density

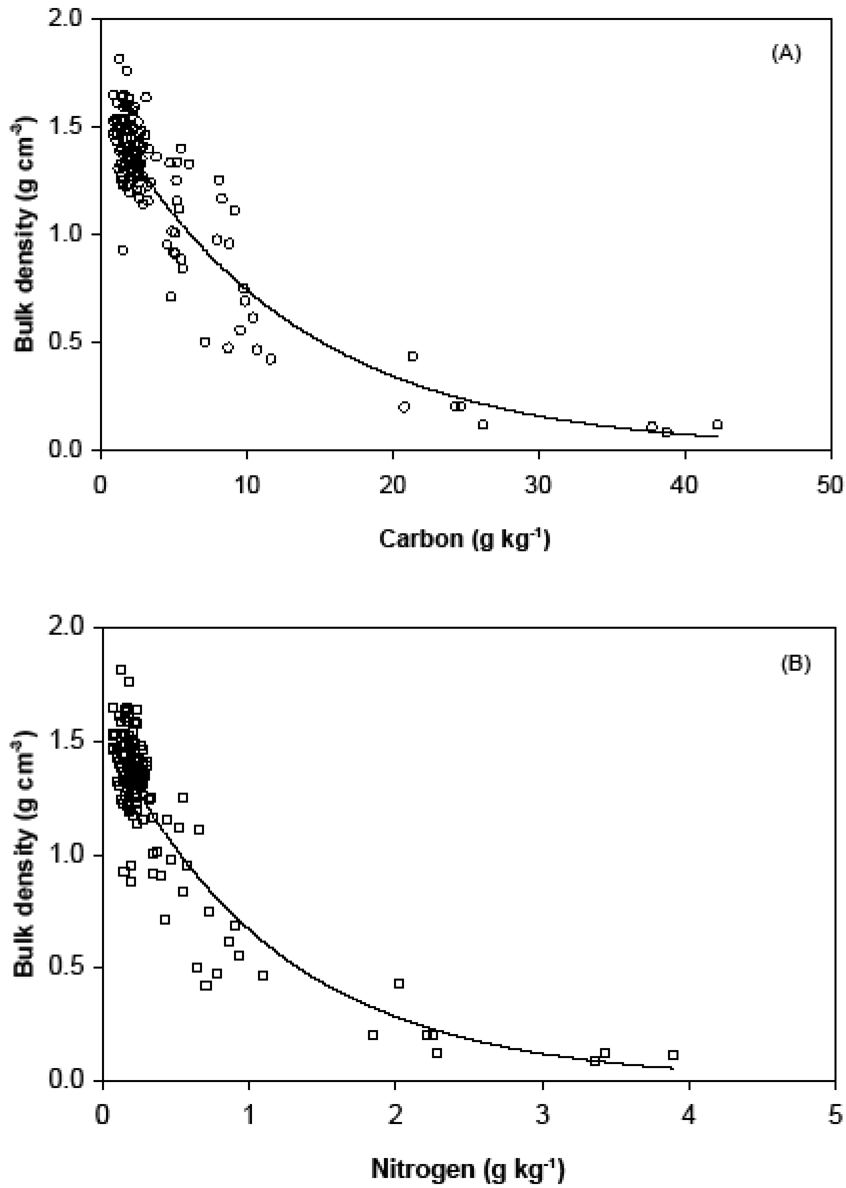


**Fig. 1.** Exponential model fit between 0-10 cm soil bulk density (g $cm^{-3}$) and 0-10 cm soil organic carbon concentration (g $kg^{-1}$; A) and 0-10 cm soil total nitrogen concentration (g $kg^{-1}$; B) for 146 field study sites in southern Wisconsin.

land-use type, the modeled relationships appeared somewhat similar to the composite model result (Fig. 2a,b), but several important trends emerged. For undisturbed sites, which represented a grouping of remnant prairie, pasture, and forest sites, predictive models of 0-10 cm BD based on %SOC and %TN explained a large percentage of the observed variation, with $R^2$ values of 0.90 and 0.89, respectively (Table 2). For prairie restoration sites, the exponential models relating %SOC and %TN to BD explained a much lower portion of the variation, with $R^2$ values of 0.50 and 0.66 for %SOC and %TN, respectively (Table 2). For cropped sites, the ability to explain variations in BD with %SOC and %TN decreased substantially, with $R^2$ values of 0.25 and 0.11, respectively (Table 2). From the results presented in Table 2 and Figures 1 and 2, it is clear that the exponential model factors differed drastically between the equation arrived at for all 146 sites compared and the equations for individual land-use groupings.

*Assessment of model trends and quality of fit*

Simple 1:1 graphs, linear regression, RMSE, and prediction efficiency were used to better understand the error in the statistical models of soil BD. Model quality of fit is reported here for %SOC, which was deemed to be the best candidate (e.g., over %TN, based on correlation coefficients) to use in the future prediction of 0-10 cm BD. The model accuracy for all 146 sites using the relationships of 0-10 cm %SOC with 0-10 cm BD (Fig. 3a) showed that the exponential models slightly over-predicted low

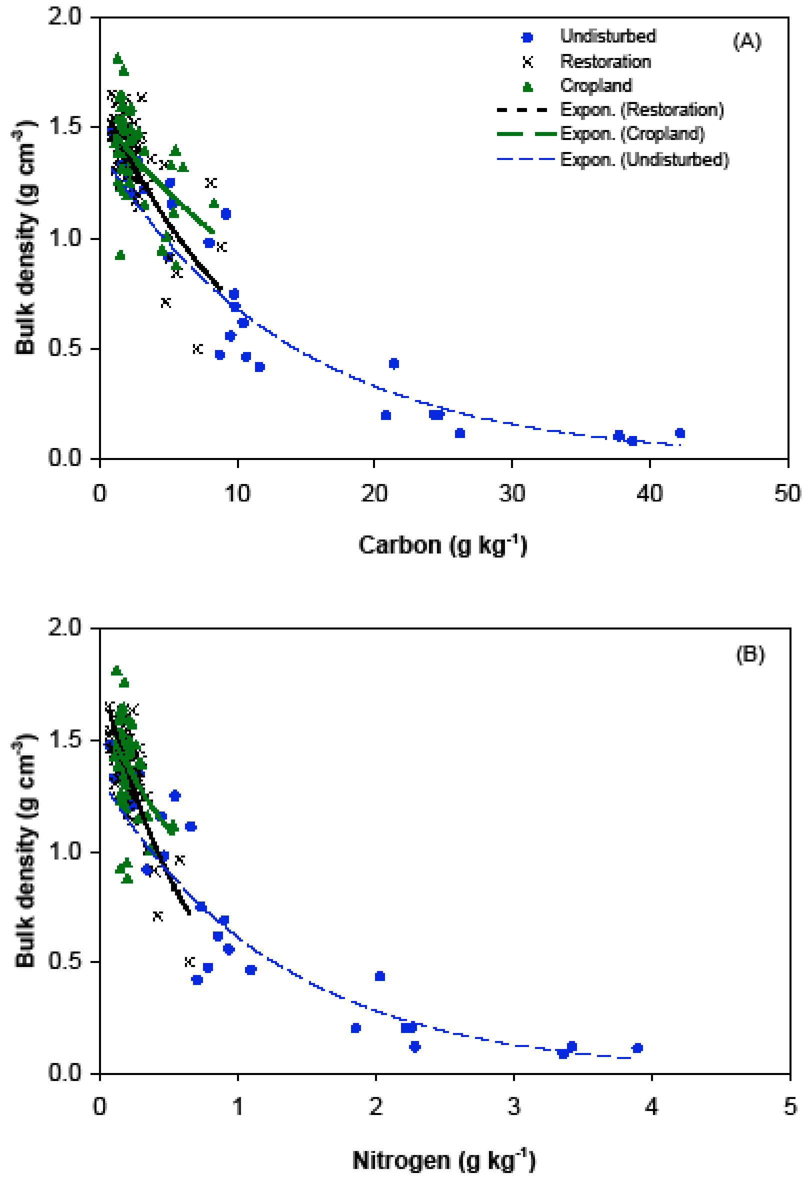


**Fig. 2.** Exponential model fit between 0-10 cm soil bulk density (g cm$^{-3}$) and 0-10 cm soil organic carbon concentration (g kg$^{-1}$; A) and 0-10 cm soil total nitrogen concentration (g kg$^{-1}$; (B) for three land-use groupings (undisturbed – remnant prairie, pasture, forest; restored prairie, and cropland) in southern Wisconsin.

 

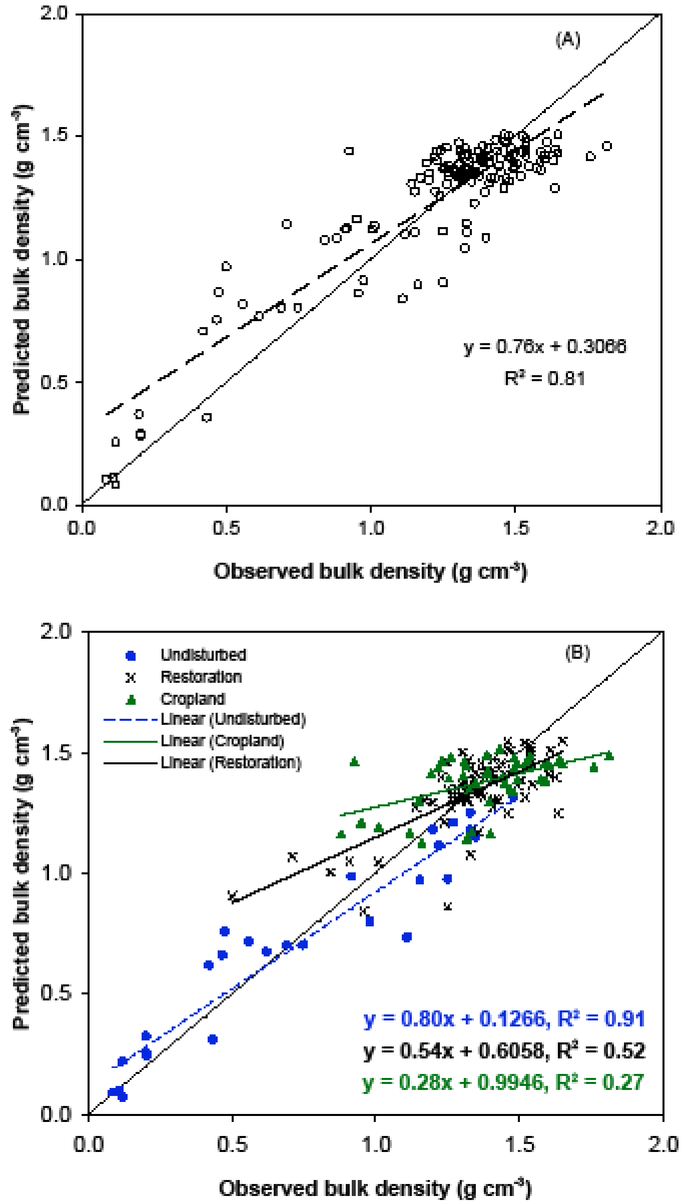


**Fig. 3.** Predicted 0-10 cm soil bulk density (g cm$^{-3}$) values from exponential model using %SOC as the predictor variable compared to observed 0-10 cm soil bulk density (g cm$^{-3}$) for all 146 sites, with corresponding 1:1 line (solid) and linear regression line (dashed) (A); predicted 0-10 cm soil bulk density (g cm$^{-3}$) values from exponential models using %SOC as the predictor variable compared to observed 0-10 cm soil bulk density (g cm$^{-3}$) for each individual land use categorization, with corresponding 1:1 line (solid) and linear regression lines (B).

BD values and slightly under-predicted large BD values (i.e., the slope of the regression was 0.76), but captured 81% of the site-to-site variability in observed BD. Model quality of fit for the separate land-use categories (Fig. 3b) showed that similar to the exponential model statistics relating %SOC and 0-10 cm BD, statistical model quality of fit for 0-10 cm soil BD was greatest for the undisturbed land, followed by the ecosystem restorations, and then cropland. The exponential model that was constructed for undisturbed land suggested that 91% of the 0-10 cm BD variability could be captured with the model based on %SOC, and also had a slope (0.8) that was closest to 1.0 compared to the other land-management categories (Fig. 3b).

Calculations of the prediction efficiency and RMSE were used to better understand model error and how predictive models could improve upon the calculation of bulk density according to land-use category compared with the alternative method of just using the study-region averages. For the exponential model fit to all bulk density data (146 sites), the RMSE was 0.158 g cm$^{-3}$, whereas the RMSE using the simple mean value was 0.361 g cm$^{-3}$. This led to a prediction efficiency of 80.9% (Table 2); therefore, the MSE was substantially reduced by using a predictive exponential model that related %SOC and BD. The RMSE for the exponential model fitting according to specific land-use categories was 0.141 for restorations, 0.154 for undisturbed lands, and 0.173 g cm$^{-3}$ for cropland, whereas the RMSE for using just the average bulk density value for each land-use category was 0.201 for restorations, 0.200 for cropland, and 0.465 g cm$^{-3}$ for undisturbed lands (Table 2). The corresponding prediction efficiencies were 25.3% for cropland, 50.4% for restorations, and 89.1% for undisturbed sites (Table 2). Thus, statistical models greatly lowered the MSE for undisturbed and restoration sites, but only led to a small improvement for cropped sites. This further suggested that there was a weak and unreliable relationship between %SOC and BD on managed lands, and that a increasing level of predictive error was associated with increasing levels of soil disturbance.

## DISCUSSION

The effectiveness of models relating soil chemical properties to BD was evaluated using soil samples collected from undisturbed lands (i.e., remnant prairie, wetlands, pasture, and forests), ecosystem restorations (i.e., prairies and grasslands as part of the CRP and other restoration efforts), and croplands across southern Wisconsin. The large range in observed soil chemical and physical properties across this relatively small region suggests that generalizations could be highly inaccurate unless the effects of specific land-use practices and varied soil textures are taken into account. While the models generally showed a strong relationship exists between %SOC and %TN and BD near the soil surface across this region regardless of land-use type, significant model differences and predictive capabilities were apparent for the various land-use categories (Fig. 2; Table 2). It was evident that the impact of various tillage practices, coupled with variations in the time of season when samples were collected in cropland soils, contributed to the significantly weaker relationship between BD and %SOC on land currently managed for crop production. As discussed by VandenBygaart et al. (2006), varied tillage practices are one of several factors that can lead to great difficulty in detecting the actual changes in soil carbon stocks and interpreting other field measurements.

The exponential model relating bulk density to %SOC for all 146 sites of combined land uses demonstrated a relatively strong relationship between carbon concentration and BD, with a relatively high $R^2$ value and a prediction efficiency of approximately 81%. When sites were separated into land-use categories for the purposes of predicting BD from %SOC, several interesting patterns were detected. As the level of disturbance increased (i.e., undisturbed to restoration to cropland), the ability to predict actual BD became less reliable when strictly considering the resulting $R^2$ values (Fig. 3b). Although highly significant, the model for cropland sites did a poor job predicting real BD values relative to the other land-use classes ($R^2$ = 0.28), and the model only reduced the MSE by 25% when compared to just using an overall average bulk density value. This is not surprising, as it might be expected that current management influences on bulk density, such as widely varying tillage practices in heavily managed lands, would mask the influence of carbon concentration variability on BD. The BD of cropped soils often fluctuates temporally, and in some cases may be completely unrelated to carbon concentration (VandenBygaart and Angers, 2006).

While variations in cropland management might make it more difficult to capture site-to-site variability, the range of observed soil BD and %SOC was significantly diminished compared to the undisturbed and restoration land-use groupings due to widespread management (Fig. 2a and 3b; Table 1). Thus, a prediction model might be presumed less likely to have large errors. However, the cropland model had the greatest RMSE (0.173) among the three specific land-use groupings (Table 2). The error attributed to using these models for specific land-use categories might be within a tolerable range, but the actual predicted value may be too uncertain for any individual cropland site to determine meaningful changes in soil carbon mass, particularly in the case when converting to conservation tillage or no-tillage practices.

## SUMMARY AND CONCLUSIONS

A model for determination of soil carbon by weight from %SOC and BD could help support more specific carbon offset credit allocation, as opposed to the current program that allocates the same number of credits (e.g., 2.47 mT $CO_2$ $ha^{-1}$ for grassland restoration in Wisconsin, or 1 and 1.5 mT $CO_2$ $ha^{-1}$ for conservation tillage) to landowners over large (e.g., statewide and greater) geographic areas, regardless of soil texture and climate (CCX, 2007). Kucharik (2007) reported that in southern Wisconsin, rates of carbon sequestration associated with the CRP declined as prairie restorations matured, with an average rate of 13 g C $m^{-2}$ $yr^{-1}$ for prairies that were 10 years in age and older. This observed rate is approximately 80% lower than is currently prescribed for grassland restorations as part of the Chicago Climate Exchange. Therefore, it is possible that in the long term, the offsets being assigned to permanent grassland plantings in southern Wisconsin will be excessively high, and could lead to a false assumption about the true availability of regional carbon offsets.

Site- or project-specific verification is time and cost prohibitive under the current program and cannot be easily generalized to larger areas, but integration with other on-going programs, such as the dairy farm nutrient management plan in Wisconsin, hold promise to assign carbon credits based on additional spatial information. A key step forward to implementing such a plan is to build reliable numerical models that relate those soil properties that are needed to track carbon mass changes, but are not always measured across large scales. It was concluded that models attempting to predict one soil property from another quantity or several others should realistically account for land-use differences and not mix varied land uses together.

The limitations in estimating BD from simple chemical properties for the purposes of evaluating changes in carbon mass – as revealed by our study – suggest several directions for future research. Expanding the regional database and separating cropland sites into varied tillage practice categories could potentially alleviate some of the issues with accurate prediction of BD from %SOC. Additionally, including soils from several other regions (e.g., more sandy and clayey soils compared to the loamy soils that are present in this particular study) exposed to slightly different climates, such as central and northern Wisconsin, may help improve understanding of these relationships and what is likely to create additional variability. In general, this type of analysis could be greatly improved by including additional types of environmental data, such as digitized elevation data, digitized soil surveys, and even remotely sensed information from satellites, to account for additional soil forming factors that influence SOC variability across regions (McBratney et al., 2000). Given increasing computing resources and application of geographic information systems in environmental research, coupling multiple sources of landscape information, particularly the factors that greatly influence SOC with statistical models and even ecosystem models, could lead to a much better understanding of the impacts of land-use practices on soil physical and chemical properties.

This type of research will be important to conduct in other regions of the U.S., as carbon-trading markets will move forward with or without a solid verification infrastructure. It is crucial that the scientific community play an active role in improving estimation and verification protocols to ensure the success of market-based trading schemes in the future.

## ACKNOWLEDGMENTS

This research was supported by a grant from Madison Gas and Electric Corp., the College of Agriculture and Life Sciences at the University of Wisconsin-Madison, and a Roy F. Weston Distinguished Fellowship to NAJ. We thank the course instructors of Biology 152 during the Fall 2007 semester at UW-Madison for additional mentoring of RMS. We extend our gratitude to the two anonymous reviewers and co-editor Kristofor R. Brye; all of these individuals provided many important suggestions for improvement of the manuscript.

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