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Innovation in Transportation

# Assessing the Potential to Sequester Carbon within State Highway Rights-of-way in New Mexico

## Phase I: Inventory of Soil Organic Carbon and Current Management Practices

Prepared by:
New Mexico Department of Transportation
Research Bureau
7500B Pan American Freeway NE
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In Cooperation with:
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# Assessing the Potential to Sequester Carbon within State Highway Rights-of-way in New Mexico

Phase I: Inventory of Soil Organic Carbon and Current Management Practices

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14. **Abstract**
A study to assess carbon sequestered in soils (soil organic carbon (SOC)) within state highway rights-of-way in New Mexico was initiated in April 2011. During October–November, 2011, we gathered soil and vegetation samples at 117 randomly located sites in 3 biomes (19 upper montane, 54 lower montane, 44 prairie) throughout areas of the state that receive ≥35 cm precipitation. Samples were obtained along 3 transects/site and in up to 4 right-of-way (ROW) zones per transect. Physical and chemical characteristics were measured from 854 soil samples. Composition, cover, and biomass were measured for vegetation within 0.5-$m^2$ quadrats, placed centrally within each zone of each transect. Environmental characteristics of each site were captured via Geographic Information Systems (GIS). Total and mean SOC were estimated to be 153,481 Mg and 57.9 Mg/ha in the Upper Montane; 204,311 Mg and 36.2 Mg/ha in the Lower Montane; and 591,822 Mg and 42.9 Mg/ha in the Prairie biomes. Relative precision for mean SOC was 7.7% across the study area and 11–12% for individual biomes. These values were within, or close to, the 10% precision required by the Chicago Climate Exchange for trading or selling carbon credits.

We developed regression models using untransformed variables ("standard model") and variables grouped via factor analysis ("factor model") to determine associations between the variables we measured and SOC. Annual precipitation, clay, litter, and grass in the managed and inflection ROW zones were associated with SOC in the standard model. In the factor model, Factor 1 (characterized by annual precipitation, elevation, Fraction of Absorbed Photosynthetically Active Radiation, and evaporation) and Factor 2 (characterized by grass/vegetation cover) explained 30% of the variance; seven factors explained 62% of the variance.

Spatial and temporal patterns of mowing and chemical spraying were analyzed using NMDOT's Highway Maintenance Management System database to determine if adjusting these management practices might contribute to carbon sequestration. Both practices were most common in the prairie districts. We identified 56 highways in which reducing the number of visits to mow to the average for the district would result in 1,893 fewer miles mowed annually (3.1% of the statewide total). We also identified 86 highways where mowing might be limited to the dormant season. We found little potential for contributing to carbon sequestration by reducing the number of passes by mowers or by limiting chemical spraying.

For the next phase of the study, we recommend testing the effects of different rates of removal of biomass and different methods to enhance growth of plants to determine which provide optimal sequestration of carbon in ROW soils. We also outline 3 steps in development of a ROW carbon offset protocol for marketing carbon credits.

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## PREFACE

New Mexico Department of Transportation (NMDOT) was selected by the Federal Highway Administration (FHWA) to determine the feasibility of maximizing carbon sequestration within state highway rights-of-way (ROW). Ecosystem Management, Inc. was contracted by NMDOT to conduct Phase 1 of this project. Primary objectives of this phase are to (1) determine carbon currently sequestered within state-highway ROWs, (2) document current ROW management practices, and (3) suggest new practices to increase sequestration of carbon.

## NOTICE



## DISCLAIMER

## Abstract

A study to assess carbon sequestered in soils (soil organic carbon (SOC)) within state highway rights-of-way in New Mexico was initiated in April 2011. During October–November, 2011, we gathered soil and vegetation samples at 117 randomly located sites in 3 biomes (19 upper montane, 54 lower montane, 44 prairie) throughout areas of the state that receive $\geq$35 cm precipitation. Samples were obtained along 3 transects/site and in up to 4 right-of-way (ROW) zones per transect. Physical and chemical characteristics were measured from 854 soil samples. Composition, cover, and biomass were measured for vegetation within 0.5-$m^2$ quadrats, placed centrally within each zone of each transect. Environmental characteristics of each site were captured via Geographic Information Systems (GIS). Total and mean SOC were estimated to be 153,481 Mg and 57.9 Mg/ha in the Upper Montane; 204,311 Mg and 36.2 Mg/ha in the Lower Montane; and 591,822 Mg and 42.9 Mg/ha in the Prairie biomes. Relative precision for mean SOC was 7.7% across the study area and 11–12% for individual biomes. These values were within, or close to, the 10% precision required by the Chicago Climate Exchange for trading or selling carbon credits.

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For the next phase of the study, we recommend testing the effects of different rates of removal of biomass and different methods to enhance growth of plants to determine which provide optimal sequestration of carbon in ROW soils. We also outline 3 steps in development of a ROW carbon offset protocol for marketing carbon credits.

## Acknowledgements

We thank D. Romig of Golder Associates for helping plan and oversee all aspects of this project; M. Avery, J. Davis, W. Plafcan, L. Platero, and J. Raaum for diligently collecting field data and assisting with lab measurements on soil and vegetation samples; M. Konen and his staff at Northern Illinois University for measuring carbon and nitrogen in samples collected during the pilot study; H. Zhang and his staff at the Oklahoma State University Forage, Water, and Soils Analysis Lab for measuring carbon and nitrogen in samples collected during the main study; J. Craig, University of New Mexico, for allowing us to dry and weigh soil and vegetation samples in his lab; S. McWilliams and G. Miller for assisting with soil analyses; R. McCullough, New Mexico Natural Heritage Program, for creating the Access© database within which we stored and analyzed data; J. Kern and his staff at Kern Statistical Services, Inc. for statistical analyses; R. Meeks and his area maintenance supervisors of District 2 and H. Sandoval and R. Garcia of District 4 for providing valuable information about the feasibility of adjusting ROW management to increase carbon sequestration; and B. Hevron, M. Tremble, M. Brooks, and S. Lee of Ecosystem Management, Inc. for editorial assistance. Funding for this project was provided by the Federal Highway Administration of the U. S. Department of Transportation and the New Mexico Department of Transportation.

## TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

# INTRODUCTION

Mitigating global climate change by reducing atmospheric carbon is one of the foremost environmental challenges of our time. Soils are the largest terrestrial reservoir of carbon (Schimel 1995) and improving their storage capabilities may contribute significantly to solving climate change. However, carbon is in constant flux with substantial amounts transferred between soils and atmosphere annually (Fig. 1). Thus, key to reducing atmospheric carbon is enhancing the ability of vegetation to transfer carbon from atmosphere to soil and the ability of soil to store (sequester) carbon for the long term. Doing so is not an easy endeavor; increases in soil organic carbon (SOC) through management of vegetation and soil have proved to be small per unit area and require several years to detect (Conant et al. 2001, Smith 2004). This is especially true in arid climates where density of SOC tends to be low (Brown et al. 2010). Therefore, any meaningful increase in SOC requires controlled management of large areas over long periods. Highway rights-of way (ROWs) fit this description. They encompass large areas subject to consistent long-term management and contain reasonably homogeneous vegetation growing on soils that remain relatively undisturbed.

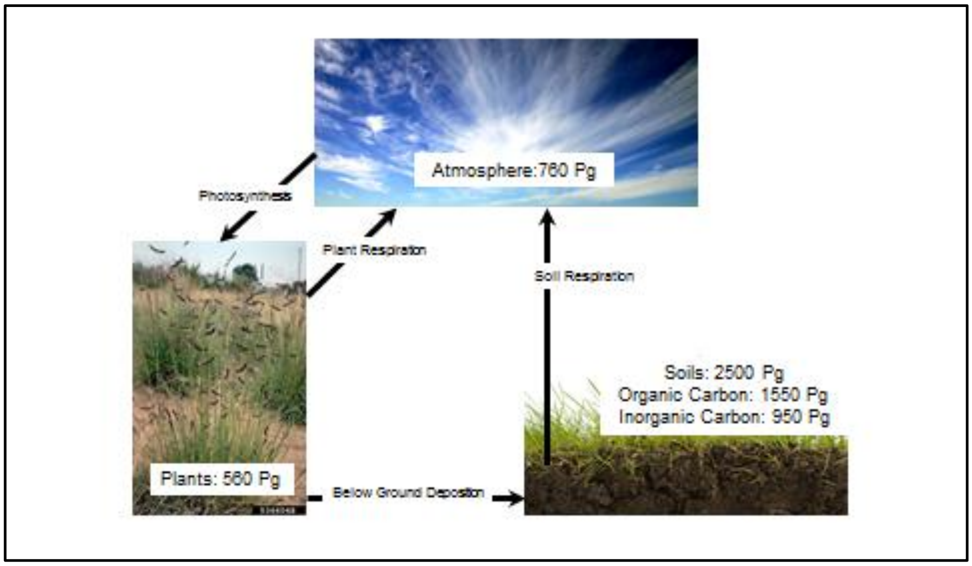



**Figure 1**. The pathways of carbon. Carbon is constantly moving among the atmosphere, vegetation, and soils. Soils are the largest terrestrial reservoir of carbon and improving their ability to store carbon is one key to solving global climate change. Petagrams (Pg) = 1 billion metric tons.

The Federal Highway Administration (FHWA) recognized the potential of ROWs to sequester carbon. Through a competitive process, New Mexico Department of Transportation (NMDOT) was the first state transportation agency chosen to development a carbonassessment protocol for ROWs and to determine what opportunities exist for management and augmentation of vegetation and soil to increase carbon sequestration. Besides mitigating global climate change, increasing SOC within ROWs could provide funding to NMDOT through sale of carbon credits within a cap-and-trade program. A two-phase study was developed by NMDOT. The focus of Phase 1 would be to measure SOC within state-highway ROWs in a scientifically defensible manner, document current ROW management practices, and suggest new practices that might increase sequestration. Phase 2 would consist of implementing new management practices, documenting resulting changes in SOC, and completing steps to market carbon credits.

In spring 2011, Ecosystem Management, Inc. (EMI) was awarded a contract to conduct Phase 1. Here we report on the results of work accomplished by EMI and subcontractors Golder Associates and Kern Statistical Services, Inc. Specifically, this work included (1) measuring SOC at randomly selected sites and using the resulting data to estimate SOC for all state highway ROWs; (2) determining if our estimates of SOC met the precision requirements of the Chicago Climate Exchange (CCX) for obtaining carbon credits[1] and, if not, determining how we could do so; (3) developing a clear, easily interpretable regression model that shows realistic relationships between SOC and related environmental and physical variables; and (4) analyzing current ROW management practices and the potential contribution of adjusting these practices to sequester carbon.

## METHODS

### Inventory of SOC

Our approach to determining SOC within state-highway ROWs was to conduct extensive sampling of soil and vegetation at a large number of randomly selected sites, thereby providing a strong foundation for statistical analysis. Doing this also allowed us to capture the range of variability in SOC caused by a wide variety of natural and anthropogenic processes that cross four spatiotemporal scales: (1) Regional—elevation gradients and regional physiography affecting temperature and moisture regimes; (2) Landscape—local geologic materials, depositional environments, and landforms affecting composition and textural variation of soil parent materials and distribution of native plant communities; (3) Site—longitudinally and lateral variations within a ROW affecting soil composition and vegetation type (Box 1); and (4) Point—within-sample variation caused by horizontal and vertical spatial heterogeneity of soil organic carbon, surface litter, and vegetation.

The study area encompassed all state-highway ROWs where annual precipitation exceeds 35 cm (13.8 inches), which is near the lower limit of precipitation for rangelands recommended

[1] SOC must be estimated to within 10% relative error with 90% level of confidence.

for carbon credits (Brown et al. 2009) (Fig. 2). We defined our study area by this criterion because New Mexico ROWs generally are dominated by grasses and herbaceous vegetation, making them most similar to rangelands. Additionally, low amounts of carbon and high variability of sequestration rates in climates drier than 35 cm renders it extremely difficult to detect changes in SOC with precision acceptable to carbon-trading markets. Selection of sites for data collection was random, but stratified by biome—upper montane, lower montane, and prairie[2]. Stratification served to improve precision of the state-wide estimate by isolating and reducing the effect of between-stratum variation (Cochran 1977). The combined estimate

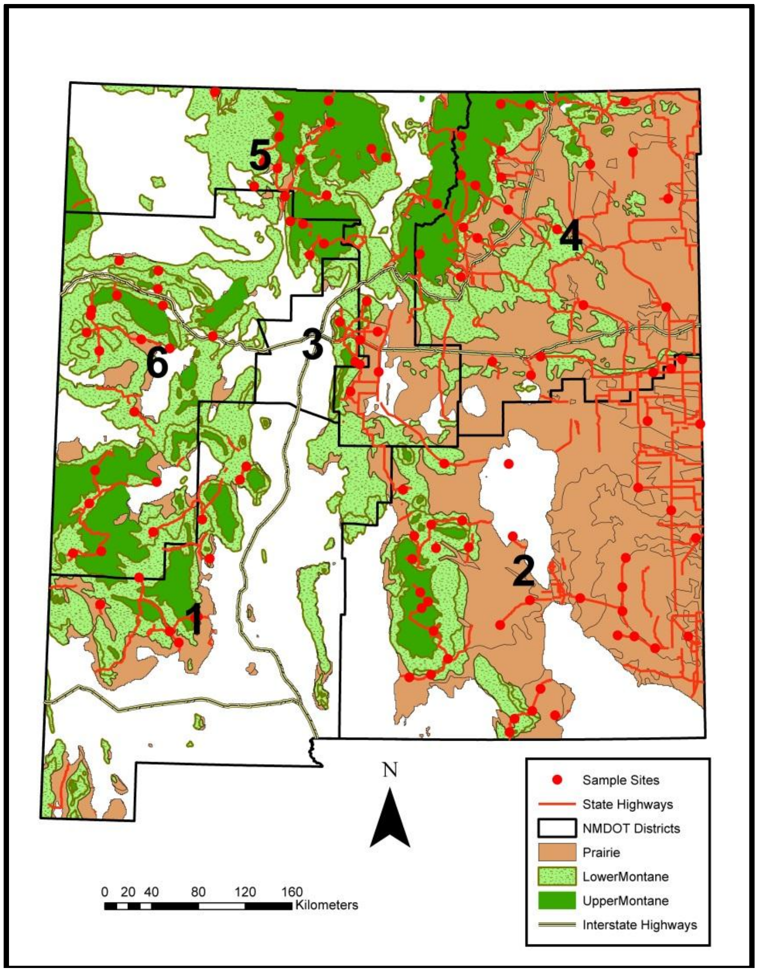



**Figure 2**. The study area and sites (red dots) in New Mexico where soils and vegetation were sampled during October–November 2011 to determine soil organic carbon (SOC) within state-highway ROWs. Number of sites by biome: Upper Montane 19; Lower Montane 54; Prairie 44. Large black numerals are NMDOT administrative district labels.

2 Stratification was based on GAP Analysis Vegetation types (http://gapanalysis.usgs.gov/). Upper Montane: Subalpine grassland, mixed conifer forest, ponderosa pine woodland, madrean pine–oak woodland. Lower montane: Pinyon–Juniper woodland, Juniper Savannah, montane shrubland, Intermountain shrub steppe; Prairie: shortgrass prairie, semi-desert grassland steppe, mesquite scrub, creosote scrub.

based on the three groups would be more precise than if between-stratum variability was ignored (i.e., analyzing all samples as one group).

**Field Data Collection**

In early summer 2011, we conducted a pilot study to determine sample sizes that would provide the precision required by CCX for obtaining carbon credits and the design that would best address within-site variability. Data were collected at 10 sites each in the montane (we did not differentiate between upper and lower montane) and prairie biomes. Sites were selected by randomly generating UTM coordinates and using ArcGIS 9.3.1© (Environment Studies Resources Institute, Redlands, CA) to mark the nearest point along eligible state highways. In the field, sites were positioned at the next milepost beyond the UTM coordinate in the direction of travel where at least 100 m of ROW was relatively homogeneous. We recorded location of each site (UTM coordinates via Global Positioning System (GPS; Garmin, Inc. Olathe, KS) as well as slope and aspect of the road.

Three transects were placed 25 m apart from each other, perpendicular to the road, extending the width of the ROW; the first transect was placed 5 m past the milepost. Along each transect, a square quadrat (0.5 $m^2$) was placed at the center of each of up to four ROW zones (Box 1), within which we estimated areal cover (%) of plant species, litter, rock, and bare ground. These zones were delineated to reflect differences in disturbance because of road construction and subsequent maintenance activities. Disturbances during road construction ranged from none (Natural Zone) to complete (Managed Zone). Complete disturbance was characterized by total removal, mixing and homogenization of soil layers, as well as complete removal of vegetation; subsequent annual maintenance may have included mowing, chemical spraying, snow plowing, and drainage clearing.

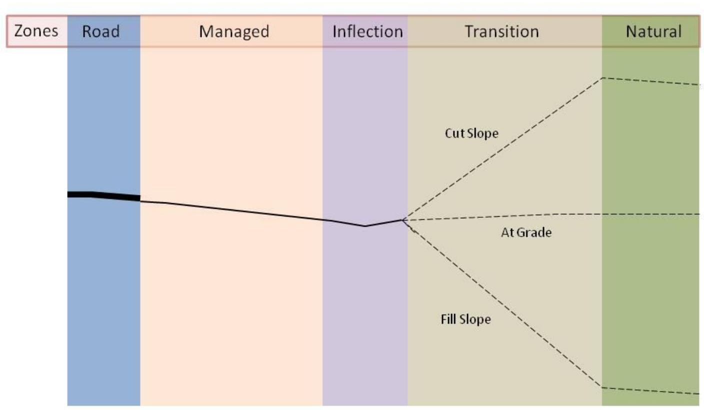
We measured width and slope of each zone. Soil samples were collected within or immediately adjacent to each quadrat, but we avoided sampling where road asphalt was mixed in the soil. We used a handheld auger to collect two 20-cm-deep soil samples for determining carbon and nitrogen content (hereafter “SOC samples”). Deeper samples have been collected elsewhere, but > 80% of SOC occurs in the upper 20 cm—even in old growth coniferous forests (Conant et al. 2001, Conant et al. 2003)—almost all root biomass occurs from 0–20 cm in arid grasslands (Derner et al. 2006), and data collected from 0–20 cm is commonly used to model SOC dynamics (Ogle et al. 2007). The amount of carbon in these samples is based on weight (g-carbon/kg-soil), which does not allow comparison among samples because density can vary greatly with soil type. To enable comparison among samples, another soil sample was collected by driving a 10 x 25-cm cylindrical sleeve into the ground and collecting the soil captured within it (core method), or by excavating soil from a hole and filling the hole with a measured amount of sand (excavation method)

## Box 1. Conceptual Model of Highway Rights-of-Ways

A cross-section of a typical highway ROW is not homogeneous, but varies due to both natural and anthropogenic processes. Each transect we sampled crossed up to four zones:

1. Managed Zone—Immediately adjacent to the pavement and either level or sloping away from the road. In that it is an extension of the road shoulder, there is potential for soils to be compacted and interspersed with substantial amounts of asphalt. These areas are also affected by operation and maintenance activities including mowing, grading, herbicides (all of which serve to maintain vegetation in a low-successional state) and possible contamination from petroleum products and/or road salts. However, this zone may support very productive vegetation due to additional moisture provided by runoff from the road.
2. Inflection Zone—Characterized by a change in slope, although the inflection may be very minor. This zone may hold water or convey it away from the ROW into a natural drainage, particularly in areas below a cut slope. Adjacent to fill slopes, the inflection transitions to an embankment outslope. Management activities in this zone are infrequent, but sediment removal to clear drainage channels can be destructive to vegetation. If left undisturbed, the increase in soil moisture can make this zone very productive with the potential to add significant amounts of carbon to soils.
3. Transition Zone—Initially disturbed during road construction, but lack of subsequent disturbance allows vegetation to return to a natural composition of species. This zone can be a cut slope, an embankment (fill) slope, or a more level grade. We view this zone, particularly on gentle slopes, as an experimental control relative to management of other zones closer to the road.
4. Natural Zone—On the periphery of the ROW near the boundary fence and not impacted by road construction or ROW maintenance. These zones have potential to represent the overall site potential to store SOC.

**ROW Cross Section**
**Conceptual Site Model**



(National Soil Survey Handbook: http://soils.usda.gov/ technical/handbook/). Bulk density ($g\text{-}cm^{-3}$) was then measured from these samples. Large amounts of rock fragments, as was found in the soils we collected, can introduce substantial error in bulk density measurements (Saxton et al, 1986, Saxton and Rawls 2006). To rectify this, we used the Soil Water Characteristics model (Saxton and Rawls 2006; hydrolab.arsusda.gov/soilwater/Index.htm), which corrects for particle size distribution (texture) and gravimetric rock content.

We conducted the main field study during October–November, 2011. This period is when herbaceous vegetation has lapsed into senescence but oxidation has not caused significant loss of biomass; additionally, most management of vegetation along ROWs has ceased. Sites were selected as described above, and the number selected was based on analysis of SOC variance found in the pilot study. We also used the same methods to sample soils except only one sample was collected in each zone for SOC analysis.

We estimated areal cover within each quadrat as described above as well as above-ground biomass (g) of three types of herbaceous material: grass, forbs, and litter (defined as all herbaceous material). In one randomly selected quadrat per transect, all aboveground herbaceous material was collected and weighed (green weight (g)) by type.

**Laboratory Analyses**

Samples used to determine physical characteristics of soils were weighed, dried at $105^{o}$ C for 24 hours, if needed, passed through a grinder to break up indurated peds, and then through a #10 sieve to separate fine (< 2 mm) and coarse materials. Each type of material was weighed; the difference in their combined weight and the weight of the sample before drying was the amount of soil moisture. Soil color was determined by comparing a moist subsample of fine material with a Munsell color chart to estimate color, hue, and chroma; darker shades indicate higher levels of carbon (Konen et al. 2003, Wills et al. 2007). Proportions of sand and clay were estimated by the bolus method, that is, feeling the texture and observing the adherence of moistened soil (Schoeneberger et al., 2002). Estimates were made by two soil scientists, each with > 20 years of experience employing this method. Classification of texture (sandy loam, silty, clay, etc.) was based on proportions of sand, silt, and clay. Relative presence of carbonates was indicated by effervescence (none, slight, strong, violent) resulting from adding a drop of 10% HCl to subsamples.

We thoroughly mixed the fine material of each SOC sample and sent 100 g to the Soil, Water, and Forage Analytical Lab at Oklahoma State University for measurement of carbon and nitrogen. A 0.5-g subsample was burned at $1000^{o}$ C in a LECO CN2000 furnace (LECO Corp., St. Joseph, MI). Following Rabenhorst (1988), a second 0.5-g subsample was burned at $575^{o}$ C. The purpose of the first ignition was to measure total carbon and nitrogen, whereas the purpose of the second ignition was to measure organic carbon. Inorganic carbon was the difference between total and organic carbon. Detection and reporting limits were 0.02 and 0.1%, respectively (H. Zhang, Oklahoma State University, personal communication). All measures were normalized by density of the soil samples (bulk density) from which they were derived.

All herbaceous material harvested from within the quadrats was dried at $60^{o}$ C for 24 hours and then weighed. Biomass of vegetation was converted to g-carbon- $m^{-2}$ assuming a biomass carbon content of 50% (Anderson-Teixeira et al. 2011).

**GIS Data**

We obtained environmental characteristics of each site via ArcGIS 9.3.1© by intersecting a shapefile of sites with shapefiles or rasters of annual precipitation (cm) (http://www.prism.oregonstate.edu), the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), a unitless measure of the amount of radiation within the 0.4–0.7-nm spectral range is absorbed by vegetation, potential evapotranspiration (cm-$yr^{-1}$) (http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php), and elevation (m) (http://ned.usgs.gov/ned/).

**Inventory of Current and Examination of New Management Practices**

We obtained data from the NMDOT Highway Maintenance Management System (HMMS) digital database for 1998–2011 and extracted records for widespread (not localized or "spot") mowing and chemical spraying along highways that occurred within the study area. We limited analysis to these two activities because both affect the ability of vegetation to capture carbon and occur over large areas. In each record of HMMS, beginning and ending highway mileposts designated each activity's geographic extent, which often varied among years. We standardized measures for all highways and years by summing the number of HMMS records by activity and year of occurrence at each highway milepost within the study area. This resulted in the number of visits made to each milepost annually for either mowing or spraying. We then calculated the number of passes by dividing the total miles in each record by the difference between the beginning and ending mileposts. Finally, we categorized visits by mowers into periods when warm-season grasses were actively growing (July–September) or were dormant (March–June, October–December).

We investigated new, and adjustments to current, management practices that would be applicable over large areas (>1000 ha), effective for long periods ($\geq$1 decade), and that might increase the ability of ROW vegetation to capture atmospheric carbon and convert it to SOC. The investigation included an extensive literature review, consultation with restoration and plant ecologists and NMDOT construction and maintenance staff. As part of this effort, we met with maintenance supervisors in two of six NMDOT administrative districts (Fig. 3).

We focused on Districts 2 and 4 because they contain the most ROWs and because we want to concentrate most experimentation with new treatments in the Prairie biome where environmental homogeneity likely reduces the effect of potential confounding factors such as changes in topography and vegetation.

**Statistical Analyses**

Statistical significance to determine differences SOC among biomes and zones was $\alpha = 0.1$ to match CCX precision requirements. Statistical significance for all other analyses was $\alpha = 0.05$. Randomly selected sites served as the primary experimental units, each contributing one degree of freedom to statistical analyses. Values collected along transects within sites were averaged by zone prior to statistical analyses. These replicate subsamples ($n$ = 3/zone/site) served to improve precision of SOC estimates. Arithmetic and geometric means of SOC and ROW width were calculated using well-known formulas for analyzing stratified random samples (Cochran 1977; Appendix A). Total SOC was the product of average SOC and average ROW width; estimation of the variance was based on formulas for products of random variables (Goodman 1960). Confidence intervals were based on the assumption that the product of SOC and ROW width was normally distributed. The relative precision of the estimate was defined to be the confidence interval half-width divided by the SOC estimate.

A nested analysis of variance (ANOVA) was used to test for differences in log (SOC) among biomes and zones within biomes. Estimated means and confidence intervals were plotted graphically, and non-overlapping confidence intervals were indicative of differences between pairs of biomes and zones. We used a two-way ANOVA to determine differences in rock cover among biomes and zones.

We used environmental and physical characteristics measured in the field and via GIS to develop regression models that would (1) determine mechanisms governing SOC, (2) improve the precision of SOC estimates, and (3) provide a tool to predict SOC based on values of associated variables. Predicting SOC using regression coefficients that represent statistically significant associations between variables and SOC can be markedly more cost-effective than relying solely on physical measurements. We used a mixed-effects linear model (PROC MIXED; SAS Institute Inc.) for all regression analyses, which allows for adjustment of the degrees of freedom and standard errors (Littell et al. 1996). Although each sample site was considered a primary experimental unit, some variables used for modeling varied among quadrats within sites (e.g., vegetation cover, percent clay), necessitating analysis at the quadrat level. This can be problematic in that it represents a form of pseudoreplication (Hurlbert 1984), which will result in inflated degrees of freedom, and in turn, a higher probability of Type I error rates (Cochran 1977). In our mixed-effects linear models, measurements on each quadrat were treated as repeated measures to account for this dependence.

We initiated our modeling using untransformed variables that, based on previous research (Conant et al. 2001, Derner et al. 2006, Anderson-Teixera 2011), we hypothesized would be strongly associated with SOC. These included biome, zone, elevation, annual precipitation, nitrogen, percent clay, biomass of grass (dry wt.-g) and litter (dry wt.-g). The resulting model (hereafter "standard model") provided a preliminary indication of the strength of associations between variables and log (SOC).

A foundational requirement of multiple regression analysis is that predictor variables need to be statistically independent. In the above model, dependence among variables was avoided by eliminating one variable of each correlated pair. However, this precludes discovery of relationships between partially redundant predictors (e.g., precipitation and elevation) and SOC. To address this, we employed factor analysis (Johnson and Wichern 2007) in which independent factors are derived, each containing a set of correlated predictor variables with common variances. We began by developing a correlation matrix of all variables and deriving Eigenvalues from it, which explained how much variance in the model was explained by each factor. The contribution of each predictor variable to the eigenvalue is termed a factor loading. These range from −1 to +1 and are considered statistically meaningful if they exceed ± 0.4 (Stevens 2009). Once derived, factors, instead of the predictor variables themselves, were incorporated into a regression analysis (hereafter "factor model").

For both the standard and factor model, we used Conditional Test Significance to measure the significance of each log (SOC)–variable relationship accounting for the presence of other variables in the model (Neter et al. 1996):

$$CTS = \frac{SS_{Reduced} - SS_{Full}}{SS_{Residual}} \qquad [1]$$

where *CTS* is the conditional test significance, $SS_{Reduced}$ is the sum of squares of the model using all variables except the one of interest, $SS_{Full}$ is the sum of squares for the model in which all variablevariables are used, $SS_{Residual}$ is the residual sum of squares. For classification variables such as biome, all levels of the variable were used in the full model and all were excluded in the reduced model.

We used regression coefficients and 95% confidence intervals around them from the standard model to predict the amount of change in SOC that would be produced by a change in associate variables as follows:

$$\Delta SOC = (e^{\Delta c \times \beta} - 1) \times 100 \qquad [2]$$

where $\Delta SOC$ is the change in SOC expressed as a percent and $\Delta C \times \beta$ is the change in the selected variable multiplied by its regression coefficient. For example, if $\beta$ for biomass of grass (dry wt.-g) is 0.005 and $\Delta C$ is 10 (an increase of 10 g per 0.5 $m^2$ (the size of the quadrat from which herbaceous biomass was measured in this study) ), $\Delta soc$ would equate to a 5% increase in the amount of carbon sequestered.

For analysis of mowing and chemical spraying, we grouped visits and passes by highway and district and calculated means, standard deviations, and 95% confidence intervals. We then identified highways in which the mean number of visits or passes per year was $\geq$ 0.5 greater than the mean number of visits or passes for all highways within the district in which the highway occurred. We considered these as candidates in which mowing or spraying might be reduced by at least one visit or pass per season. We multiplied the potential reduction in visits or passes by the length of the highway to determine the reduction in miles mowed annually. Finally, we identified highways in which the number of visits by mowers during the active growing period for warm-season grasses was $\leq$ 1. We considered these as candidates in which mowing might be limited to the dormant period.

## RESULTS

### Inventory of SOC

We found substantial variance in SOC among sites during the pilot study. Montane sites were more variable than Prairie sites, and SOC generally was higher in Upper versus Lower Montane sites (Fig. 3). Variance in SOC increased up to 40% when transects/site were reduced from three to two, but < 10% if soil samples/quadrat were reduced from two to one. Thus, for the main study, we sampled three transects/site and collected one SOC and one bulk-density sample at each quadrat. Sample sizes to meet the CCX precision requirements were predicted to be 132 and 40 sites in the Montane, and Prairie biomes, respectively. Estimates also were derived for a three-biome stratification (Prairie 90, Upper Montane 71, Lower Montane 161) but were considered less reliable because the small sample of sites in each biome resulted in substantial variance in the data.

During the main study, we visited 73 Montane (19 Upper, 54 Lower) and 44 Prairie sites (55 and 110% of the number of needed sites estimated in the pilot study, respectively) located along 7,700 km of state highways. Measured ROW widths at sample sites multiplied by the length of state highways equated to 22,557 ha (95% CI = 20,510–24,604 ha) that potentially could be managed for sequestration of carbon. The proportion of state highways within each biome did not differ from the proportion of each biome within the study area ($\chi^2_{3,3} = 0.0032$, $p = 0.99$) (Table 1). Annual precipitation was highest in the Upper Montane biome and equivalent between Lower Montane and Prairie biomes. Evaporation was equal among biomes, but the Prairie biome had the highest mean value. Net primary production in the Upper Montane biome was approximately double that of values for the Lower Montane and Prairie biomes.

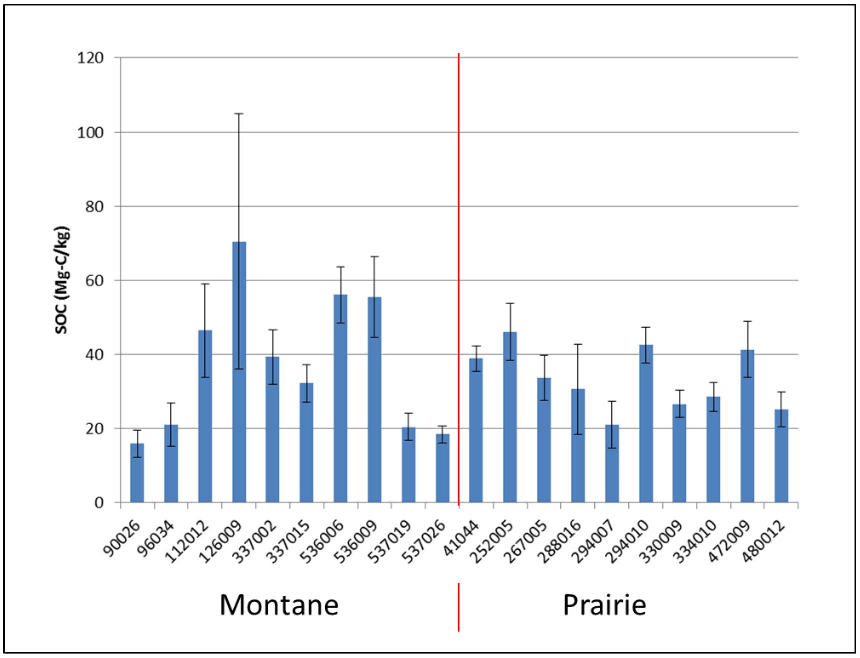



**Figure 3**. Values of SOC at individual sites in Montane and Prairie biomes that were sampled during the pilot study. Bars are mean values; vertical lines are 95% confidence intervals. Lower montane sites were 90026, 96034, 337015, 537019, and 537026.

**Table 1**. Characteristics of 117 sites within 3 biomes sampled during October and November, 2011, to measure soil organic carbon (SOC) within state highway rights-of-way (ROW) in New Mexico. Values for potentially manageable ROW, elevation, annual precipitation, potential evapotranspiration (PET), and net primary production are means with 95% confidence intervals in parentheses. Area of Potentially Manageable ROW was calculated using double (for both sides of highways) the mean ROW width measured at sites within each biome. Number of sites by biome: Upper Montane 19; Lower Montane 54; Prairie 44.

| Variable | Upper Montane | Lower Montane | Prairie |
|---|---|---|---|
| Length of state highways (km) | 894 | 2,109 | 4,697 |
| Potentially Manageable ROW (ha) | 2,646 (± 268) | 5,820 (± 464) | 14,091 (± 1,315) |
| Elevation (m) | 2,408 (± 91.0) | 2,046 (± 60.4) | 1,509 (± 89.3) |
| Annual Precipitation (cm) | 58.1 (± 5.2) | 41.6 (± 2.0) | 41.9 (± 1.3) |
| PET (cm) | 186.4 (± 208) | 185.4 (± 124) | 216.5 (± 83) |
| Net Primary Production (Mg-C/ha) | 83,620 (± 7,320) | 48,210 (± 3,830) | 40,180 (± 1,820) |

We sampled soil and vegetation at 845 quadrats (141 Upper Montane, 405 Lower Montane, 299 Prairie) within the 117 sites (Appendices B and C). Total SOC within all ROWs was estimated to be 950,677 Mg (SD 57,891 Mg); this included 153,481 Mg in the Upper Montane, 204,311 Mg in the Lower Montane, and 591,822 Mg in the Prairie biomes. Mean SOC within all ROWs was estimated to be 42 Mg-C/Ha (95% CI = 39–45); values were higher in the Upper Montane than Lower Montane or Prairie biomes (Fig. 4a). Values of SOC were equal for most pairs of zones (Fig. 4b). However, Managed, Transition, and Natural zones of the Upper Montane and the Managed zone of the Prairie biomes contained more SOC than most other zones (Table 2). Relative precision was 10% for total SOC and 7.7% for mean SOC/ha across the study area, 11–12% for mean SOC/ha for individual biomes, and 18.9% (range = 11.5–25.6%) for mean SOC/ha for individual zones (Appendix C).

**The Regression Models**

In the standard model, log (SOC) was positively associated with annual precipitation (cm), grass (dry wt-g) in the managed and inflection zones, litter (dry wt-g), and clay (%) (Appendix D; Table 3). Based on the regression coefficients, a 10 g-m$^{-2}$ increase in the biomass of grass (dry wt.-g) would be predicted to result in a 4.4% (95% CI: 0.5-8.5%) and a 6% (95% CI: 0-12%) increase in SOC in the Managed and Inflection zones, respectively (Table 3)[3,4]. An equivalent increase in litter would result only in 1% (95% CI: 0.3-0.1.5%) increase in SOC[5].

In the factor regression model, no single factor explained a large proportion of variance among the variables; eigenvalues from ten factors were required to explain 80% of the total variance (Fig. 6a). However, the rate of decline between successive eigenvalues diminished noticeably after Factor 7 (Fig. 6b); thus, we focused on associations identified by the first seven factors. These included (1) Factor 1—precipitation/elevation/FAPAR/evaporation; Factor 2—vegetative and grass cover; Factor 3—litter; Factor 4—soil color (i.e., value and chroma)[6]; Factor 5—rock cover; Factor 6—forbs (i.e., forb/grass richness, forb dry wt.); and Factor 7—clay and nitrogen (Table 4). Eigenvalues for Factors 1 and 2 contributed substantially more than other factors (68% and 39% higher than Factor 3, respectively) in explaining the variance of the dataset. In the regression model, grass and vegetative cover (Factor 2) had the strongest positive association with log (SOC), followed by precipitation

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[3] $\Delta SOC = (exp(10g \times 0.0044) - 1) \times 100 = 4.4\%$

[4] This would equate to approximately a 20 and 27% increase in biomass of grass in the Managed and Inflection zones. However, these estimates should be viewed with caution insofar they are based on data collected when annual precipitation in New Mexico varied from 30-70% of normal.

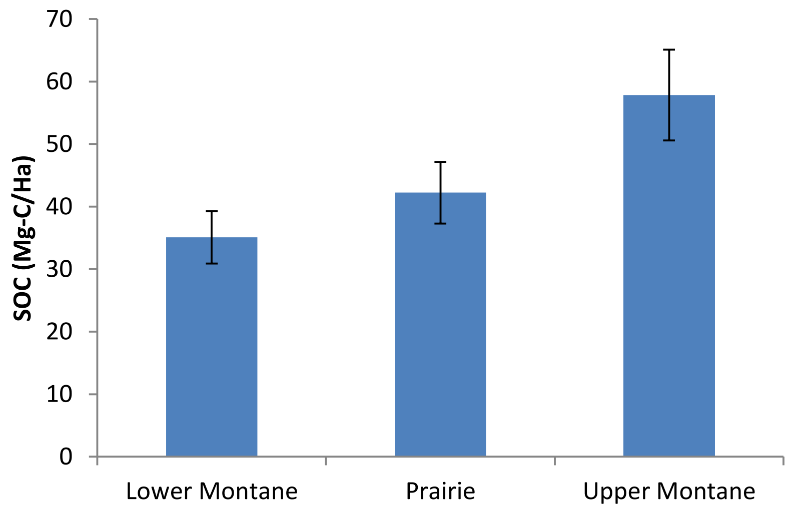
[5] This would equate to approximately 16 % increase in biomass of litter.

[6] Higher values equate to lower amounts of carbon (Konen et al. 2003)

(Factor 1) (Table 5). The association between log (SOC) and soil color was strongly negative; log (SOC) and forbs (Factor 6) were not associated.

We investigated the association between rock cover and log (SOC) further because a clear ecological relationship was not evident. Differences in rock cover were found among biomes, zones, and biomes x zones (Biomes: $F_{2,847} = 6.6$, $P = 0.0015$; Zones: $F_{3,847} = 10.5$, $P < 0.001$; Biomes x Zone: $F_{6,847} = 2.1$; $P = 0.05$). Based on 95% confidence intervals, rock cover in the Managed zones of the Upper and Lower Montane biomes were equal to each other and higher than all other zones.

a




b

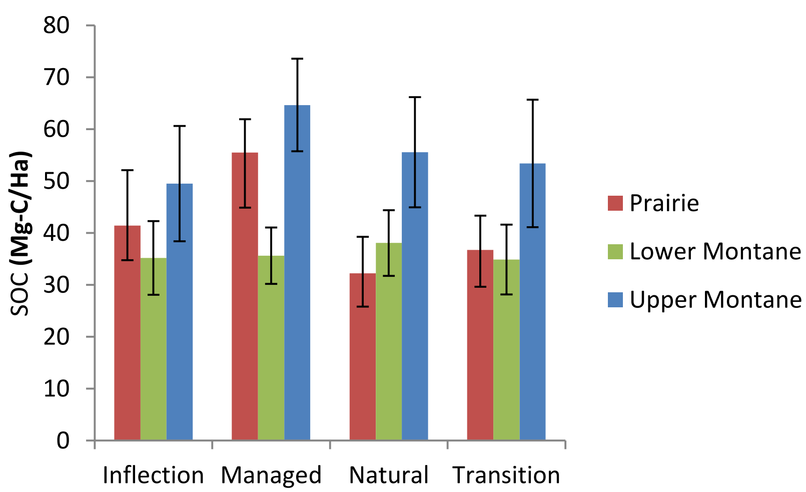



**Figure 4**. Soil Organic Carbon (SOC) found within (a) 3 biomes and (b) 4 right-of-way (ROW) zones along state highways in New Mexico, October–November, 2011. Bars are mean values; vertical lines are 90% confidence intervals.

**Table 2**. Pair-wise relationships in soil organic carbon (SOC) values among right-of-way zones within three biomes and four zones sampled along state highways in New Mexico, October–November 2011. Relationships show how zones in the left column compare to each zone in the upper row (e.g., Upper Montane-managed > Lower Montane managed; Lower Montane managed < Prairie managed).

| Biome | Zone | Upper Montane | | | | Lower Montane | | | | Prairie | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Managed | Inflection | Transition | Natural | Managed | Inflection | Transition | Natural | Managed | Inflection | Transition | Natural |
| Upper Montane | Managed | | = | = | = | > | > | > | > | = | > | > | > |
| | Inflection | | | = | = | = | = | = | = | = | = | = | = |
| | Transition | | | | = | > | = | > | = | = | = | = | > |
| | Natural | | | | | > | > | > | > | = | = | > | > |
| Lower Montane | Managed | | | | | | = | = | = | < | = | = | = |
| | Inflection | | | | | | | = | = | < | = | = | = |
| | Transition | | | | | | | | = | < | = | = | = |
| | Natural | | | | | | | | | < | = | = | = |
| Prairie | Managed | | | | | | | | | | = | > | > |
| | Inflection | | | | | | | | | | | = | = |
| | Transition | | | | | | | | | | | | = |
| | Natural | | | | | | | | | | | | |

**Table 3**. Standard regression model to determine associations of untransformed variables with log (SOC). Data were collected October–November 2011 at 117 random sites within state-highway ROWs in New Mexico.

| Effect | Category | Regression Coefficient | Lower 95% CI | Upper 95% CI | Standard Error | DF | t Value | Pr > \|t\| | Conditional Test Significance |
|---|---|---|---|---|---|---|---|---|---|
| Intercept | | 2 | 1.62 | 2.38 | 0.1929 | 261 | 10.36 | <0.0001 | NA |
| Annual Precipitation | | 0.03 | 0.02 | 0.03 | 0.0037 | 261 | 7.16 | <0.0001 | <0.0001 |
| Clay (%) | | 0.01 | 0 | 0.02 | 0.0031 | 93 | 3.45 | 0.0009 | 0.0009 |
| Grass (dry wt-g) | | −0.0003 | -0.003 | 0.0024 | 0.0014 | 93 | −0.21 | 0.8365 | 0.0146 |
| Litter (dry wt-g) | | 0.0009 | 0.0003 | 0.0015 | 0.0003 | 93 | 2.96 | 0.0039 | 0.0039 |
| Grass (dry wt-g) *Zone | Inflection | 0.0058 | -0.0001 | 0.0117 | 0.003 | 93 | 1.95 | 0.0544 | |
| | Managed | 0.0044 | 0.0005 | 0.0083 | 0.002 | 93 | 2.16 | 0.0331 | 0.0605 |
| | Natural | 0.0005 | -0.0038 | 0.0048 | 0.0022 | 93 | 0.20 | 0.8388 | |
| | Transition | 0 | 0 | 0 | . | . | . | . | |
| Zone | Inflection | −0.13 | -0.4 | 0.15 | 0.1385 | 261 | −0.91 | 0.3642 | 0.6283 |
| | Managed | −0.02 | -0.25 | 0.2 | 0.1144 | 261 | −0.19 | 0.852 | |
| | Natural | −0.13 | -0.38 | 0.11 | 0.1201 | 261 | −1.06 | 0.2892 | |
| | Transition | 0 | | 0 | . | . | . | . | |

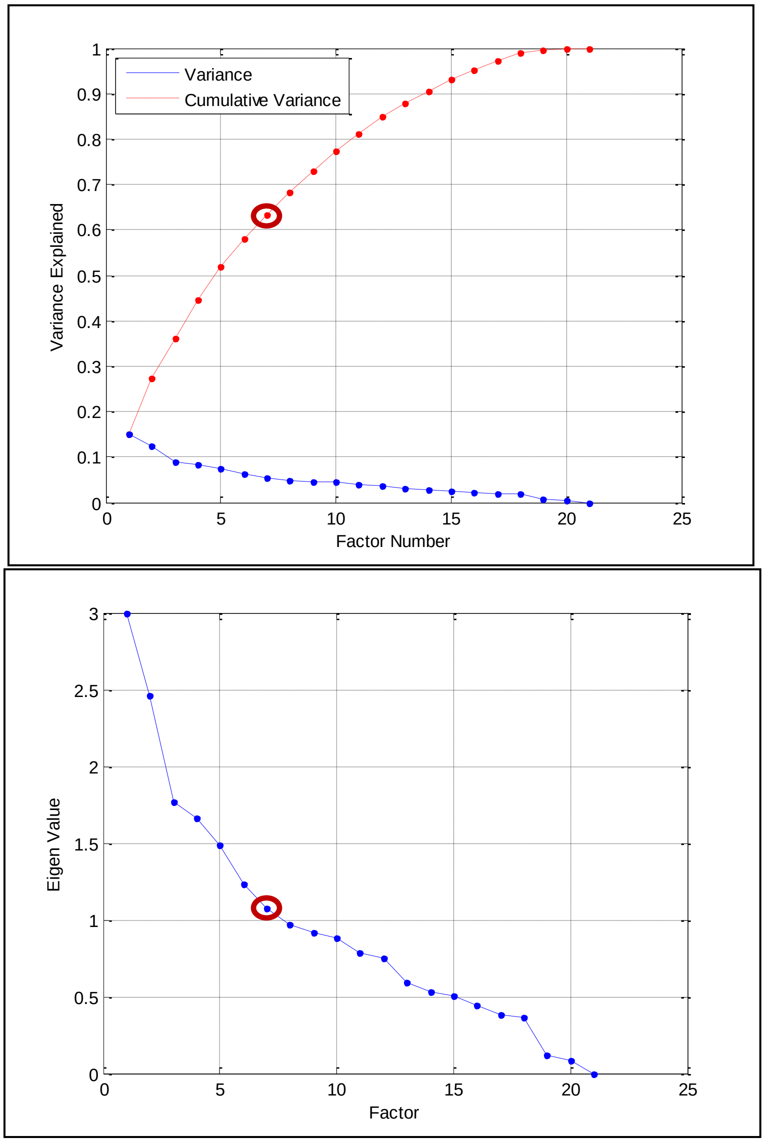



**Figure 5.** (a) Cumulative and proportion of variance explained by each factor derived from variables used to predict SOC along state-highway ROWs in New Mexico. Red circle represents the cumulative variance of the 7 factors used in the regression model. (b) Eigenvalues of factors used in analysis of variables used to predict SOC along state-highway ROWs in New Mexico. Red circle represents the inflection point of the seventh factor.

**Table 4**. Eigenvalues for each factor and factor loadings for each predictor variable measured during October–November 2011 at 117 random sites within state-highway ROWs in New Mexico. Loading values range from −1 to +1 and are considered to be associated with log (SOC) if they exceed ±0.4. Loadings of those variables that meet this criterion are shown in bold print. Factor 6 was not significantly associated with log (SOC).

| Variable | Factor1 | Factor2 | Factor3 | Factor4 | Factor5 | Factor6 | Factor7 |
|---|---|---|---|---|---|---|---|
| Eigenvalues | 2.99 | 2.46 | 1.77 | 1.67 | 1.49 | 1.24 | 1.07 |
| Annual Precipitation | **0.45** | 0.16 | 0.04 | **−0.50** | 0.07 | −0.14 | 0.03 |
| FAPAR | **0.68** | −0.28 | 0.03 | −0.07 | −0.04 | −0.01 | 0.13 |
| Evaporation | **−0.85** | 0.00 | 0.16 | 0.05 | 0.08 | −0.06 | −0.03 |
| Slope of Highway (%) | 0.04 | −0.06 | −0.05 | 0.00 | −0.02 | 0.03 | −0.04 |
| Sin (aspect) | 0.08 | 0.09 | 0.02 | 0.09 | 0.05 | −0.05 | −0.07 |
| Cos (aspect) | −0.01 | −0.03 | −0.04 | −0.05 | −0.07 | 0.03 | 0.03 |
| Elevation | **0.92** | 0.02 | −0.06 | −0.17 | −0.06 | 0.02 | 0.11 |
| Woody Only | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nitrogen ($g\text{-}kg^{-1}$) | 0.05 | −0.16 | 0.07 | −0.13 | −0.06 | 0.01 | **0.53** |
| Rock Cover (%) | 0.08 | −0.26 | −0.20 | 0.00 | **0.77** | 0.00 | −0.26 |
| Litter Cover (%) | 0.01 | −0.06 | **0.91** | 0.00 | −0.06 | −0.03 | −0.07 |
| Bare Ground Cover | −0.12 | **−0.65** | −0.38 | 0.03 | **−0.42** | −0.10 | 0.20 |
| Soil Rock (%) | −0.33 | 0.02 | 0.03 | −0.10 | **0.75** | −0.05 | 0.20 |
| Value | 0.00 | 0.00 | −0.01 | **0.84** | 0.07 | −0.06 | 0.14 |
| Chroma | −0.22 | −0.12 | −0.06 | **0.78** | −0.14 | −0.03 | −0.02 |
| Clay (%) | 0.29 | 0.11 | −0.13 | 0.2 | −0.03 | −0.06 | **0.79** |
| Total Cover (%) | 0.00 | **0.86** | 0.00 | −0.08 | −0.20 | 0.16 | 0.08 |
| Richness Grass Forb | 0.06 | 0.18 | −0.14 | −0.03 | 0.04 | **0.76** | −0.20 |
| Forb Wt Dry (g) | −0.01 | −0.07 | 0.12 | −0.03 | −0.07 | **0.84** | 0.12 |
| Grass Wt Dry (g) | −0.26 | **0.75** | −0.01 | −0.11 | −0.10 | −0.12 | 0.05 |
| Litter Wt Dry (g) | −0.19 | 0.15 | **0.82** | −0.08 | −0.04 | 0.02 | 0.01 |

**Table 5**. Regression model to determine the association between log (SOC) and factors derived through factor analysis. Factors are labeled by variables that contributed significantly to their association with log (SOC). No association was found between log (SOC) and Factor 6 (Forbs). Data were collected October–November 2011 at 117 random sites within state-highway ROWs in New Mexico.

| Effect | Category | Regression Coefficient | Lower 95% CI | Upper 95% CI | Standard Error | DF | t Value | Pr > \|t\| | Conditional Test Significance |
|---|---|---|---|---|---|---|---|---|---|
| Intercept | | 3.571 | 3.368 | 3.775 | 0.103 | 170 | 34.63 | <0.0001 | |
| Precipitation/FAPAR/ Evaporation/Elevation (Factor 1) | | 0.121 | 0.012 | 0.230 | 0.054 | 49 | 2.23 | 0.031 | 0.031 |
| Grass (Factor 2) | | 0.152 | 0.082 | 0.221 | 0.035 | 49 | 4.39 | <0.0001 | 0.000 |
| Litter (Factor 3) | | 0.057 | −0.010 | 0.124 | 0.033 | 49 | 1.71 | 0.093 | 0.093 |
| Soil Color (Factor 4) | | −0.169 | −0.240 | −0.100 | 0.035 | 49 | −4.760 | <0.0001 | 0.000 |
| Rock Percent/Cover (Factor 5) | | 0.105 | 0.04 | 0.169 | 0.032 | 49 | 3.26 | 0.002 | 0.002 |
| Clay/Nitrogen (Factor 7) | | 0.118 | 0.047 | 0.189 | 0.035 | 49 | 3.34 | 0.002 | 0.002 |
| | Lower Montane | −0.168 | −0.387 | 0.050 | 0.111 | 170 | −1.520 | 0.13 | |
| Biome | Prairie | 0.069 | −0.258 | 0.397 | 0.166 | 170 | 0.42 | 0.678 | 0.023 |
| | Upper Montane | 0 | . | . | . | . | . | . | |

## Current Management Practices

Number of visits and passes for mowing were highest in the southwestern (District1) and eastern (Districts 2 and 4) regions of the state (Figs. 6 and 7). Mowing all highways no more than the mean for the district in which they reside could translate to a reduction in visits and passes along 104 and 125 highways, respectively. Of these, visits and passes were ≥ 0.5 than the district mean along 56 and 31 highways, respectively. Most of these candidate highways were in Districts 2 (34% visits; 29% passes) and 4 (32% visits; 39% passes). Reducing visits along the 56 candidate highways to the District mean would translate to 1,893 fewer miles mowed annually, 3.1% of the average annual mowing effort (Appendix E). Reducing passes to the District mean along the 31 candidate highways would translate to 373 fewer miles mowed annually (Appendix F). Mowing during the active growing period for warm-season grasses was most frequent in districts 4, 5, and 6 (Fig. 8); however, 86 of 236 highways (36.4%) statewide were visited ≤ 1 time by mowers during this period (Appendix G).

Chemical spraying was most frequent in Districts 2, 4 and 5 (Fig. 9). Intensity of spraying varied little among districts, averaging ≤ 1 pass per visit. Of these, the number of visits and passes is ≥ 0.5 than the district mean along 42 and 11 highways, respectively (Appendices H and I.). Reducing the frequency for the 42 highways to the district mean would translate to 1,468 fewer miles sprayed annually; reducing the intensity along the 11 candidate highways would translate to 125 fewer miles sprayed annually.

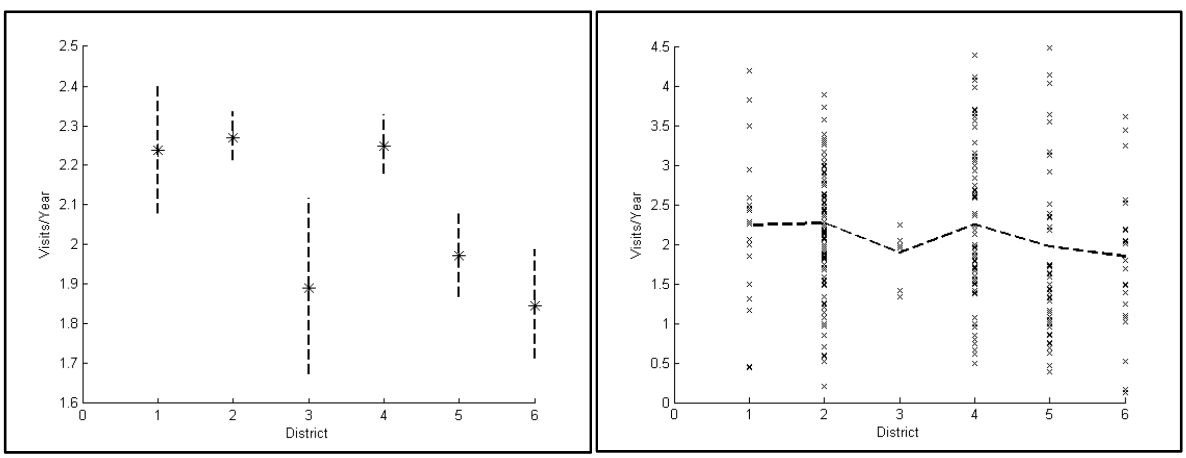



**Figure 6**. (a) Number of visits by mowers along state highways in New Mexico per year, 1998–2011. Asterisks are means for each district; dashed lines are 95% confidence intervals. (b) Number of visits by mowers to each state highway in New Mexico per year, 1998–2011. X = mean visits for each highway. Dashed line represents the mean visits for each District. Data are from the Highway Maintenance Management System.

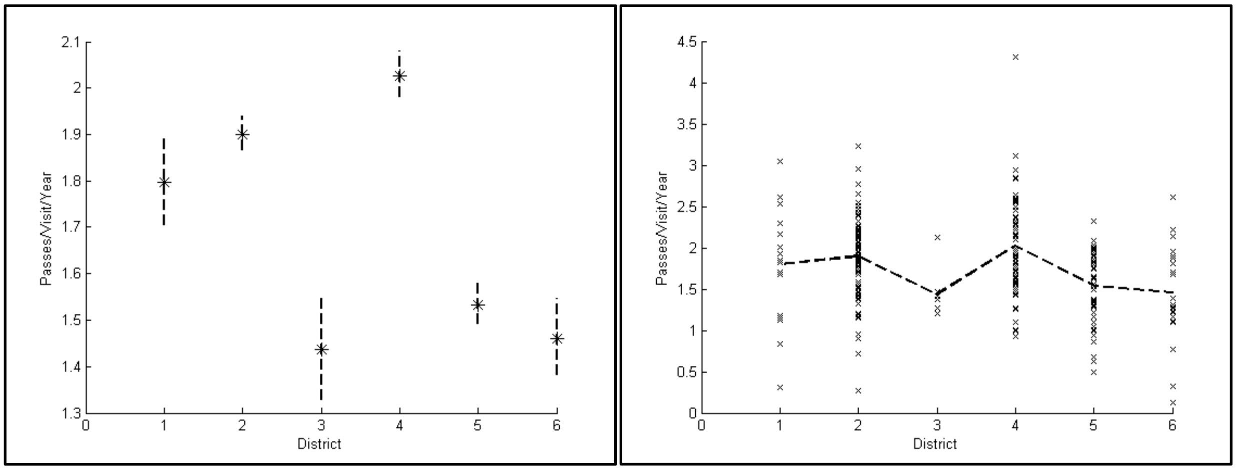



**Figure 7**. (a) Number of passes by mowers along state highways in New Mexico per year, 1998–2011. Asterisks are means for each district; dashed lines are 95% confidence intervals. (b) Number of passes by mowers along each state highway in New Mexico per year, 1998–2011. X = mean passes for each highway. Dashed line represents the mean passes for each District. Data are from the Highway Maintenance Management System.

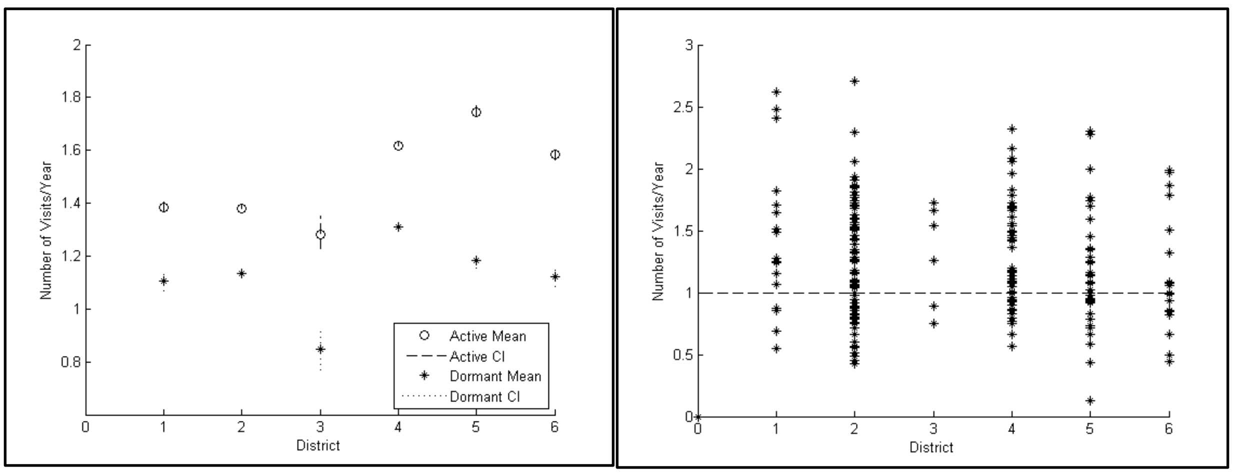



**Figure 8**. (a) Number of visits per year by mowers along state highways in New Mexico during the active-growing (July–September) and dormant periods (April–June, October–December) for warm-season grasses. (b) Number of visits per year along each state highway in New Mexico. Dashed line separates highways that were visited more or less than a single visit during the active growing period. Data are from the Highway Maintenance Management System, 1998–2011.

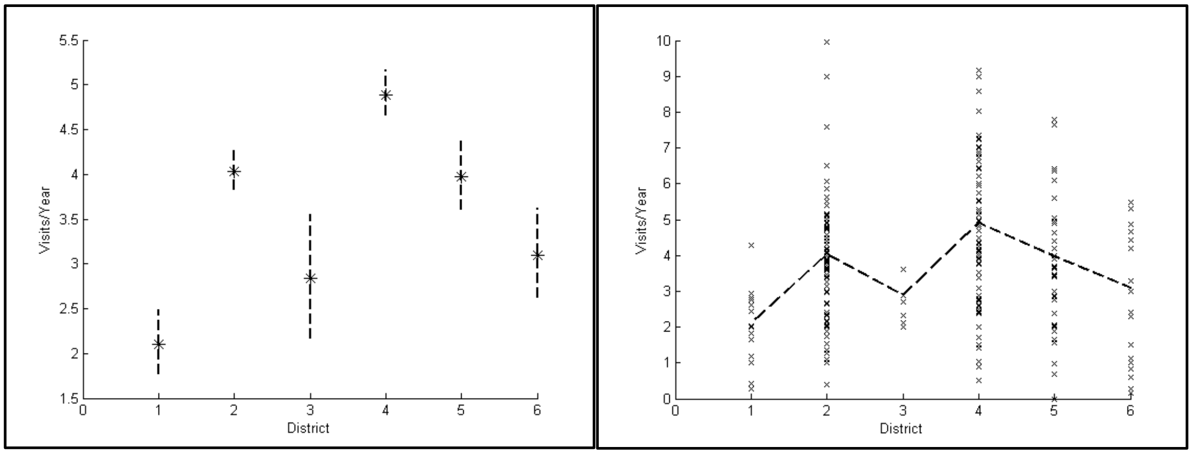



**Figure 9**. (a) Number of visits to chemically spray along state highways by NMDOT district in New Mexico per year, 1998–2011. Asterisks are means for each District; dashed lines are 95% confidence intervals. (b) Number of visits to chemically spray along each state highway in New Mexico per year, 1998–2011. X = mean visits to each highway. Dashed line represents the mean visits for each district. Data are from the Highway Maintenance Management System, 1998–2011.

## New Management Practices

We investigated nine management practices that occur over large areas, are effective for long periods, and that might increase carbon sequestration. These included (1) reseeding after new construction or major rehabilitation of roads; (2) adding arbuscular mycorrhizal fungi to soil to enhance the ability of plants to capture nutrients; (3) increasing water availability by adding water retention polymers to the soil; (4) increasing water availability by imprinting offset divots in the soil; (5) increasing nitrogen availability through fertilization; (6) increasing nitrogen availability by interseeding legumes into established vegetative communities; (7) increasing mowing heights from 15 to 20 cm, thereby leaving more live biomass to capture atmospheric carbon; (8) mowing only at the onset of the dormant season; (9) planting trees and shrubs outside of the clear zone. Of these, soil imprinting, interseeding with legumes, increasing mowing heights from 15 to 20 cm, and mowing only at the onset of the dormant season appeared to have the highest potential to enhance carbon sequestration. A complete review of how each practice might affect carbon sequestration is provided in *The Path Forward: An Implementation Plan for Phase 1*.

Discussions with maintenance supervisors of Districts 2 and 4 about implementing new management practices to increase carbon sequestration were focused on adjusting mowing regimes, interseeding with legumes to provide nitrogen for vegetation, and imprinting soils. Because of a xeric climate and resulting low potential for vegetative growth, the participating maintenance supervisors of District 2 were open to considering a more conservative mowing regime including a reduction in the frequency of mowing along many roads, a reduction in the mower width from 4.6 m to 3.1 m by not using the wing on the right side of the mower, and an increase in the height of mowing from 15 to 20 cm. They also identified 86 km undergoing road rehabilitation (US54- 64 km; NM18 16 km; Carlsbad relief route-10 km) and 10 km of ROW along the Alamogordo relief route where a pipeline is being buried that might be candidates for experimenting with reseeding treatments to increase SOC. Lastly, they suggested the ROW of NM37, where a forest fire occurred last summer, may provide an opportunity to determine the effectiveness of planting shrubs (outside of the clear zone) to sequester carbon.

The participating maintenance supervisors of District 4 emphasized that their district has the highest rate of vegetative growth in the state and mowing already has been reduced as much as feasible. At a minimum, they must maintain current levels to provide safe ROWs. However, they would be open to considering interseeding with legumes along selected stretches of several highways (e.g ., US 64, US56, NM 518, NM104, NM 120, NM39, NM161, NM97) in the central and northern parts of the district to enhance the fitness of adjacent warm season grasses. Additionally, ROWs near Tucumcari are characterized by red clays that currently support little vegetation. The maintenance supervisors requested assistance in investigating methods to increase vegetative cover.

## DISCUSSION

### Inventory of SOC

Randomly selecting sites and systematically sampling within sites served to minimize bias and provide scientifically defensible data. Our findings also suggest it was prudent to obtain empirical data to determine SOC instead of relying solely on modeling using values from the literature. In some cases, pertinent data were only available from other regions; in other cases, data from other studies in the same region differed substantially from what we found. For example, SOC we measured in the Prairie biome ($\bar{X}$ = 42.1 Mg-C/ha) was substantially higher than what was found in both grazed ($\bar{X}$ = 33.1 Mg-C/ha; 2.3 SD) and ungrazed ($\bar{X} = 25.2$ Mg-C/ha; SD 0.82) shortgrass prairie of north-central Colorado (Derner et al. 2006), the same ecosystem as found in northeastern New Mexico.

The values of SOC we obtained were precise enough at the scale of the entire study area and almost precise enough at the scale of individual biomes to meet the 10% precision requirement of CCX for trading or selling carbon credits. Precision at the scale of individual zones, however, was substantially higher than 10%. This was not surprising; the effect of factors contributing to high heterogeneity of soils (see Methods) becomes more evident at smaller scales. For example, soil characteristics varied by at least an order of magnitude across samples (*n* = 377) obtained in a flat 48-ha pasture in Wisconsin (Robertson et al. 1997). These findings strongly support measuring changes in SOC across large scales and over long periods.

We sampled fewer sites per biome than numbers prescribed by the results of our pilot study, yet the resulting data still were adequately precise for the statewide estimate. Recommendations emanating from the pilot study were purposefully conservative to ensure a better probability of achieving the target precision. Undoubtedly, the variance resulting from a small sample of sites visited during the pilot study contributed to the large sample estimated to achieve adequate precision.

Comparisons in SOC among zones were surprisingly equivocal given the differences in management intensity (Table 2; Fig. 3). Three exceptions were Managed zones in the Upper Montane and Prairie biomes and the Natural zone in the Upper Montane biome. Runoff from the adjacent roads likely contributed to high SOC in Managed zones; biomass of vegetation and litter from shrub and forest vegetation likely contributed to high SOC in the Natural zone of the Upper Montane. The equivocal results do not necessarily mean that it would not be useful to manage ROWs by individual zones. Differences in structure, management activities, and vegetation among zones may not have affected the current amount of SOC but may play a significant role in how individual zones can be manipulated to increase the rate of sequestration.

**The Regression Models**

The standard regression model provided a formal framework from which to test hypotheses concerning variable–log (SOC) associations, and the results confirmed our assumptions of what potentially drives SOC, namely annual precipitation, clay, grass (specifically in the Managed and Inflection zones), and litter. The factor model provided a post-hoc descriptive framework to unveil more detailed relationships of which several are noteworthy. Factor 1 highlighted not only the obvious relationship between precipitation and plant growth (FAPAR), but also underscored that elevation, via adiabatic lapse rate (Smith 1996), and evaporation contribute to net availability of moisture to plants. Annual precipitation is not a manageable entity, but techniques that retard moisture loss from soil may lead to substantial increases in SOC (Marlett and Hyder 1970, Haferkamp et al. 1987). Additionally, consideration of all variables from Factor 1 may improve choices where managing for SOC would be most beneficial. For example, two areas may receive equivalent moisture but one may not be a good candidate for management because it is characterized by persistent desiccating winds.

The strong association between grass/litter and SOC in Factors 2 and 3 further emphasizes the essential role of vegetation in converting atmospheric carbon to SOC; it also suggests that the Lower Montane and Prairie biomes, both with herbaceous components generally dominated by warm-season grasses, may be worthy of primary management focus. Warm-season grasses generally possess finer root systems and higher root: shoot ratios than cool-season grasses. This enables warm-season grasses to more readily partition carbon to roots (Derner et al 1997, Reeder and Schuman 2002, Reeder et al 2004, Derner and Schuman 2007). The higher rate of decomposition of fine roots of warm-season grasses facilitates the contribution of carbon to soil organic matter (Gill et al. 2002). However, the ability of warm-season grasses to increase SOC is dependent on how these species are managed (discussed below in Current Management Practices).

The lack of association between forbs and log (SOC) (Factor 6) was likely due to small sample size, not because this relationship lacks importance. In particular, the association between nitrogen and log SOC (Factor 7) suggests that nitrogen-fixing forbs may contribute to enhanced SOC. Indeed, interseeding with legumes has been shown to yield substantial increases in biomass and carbon of individual plants as well as long-term increases in SOC (Burity et al. 1989, Mortenson et al. 2004). Soil color and clay content (Factors 4 and 7) cannot be managed, but areas where soils contain high percentages of clay may be worth managing in other ways (see Recommendations for Phase 2 below) SOC accumulation (Konen et al. 2003). Lastly, the association between rock cover and log (SOC) was initially confounding, but the discovery that Managed zones are the source of this relationship suggests two plausible explanations, namely emigration of aggregate material from the adjacent road and addition of cinder during winter to improve traction.

**Current Management Practices**

Mowing and chemical spraying are required to maintain federal highway safety and environmental standards. The purpose of our analysis of the HMMS database was not to advocate major shifts in use of these management practices, but to identify if and where they, and the carbon emitted to accomplish them, might be reduced. Any reduction in emissions would be a positive contribution to the overall carbon budget of managing ROWs, which in turn would contribute to carbon credits. For both activities, our results suggest reducing the number of visits might be beneficial, but virtually nothing would be gained by reducing the number of passes during a given visit.

We analyzed mowing during the growing period of warm-season grasses because it may affect SOC accumulation in a variety of ways. Grazing, of which mowing is somewhat analogous, is illustrative. Intensive grazing in shortgrass and mixed-grass systems can increase the proportion of warm-season grasses—species morphologically structured to facilitate SOC accumulation. Conversely, intense defoliation (such as occurs when ROWs are mowed to 15 cm) during the growing period may adversely impact SOC accumulation via cessation of root growth (Troughton 1981, Briske 1991). Lastly, mowing during dormancy likely does not affect root growth, so it should pose no impediment to flow of carbon to soils and may enhance SOC via its contribution of litter.

All in all, any adjustments to current management will need to meet three goals: (1) they can be accomplished feasibly within the fiscal and staffing budgets of NMDOT; (2) they maintain federal highway safety and environmental standards; and (3) they result in a net increase in carbon sequestered in ROW soils. Most important, our findings need to be interpreted in the context of observations and practices of field personnel. Our discussions with maintenance supervisors in Districts 2 and 4 highlighted how variability in climate and road conditions across the state require management to be governed by local conditions. Thus, no single change in management likely will be applicable throughout an entire district or across the state.

## Recommendations for Phase 2

*Test New Practices*

We propose testing 11 treatments to determine their effect in increasing SOC. Testing would be within a standard Before-After-Control-Treatment framework and would be conducted at sites in the Lower Montane and Prairie biomes where topography and vegetation are relatively homogeneous. Sites will be selected from those sampled during Phase 1. The exact experimental design and sample sizes of sites and treatments will be determined through analysis of data collected during Phase 1. Of importance, sample sizes will be large enough to detect changes in SOC over the life of the experiment within the precision requirements of CCX (10% relative error with 90% confidence level). To maximize statistical rigor, we likely will emphasize a high number of sites over a high number of samples/site. Sites are the sample units and the basis for degrees of freedom upon which statistical differences are determined. Multiple samples/site simply provide a more precise value to assign to the site. Thus, we likely will opt to increase the number of sites with a commensurate reduction in treatments tested and samples collected.

At each site, the control would represent continuation of current management, i.e., no change in the frequency and intensity of mowing and chemical spraying. Treatments would include methods that would vary removal of biomass removal (i.e., mowing) and enhancement of plant growth (Table 6). Plots within which individual treatments would be tested would be placed linearly along the ROW and may or may not encompass all ROW zones depending on the applicability of the treatment (Fig 10). Plot lengths would be sufficient to adequately test treatments and minimize confounding effects of adjacent treatments (likely <400 m). Soil and vegetative characteristics collected during Phase 1 will be measured at the mid-points within ROW zones along 3 transects that cross the width of each plot. Vegetation characteristics will be measured annually. Soil will be measured at initiation and completion of treatments because changes in SOC occur slowly and likely would not change detectably from year to year.

*Develop a ROW Carbon Sequestration Offset Protocol*

The ultimate objective for NMDOT is to eventually manage ROWs so that SOC is increased and carbon credits are available for purchase in a cap-and-trade system. This first requires the development of scientifically defensible ROW protocol acceptable within the carbon-commodity markets. Such a protocol would encompass the findings from the experiment described above and would include three components:

a. Report findings from Phase 1 in peer-reviewed papers. Input from experts in the field would increase the scientific rigor of the study. Dissemination within the scientific community will serve to contribute new ideas to improving the potential for carbon sequestration in ROWs.

b. Model carbon flows using widely accepted and well-developed models that quantify soil carbon stocks or changes to them based on changes in the biogeochemical environment. Using mechanistic carbon models not only would provide clarity to the results of the regression model developed in Phase 1 but would also help determine changes in ROW carbon under different management regimes and time periods.

c. Prepare a technical paper with specific data and steps to guide protocol development. This paper would synthesize our findings as well as data and findings from other regions. Therefore, we recommend as part of this effort outreach and coordination with FHWA and other states that may be considering managing ROWs for carbon sequestration.

Table 6. Potential treatments that may increase soil organic carbon in state highway Rights-of-Way in New Mexico. Current mowing frequency generally averages one visit during the growing season and one in the fall at the onset of the dormant season. Mowing height is approximately 15 cm which generally is >50% of the above ground biomass of warm season grasses.

| | | Biomass Removal | | |
|---|---|---|---|---|
| | | Maintain Current Mowing | Harvest ≤50% of live biomass | Mowing only during dormancy |
| Plant Growth Enhancement | | Less | **Live Biomass** → | More |
| None | Less | **Control** | Treatment | Treatment |
| Legume Seeding | | Treatment | Treatment | Treatment |
| Imprinting | **Plant Growth** ↓ | Treatment | Treatment | Treatment |
| Imprinting + Legume Seeding | More | Treatment | Treatment | Treatment |

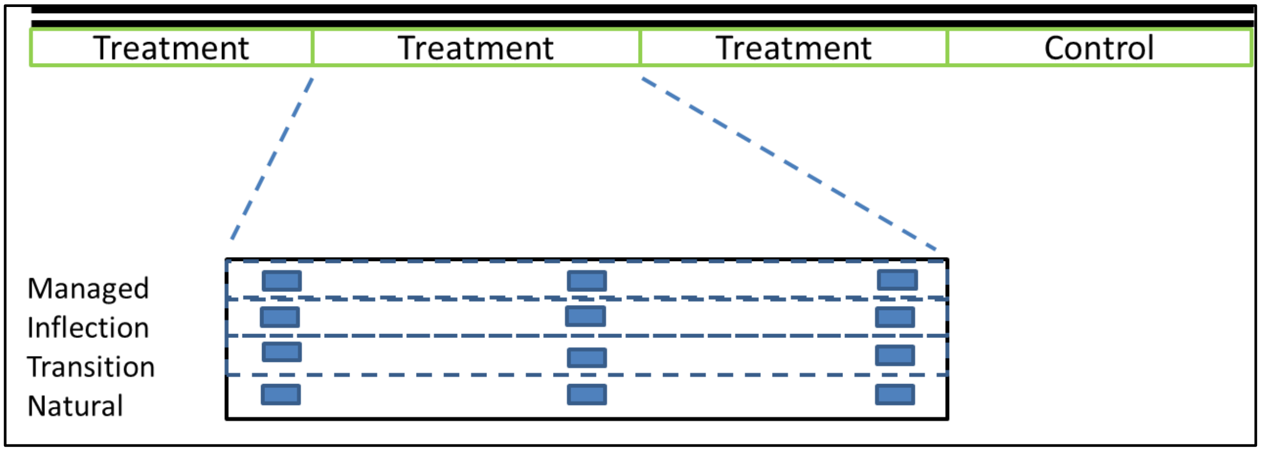



Figure 10. Potential design for experimental plots. The 3 boxes within each ROW zone represent quadrats where soil and vegetation characteristics would be measured.

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**Appendix A.** Formulas used to calculate total SOC based on stratified random sampling and variance formulas for the product of two independent random variables.

**Appendix A.** Formulas used to calculate total SOC based on stratified random sampling and variance formulas for the product of two independent random variables.

Following conventions developed in the sample survey literature, formulas use lower case variables to represent measurements and averages of random variables, whereas upper case symbols are used to represent constants such as length (L) and estimates of totals such as total SOC.

We define $soc_{ij}$ and $w_{ij}$ to be the average SOC and ROW-width respectively at the $i^{th}$ site within the $j^{th}$ biome; j=1,2,3 and i=1,2,.., $n_j$. Further we define $L_i$ to be the total length of road within the $i^{th}$ biome and $L = \sum_{1=1}^{3} L_i$ to be the total length of state highways in New Mexico.

The overall average SOC (kg-C/m$^2$) is:

$$\widehat{soc} = \frac{\sum_{j=1}^{3} L_j \times \frac{\sum_{i=1}^{n_j} soc_{ij}}{n_j}}{L} = \frac{\sum_{j=1}^{3} L_j \times \overline{soc}_j}{L};$$

and the variance of the mean ($\widehat{soc}$) is:

$$var(\widehat{soc}) = \frac{\sum_{j=1}^{3} L_j^2 \times var\left(\overline{soc}_j\right)}{L^2};$$

where $var\left(\overline{soc}_j\right) = \frac{1}{n_j} \frac{\sum_{i=1}^{n_j} \left(soc_{ij} - \overline{soc}_j\right)^2}{(n_j - 1)}$ is the sampling variance of the mean SOC in the $j^{th}$ stratum. Replacing the variable (soc) with width in these formulas we arrive at estimates of average ROW width $\overline{w}$ and it's variance $var(\overline{w})$.

The estimated total SOC (kg-C) is given by

$$\widehat{SOC} = L \times \widehat{soc} \times \overline{w}$$

And the variance of total SOC is

$$var\left(\widehat{SOC}\right) = L^2 \times \left\{\left(\widehat{SOC}\right)^2 \times var(\overline{w}) + \overline{w}^2 \times var\left(\widehat{SOC}\right)\right\}.$$

Finally, approximate 90% confidence intervals are given by

$$\widehat{SOC} \pm 1.64 \times \sqrt{var\left(\widehat{SOC}\right)}.$$

Relative precision is defined to be the interval half width divided by the SOC estimate

$Relative\ Precision = \frac{1.64 \times \sqrt{var(\widehat{SOC})}}{\widehat{SOC}}.$

**Appendix B.** Descriptive statistics of soil, vegetation, topographical, and climatic variables tested for association with soil organic carbon collected**.**

**Appendix B.** Descriptive statistics of soil, vegetation, topographical, and climatic variables tested for association with soil organic carbon collected**.** Data were collected at 117 sites along state highways in New Mexico, October–November 2011. Biomass values are amounts harvested within $0.5m^2$ quadrats. FAPAR is the Fraction of Absorbed Photosynthetically Active Radiation, a unitless measure of the amount of radiation within the 0.4–0.7 nm spectral range are absorbed by vegetation.

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Lower Montane | Managed | Annual Prec (cm) | 105 | 28.71 | 61.62 | 41.18 | 7.15 |
| Lower Montane | Inflection | Annual Prec (cm) | 48 | 28.71 | 61.62 | 42.25 | 8.35 |
| Lower Montane | Transition | Annual Prec (cm) | 63 | 31.14 | 61.62 | 42.02 | 7.10 |
| Lower Montane | Natural | Annual Prec (cm) | 79 | 31.52 | 57.85 | 41.84 | 7.63 |
| Lower Montane | Managed | FAPAR | 76 | 14.00 | 60.00 | 36.09 | 11.83 |
| Lower Montane | Inflection | FAPAR | 37 | 19.00 | 63.00 | 40.95 | 12.36 |
| Lower Montane | Transition | FAPAR | 48 | 14.00 | 57.00 | 34.42 | 12.07 |
| Lower Montane | Natural | FAPAR | 55 | 14.00 | 63.00 | 37.02 | 14.40 |
| Lower Montane | Managed | Evaporation (cm) | 105 | 40.00 | 70.00 | 52.48 | 5.68 |
| Lower Montane | Inflection | Evaporation (cm) | 48 | 40.00 | 75.00 | 53.33 | 7.17 |
| Lower Montane | Transition | Evaporation (cm) | 63 | 40.00 | 75.00 | 54.29 | 7.12 |
| Lower Montane | Natural | Evaporation (cm) | 79 | 45.00 | 75.00 | 53.35 | 6.44 |
| Lower Montane | Managed | Slope of Highway (%) | 105 | −6.00 | 20.00 | 1.26 | 4.51 |
| Lower Montane | Inflection | Slope of Highway (%) | 48 | −15.00 | 7.00 | −0.15 | 4.92 |
| Lower Montane | Transition | Slope of Highway (%) | 63 | −15.00 | 180.00 | 10.79 | 44.62 |
| Lower Montane | Natural | Slope of Highway (%) | 79 | −15.00 | 180.00 | 7.44 | 35.25 |
| Lower Montane | Managed | Sin (aspect) | 103 | −0.98 | 1.00 | 0.08 | 0.66 |
| Lower Montane | Inflection | Sin (aspect) | 46 | −0.87 | 1.00 | 0.36 | 0.58 |
| Lower Montane | Transition | Sin (aspect) | 61 | −0.98 | 1.00 | 0.00 | 0.68 |
| Lower Montane | Natural | Sin (aspect) | 79 | −0.87 | 1.00 | 0.22 | 0.58 |
| Lower Montane | Managed | Cos (aspect) | 103 | −1.00 | 1.00 | 0.05 | 0.75 |
| Lower Montane | Inflection | Cos (aspect) | 46 | −1.00 | 0.98 | −0.11 | 0.73 |
| Lower Montane | Transition | Cos (aspect) | 61 | −1.00 | 1.00 | 0.10 | 0.74 |
| Lower Montane | Natural | Cos (aspect) | 79 | −1.00 | 1.00 | −0.05 | 0.79 |
| Lower Montane | Managed | Elevation (m) | 103 | 1366.00 | 2433.00 | 2007.89 | 252.34 |
| Lower Montane | Inflection | Elevation (m) | 46 | 1740.00 | 2433.00 | 2072.43 | 193.19 |
| Lower Montane | Transition | Elevation (m) | 61 | 1366.00 | 2433.00 | 2008.49 | 235.22 |
| Lower Montane | Natural | Elevation (m) | 79 | 1390.00 | 2372.00 | 2038.11 | 219.17 |
| Lower Montane | Managed | Woody Only | 105 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lower Montane | Inflection | Woody Only | 48 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lower Montane | Transition | Woody Only | 63 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lower Montane | Natural | Woody Only | 79 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lower Montane | Managed | Nitrogen_g_kg | 105 | 0.00 | 10.77 | 0.72 | 2.06 |
| Lower Montane | Inflection | Nitrogen_g_kg | 48 | 0.03 | 8.90 | 0.96 | 2.31 |
| Lower Montane | Transition | Nitrogen_g_kg | 63 | 0.03 | 0.27 | 0.12 | 0.06 |

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Lower Montane | Natural | Nitrogen_g_kg | 79 | 0.03 | 9.09 | 0.71 | 1.88 |
| Lower Montane | Managed | Rock Cover (%) | 105 | 0.00 | 90.00 | 23.37 | 25.26 |
| Lower Montane | Inflection | Rock Cover (%) | 48 | 0.00 | 96.00 | 11.00 | 21.24 |
| Lower Montane | Transition | Rock Cover (%) | 63 | 0.00 | 80.00 | 13.87 | 21.07 |
| Lower Montane | Natural | Rock Cover (%) | 79 | 0.00 | 100.00 | 11.86 | 22.00 |
| Lower Montane | Managed | Litter Cover (%) | 105 | 0.00 | 85.00 | 16.15 | 18.85 |
| Lower Montane | Inflection | Litter Cover (%) | 48 | 0.00 | 65.00 | 11.81 | 15.61 |
| Lower Montane | Transition | Litter Cover (%) | 63 | 0.00 | 83.00 | 13.84 | 17.24 |
| Lower Montane | Natural | Litter Cover (%) | 79 | 0.00 | 100.00 | 18.52 | 27.54 |
| Lower Montane | Managed | BareGroundCover(%) | 105 | 0.00 | 55.00 | 7.84 | 12.18 |
| Lower Montane | Inflection | BareGroundCover(%) | 48 | 0.00 | 91.00 | 19.71 | 26.32 |
| Lower Montane | Transition | BareGroundCover(%) | 63 | 0.00 | 90.00 | 19.59 | 25.09 |
| Lower Montane | Natural | BareGroundCover(%) | 79 | 0.00 | 85.00 | 22.81 | 24.57 |
| Lower Montane | Managed | Soil Rock (%) | 105 | 0.00 | 50.00 | 2.44 | 5.93 |
| Lower Montane | Inflection | Soil Rock (%) | 48 | 0.00 | 12.00 | 0.81 | 2.16 |
| Lower Montane | Transition | Soil Rock (%) | 63 | 0.00 | 13.00 | 1.05 | 2.14 |
| Lower Montane | Natural | Soil Rock (%) | 79 | 0.00 | 35.00 | 1.53 | 4.65 |
| Lower Montane | Managed | Value | 105 | 0.00 | 5.00 | 3.15 | 0.79 |
| Lower Montane | Inflection | Value | 48 | 0.00 | 4.00 | 2.98 | 1.08 |
| Lower Montane | Transition | Value | 63 | 0.00 | 4.00 | 3.21 | 0.68 |
| Lower Montane | Natural | Value | 79 | 0.00 | 10.00 | 3.08 | 1.07 |
| Lower Montane | Managed | Chroma | 105 | 0.00 | 4.00 | 2.60 | 0.89 |
| Lower Montane | Inflection | Chroma | 48 | 0.00 | 6.00 | 2.48 | 1.22 |
| Lower Montane | Transition | Chroma | 63 | 0.00 | 4.00 | 2.71 | 1.08 |
| Lower Montane | Natural | Chroma | 79 | 0.00 | 4.00 | 2.33 | 0.93 |
| Lower Montane | Managed | Clay (%) | 105 | 7.00 | 48.00 | 24.16 | 11.08 |
| Lower Montane | Inflection | Clay (%) | 48 | 12.00 | 45.00 | 30.14 | 10.24 |
| Lower Montane | Transition | Clay (%) | 63 | 5.00 | 48.00 | 27.53 | 12.10 |
| Lower Montane | Natural | Clay (%) | 79 | 5.00 | 45.00 | 26.51 | 12.10 |
| Lower Montane | Managed | Total Cover (%) | 105 | 4.00 | 108.00 | 54.97 | 23.15 |
| Lower Montane | Inflection | Total Cover (%) | 48 | 4.00 | 100.00 | 53.42 | 25.74 |
| Lower Montane | Transition | Total Cover (%) | 63 | 5.00 | 111.00 | 47.38 | 26.65 |
| Lower Montane | Natural | Total Cover (%) | 79 | 5.00 | 180.00 | 58.41 | 35.09 |
| Lower Montane | Managed | Richness Grass Forb | 105 | 1.00 | 10.00 | 3.14 | 1.75 |
| Lower Montane | Inflection | Richness Grass Forb | 48 | 1.00 | 7.00 | 2.73 | 1.55 |
| Lower Montane | Transition | Richness Grass Forb | 63 | 1.00 | 7.00 | 3.03 | 1.23 |
| Lower Montane | Natural | Richness Grass Forb | 79 | 1.00 | 6.00 | 2.80 | 1.43 |
| Lower Montane | Managed | Forb Wt Dry (g) | 65 | 0.00 | 66.00 | 8.82 | 13.39 |
| Lower Montane | Inflection | Forb Wt Dry (g) | 29 | 0.00 | 29.00 | 6.38 | 8.94 |

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Lower Montane | Transition | Forb Wt Dry (g) | 35 | 0.00 | 114.00 | 10.23 | 19.87 |
| Lower Montane | Natural | Forb Wt Dry (g) | 39 | 0.00 | 105.00 | 9.44 | 19.78 |
| Lower Montane | Managed | Grass Wt Dry (g) | 65 | 0.00 | 168.00 | 31.78 | 30.10 |
| Lower Montane | Inflection | Grass Wt Dry (g) | 29 | 0.00 | 90.00 | 28.83 | 26.48 |
| Lower Montane | Transition | Grass Wt Dry (g) | 35 | 0.00 | 92.00 | 21.97 | 20.98 |
| Lower Montane | Natural | Grass Wt Dry (g) | 39 | 0.00 | 151.00 | 27.31 | 37.32 |
| Lower Montane | Managed | Litter Wt Dry (g) | 65 | 0.00 | 260.00 | 42.03 | 51.06 |
| Lower Montane | Inflection | Litter Wt Dry (g) | 29 | 0.00 | 270.00 | 51.38 | 68.58 |
| Lower Montane | Transition | Litter Wt Dry(g) | 35 | 0.00 | 404.00 | 54.06 | 85.29 |
| Lower Montane | Natural | Litter Wt Dry (g) | 39 | 0.00 | 893.00 | 92.62 | 172.82 |
| Prairie | Managed | Annual Prec (cm) | 95 | 34.91 | 49.87 | 41.35 | 3.97 |
| Prairie | Inflection | Annual Prec (cm) | 32 | 35.40 | 47.96 | 42.04 | 3.49 |
| Prairie | Transition | Annual Prec (cm) | 86 | 34.91 | 55.90 | 42.03 | 4.83 |
| Prairie | Natural | Annual Prec (cm) | 79 | 35.40 | 55.90 | 41.50 | 4.28 |
| Prairie | Managed | FAPAR | 43 | 1.00 | 46.00 | 25.12 | 13.48 |
| Prairie | Inflection | FAPAR | 8 | 14.00 | 28.00 | 20.88 | 6.62 |
| Prairie | Transition | FAPAR | 49 | 9.00 | 54.00 | 28.53 | 14.59 |
| Prairie | Natural | FAPAR | 39 | 1.00 | 54.00 | 27.82 | 16.48 |
| Prairie | Managed | Evaporation (cm) | 95 | 50.00 | 80.00 | 68.11 | 10.32 |
| Prairie | Inflection | Evaporation (cm) | 32 | 50.00 | 80.00 | 64.69 | 10.47 |
| Prairie | Transition | Evaporation (cm) | 86 | 50.00 | 80.00 | 69.94 | 9.99 |
| Prairie | Natural | Evaporation (cm) | 79 | 50.00 | 80.00 | 68.92 | 9.29 |
| Prairie | Managed | Slope of Highway (%) | 95 | −5.00 | 10.00 | 0.09 | 2.37 |
| Prairie | Inflection | Slope of Highway (%) | 32 | −3.00 | 10.00 | 0.66 | 2.66 |
| Prairie | Transition | Slope of Highway (%) | 86 | −5.00 | 15.00 | 0.56 | 3.36 |
| Prairie | Natural | Slope of Highway (%) | 79 | −5.00 | 15.00 | 0.96 | 3.60 |
| Prairie | Managed | Sin (aspect) | 72 | −1.00 | 1.00 | −0.07 | 0.70 |
| Prairie | Inflection | Sin (aspect) | 24 | −1.00 | 1.00 | 0.02 | 0.76 |
| Prairie | Transition | Sin (aspect) | 70 | −1.00 | 1.00 | 0.04 | 0.68 |
| Prairie | Natural | Sin (aspect) | 61 | −0.98 | 1.00 | 0.02 | 0.73 |
| Prairie | Managed | Cos (aspect) | 72 | −1.00 | 1.00 | 0.07 | 0.72 |
| Prairie | Inflection | Cos (aspect) | 24 | −0.98 | 0.99 | 0.05 | 0.68 |
| Prairie | Transition | Cos (aspect) | 70 | −1.00 | 0.99 | −0.29 | 0.68 |
| Prairie | Natural | Cos (aspect) | 61 | −0.98 | 1.00 | 0.02 | 0.69 |
| Prairie | Managed | Elevation (m) | 95 | 1128.00 | 2208.00 | 1528.03 | 307.35 |
| Prairie | Inflection | Elevation (m) | 32 | 1211.00 | 2071.00 | 1566.91 | 278.25 |
| Prairie | Transition | Elevation (m) | 86 | 1060.00 | 2208.00 | 1509.36 | 299.98 |
| Prairie | Natural | Elevation (m) | 79 | 1060.00 | 2208.00 | 1495.99 | 282.63 |
| Prairie | Managed | Woody Only | 95 | 0.00 | 0.00 | 0.00 | 0.00 |

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Prairie | Inflection | Woody Only | 32 | 0.00 | 0.00 | 0.00 | 0.00 |
| Prairie | Transition | Woody Only | 86 | 0.00 | 0.00 | 0.00 | 0.00 |
| Prairie | Natural | Woody Only | 79 | 0.00 | 0.00 | 0.00 | 0.00 |
| Prairie | Managed | Nitrogen_g_kg | 95 | 0.02 | 4.84 | 0.30 | 0.73 |
| Prairie | Inflection | Nitrogen_g_kg | 32 | 0.06 | 0.23 | 0.13 | 0.04 |
| Prairie | Transition | Nitrogen_g_kg | 86 | 0.06 | 3.58 | 0.22 | 0.50 |
| Prairie | Natural | Nitrogen_g_kg | 79 | 0.03 | 0.26 | 0.12 | 0.05 |
| Prairie | Managed | Rock Cover (%) | 95 | 0.00 | 82.00 | 10.99 | 20.28 |
| Prairie | Inflection | Rock Cover (%) | 32 | 0.00 | 75.00 | 3.19 | 13.28 |
| Prairie | Transition | Rock Cover (%) | 86 | 0.00 | 95.00 | 9.90 | 19.54 |
| Prairie | Natural | Rock Cover (%) | 79 | 0.00 | 65.00 | 5.32 | 14.41 |
| Prairie | Managed | Litter Cover (%) | 95 | 0.00 | 90.00 | 32.48 | 26.76 |
| Prairie | Inflection | Litter Cover (%) | 32 | 0.00 | 66.00 | 23.06 | 19.90 |
| Prairie | Transition | Litter Cover (%) | 86 | 0.00 | 82.00 | 15.00 | 17.43 |
| Prairie | Natural | Litter Cover (%) | 79 | 0.00 | 85.00 | 16.52 | 20.30 |
| Prairie | Managed | BareGroundCover(%) | 95 | 0.00 | 95.00 | 6.77 | 15.48 |
| Prairie | Inflection | BareGroundCover(%) | 32 | 0.00 | 80.00 | 15.63 | 23.41 |
| Prairie | Transition | BareGroundCover(%) | 86 | 0.00 | 90.00 | 26.10 | 30.55 |
| Prairie | Natural | BareGroundCover(%) | 79 | 0.00 | 80.00 | 23.06 | 23.68 |
| Prairie | Managed | Soil Rock (%) | 95 | 0.00 | 60.00 | 4.41 | 10.26 |
| Prairie | Inflection | Soil Rock (%) | 32 | 0.00 | 3.00 | 0.28 | 0.63 |
| Prairie | Transition | Soil Rock (%) | 86 | 0.00 | 60.00 | 4.23 | 11.14 |
| Prairie | Natural | Soil Rock (%) | 79 | 0.00 | 20.00 | 1.32 | 3.95 |
| Prairie | Managed | Value | 95 | 0.00 | 6.00 | 3.19 | 0.85 |
| Prairie | Inflection | Value | 32 | 0.00 | 4.00 | 2.47 | 1.24 |
| Prairie | Transition | Value | 86 | 0.00 | 6.00 | 3.17 | 0.64 |
| Prairie | Natural | Value | 79 | 2.00 | 5.00 | 3.28 | 0.58 |
| Prairie | Managed | Chroma | 95 | 0.00 | 6.00 | 2.82 | 1.18 |
| Prairie | Inflection | Chroma | 32 | 0.00 | 4.00 | 2.28 | 1.42 |
| Prairie | Transition | Chroma | 86 | 0.00 | 6.00 | 3.07 | 1.11 |
| Prairie | Natural | Chroma | 79 | 2.00 | 6.00 | 3.23 | 1.01 |
| Prairie | Managed | Clay (%) | 95 | 5.00 | 45.00 | 24.86 | 9.93 |
| Prairie | Inflection | Clay (%) | 32 | 13.00 | 39.00 | 24.38 | 7.46 |
| Prairie | Transition | Clay (%) | 86 | 10.00 | 44.00 | 23.78 | 9.93 |
| Prairie | Natural | Clay (%) | 79 | 10.00 | 42.00 | 25.50 | 9.39 |
| Prairie | Managed | Total Cover (%) | 94 | 5.00 | 100.00 | 45.96 | 24.99 |
| Prairie | Inflection | Total Cover (%) | 32 | 10.00 | 100.00 | 52.88 | 24.41 |
| Prairie | Transition | Total Cover (%) | 86 | 3.00 | 143.00 | 51.49 | 32.59 |
| Prairie | Natural | Total Cover (%) | 79 | 5.00 | 180.00 | 55.10 | 27.63 |

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Prairie | Managed | Richness Grass Forb | 95 | 1.00 | 8.00 | 2.66 | 1.40 |
| Prairie | Inflection | Richness Grass Forb | 32 | 1.00 | 6.00 | 2.72 | 1.22 |
| Prairie | Transition | Richness Grass Forb | 86 | 1.00 | 7.00 | 2.74 | 1.51 |
| Prairie | Natural | Richness Grass Forb | 79 | 1.00 | 7.00 | 2.57 | 1.22 |
| Prairie | Managed | Forb Wt Dry (g) | 43 | 0.00 | 27.00 | 1.98 | 4.86 |
| Prairie | Inflection | Forb Wt Dry (g) | 17 | 0.00 | 136.00 | 12.88 | 33.07 |
| Prairie | Transition | Forb Wt Dry (g) | 45 | 0.00 | 38.00 | 6.31 | 10.84 |
| Prairie | Natural | Forb Wt Dry (g) | 40 | 0.00 | 118.00 | 7.10 | 20.78 |
| Prairie | Managed | Grass Wt Dry (g) | 43 | 0.00 | 100.00 | 35.35 | 31.83 |
| Prairie | Inflection | Grass Wt Dry (g) | 17 | 0.00 | 146.00 | 26.06 | 36.18 |
| Prairie | Transition | Grass Wt Dry (g) | 45 | 0.00 | 162.00 | 33.78 | 44.29 |
| Prairie | Natural | Grass Wt Dry (g) | 40 | 0.00 | 124.00 | 31.93 | 31.48 |
| Prairie | Managed | Litter Wt Dry (g) | 43 | 0.00 | 320.00 | 104.93 | 91.36 |
| Prairie | Inflection | Litter Wt Dry (g) | 17 | 0.00 | 316.00 | 55.41 | 82.16 |
| Prairie | Transition | Litter Wt Dry (g) | 45 | 0.00 | 247.00 | 54.78 | 62.05 |
| Prairie | Natural | Litter Wt Dry (g) | 40 | 0.00 | 471.00 | 59.85 | 98.65 |
| Upper Montane | Managed | Annual Prec (cm) | 29 | 41.06 | 74.28 | 60.49 | 10.19 |
| Upper Montane | Inflection | Annual Prec (cm) | 19 | 40.23 | 71.96 | 57.09 | 12.12 |
| Upper Montane | Transition | Annual Prec (cm) | 18 | 40.23 | 71.96 | 54.55 | 9.37 |
| Upper Montane | Natural | Annual Prec (cm) | 21 | 40.23 | 71.24 | 53.27 | 10.75 |
| Upper Montane | Managed | FAPAR | 23 | 9.00 | 89.00 | 52.57 | 31.16 |
| Upper Montane | Inflection | FAPAR | 14 | 17.00 | 89.00 | 67.50 | 20.69 |
| Upper Montane | Transition | FAPAR | 14 | 10.00 | 82.00 | 62.14 | 24.04 |
| Upper Montane | Natural | FAPAR | 14 | 31.00 | 82.00 | 64.36 | 15.26 |
| Upper Montane | Managed | Evaporation (cm) | 29 | 45.00 | 55.00 | 48.97 | 3.38 |
| Upper Montane | Inflection | Evaporation (cm) | 19 | 45.00 | 55.00 | 47.37 | 3.06 |
| Upper Montane | Transition | Evaporation (cm) | 18 | 45.00 | 55.00 | 48.89 | 3.66 |
| Upper Montane | Natural | Evaporation (cm) | 21 | 45.00 | 55.00 | 47.38 | 3.01 |
| Upper Montane | Managed | Slope of Highway (%) | 28 | −3.00 | 60.00 | 8.68 | 18.70 |
| Upper Montane | Inflection | Slope of Highway (%) | 19 | −2.00 | 10.00 | 2.84 | 3.25 |
| Upper Montane | Transition | Slope of Highway (%) | 18 | −3.00 | 10.00 | 3.22 | 4.25 |
| Upper Montane | Natural | Slope of Highway (%) | 18 | 0.00 | 60.00 | 13.89 | 21.47 |
| Upper Montane | Managed | Sin (aspect) | 28 | −0.64 | 0.98 | 0.38 | 0.55 |
| Upper Montane | Inflection | Sin (aspect) | 19 | −0.94 | 0.96 | 0.16 | 0.50 |
| Upper Montane | Transition | Sin (aspect) | 18 | −0.5 | 0.98 | 0.21 | 0.50 |
| Upper Montane | Natural | sin( aspect) | 18 | −0.94 | 0.96 | −0.03 | 0.61 |
| Upper Montane | Managed | Cos (aspect) | 28 | −1.00 | 1.00 | −0.16 | 0.75 |
| Upper Montane | Inflection | Cos (aspect) | 19 | −1.00 | 1.00 | 0.06 | 0.88 |
| Upper Montane | Transition | Cos (aspect) | 18 | −1.00 | 1.00 | 0.31 | 0.81 |

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Upper Montane | Natural | Cos (aspect) | 18 | −1.00 | 1.00 | 0.06 | 0.82 |
| Upper Montane | Managed | Elevation (m) | 29 | 2025.00 | 2802.00 | 2372.28 | 196.03 |
| Upper Montane | Inflection | Elevation (m) | 19 | 2025.00 | 2802.00 | 2447.00 | 184.43 |
| Upper Montane | Transition | Elevation (m) | 18 | 2029.00 | 2438.00 | 2297.50 | 134.25 |
| Upper Montane | Natural | Elevation (m) | 21 | 2025.00 | 2659.00 | 2437.33 | 158.20 |
| Upper Montane | Managed | Woody Only | 29 | 0.00 | 0.00 | 0.00 | 0.00 |
| Upper Montane | Inflection | Woody Only | 19 | 0.00 | 0.00 | 0.00 | 0.00 |
| Upper Montane | Transition | Woody Only | 18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Upper Montane | Natural | Woody Only | 21 | 0.00 | 0.00 | 0.00 | 0.00 |
| Upper Montane | Managed | Nitrogen_g_kg | 29 | 0.04 | 7.09 | 0.91 | 1.95 |
| Upper Montane | Inflection | Nitrogen_g_kg | 19 | 0.08 | 9.33 | 1.00 | 2.56 |
| Upper Montane | Transition | Nitrogen_g_kg | 18 | 0.06 | 3.03 | 0.41 | 0.70 |
| Upper Montane | Natural | Nitrogen_g_kg | 21 | 0.08 | 12.66 | 1.56 | 2.94 |
| Upper Montane | Managed | Rock Cover  (%) | 29 | 0.00 | 70.00 | 16.93 | 20.68 |
| Upper Montane | Inflection | Rock Cover (%) | 19 | 0.00 | 60.00 | 9.42 | 16.75 |
| Upper Montane | Transition | Rock Cover (%) | 18 | 0.00 | 40.00 | 9.00 | 14.02 |
| Upper Montane | Natural | Rock Cover (%) | 21 | 0.00 | 80.00 | 6.71 | 18.51 |
| Upper Montane | Managed | Litter Cover (%) | 29 | 0.00 | 70.00 | 12.62 | 16.79 |
| Upper Montane | Inflection | Litter Cover (%) | 19 | 0.00 | 74.00 | 17.58 | 23.28 |
| Upper Montane | Transition | Litter Cover (%) | 18 | 0.00 | 70.00 | 12.39 | 18.55 |
| Upper Montane | Natural | Litter Cover (%) | 21 | 0.00 | 100.00 | 24.76 | 32.84 |
| Upper Montane | Managed | BareGroundCover(%) | 29 | 0.00 | 90.00 | 8.24 | 21.81 |
| Upper Montane | Inflection | BareGroundCover(%) | 19 | 0.00 | 70.00 | 13.00 | 20.17 |
| Upper Montane | Transition | BareGroundCover(%) | 18 | 0.00 | 91.00 | 17.22 | 26.59 |
| Upper Montane | Natural | BareGroundCover(%) | 21 | 0.00 | 60.00 | 16.24 | 22.57 |
| Upper Montane | Managed | Soil Rock (%) | 29 | 0.00 | 10.00 | 2.14 | 3.26 |
| Upper Montane | Inflection | Soil Rock (%) | 19 | 0.00 | 8.00 | 1.00 | 2.31 |
| Upper Montane | Transition | Soil Rock (%) | 18 | 0.00 | 2.00 | 0.22 | 0.55 |
| Upper Montane | Natural | Soil Rock (%) | 21 | 0.00 | 3.00 | 0.19 | 0.68 |
| Upper Montane | Managed | Value | 29 | 2.00 | 4.00 | 2.86 | 0.44 |
| Upper Montane | Inflection | Value | 19 | 0.00 | 4.00 | 2.47 | 0.84 |
| Upper Montane | Transition | Value | 18 | 2.00 | 3.00 | 2.72 | 0.46 |
| Upper Montane | Natural | Value | 21 | 2.00 | 4.00 | 2.86 | 0.73 |
| Upper Montane | Managed | Chroma | 29 | 1.00 | 4.00 | 2.07 | 0.65 |
| Upper Montane | Inflection | Chroma | 19 | 0.00 | 3.00 | 1.58 | 0.69 |
| Upper Montane | Transition | Chroma | 18 | 1.00 | 4.00 | 1.94 | 0.87 |
| Upper Montane | Natural | Chroma | 21 | 1.00 | 4.00 | 2.19 | 0.81 |
| Upper Montane | Managed | Clay (%) | 29 | 6.00 | 54.00 | 27.60 | 13.29 |
| Upper Montane | Inflection | Clay (%) | 19 | 7.00 | 45.00 | 29.87 | 9.82 |

| Biome Category | Zone | Variable | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Upper Montane | Transition | Clay (%) | 18 | 17.00 | 43.00 | 32.94 | 9.25 |
| Upper Montane | Natural | Clay (%) | 21 | 12.00 | 47.00 | 32.55 | 7.95 |
| Upper Montane | Managed | Total Cover (%) | 29 | 10.00 | 100.00 | 61.14 | 28.43 |
| Upper Montane | Inflection | Total Cover (%) | 17 | 10.00 | 95.00 | 55.12 | 24.61 |
| Upper Montane | Transition | Total Cover (%) | 18 | 6.00 | 381.00 | 78.44 | 81.23 |
| Upper Montane | Natural | Total Cover (%) | 21 | 8.00 | 130.00 | 62.38 | 33.06 |
| Upper Montane | Managed | Richness Grass Forb | 29 | 1.00 | 6.00 | 3.03 | 1.27 |
| Upper Montane | Inflection | Richness Grass Forb | 19 | 2.00 | 6.00 | 3.05 | 1.13 |
| Upper Montane | Transition | Richness Grass Forb | 18 | 2.00 | 5.00 | 3.11 | 1.18 |
| Upper Montane | Natural | Richness Grass Forb | 21 | 1.00 | 4.00 | 2.29 | 0.78 |
| Upper Montane | Managed | Forb Wt Dry (g) | 23 | 0.00 | 33.00 | 4.48 | 8.89 |
| Upper Montane | Inflection | Forb Wt Dry (g) | 13 | 0.00 | 22.00 | 7.85 | 7.28 |
| Upper Montane | Transition | Forb Wt Dry (g) | 11 | 0.00 | 21.00 | 5.55 | 6.70 |
| Upper Montane | Natural | Forb Wt Dry (g) | 15 | 0.00 | 19.00 | 3.40 | 5.07 |
| Upper Montane | Managed | Grass Wt Dry (g) | 23 | 0.00 | 114.00 | 43.22 | 38.32 |
| Upper Montane | Inflection | Grass Wt Dry (g) | 13 | 2.00 | 62.00 | 23.54 | 20.48 |
| Upper Montane | Transition | Grass Wt Dry (g) | 11 | 1.00 | 242.00 | 58.27 | 69.05 |
| Upper Montane | Natural | Grass Wt Dry (g) | 15 | 0.00 | 93.00 | 21.20 | 24.24 |
| Upper Montane | Managed | Litter Wt Dry (g) | 23 | 0.00 | 729.00 | 74.87 | 153.75 |
| Upper Montane | Inflection | Litter Wt Dry (g) | 13 | 0.00 | 119.00 | 20.54 | 35.94 |
| Upper Montane | Transition | Litter Wt Dry (g) | 11 | 0.00 | 160.00 | 38.73 | 46.17 |
| Upper Montane | Natural | Litter Wt Dry (g) | 15 | 0.00 | 561.00 | 103.73 | 166.64 |

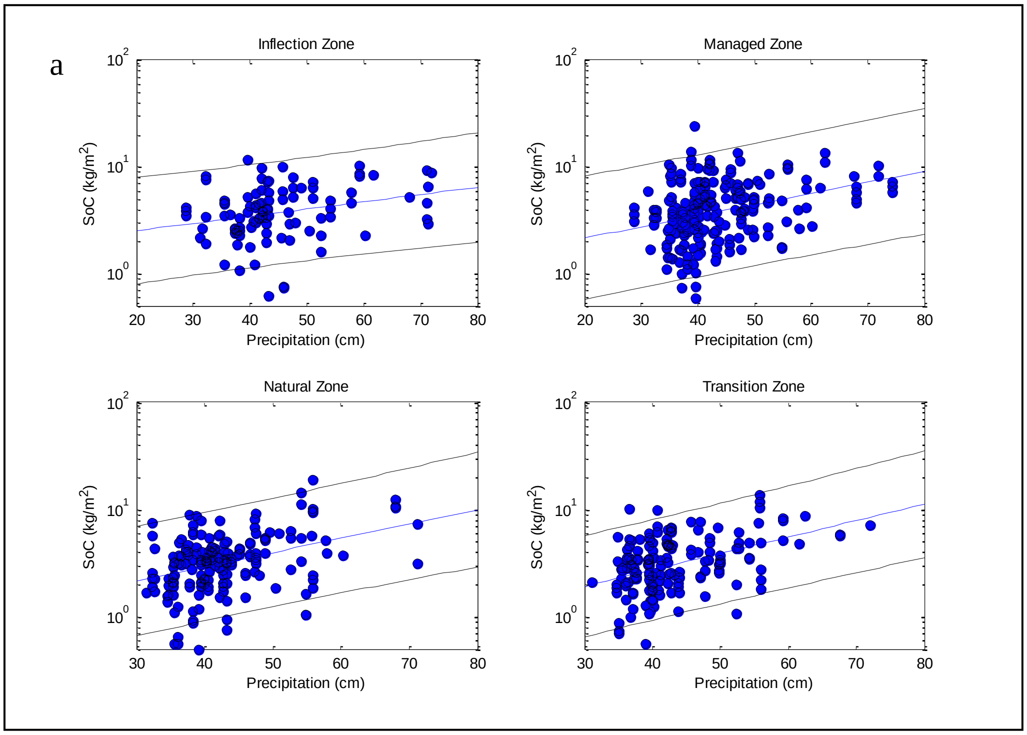
**Appendix C.** Sampling effort, mean SOC values (95% CI), relative precision of SOC values, and mean widths of ROW (95% CI) zones at sites visited along state highways in New Mexico, October–November 2011**.**

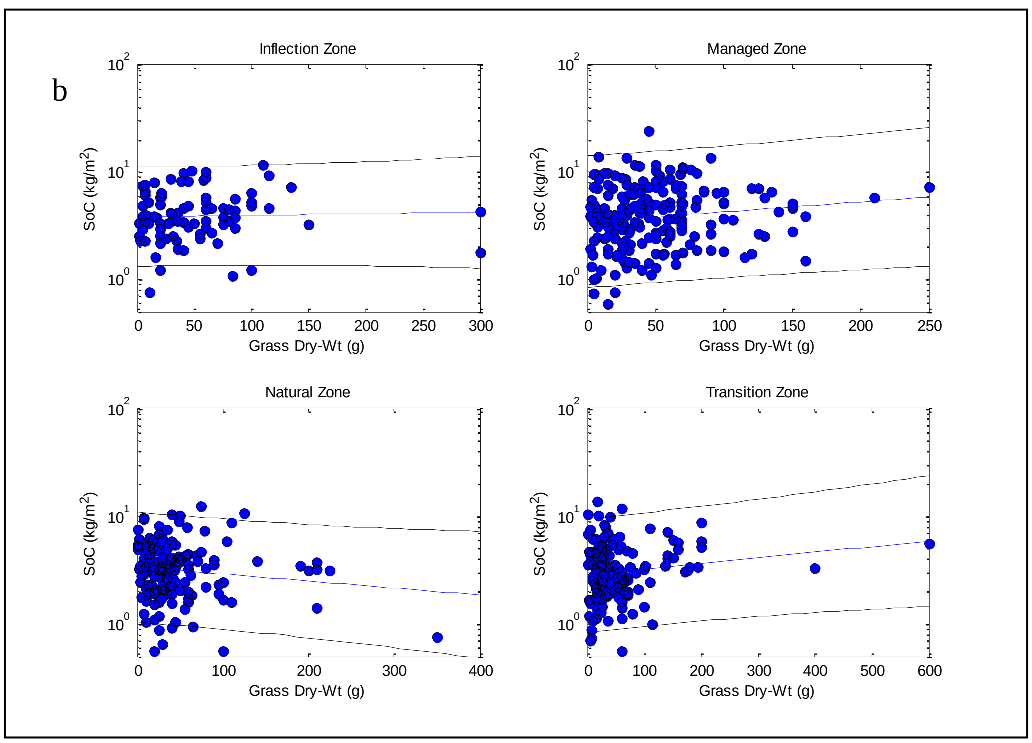
**Appendix C.** Sampling effort, mean SOC values (95% CI), relative precision of SOC values, and mean widths of ROW (95% CI) zones at sites visited along state highways in New Mexico, October–November 2011**.**

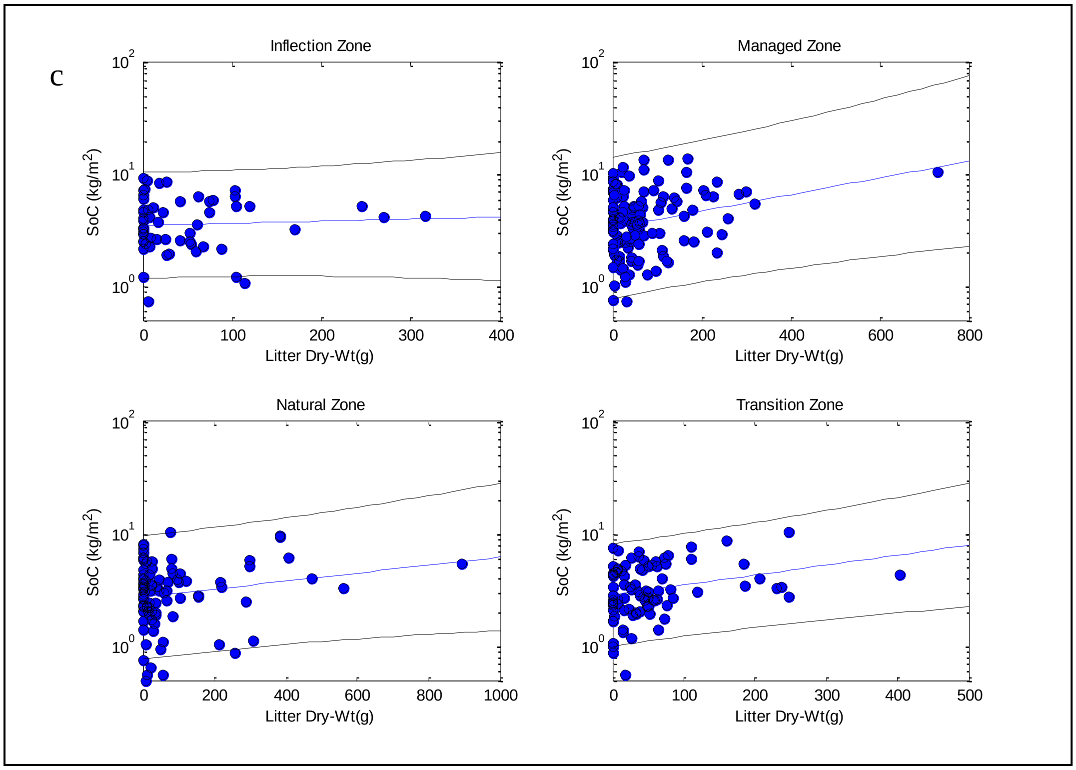
| Biome | Sampling Sites | Site–Zone Combinations | SOC (Mg/ha) | Relative Precision (%) | Zone Width (m) |
|---|---|---|---|---|---|
| **Upper Montane** | **19** | **49** | **56.9 (6)** | **11.9** | **14.8 (1.5)** |
| Managed | | 17 | 64.6 (9) | 13.8 | 3.6 |
| Inflection | | 11 | 49.5 (11) | 22.4 | 2.7 |
| Transition | | 9 | 53.4 (12) | 23 | 6.1 |
| Natural | | 12 | 55.5 (10) | 19.1 | 11.8 |
| **Lower Montane** | **55** | **137** | **36.0 (4)** | **11.7** | **13.8 (1.1)** |
| Managed | | 46 | 35.6 (6) | 15.2 | 3.7 |
| Inflection | | 27 | 35.2 (7) | 20.1 | 2.9 |
| Transition | | 30 | 34.9 (7) | 19.2 | 6 |
| Natural | | 34 | 38.1 (6) | 16.6 | 8.8 |
| **Prairie** | **44** | **103** | **42.1 (5)** | **11.3** | **15.0 (1.4)** |
| Managed | | 33 | 55.5 (6) | 11.5 | 3.7 |
| Inflection | | 12 | 41.4 (10) | 25.6 | 2.7 |
| Transition | | 31 | 36.7 (7) | 18 | 6.9 |
| Natural | | 27 | 32.2 (7) | 22 | 10.8 |

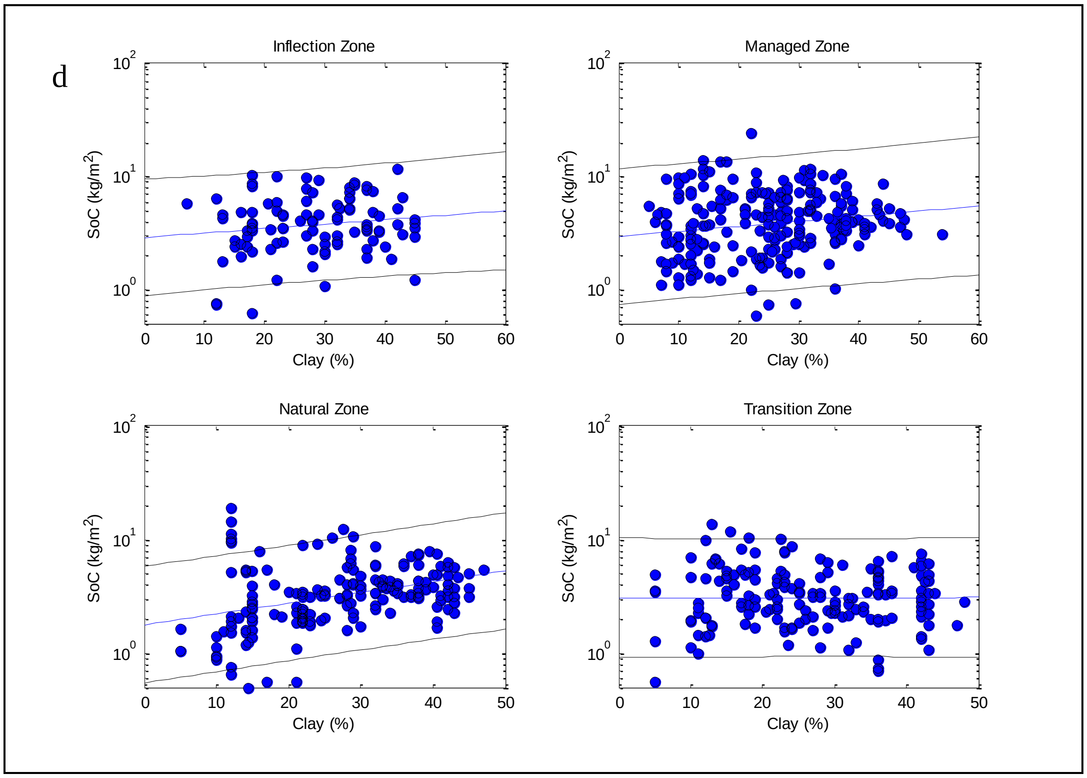
**Appendix D.** Regression plots by management zone for 4 variables significantly associated with log(SOC).

**Appendix D.** Regression plots by management zone for 4 variables significantly associated with log(SOC) (see Table 3 for regression coefficients). Regression lines are in the center; outer lines represent 95% confidence intervals. Variables include (a) annual precipitation; (b) grass (dry wt-g); (c) litter (dry wt-g); (d) clay (%).




c
Inflection Zone
Managed Zone
Natural Zone
Transition Zone
SoC (kg/m2)
Litter Dry-Wt(g)


d
Inflection Zone
Managed Zone
Natural Zone
Transition Zone
SoC (kg/m2)
Clay (%)

**Appendix E.** State Highways in New Mexico in which the number of visits to mow were $\geq$ 0. 5 than the mean number of visits for the District where the highway is found.

**Appendix E.** State Highways in New Mexico in which the number of visits to mow were $\geq$ 0. 5 than the mean number of visits for the District where the highway is found. Reduction in miles mowed/year represents how much less mowing would be required if the number of visits was reduced to the District mean. Data to derive the number of visits were from the NMDOT Highway Maintenance Management System database, 1998–2011.

| Highway | District | Visits/Year | Visits>District Mean | Reduction in Miles mowed/Yr |
|---|---|---|---|---|
| 78 | 1 | 3.50 | 1.26 | 17.67 |
| 169 | 1 | 4.19 | 1.95 | 17.59 |
| 211 | 1 | 3.82 | 1.58 | 7.92 |
| 293 | 1 | 2.94 | 0.70 | 2.11 |
| 20 | 2 | 3.26 | 0.99 | 20.87 |
| 37 | 2 | 2.97 | 0.71 | 9.17 |
| 42 | 2 | 3.29 | 1.02 | 0.00 |
| 55 | 2 | 3.10 | 0.83 | 8.29 |
| 89 | 2 | 2.81 | 0.54 | 5.42 |
| 114 | 2 | 3.04 | 0.77 | 34.63 |
| 203 | 2 | 3.33 | 1.06 | 7.43 |
| 206 | 2 | 2.91 | 0.64 | 52.44 |
| 209 | 2 | 2.86 | 0.59 | 23.07 |
| 212 | 2 | 3.57 | 1.30 | 3.91 |
| 236 | 2 | 2.86 | 0.60 | 11.90 |
| 267 | 2 | 3.16 | 0.89 | 26.76 |
| 272 | 2 | 3.89 | 1.62 | 9.71 |
| 294 | 2 | 2.90 | 0.63 | 9.42 |
| 312 | 2 | 3.73 | 1.46 | 4.39 |
| 368 | 2 | 3.39 | 1.12 | 19.03 |
| 467 | 2 | 3.00 | 0.73 | 11.62 |
| 469 | 2 | 3.31 | 1.04 | 2.08 |
| 247 | 2 | 3.25 | 0.98 | 48.12 |
| 39 | 4 | 3.98 | 1.73 | 159.57 |
| 91 | 4 | 4.39 | 2.14 | 23.52 |
| 104 | 4 | 4.12 | 1.87 | 194.31 |
| 120 | 4 | 3.29 | 1.04 | 121.69 |
| 129 | 4 | 3.48 | 1.23 | 19.75 |
| 209 | 4 | 4.07 | 1.82 | 74.67 |
| 210 | 4 | 3.11 | 0.86 | 0.86 |
| 252 | 4 | 3.65 | 1.40 | 41.90 |
| 268 | 4 | 3.71 | 1.46 | 11.66 |
| 275 | 4 | 3.00 | 0.75 | 0.75 |
| 312 | 4 | 3.70 | 1.45 | 4.34 |
| 392 | 4 | 3.04 | 0.79 | 11.12 |
| 419 | 4 | 3.07 | 0.83 | 37.99 |

| Highway | District | Visits/Year | Visits>District Mean | Reduction in Miles mowed/Yr |
|---|---|---|---|---|
| 442 | 4 | 2.93 | 0.68 | 13.60 |
| 469 | 4 | 3.56 | 1.32 | 51.31 |
| 518 | 4 | 2.84 | 0.59 | 24.18 |
| 540 | 4 | 3.61 | 1.36 | 4.08 |
| 420 | 4 | 3.15 | 0.90 | 17.95 |
| 3 | 5 | 3.55 | 1.57 | 67.72 |
| 41 | 5 | 4.14 | 2.16 | 103.84 |
| 42 | 5 | 4.04 | 2.07 | 70.26 |
| 55 | 5 | 4.48 | 2.50 | 162.76 |
| 75 | 5 | 2.51 | 0.53 | 6.93 |
| 96 | 5 | 2.92 | 0.94 | 20.77 |
| 333 | 5 | 3.17 | 1.20 | 11.97 |
| 337 | 5 | 3.63 | 1.66 | 13.30 |
| 344 | 5 | 3.54 | 1.57 | 25.12 |
| 542 | 5 | 3.13 | 1.16 | 16.19 |
| 12 | 6 | 3.24 | 1.39 | 101.71 |
| 15 | 6 | 2.56 | 0.72 | 1.44 |
| 36 | 6 | 2.52 | 0.67 | 37.07 |
| 53 | 6 | 3.62 | 1.77 | 76.18 |
| 117 | 6 | 3.45 | 1.60 | 11.21 |

**Appendix F.** State Highways in New Mexico in which the number of passes to mow were $\geq$ 0.5 than the mean number of passes for the District where the highway is found.

**Appendix F**. State Highways in New Mexico in which the number of passes to mow were ≥ 0.5 than the mean number of passes for the District where the highway is found. Reduction in Miles mowed/year represents how much less mowing would be required if the number of passes was reduced to the District mean. Data to derive the number of passes were from the NMDOT Highway Maintenance Management System database, 1998–2011.

| Highway | District | Passes/Visit | Passes>District Mean | Reduction in miles mowed/Yr |
|---|---|---|---|---|
| 78 | 1 | 3.05 | 1.25 | 17.48 |
| 153 | 1 | 2.61 | 0.81 | 1.62 |
| 211 | 1 | 2.54 | 0.74 | 3.71 |
| 2 | 2 | 2.96 | 1.06 | 21.11 |
| 18 | 2 | 2.65 | 0.75 | 36.9 |
| 83 | 2 | 2.76 | 0.86 | 9.50 |
| 209 | 2 | 2.43 | 0.53 | 20.56 |
| 224 | 2 | 2.41 | 0.51 | 7.10 |
| 245 | 2 | 2.55 | 0.65 | 3.90 |
| 256 | 2 | 2.47 | 0.57 | 2.27 |
| 311 | 2 | 2.50 | 0.60 | 13.3 |
| 469 | 2 | 3.23 | 1.33 | 2.66 |
| 165 | 3 | 2.13 | 0.69 | 1.37 |
| 39 | 4 | 2.64 | 0.61 | 56.12 |
| 58 | 4 | 2.83 | 0.80 | 13.66 |
| 102 | 4 | 2.56 | 0.54 | 24.23 |
| 268 | 4 | 2.55 | 0.53 | 4.20 |
| 275 | 4 | 3.11 | 1.08 | 1.08 |
| 392 | 4 | 2.57 | 0.54 | 7.58 |
| 402 | 4 | 2.60 | 0.57 | 34.82 |
| 445 | 4 | 2.59 | 0.56 | 6.16 |
| 468 | 4 | 2.84 | 0.82 | 0.82 |
| 469 | 4 | 2.95 | 0.92 | 35.91 |
| 505 | 4 | 2.94 | 0.92 | 2.75 |
| 540 | 4 | 4.31 | 2.28 | 6.85 |
| 41 | 5 | 2.08 | 0.55 | 26.44 |
| 333 | 5 | 2.33 | 0.79 | 7.95 |
| 15 | 6 | 2.61 | 1.15 | 2.31 |
| 122 | 6 | 2.21 | 0.75 | 0.75 |
| 612 | 6 | 2.14 | 0.68 | 0.68 |

**Appendix G.** State highways in New Mexico in which the number of visits by mowers during the active growing period (July–September) was < 1.

**Appendix G.** State highways in New Mexico in which the number of visits by mowers during the active growing period (July–September) was < 1. Data to derive the number of passes were from the NMDOT Highway Maintenance Management System database, 1998–2011.

| State Highway | District | Visits During Active Period | State Highway | District | Visits During Active Period |
|---|---|---|---|---|---|
| 15 | 1 | 0.87 | 237 | 4 | 0.56 |
| 59 | 1 | 0.86 | 266 | 4 | 0.90 |
| 81 | 1 | 0.69 | 271 | 4 | 1.00 |
| 356 | 1 | 0.55 | 283 | 4 | 0.95 |
| 133 | 2 | 0.98 | 286 | 4 | 1.00 |
| 175 | 2 | 0.43 | 329 | 4 | 1.00 |
| 190 | 2 | 0.75 | 370 | 4 | 0.93 |
| 234 | 2 | 0.89 | 386 | 4 | 1.00 |
| 238 | 2 | 0.45 | 406 | 4 | 0.93 |
| 243 | 2 | 0.86 | 410 | 4 | 0.79 |
| 244 | 2 | 0.88 | 411 | 4 | 0.83 |
| 249 | 2 | 0.71 | 432 | 4 | 0.67 |
| 253 | 2 | 0.51 | 445 | 4 | 0.85 |
| 254 | 2 | 0.6 | 453 | 4 | 1.00 |
| 255 | 2 | 0.49 | 455 | 4 | 0.77 |
| 258 | 2 | 0.85 | 505 | 4 | 0.75 |
| 261 | 2 | 0.67 | 526 | 4 | 0.95 |
| 262 | 2 | 0.87 | 538 | 4 | 1.00 |
| 289 | 2 | 0.56 | 551 | 4 | 0.96 |
| 322 | 2 | 0.76 | 17 | 5 | 0.93 |
| 339 | 2 | 0.80 | 73 | 5 | 0.92 |
| 340 | 2 | 0.82 | 95 | 5 | 0.98 |
| 396 | 2 | 1.00 | 110 | 5 | 1.00 |
| 409 | 2 | 0.94 | 134 | 5 | 0.59 |
| 438 | 2 | 0.75 | 162 | 5 | 0.93 |
| 483 | 2 | 0.80 | 221 | 5 | 0.73 |
| 508 | 2 | 0.95 | 230 | 5 | 0.95 |
| 521 | 2 | 0.71 | 475 | 5 | 0.13 |
| 529 | 2 | 0.76 | 502 | 5 | 0.44 |
| 532 | 2 | 0.79 | 512 | 5 | 0.95 |
| 558 | 2 | 0.91 | 513 | 5 | 0.67 |
| 559 | 2 | 0.57 | 519 | 5 | 0.71 |
| 560 | 2 | 0.83 | 531 | 5 | 0.79 |
| 563 | 2 | 1.00 | 573 | 5 | 0.83 |
| 165 | 3 | 0.75 | 103 | 6 | 0.44 |
| 536 | 3 | 0.89 | 159 | 6 | 0.50 |

| State Highway | District | Visits During Active Period | State Highway | District | Visits During Active Period |
|---|---|---|---|---|---|
| 38 | 4 | 0.87 | 174 | 6 | 0.82 |
| 50 | 4 | 1.00 | 290 | 6 | 0.99 |
| 67 | 4 | 0.94 | 371 | 6 | 0.85 |
| 119 | 4 | 0.67 | 400 | 6 | 0.86 |
| 223 | 4 | 1.00 | 485 | 6 | 0.67 |
| 231 | 4 | 1.00 | 547 | 6 | 1.00 |
| | | | 566 | 6 | 0.93 |

**Appendix H.** State Highways in New Mexico in which the number of visits to chemically spray were $\geq$ 0. 5 than the mean number of visits for the District where the highway is found.

**Appendix H.** State Highways in New Mexico in which the number of visits to chemically spray were ≥ 0. 5 than the mean number of visits for the District where the highway is found. Reduction in Miles mowed/year represents how much less spraying would be required if the number of visits was reduced to the District mean. Data to derive the number of visits were from the NMDOT Highway Maintenance Management System database, 1998–2011.

| Highway | District | Visits/Year | Visits>District Mean | Reduction in Miles Sprayed/Yr |
|---|---|---|---|---|
| 55 | 1 | 2.58 | 0.34 | 6.51 |
| 78 | 1 | 3.5 | 1.26 | 17.67 |
| 169 | 1 | 4.19 | 1.95 | 17.59 |
| 293 | 1 | 2.94 | 0.70 | 2.11 |
| 20 | 2 | 3.26 | 0.99 | 20.87 |
| 37 | 2 | 2.97 | 0.71 | 9.17 |
| 42 | 2 | 3.29 | 1.02 | 0.00 |
| 55 | 2 | 3.10 | 0.83 | 8.29 |
| 89 | 2 | 2.81 | 0.54 | 5.42 |
| 114 | 2 | 3.04 | 0.77 | 34.63 |
| 206 | 2 | 2.91 | 0.64 | 52.44 |
| 212 | 2 | 3.57 | 1.30 | 3.91 |
| 236 | 2 | 2.86 | 0.60 | 11.90 |
| 246 | 2 | 2.77 | 0.50 | 34.23 |
| 267 | 2 | 3.16 | 0.89 | 26.76 |
| 272 | 2 | 3.89 | 1.62 | 9.71 |
| 294 | 2 | 2.90 | 0.63 | 9.42 |
| 312 | 2 | 3.73 | 1.46 | 4.39 |
| 467 | 2 | 3.00 | 0.73 | 11.62 |
| 469 | 2 | 3.31 | 1.04 | 2.08 |
| 247 | 2 | 3.25 | 0.98 | 48.12 |
| 39 | 4 | 3.98 | 1.73 | 159.57 |
| 91 | 4 | 4.39 | 2.14 | 23.52 |
| 104 | 4 | 4.12 | 1.87 | 194.31 |
| 129 | 4 | 3.48 | 1.23 | 19.75 |
| 209 | 4 | 4.07 | 1.82 | 74.67 |
| 210 | 4 | 3.11 | 0.86 | 0.86 |
| 252 | 4 | 3.65 | 1.40 | 41.90 |
| 268 | 4 | 3.71 | 1.46 | 11.66 |
| 312 | 4 | 3.70 | 1.45 | 4.34 |
| 402 | 4 | 2.61 | 0.36 | 22.15 |
| 419 | 4 | 3.07 | 0.83 | 37.99 |
| 518 | 4 | 2.84 | 0.59 | 24.18 |
| 420 | 4 | 3.15 | 0.90 | 17.95 |
| 41 | 5 | 4.14 | 2.16 | 103.84 |
| 42 | 5 | 4.04 | 2.07 | 70.26 |

| Highway | District | Visits/Year | Visits>District Mean | Reduction in Miles Sprayed/Yr |
|---|---|---|---|---|
| 55 | 5 | 4.48 | 2.50 | 162.76 |
| 75 | 5 | 2.51 | 0.53 | 6.93 |
| 96 | 5 | 2.92 | 0.94 | 20.77 |
| 333 | 5 | 3.17 | 1.20 | 11.97 |
| 344 | 5 | 3.54 | 1.57 | 25.12 |
| 542 | 5 | 3.13 | 1.16 | 16.19 |

**Appendix I.** State Highways in New Mexico in which the number of passes to chemically spray were ≥ 0.5 than the mean number of passes for the District where the highway is found.

**Appendix I.** State Highways in New Mexico in which the number of passes to chemically spray were ≥ 0.5 than the mean number of passes for the District where the highway is found. Reduction in Miles mowed/year represents how much less spraying would be required if the number of passes was reduced to the District mean. Data to derive the number of passes were from the NMDOT Highway Maintenance Management System database, 1998–2011.

| Highway | District | Visits/Year | Visits>District Mean | Reduction in Miles Sprayed |
|---|---|---|---|---|
| 78 | 1 | 3.05 | 1.25 | 17.48 |
| 153 | 1 | 2.61 | 0.81 | 1.62 |
| 211 | 1 | 2.54 | 0.74 | 3.71 |
| 83 | 2 | 2.76 | 0.86 | 9.5 |
| 165 | 3 | 2.13 | 0.69 | 1.37 |
| 39 | 4 | 2.64 | 0.61 | 56.12 |
| 58 | 4 | 2.83 | 0.8 | 13.66 |
| 392 | 4 | 2.57 | 0.54 | 7.58 |
| 445 | 4 | 2.59 | 0.56 | 6.16 |
| 468 | 4 | 2.84 | 0.82 | 0.82 |
| 333 | 5 | 2.33 | 0.79 | 7.95 |

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