The Devil's in bulk density: Considering USDA-NRCS data to estimate forest soil bulk density

Allan R. Bacon, Madison K. Akers, Josh Cucinella, Sabine Grunwald,
Eric J. Jokela, Marshal A. Laviner, Daniel Markewitz, & Jason G. Vogel

Introduction

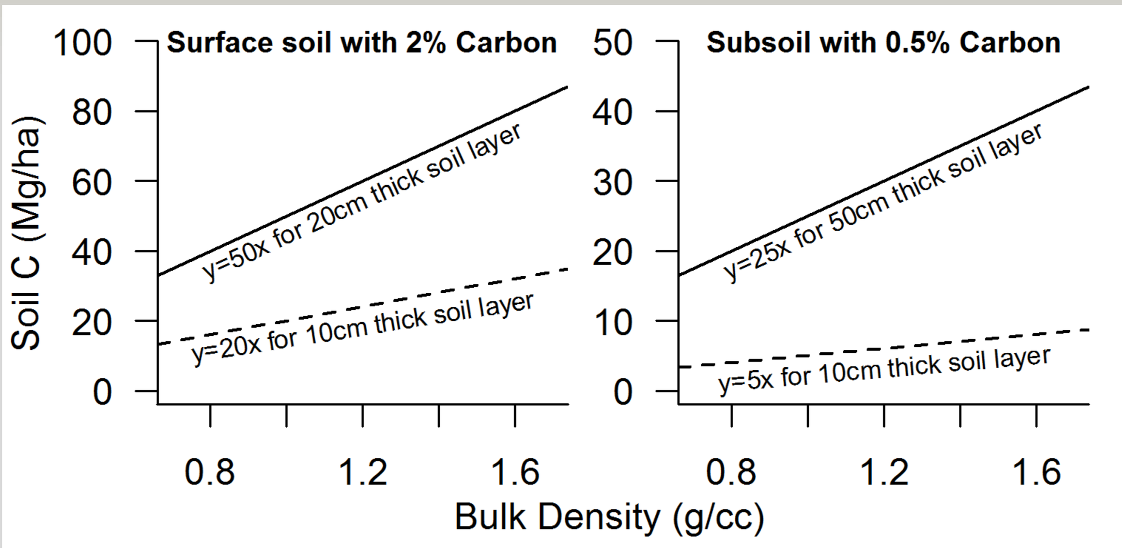

Figure 1. Linear relationship between soil bulk density and soil C content in hypothetical surface soil and subsoil layers with two thicknesses.

Bulk density (Db) is the mass of soil per volume of soil, often expressed in grams per cubic centimeter (g/cc). Beyond governing numerous edaphic processes, Db is a required multiplier when scaling elemental concentrations to contents in soil. Depending on a soil layer's thickness and C concentration a Db change of 0.1 g/cc may modify soil carbon (C) content estimates by approximately 5 Mg/ha (Figure 1). Considering that the C response of loblolly pine biomass to most contemporary experimental cultural treatments rarely exceeds 10Mg/ha, Db is a critical component of full ecosystem C budgets both within and beyond PINEMAP.

In the absence of direct Db observations an often employed tactic is to use Db observations from the USDA-NRCS National Cooperative Soil Survey (NCSS). The NCSS database contains more than 20,000 Db observations from various soil layers across the United States. NCSS observations can be extracted as point data and then stratified or modeled by a variety soil, geographic, and environmental factors to predict Db. Additionally, NCSS data underpin the popular Soil Survey Geographic (SSURGO) database which provides continuous Db estimates across most counties in the United States.

Our objectives are two-fold. First, we aim to create pedotransfer functions that predict Db values that have not been directly measured across the PINEMAP Tier II network. Second, we consider and evaluate, for the first time, the utility of NCCS observations to estimate Db of forest soils.

Methods

TABLE 1. LIST AND DESCRIPTION OF PREDICTOR VARIABLES FIT TO BULK DENSITY OBSERVATIONS IN THREE TYPES OF MODELS

Predictor Variable	Description	Db Above Models	Db Below Models	Taxonomy Models
depth	fixed depth of the Db record of interest (0-10,10-20,20-50, or 50-100cm)	✓	✓	✓
great group	great group of the profile that contains the Db record of interest (from SSURGO)	✓	✓	✓
great group mean	the depth and great group dependent mean Db of the NCSS database	✓	✓	✓
great group median	the depth and great group dependent median Db of the NCSS database	✓	✓	✓
particle size class	particle size family of the profile that contains the Db record of interest (from SSURGO)	✓	✓	✓
mineralogy class	mineralogy family of the profile that contains the Db record of interest (from SSURGO)	✓	✓	✓
Db above	direct observation of Db in soil layer above the Db record of interest	✓		
DAD above	fixed depth of Db above (0-10,10-20,20-50, or 50-100cm)	✓		
Db below	direct observation of Db in soil layer below the Db record of interest		✓	
DAD below	fixed depth of Db below (0-10,10-20,20-50, or 50-100cm)		✓	

To predict missing Db records we fit Db observations from the NCSS database and the PINEMAP Tier II network to modest and easily obtainable predictor variables with Random Forest models (Table 1). We created three types of models, each defined by a unique combination of predictor variables, to accommodate the various ways a missing Db record could be related to a Db observation within a given soil profile:
Db Above Models assume that that a Db observation is available above a missing Db record in the same soil profile,
Db Below Models assume that that a Db observation is available below a missing Db record in the same soil profile, and
Taxonomic Models assume that a Db observation is not available in the same soil profile as a missing Db record .

To evaluate the utility of NCSS Db observations to estimate forest soil Db we fit the all three model types (described above) to three distinct calibration data sets:
a **NCSS only** dataset that did not contained observations from the PINEMAP Tier II network,
a **PINEMAP Tier II only** dataset that did not contained observations from the NCSS, and
a **NCSS+ PINEMAP Tier II** dataset that contained observations from both sources.

Prior to analysis the entire NCSS database was subset geographically and taxonomically to conform to the PINEMAP Tier II network. Additionally, since NCSS Db observations were reported by genetic soil horizon, we calculated the depth weighted mean Db for the 0-10, 10-20, 20-50, and 50-100 cm fixed depths from the reported soil horizon tops and bottoms. We calibrated all nine Random Forest models (3 model types x 3 calibration data sets) by growing 2000 decision trees without pruning and identifying the best split at each decision node by randomly sampling one third of the input variables. We validated all nine models by comparing model Db predictions to Db observations in a validation data set comprised of a 30% random subsample of PINEMAP Tier II (Figure 3, Table 3). These validation data were not used for model fitting/calibration.

Central tendencies of Db in the NCSS database and the PINEMAP Tier II Network

TABLE 2. SUMMARY STATISTICS OF BULK DENSITY (g/cc) OBSERVATIONS FROM THE STRATIFIED NCSS DATABASE AND THE PINEMAP TIER II NETWORK

Depth	n	Mean	SD	%CV	Med	IQR	Min	Max	Skew
NCSS Database									
0-10	640	1.49	0.21	14	1.51	0.26	0.62	1.98	-0.8
10-20	711	1.57	0.17	11	1.58	0.19	0.74	2.02	-1.0
20-50	728	1.63	0.15	9	1.51	0.17	1.06	2.25	-0.1
50-100	691	1.67	0.16	9	1.68	0.20	1.10	2.09	-0.2
all depths	2770	1.59	0.18	12	1.61	0.22	0.62	2.25	-0.8
PINEMAP Tier II Network									
0-10	480	1.12	0.26	23	1.10	0.34	0.37	2.08	0.3
10-20	485	1.29	0.33	26	1.30	0.45	0.12	2.41	0.2
20-50	215	1.46	0.18	12	1.47	0.25	0.91	1.95	-0.1
50-100	195	1.46	0.19	13	1.46	0.23	0.73	2.08	-0.3
all depths	1375	1.28	0.30	24	1.30	0.43	0.12	2.41	0.0

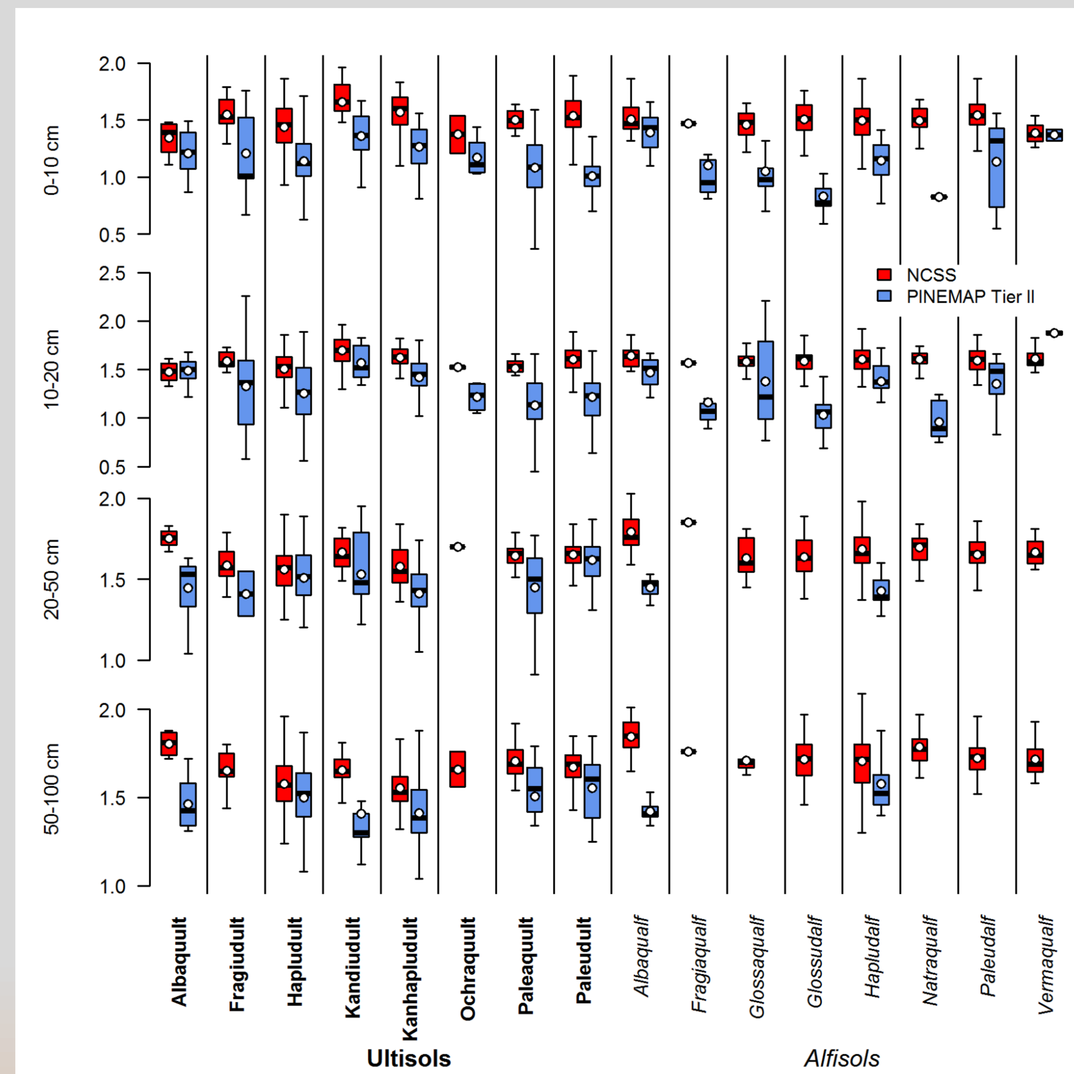

Figure 2. Bulk density observations (g/cc) from the stratified NCSS database and the PINEMAP Tier II network. Data are separated by soil taxonomy to include great groups in the Ultisol and Alfisol orders across the PINEMAP TIER II network.

Note that the 16 great groups presented here cover 80% of the PINEMAP Tier II network.

Comparing Db central tendencies in the NCSS database and the PINEMAP Tier II network clearly identifies the potential for NCSS observations to overestimate forest soil Db throughout the top 100 cm of soil.

Although land use information in the NCSS database is scarce, we suggest that the tendency for NCSS observations to be higher than those of the PINEMAP Tier II network reflects an inherent agricultural bias of NCSS data.

In the 0-10, 10-20, 20-50, and 50-100 cm depths across the entirety of both data sources mean Db is 33, 22, 11, and 14% higher respectively in the NCSS database while median Db is 37, 22, 3, and 15% higher respectively in the NCSS database. In the 0-10 and 10-20 cm depths these central tendency differences coincide with distribution differences where Db is slightly positively skewed in the PINEMAP Tier II network but highly negatively skewed in the NCSS database (Table 2).

At the soil taxonomic level of great group Db overestimates by the NCSS database are evident across a broad spectrum of soils (Figure 2). Out of the 49 paired comparisons in Figure 2, central tendencies from the PINEMAP Tier II network were higher than those of the NCSS database only three times.

Random Forest model validation

TABLE 3. VALIDATION STATISTICS FOR THE NINE RANDOM FOREST MODELS

Calibration Data	RMSPE (g/cc)	RPIQ	MPE (g/cc)	Error (%)
Db Above Models				
NCSS only	0.29	1.2	0.13	21
NCSS + PINEMAP Tier II	0.22	1.7	0.03	16
PINEMAP Tier II only	0.21	1.7	0.00	15
Db Below Models				
NCSS only	0.27	1.5	0.17	22
NCSS + PINEMAP Tier II	0.19	2.2	0.06	15
PINEMAP Tier II only	0.18	2.4	0.01	14
Taxonomy Models				
NCSS only	0.39	1.1	0.26	30
NCSS + PINEMAP Tier II	0.28	1.5	0.11	22
PINEMAP Tier II only	0.25	1.7	-0.01	19

RMSPE is the residual mean squared prediction error; a measure of prediction accuracy.
RPIQ is the ratio of performance to interquartile distance; a measure model performance.
MPE is the mean prediction error; a measure of prediction bias.

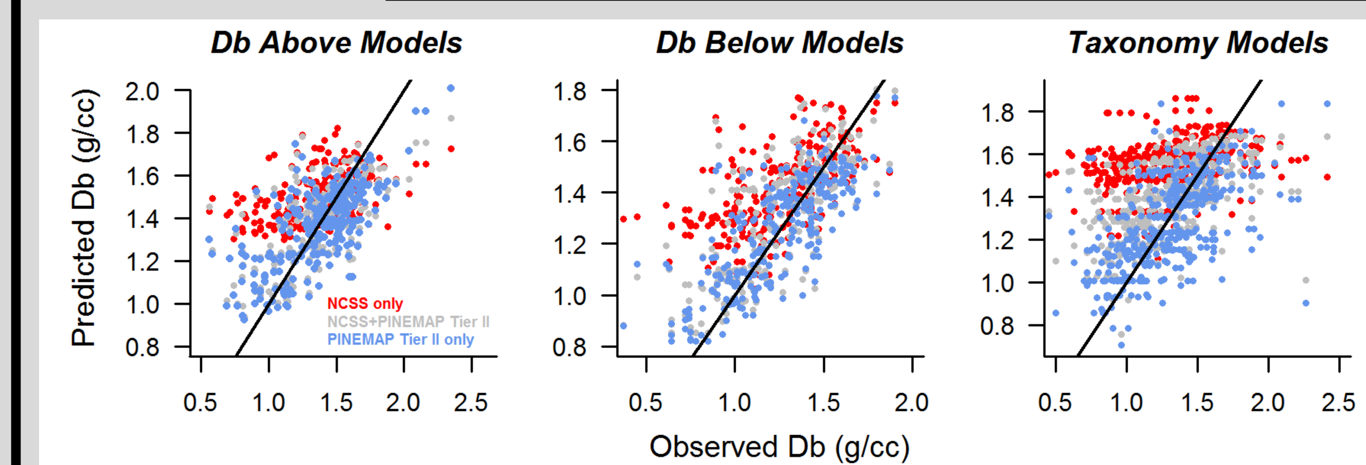

Figure 3. Observed vs. predicted bulk density in the PINEMAP Tier II network for three model types and three calibration data sets. The black line identifies a 1:1 relationship.

The best performing (RPIQ), most accurate (RMSPE), and least biased (MPE) Db models are those that were calibrated without NCSS observations (Table 1).

Using NCSS data for model calibration leads to positively biased forest soil Db predictions.

Models calibrated with only NCSS data tend to overestimate Db in the PINEMAP Tier II network by an average of 0.13 to 0.26 g/cc. In sharp contrast, models calibrated with only PINEMAP Tier II Db observations have essentially no bias as MPE ranges from -0.01 to 0.01 g/cc (Table 3). Across all models types positive bias introduced by the NCSS database is most pronounced when Db is less than approximately 1.5 g/cc (Figure 3).

Implications

The pedotransfer functions we've developed are critical for incorporating soils and their contents into plot-based ecosystem analyses of C and N across the PINEMAP Tier II network. An unprecedented region-wide sampling campaign by the PINEMAP field crews provides over 1300 observations of forest soil Db. These observations can be fit to extremely modest and easily attainable predictor variables to estimate ANY missing Db value across the PINEMAP Tier II network with negligible bias and approximately 14-20% error (Table 3), well within the published bounds of analogous Db prediction exercises [1,2,3,4].

Our regional comparison of Db from the PINEMAP Tier II network and the NCSS database clearly identifies that latter tends to overestimates Db in southeastern US forest soils. Since Db and elemental soil contents are positively related (Figure 1), utilizing NCSS (or SSURGO) derived Db will positively bias soil content estimates of forest soils. Considering this bias and its potential implications to soil and ecosystem budgets is important to regional modeling efforts within PINEMAP as well as any investigations external to PINEMAP that use NCSS derived Db.

References

[1] Sequeira, C.H., et al. "Predicting soil bulk density for incomplete databases." Geoderma 213 (2014): 64-73.
[2] De Vos, B., et al. "Predictive quality of pedotransfer functions for estimating bulk density of forest soils." Soil Science Society of America Journal 69.2 (2005): 500-510.
[3] Huang, S., et al. "A critical look at procedures for validating growth and yield models." Modelling forest systems (2003): 271-293.
[4] Nemes, A.B.,et al. "Ensemble approach to provide uncertainty estimates of soil bulk density." Soil Science Society of America Journal 74.6 (2010): 1938-1945.