Neutron Moisture Meter Calibration

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Introduction

The neutron moisture meters (NMMs) used by the Jornada LTER to measure soil water content for the NPP and LTER-I transect studies use neutron scattering techniques to relate changes in thermalized neutrons to changes in soil water content. Significant benefits of the NMM include low measurement error (stderr < 0.01 $m^3 m^{-3}$), large measurement volumes, and insensitivity to salinity or ion exchange capacity (Gardner 1986, Hignett and Evett 2002, Evett et al. 2007). The calibration curve previously used by the LTER was created in 1990 at one location near the mid-point of the LTER-I transect. At that time, the main methodological reference suggested that soil specific calibrations were not necessary (Gardner 1986). However, more recent methodological volumes strongly suggest soil specific calibrations be used due to influences of soil bulk density and mineralogy on the concentration of thermalized neutrons (Hignett and Evett 2002).

Thus, soil-specific calibration curves were needed for accurate soil water content measurements at Jornada LTER NMM studies. To more accurately measure soil water content at the Jornada LTER, we undertook developing soil specific calibration equations. We also developed an approach to facilitate collection of shallow soil water content data with the NMM. These efforts are thoroughly documented in the Thesis by Crossland (2012). We provide here a summary of the work done by Crossland (2012) as well as final guidance on best calibration equations for application to the LTER NPP study.

Methods

Access tube installation

We installed paired NMM access tubes to collect calibration data at each of the 15 NPP sites. In 2004, the USDA-NRCS excavated soil pits adjacent to the NPP sites, collected samples for laboratory analysis, and described the soil profiles. The NMM access tubes used for this study were located in undisturbed ground adjacent to the location of the 2004 NRCS soil pits, except in the Mesquite sites. At sites M-RABB and M-NORT, the NRCS profiles were located directly in the middle of a coppice dune. The proposed irrigation treatments would not be possible in the coppice dunes. Additionally, based on data from the NRCS, the shallow depths at the IBPE site were similar in properties to the coppice dunes. Therefore, we conducted the calibrations at M-RABB and M-NORT in the coppice dune interspaces. Based on soil cores taken from within the sites, the NRCS soil pit at M-WELL was not representative of the NPP site. Therefore, we did not locate the access tubes adjacent to the NRCS pit but instead located them west of the NRCS pit in a location where, based on auger holes, the soils appeared similar to the soils observed within the NPP site.

Calibration NMM access tubes were installed in the summer of 2006. Aluminum irrigation pipe of the same material and geometry as currently installed in the LTER NPP plots was used for the calibration access tubes (55 mm outside diameter, 2 mm wall thickness, and 340cm in length). The two access tubes at each site were installed approximately 2 m apart. This spacing was selected so that access tubes were close enough so soils would likely be similar but far enough apart so that installation and sampling disturbance would not affect the adjacent tube. To insert tubes into the soil, holes were bored using a manual bucket auger with an outside diameter of 55 mm, except in petrocalcic or other hard soil conditions. In these hard soils, a trailer mounted Giddings screw power auger was utilized with an outside diameter of 60 mm. Holes at each site were augured to a depth of 315 cm (if possible) to ensure the neutron source at the 300cm reading was not touching soil at the bottom of the hole. To minimize soil surface disturbance, a board 1.5m x 1.5m with a circular hole in the middle was placed on the ground during tube installation.

Despite our best efforts to minimize gaps, there was often a 2-5mm gap around the access tube after installation. It has been shown that there is an effect of gap between access tube and soil on neutron counts (Li et al. 2003). To minimize this effect soil that was being removed from the hole was placed in piles on a tarp grouped by horizon. The soil was sieved through a 2 mm sieve and then poured into the gap around the access tube with an attempt to replace soil to corresponding depths. During excavations that occurred during calibration procedures, no voids were observed between the access tube and soil.

Treatment Application

To achieve a wide spread in water contents, we artificially wet the soil profile at one access tube (wet treatment) and sampled the other access tube when the soil conditions were naturally dry (dry treatment). To wet the soil profile around the wet treatment access tube, we built a low dike (approximately15 cm tall) around the down slope access tube. This created a small basin approximately 1 m across with the wet treatment access tube in the middle. Water was applied to the wet treatment repeatedly over a period of a few weeks in the winter of 2006-07. The wet treatments were applied during the winter to minimize water loss due to evaporation and transpiration. During application, a small board was placed on the soil surface within the basin to prevent soil surface disturbance during water application. We attempted to wet the entire soil profile to near maximum VWC measured by the LTER. This was achieved for most depths at most sites. We waited three days after the last water application before sampling to allow time for rapid drainage to occur, thereby preventing any rapid changes in profile moisture content during sampling. Long-term soil water content from the NPP sites indicates the driest soil conditions occur in the spring. Site readiness for the dry treatment sampling was determined in a similar manner as the wet treatment except we were waiting until field measurements were near long-term minimum contents, which were met in the spring of 2008.

Sampling

The Jornada LTER uses two Campbell Pacific Nuclear Corporation model 503DR with 50mci Americium-241/Beryllium neutron source. All calibrations were done using the primary NMM (Serial #3900). The LTER keeps a backup NMM (Serial # 7085) to use when the primary probe is unavailable (not functional or sent in for updates). To facilitate cross-calibration of the two LTER NMM probes, we used paired counts in water (55 gallon drum) and paired dry treatment measures.

For both wet and dry treatment sampling periods, paired NMM counts and directly measured VWC were collected. Neutron probe standard counts were taken each day on a depth control stand described in (Evett et al. 2007). Standard counts are taken to test probe function and to account for any temperature effects on fast neutron generation. After the standard counts were taken, the depth control stand was placed over the access tube and the radioactive source lowered into the access tube. Neutron counts were taken every 15cm from 15cm to 120cm depth and at 30cm intervals from 120cm to 300cm or the maximum access tube depth.

Once neutron counts were completed a trench was excavated immediately adjacent to the NMM tube sampled to allow for direct measurements of soil water content. Two volumetric soil samples were taken at each NMM sampling depth (8 to 14 depths per treatment per site) by inserting a soil core (57.5 mm diameter x 50 mm deep) horizontally and immediately adjacent to the access tube. To minimize moisture loss from the trench face prior to sampling, of particular concern during wet treatment measurements, ~10cm of soil was removed from the face of the trench immediately before a soil core was taken. This removed soil that was exposed to some air drying and created a flat surface to ensure an accurate volume of soil was sampled. Soil in the core was them immediately transferred to a soil tin and sealed. Non-volumetric (grab) samples were collected at the same depths for texture and carbonate analysis. It took anywhere from 5 to 9 hours from the time the last neutron probe reading was taken to complete soil sampling of one treatment at one site.

At some sites (C-GRAV, M-WELL, and G-IBPE) depths were encountered where sampling with soil cores was not possible due to presence of a petrocalcic horizon or large gravel. When a petrocalcic horizon was encountered a soil clod was collected and sealed in a soil tin for later volume measurement. When a gravelly soil was encountered, a modified irregular hole method was used to measure soil volume, similar to the method described by Flint and Childs (1984). A bench (~20cm x 20cm) was excavated and a frame with foam on the bottom and a circular hole was anchored to the surface of the bench by inserting threaded rods at the corners of the frame into the soil and securing with wing nuts. Plastic 6 mm beads (AirSoft BB gun ammunition) were poured into the frames circular hole level with the top of the frame and then poured into a graduated cylinder to determine the volume. This served as a tare volume accounting for the soil surface roughness. Next, soil was removed from the frame hole and sealed into a large tin and beads were again poured into the hole, removed and volume measured. The first volume (tare) was subtracted from the second volume to obtain the volume of soil removed from the bench.

Laboratory Analysis

Soil gravimetric water content (GWC) and bulk density (BD) were determined for all volumetric soil samples. GWC was measured by oven drying open soil tins at 105ºC for 24 hours (Gardner

1986). The volume of the core (129.84cm³) was used to determine the bulk density (BD) of the soil sample by taking the oven dry weight of the soil sample and dividing it by the core volume. This enabled the conversion to volumetric water content (VWC) by multiplying the GWC and BD. This conversion to VWC was necessary because the neutron probe measures water content on a volume, not a mass basis. To determine BD and VWC for petrocalcic samples gathered using the clod method Archimedes principle was applied as described by Flint and Flint (2002).

To facilitate extrapolation of calibration equations based on soil properties, soil texture and calcium carbonate were determined for each calibration depth. Because soil samples used to assess water content were subjected to oven temperatures and potential structure alteration, the grab samples were used to determine soil particle size distribution and calcium carbonate ($CaCO_3$) content. Particle size analysis was determined by the hydrometer method (Gee and Or 2002) and $CaCO_3$ was measured by the digital manometer method (Horváth et al. 2005). Soil samples for $CaCO_3$ analysis were placed in a shatter box to break down aggregates and ensure a quick reaction. Hydrochloric acid was applied to a weighed sample in a sealed reaction vessel and the amount of CO_2 evolved was measured with a digital manometer. Due to time restraints, laboratory analyses for carbonates and texture were only completed on wet treatment grab samples. We assumed wet and dry treatment properties were the same in analyses.

Statistical Analysis

Prior to performing statistical analysis, data was inspected and outliers removed. Data was examined for outliers by plotting VWC, soil properties, and neutron count by depth. There were two primary causes of errant data points we were concerned about. First, soil volume measurements are difficult to complete precisely. Examination of the data suggests that BD was greatly underestimated during dry treatment sampling at P-COLL (most BD < 1). P-COLL is a vertic soil with large and extensive cracks occurring between soil peds. During dry sampling, it is likely that while inserting the core into the dry and very hard clay soil, soil in front of the cutting edge of the core was pushed back (collapsing cracks ahead), resulting in an under sampling of soil mass. Wet treatment BD's measurements were more reasonable. Both wet treatment and NRCS BD measurements indicate there is little variability in BD with depth. Therefore, the average BD from the entire P-COLL wet treatment profile was used in converting GWC to VWC for the P-COLL dry treatment. A total of six other BD outliers were removed from other sites. Second, due to heterogeneity in water content with depth some sampling depths occurred on the boundary between horizons with contrasting water contents. Because the NMM reads a volume larger than that sampled directly, these measurements were excluded (seven in total).

Generalized linear models were used to compare the different approaches to calibration equation development (MIXED procedure; SAS version 9.2; depths > 15 cm only). The directly measured water content (VWC) was the dependent variable and NMM counts and the other class and continuous variables were independent variables. The three class variables considered were landform, NPP site, and horizon within site. Landform classes were developed by grouping NPP sites with similar landforms & parent material together (Monger 2006). Sites C-GRAV, P-TOBO and T-TAYL do not have any other sites with similar parent material so were grouped with others in similar landscape positions. Soil horizon classes within a site were developed initially based on NRCS profile descriptions and then subsequently refined (boundary depths adjusted and some horizons combined) based on texture, carbonate content, and VWC-NMM relationships. Continuous variables considered were measured soil clay and carbonate content (by weight). The multiple possible models for each approach (full and reduced models) were evaluated based on comparisons of AIC values among comparable models. AIC test statistics provide a method to select the best model among competing models based on information and likelihood theory where the model with the smallest AIC value is the best model (Burnham and Anderson 2002). Class and continuous variable based models were developed at three spatial scales: the entire basin, landform, and site. The same continuous variables were considered at each scale. The class variables were considered in a nested manner: all class variables were considered at the basin scale, only site and horizon at the landscape scale, and only horizon at the site scale. The two VWC samples taken at each depth were treated as subsamples. Each depth of each calibration tube was used as the experimental unit. Although treatments were not applied independently to the various depths within an access tube, we concluded treating each depth as an experimental unit was appropriate in this instance since we are not exploring new phenomenon but are simply developing calibration equations for a well-developed method.

Due to the known influence of soil surface proximity on shallow NMM readings, 15 cm depth models were developed separately of deeper depths. Due to lack of replication, the two 15 cm VWC samples from each tube were treated as independent samples for these models only. A similar procedure was used in model development as with deeper depths except no horizon model was considered (since there was only one horizon per site).

Results & Discussion

Model fit at different scales

Based on the approach taken, the best continuous property basin model (with lowest AIC value) includes terms for both clay and carbonates but not an interaction (Table 1). Similarly, the best class-based basin model includes both clay and carbonate classes but nothing else (Table 2). Somewhat surprisingly, it appears the best class-based model is actually better (base on AIC) than the best continuous property model. We tested a combined class-property model using the best models from each as a starting point but none of the combined models were better (based on AIC) than the landform model alone and only one (NMM Landform $CaCO_3$) was better than the best property model (AIC = -1081.3; RMSE = 0.035).

Table 1. AIC, root mean square error, and parameter estimates of top five (out of 9 considered) property-based regression models for entire basin. Predictions are in m^3 m^{-3}.

AIC	RMSE	Intercept	[1]NMM	[2]Clay	[2]$CaCO_3$	Clay x $CaCO_3$
-1079.2	0.036	-0.038	2.332E-05	-8.669E-04	-6.498E-04	
-1067.7	0.037	-0.046	2.267E-05	-7.199E-04		
-1065.1	0.037	-0.042	2.208E-05		-5.308E-04	
-1063.6	0.038	-0.048	2.171E-05			
-1059.3	0.035	-0.039	2.318E-05	-7.130E-04	-4.856E-04	-1.119E-05

[1]Neutron moisture meter counts.

[2]On per mass basis expressed as percent.

Table 2. AIC and root mean square error values for top five (out of 22 considered) class-based regression models for entire basin. Predictions are in m^3 m^{-3}.

AIC	RMSE	Model
-1105.8	0.033	[1]NMM [2]Clay [3]$CaCO_3$
-1098.6	0.035	NMM Clay
-1091.1	0.034	NMM Landform Clay
-1087.8	0.033	NMM Landform Clay $CaCO_3$
-1087.2	0.035	NMM Landform

[1]Neutron moisture meter counts as continuous variable.
[2]Four clay classes (0 – 5%, 5 – 10%, 10 – 20%, >20%).
[3]Three calcium carbonate classes (0 – 10%, 10 – 20%, > 20%, 3).

The results of the multiple model evaluation for sites within landforms show that the relationship between NMM readings and VWC for sites in the Sand Sheet and Bajada are dependent on soil attributes more so than in the other Landforms (Tables 3 & 4). For the multiple regression models based on continuous variables, the model with soil carbonates and clay were the best models for the Bajada and Sand Sheet respectively (Table 3). Based on AIC values, both class based models are a better fit for the data than the continuous variable models (using Site and clay class for the Bajada and Sand Sheet respectively; Table 4).

Table 3. AICc, root mean square error, and parameter estimates of top five (out of 9 considered) property-based regression models within each landscape unit. Predictions are in m^3 m^{-3}.

Landform	AICc	RMSE	Intercept	NMM[1]	[2]Clay	[2]$CaCO_3$	Clay x $CaCO_3$
Bajada	-334.9	0.026	-0.050	2.677E-05		-1.930E-03	
	-322.9	0.026	-0.048	2.681E-05	-4.003E-04	-1.890E-03	
	-318.5	0.031	-0.060	2.583E-05			
	-309.4	0.031	-0.050	2.611E-05	-1.726E-03		
	-305.9	0.026	-0.047	2.683E-05	-4.775E-04	-1.948E-03	6.385E-06
Playa	-144.4	0.031	-0.142	2.814E-05			
	-131.4	0.031	-0.151	2.779E-05	3.135E-04		
	-131.2	0.031	-0.142	2.814E-05		6.605E-06	
	-118.2	0.031	-0.152	2.776E-05	3.317E-04	9.294E-05	
	-103.5	0.030	-0.169	2.720E-05	9.282E-04	5.911E-03	-1.454E-04
Sand Sheet	-278.0	0.038	-0.031	2.335E-05	-4.168E-03		
	-269.6	0.042	-0.074	2.425E-05			
	-268.3	0.036	-0.019	2.360E-05	-4.414E-03	-4.580E-04	
	-256.9	0.042	-0.067	2.447E-05		-3.349E-04	
	-250.8	0.036	-0.016	2.359E-05	-4.723E-03	-5.684E-04	1.541E-05
Skirt	-362.8	0.020	-0.026	1.744E-05			
	-348.4	0.020	-0.025	1.747E-05	-5.826E-05		
	-347.3	0.020	-0.025	1.748E-05		-5.295E-05	
	-332.9	0.020	-0.025	1.749E-05	-3.109E-05	-4.781E-05	
	-313.3	0.020	-0.020	1.753E-05	-3.013E-04	-2.626E-04	9.802E-06

[1]Neutron moisture meter counts.
[2]On per mass basis expressed as percent.

Table 4. AICc and root mean square error values for top (out of 14 considered) class-based regression models for each landscape unit. Predictions are in m^3 m^{-3}.

Site	AICc	RMSE	Model
Bajada	-367.3	0.020	[1]NMM Site
Playa	-144.4	0.031	NMM
Sand Sheet	-285.2	0.034	NMM [2]Clay
Skirt	-362.8	0.020	NMM

[1]Neutron moisture meter counts as continuous variable.
[2]Four clay classes (0 – 5%, 1; 5 – 10%, 2; 10 – 20%, 3; 20%, 4).

The simplest model (just based on NMM counts) was the best model in most instances. There was no evidence that a continuous property based model performed better than the simple model at any site (Table 5). For the multiple model comparison of class-based models, the grouping by soil horizon came out as the best model for only three sites (M-NORT, M-WELL, and P-COLL; Table 6).

Table 5. AICc, root mean square error, and parameter estimates of top (out of 9 considered) property-based regression models within each site. Predictions are in m^3 m^{-3}. (Best model in all cases did not include soil properties.)

Site	AICc	RMSE	Intercept	[1]NMM
C-CALI	-69.6	0.025	-0.067	2.753E-05
C-GRAV	-29.7	0.015	-0.090	2.215E-05
C-SAND	-98.0	0.018	-0.067	2.863E-05
G-BASN	-74.8	0.012	-0.047	1.945E-05
G-IBPE	-40.9	0.037	-0.092	2.647E-05
G-SUMM	-102.8	0.016	-0.059	2.750E-05
M-NORT	-74.4	0.029	-0.066	2.277E-05
M-RABB	-57.8	0.029	-0.076	2.233E-05
M-WELL	-30.5	0.050	-0.066	2.638E-05
P-COLL	-45.2	0.026	-0.106	2.602E-05
P-SMAL	-29.1	0.020	-0.099	2.418E-05
P-TOBO	-23.6	0.027	-0.388	4.529E-05
T-EAST	-56.8	0.021	-0.038	1.913E-05
T-TAYL	-70.8	0.018	-0.026	1.795E-05
T-WEST	-78.3	0.017	-0.004	1.430E-05

[1]Neutron moisture meter counts as continuous variable.

Table 6. AICc and root mean square error values for top (out of 14 considered) class-based regression models for each site (for those different than Table 5).

Site	AICc	RMSE	Model
M-NORT	-75.3	0.024	[1]NMM [2]Horizon
M-WELL	-32.7	0.040	NMM Horizon
P-COLL	-57.0	0.011	NMM Horizon

[1]Neutron moisture meter counts as continuous variable.
[2]Genetic soil horizon at a site (horizons not grouped across sites) as a class variable.

Parameter evaluation

In all instances, the best model (based on lowest AIC value) is either a simple model with just an intercept and NMM count parameter or a model based on classes. The parameters for these models are presented in Table 7. For the basin-wide model, there is no evidence that classes high in clay (>10%) or low in carbonate (<20%) require individual adjustments to the intercept (based on overlapping 95% CI; Table 7; Fig. 1). Within landforms, the evaluation of the 95% CI also suggests some classes should be lumped. On the Bajada, only the effect of C-GRAV is different than the other sites (Fig. 2). For the Sand Sheet, only depths with <5% clay are different than the others (Fig. 3). For the other landform units, the best model only has an intercept and NMM term (Fig. 4). The best models for the individual sites are shown in Figures 5 through 9. For the Creosote (Fig. 5), Grassland (Fig. 6), and Tarbush sites (Fig. 7), the best model is a simple one without horizon or soil property adjustments.

Table 7. Best model effects and estimates for basin and landform scale models.

Scale	Effects		Estimate
Basin-wide			
	NMM		2.30E-05
	Clay		
	0 – 5%	a	-0.047
	5 – 10%	b	-0.062
	10 – 20%	c	-0.087
	> 20%	c	-0.087
	$CaCO_3$		
	0 – 10%	a	0.020
	10 – 20%	a	0.023
	> 20%	b	0
Landform			
Bajada			
	NMM		2.70E-05
	C-CALI	a	-0.0616
	C-GRAV	b	-0.0127
	C-SAND	a	-0.0557
	G-SUMM	a	-0.0553
Playa			
	NMM		2.80E-05
	Intercept		-1.42E-01
Sand Sheet			
	NMM		2.40E-05
	Clay		
	0 – 5%	a	-0.029
	5 – 10%	b	-0.083
	10 – 20%	b	-0.086
	> 20%	b	-0.096
Skirt			
	NMM		1.70E-05
	Intercept		-2.64E-02

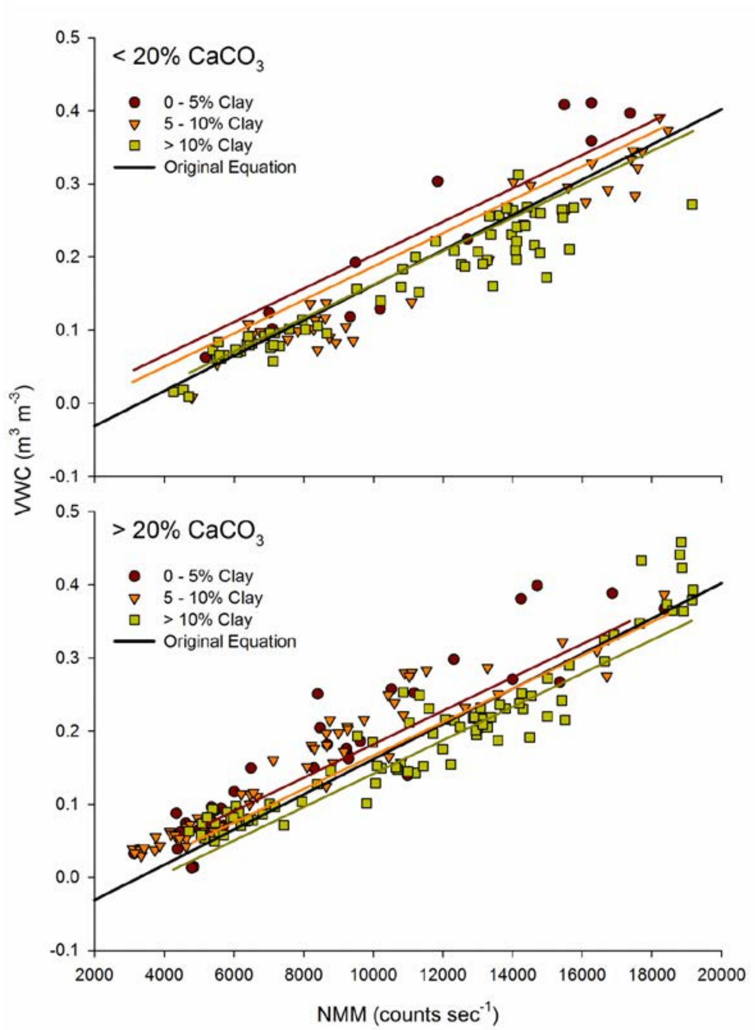

Fig. 1. Best basin-scale models compared to previous calibration equation.

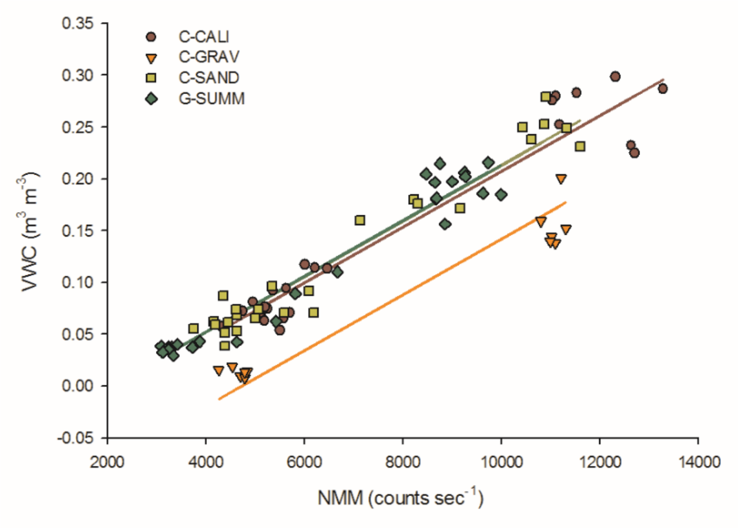

Fig. 2. Best landform-scale model for Bajada.

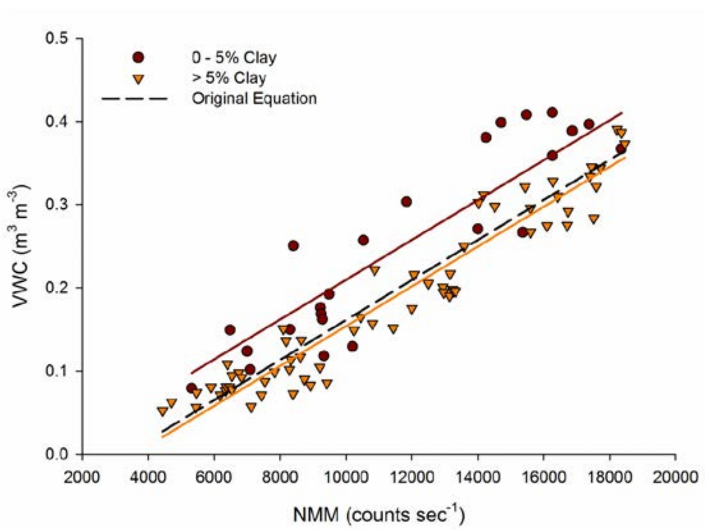

Fig. 3. Best landform-scale model for Sand Sheet.

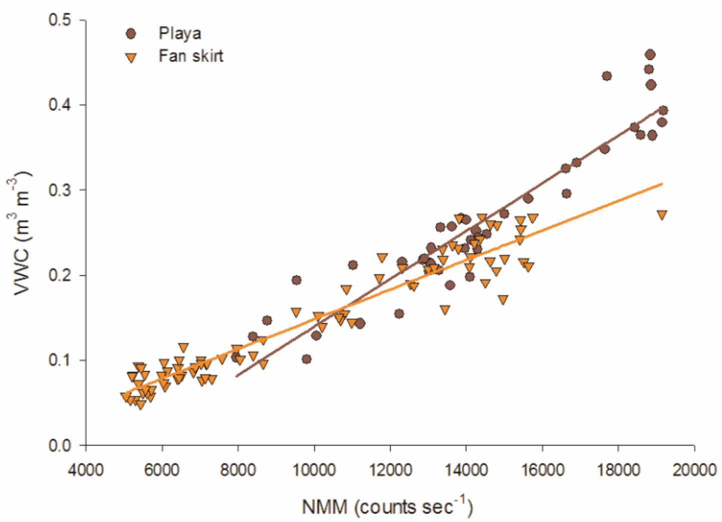

Fig. 4. Best land-form scale model for Playa and Skirt units.

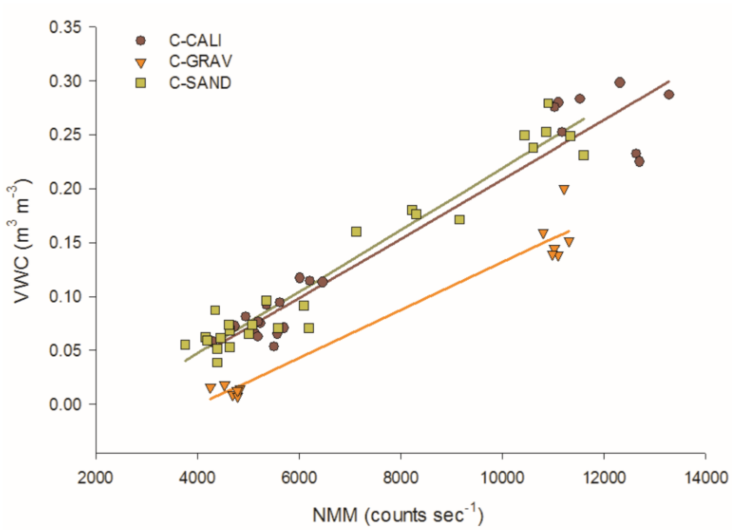

Fig. 5. Best site-scale models for creosote sites.

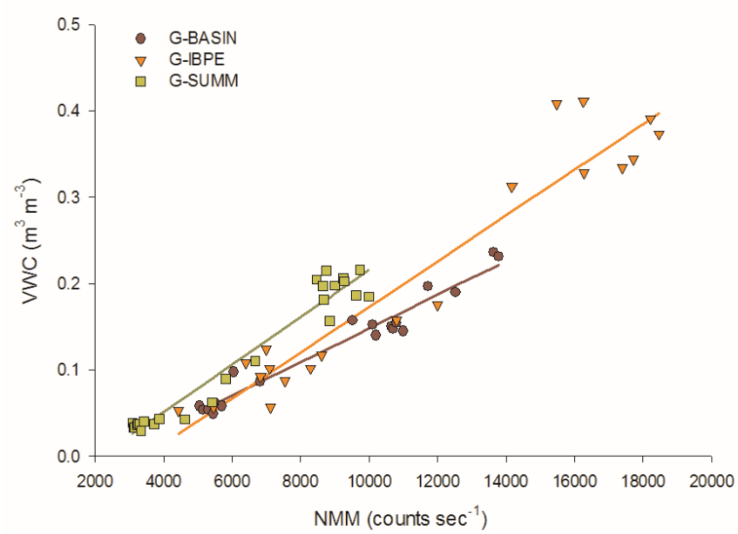

Fig. 6. Best site-scale models for grassland sites.

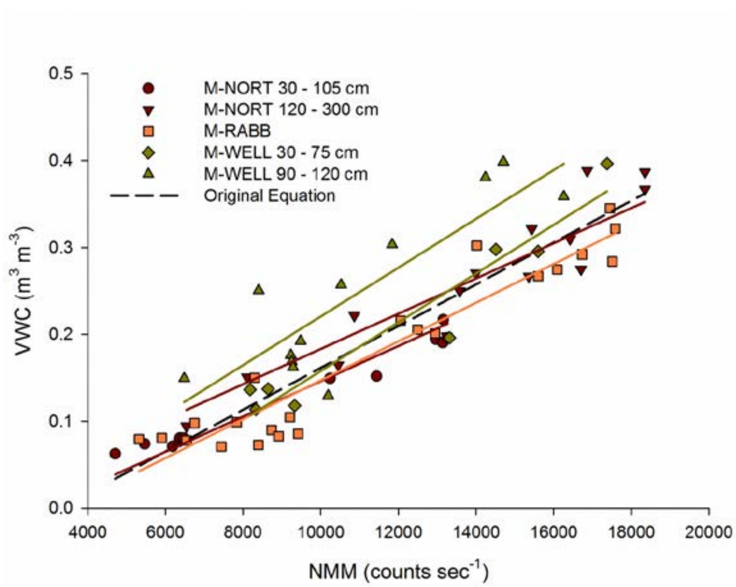

Fig. 7. Best site-scale model for mesquite sites.

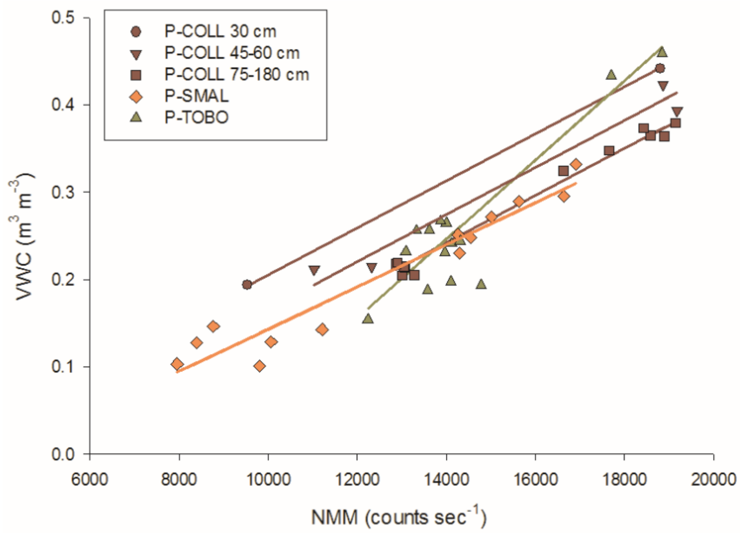

Fig. 8. Best site-scale models for playa sites.

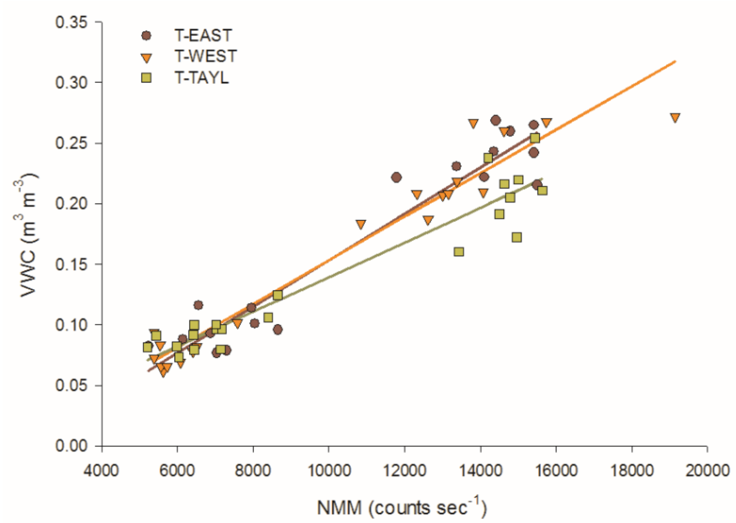

Fig. 9. Best site-scale models for tarbush sites.

Recommended models for the NPP sites

To decide on final calibration models, it is necessary to balance precision in estimates (low RMSE) with risk of calibrating based on erroneous data. We used the multi-scale model evaluation discussed above to develop recommended calibration equations for use by the Jornada LTER NPP research program. In developing our recommendations, we balanced the smaller root mean square error attained by site-scale models (e.g. site-scale models typically have lower RMSE than basin-scale model) and the increased confidence in model fitting by combining multiple sites. Direct measurement of VWC is problematic with typically low repeatability due to difficulty with bulk density sampling. This sampling noise, combined with concern about air gaps around access tube and uneven wetting of deep soils (e.g. P-TOBO; Fig. 8) or general large spread in the wet points (e.g. T-WEST; Fig. 9), makes applying site-specific equations problematic. However, the basin-wide model is likely unnecessarily broad with a larger than desirable RMSE (0.033 to 0.036 $m^3\ m^{-3}$). The landform-scale modelling approach provides a logical compromise with a lower RMSE (0.02 to 0.034 $m^3\ m^{-3}$) while still having a large enough sample size to convey confidence in the resulting equations.

For the playa sites, depths > 45 cm at P-COLL and all the depths at P-SMALL and P-TOBO should be combined together. The few really high VWC points we were able to collect at P-TOBO suggest this site should have a separate calibration but the current data does not support using a separate calibration equation. Due to likely fast neutron loss through surface cracks, it appears the 30 and 45 cm depths at P-COLL should have separate equations (Fig. 10). This approach gives us:

Playa sites (Except 30 cm at P-COLL): -0.1457 + 0.000028 x NMM

P-COLL 30 cm: -0.07972+ 0.000028 x NMM

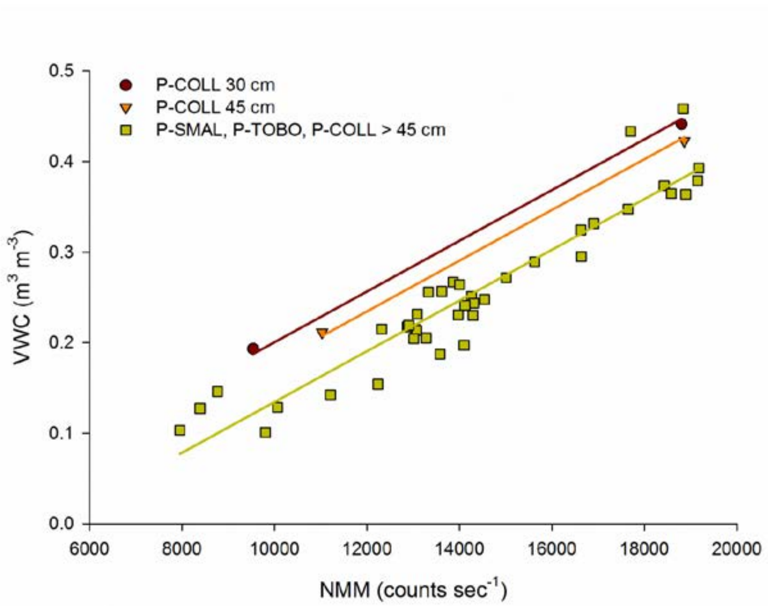

Fig. 10. Recommended model for Playa sites.

For the coarser upper Bajada sites (except C-GRAV), a simple model with shared intercept and slope can be used. We elected to use the site-specific model (including different slope and intercept; Fig. 11) for C-GRAV for three reasons: 1) This site has fairly different soils than the other Bajada sites (more rocks and different parent material), 2) the fit to the field data was very tight (Fig. 5), and using the Landscape-scale slope results in a considerable underestimation of the dry moisture contents (Fig. 2). For the fine-textured lower bajada and basin soils, we cannot see any consistent patterns that would require separate equations. Therefore we suggest combining data and using one calibration equation for these sites. The final recommended equations for these landforms are:

Bajada (except C-GRAV): -0.0626+ 0.000028 x NMM

C-GRAV: -0.0897+ 0.000022 x NMM

Skirt (including T-TAYL): -0.0264 + 0.000017 x NMM

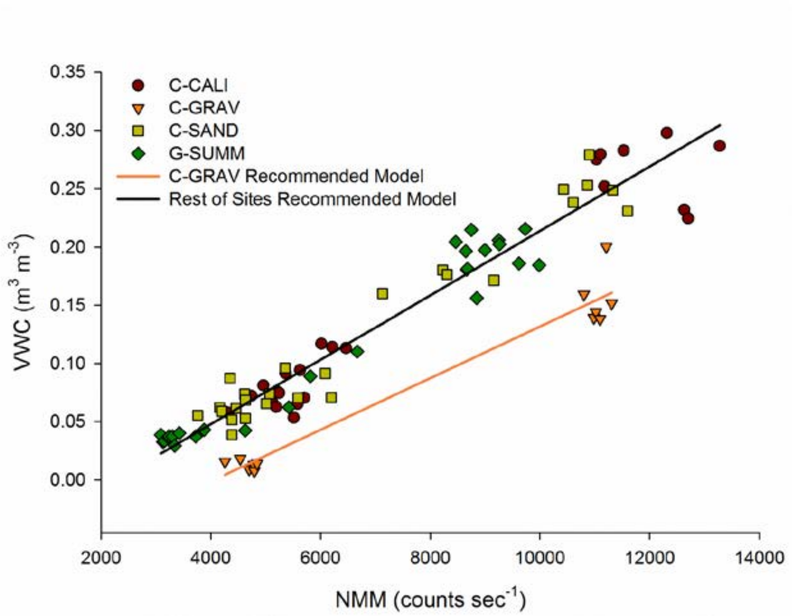

Fig. 11. Recommended models for Bajada sites.

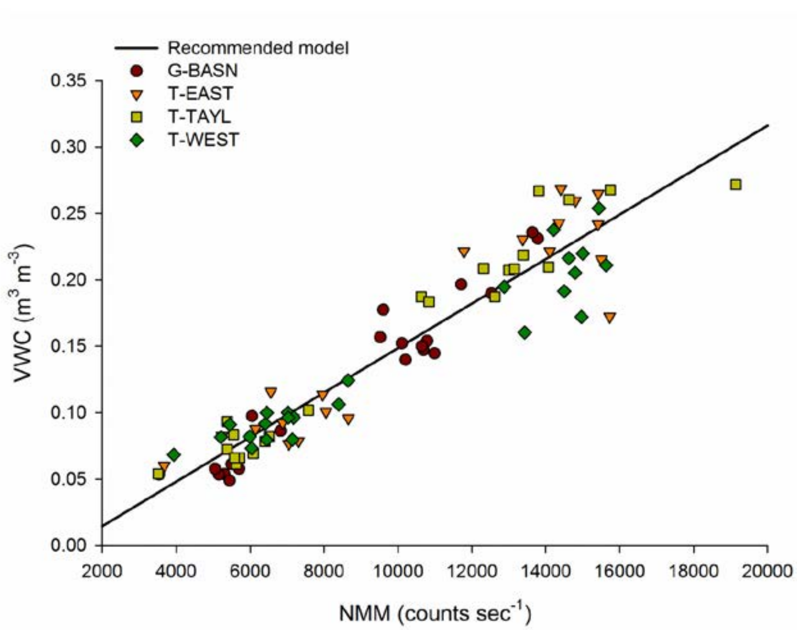

Fig. 12. Recommended model for Fan Skirt sites (with different symbols for each site to aid in interpretation).

Sites of the sand sheet have much more scatter around site-based equations, likely due to the marked heterogeneity in soil properties with depth. The within landform model suggests clay content is the property that best explains this scatter (Fig. 3; Table 7). However, the different in intercepts between low clay (< 5%) and other clay contents is rather large (~ 0.06 $m^3 m^{-3}$), the variability around the low clay mean is large (Fig. 3), and the pattern of depths with low clay unclear. For example, the low clay points are primarily deep and include C-horizons and horizons high in carbonates and/or gypsum. Additionally, application of a soil property specific equation is problematic since exact soil properties as the NPP measurement depths is unknown.

A compromise approach would be to employ a site specific model for the sand sheet sites. However, there is poor fit for many of these sites, especially M-WELL and M-NORT. Further examination reveals that the M-WELL equation is more similar to G-IBPE than the other mesquite sites (Table 5). This result is not unexpected since M-WELL and G-IBPE are close in space and both have less coppice dune formation that RABB or NORT. Therefore, we suggest combing the data from M-WELL and G-IBPE (Fig. 13), resulting in the following calibration equation for these sites:

M-WELL and G-IBPE: - 0.0696 + 0.0000258 x NMM

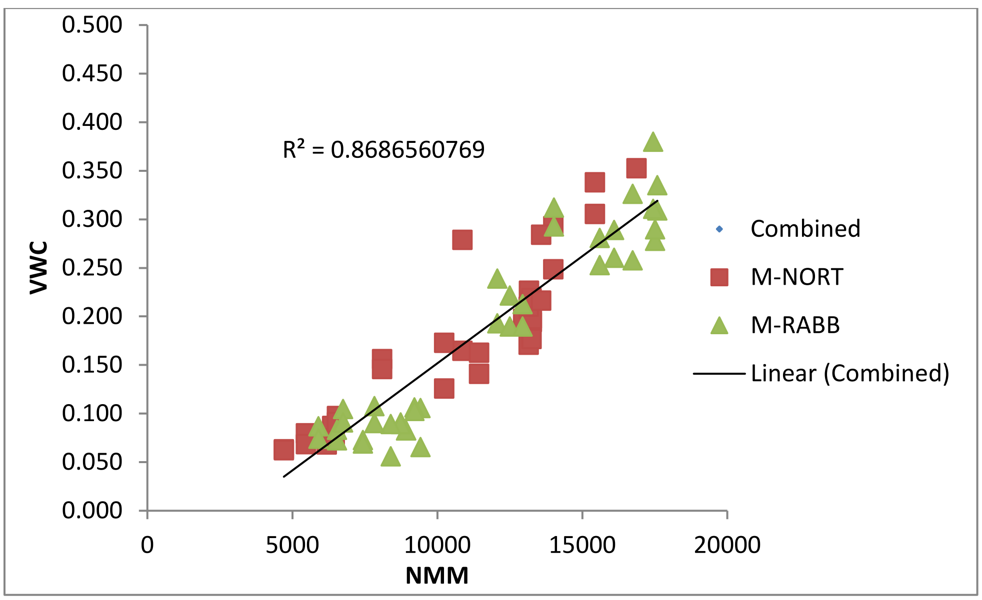

Fig. 13. Combined fit of all depths (> 15 cm) from G-IBPE and M-WELL.

Similarly, M-RABB and M-NORT are very close in space and are both dominated by coppice dunes. When combined, the data trends are similar (Fig. 14) and produce this recommended equation (after removing one outlier from the wet treatment at a depth of 210 cm at M-NORT):

M-RABB and M-NORT: - 0.0688 + 0.0000221 x NMM

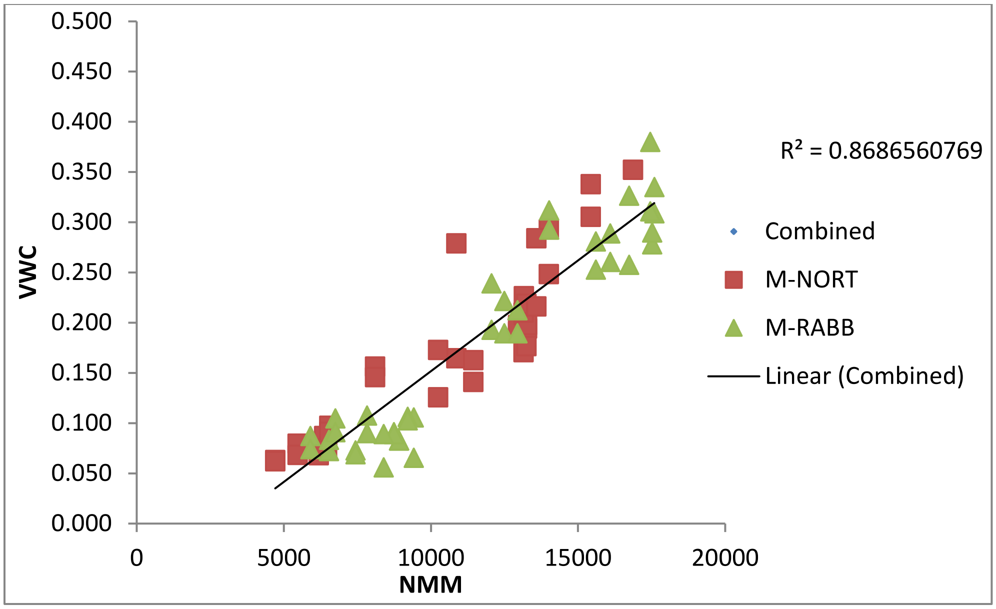

Fig. 14. Combined fit of all depths (> 15 cm) from M-NORT and M-RABB (after removing one outlier from the wet treatment at a depth of 210 cm at M-NORT).

Adjusting for probe decay and different probes used

An additional complication for applying these equations to past and future data are accounting for the different probes used and decay in the radioactive source. The radioactive source used by both probes is decaying and producing less fast neutrons each day. We can model this decay using the standard measurements collected by the LTER (Fig. 15). A logical approach is to adjust counts to a scale equivalent to when the calibration was developed. We can do this by calculating the difference in days between measurement date and the approximate calibration date and then multiply by the decay rate per day:

$$NMM_{Calibration} = NMM - (\Delta Days * A)$$

where $NMM_{Calibration}$ is the NMM reading adjusted to counts for the performance of the radioactive source when the calibrations were done, ΔDays is the days since the approximate date of calibrations (8/1/2007, negative for days prior and positive for days after, and A is the decay rate per day (-0.092 for the SN3900 and -0.1483 for the SN7085). So this adjustment slightly lowers counts prior to date of calibrations and slightly increases counts for later dates.

There is also the concern of the lower (~20% lower) standard counts for the 3900 probe prior to 1992. We suggest that this difference was due to a different approach to standard counts done by the LTER because such a large drop would be evident in the data. Inspection of several deep depths do not show a 20% change between pre- and post- 1992.

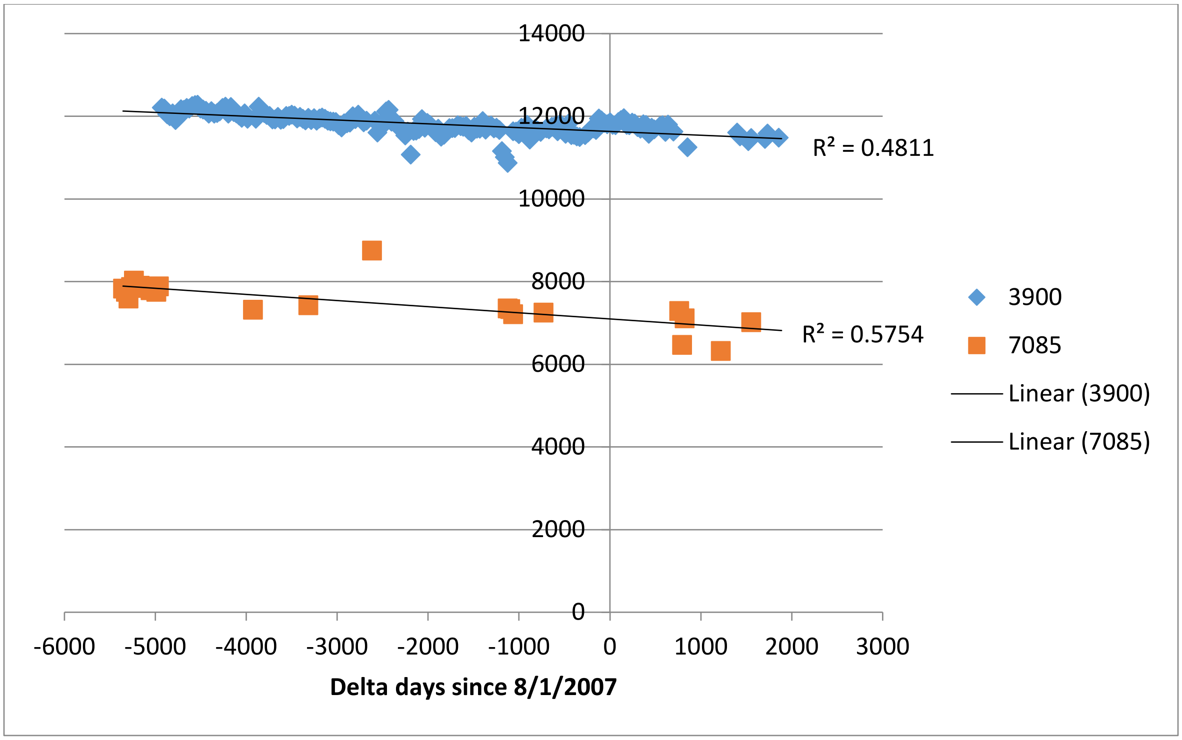

Fig. 15. Radioactive source decay since November 1992 with outliers removed. The regression line suggests the 3900 and 7085 probe is dropping 0.092 and 0.148 counts per day (respectively).

Calibration equations to convert NMM counts to VWC were done primarily with the 3900 probe. Thus, we need to convert the 7085 probe counts to 3900 equivalent counts (Fig. 16). The data collected here provides an excellent fit and a correction:

$$NMM_{3900} = 1.2624 * NMM_{7085} - 355.9$$

where NMM_{3900} is the 3900 equivalent counts and NMM_{7085} is the counts from the 7085 (after adjusting for decay).

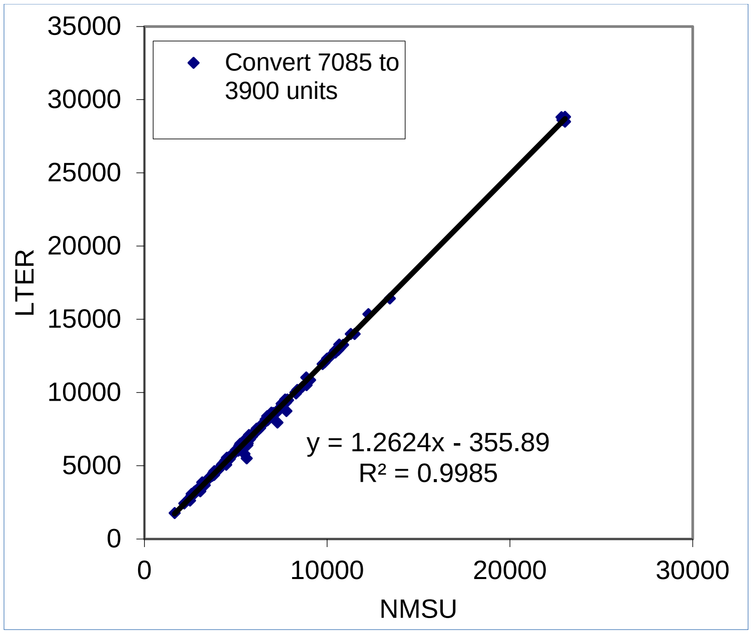

Fig. 16. Relationship between NMSU probe (7085) and LTER probe (3900) to be used to convert NMSU readings to scale matching the LTER probe prior to applying calibration equations.

Finally, due to heterogeneity in soils, particularly at M-RABB, M-NORT, and C-GRAV, we have several tubes with some depths showing negative moisture values when very, very dry. We expect this is primarily caused by intercept values being too low due to air gaps or other aspects of the soil that reduces the non-water thermalization. To account for this, we increase the intercept to make 99% of the values > 0 (based on the 1% quantile). We did not use the absolute minimum to limit the influence of outliers.

The steps are then:

1) adjust readings for decay,
2) adjust 7085 readings to 3900 equivalent (if necessary) and
3) apply NMM count to VWC equations.

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Appendix

SAS code used to apply calibration equations

```
libname NMMDB 'C:\Users\mduniway\Documents\Data\NPP_soil\JRN LTER NPP NMM
data.accdb';  run;

      proc datasets library = NMMDB;
      DELETE tblRawCountsLong tblVWC tblVWC_Cleaned;
      run; quit;

*Import Raw Data****************************************;

PROC IMPORT OUT= RawCounts
            DATAFILE=
"C:\Users\mduniway\Documents\Data\NPP_soil\RawCompiled.xlsx"
            DBMS=EXCEL REPLACE;
     RANGE="Counts$";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;

proc sort data = RawCounts ;
by Date     SerialNumber      ID  Cal Comments; run;

proc transpose data=RawCounts  out=RawCountsLong  name=DepthLabel ;
by Date     SerialNumber ID Cal Comments ;
var M10     M9     M8     M7     M6     M5     M4     M3     M2     M1;
run;
quit;

data NMMDB.tblRawCountsLong;
set RawCountsLong;
where Col1 > 0;
OrigCount = Col1;
If DepthLabel = "M10" then Depth = 30;
If DepthLabel = "M9" then Depth = 60;
If DepthLabel = "M8" then Depth = 90;
If DepthLabel = "M7" then Depth = 120;
If DepthLabel = "M6" then Depth = 150;
If DepthLabel = "M5" then Depth = 180;
If DepthLabel = "M4" then Depth = 210;
If DepthLabel = "M3" then Depth = 240;
If DepthLabel = "M2" then Depth = 270;
If DepthLabel = "M1" then Depth = 300;
keep Date SerialNumber ID Cal Comments Depth OrigCount;
run;

data NMMDB.tblVWC;
set NMMDB.qryForSASRawLong;
```

```
*Adjust for decay of 3900 so reading equivalent to function when calibrations
done;
If SerialNumber = 3900 then CntsAdj = OrigCount - ( DeltaDays * -0.092);

*Adjust for decay of 7085 so reading equivalent to function when calibrations
done;
If SerialNumber = 7085 then do;
      CntsAdj7085 = OrigCount - ( DeltaDays * -0.1483);
      *Convert 7085 counts into equivalent 3900 counts;
      CntsAdj = 1.2624*CntsAdj7085 - 355.89;
      end;

*Applying calibration equations to convert adjusted counts to VWC

SITE-ID     SITE  PhysioGroup
100   C-GRAV      C-GRAV
200   C-SAND      Bajada
300   C-CALI      Bajada
400   G-SUMM      Bajada
500   G-BASN      FanSkirt
600   G-IBPE      AP_NoCoppice
700   P-SMAL      Playa
800   P-COLL      Playa
900   P-TOBO      Playa
1000  T-TAYL      FanSkirt
1100  T-EAST      FanSkirt
1200  T-WEST      FanSkirt
1300  M-NORT      AP_Coppice
1400  M-RABB      AP_Coppice
1500  M-WELL      AP_NoCoppice;

If PhysioGroup = "Playa" then do;
      If (SITEID = 800 and Depth = 30) then VWC = -0.07972+ 0.000028 *
CntsAdj;
      Else VWC = -0.1457 + 0.000028 * CntsAdj;
      end;

If PhysioGroup = "C-GRAV" then  VWC = -0.0897+ 0.000022 * CntsAdj;
If PhysioGroup = "Bajada" then  VWC = -0.0626+ 0.000028 * CntsAdj;
If PhysioGroup = "FanSkirt" then  VWC = -0.0264 + 0.000017 * CntsAdj;
If PhysioGroup = "AP_NoCoppice" then VWC = - 0.0696 + 0.0000258 * CntsAdj;
If PhysioGroup = "AP_Coppice" then VWC = - 0.0688 + 0.0000221 * CntsAdj;
keep SerialNumber CAL comments Date DateFixed ID Depth CntsAdj VWC;
run; quit;

*These steps adjust for depths at tubes where have values less than zero;
*to minimize impacts of outliers, we just take the 1% value, if that is less
than zero;
*we then increase all the values by that much;

data VWC_for_summary;
set NMMDB.qryForSASVWCClean; run; quit;

Proc sort data=VWC_for_summary;
by  ID Depth ; run; quit;
```

```
Proc summary data = VWC_for_summary;
by  ID Depth;
output out = VWC_for_summary_p01
p1 (vwc) = VWC_01;
run; quit;

Data vwc_with_summary;
Merge VWC_for_summary VWC_for_summary_p01;
by ID Depth;
run; quit;

Data vwc_zerod;
set vwc_with_summary;
If VWC_01 < 0 then VWC = VWC - VWC_01;
drop VWC_01 _TYPE_ _FREQ_;
run; quit;

data NMMDB.tblVWC_Cleaned;
set vwc_zerod; run; quit;
```