

SOIL MOISTURE, BULK DENSITY, SOIL TEMPERATURE, AND SOIL SENSOR (VERIS 3100[®] AND GEONICS EM-38[®]) RELATIONSHIPS: PART 2 – BROOKINGS COUNTY SITE

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INTRODUCTION

Agronomists and natural resource managers are using soil sensors to aid in soil and natural resource management. There are a variety of comparable machines commercially available. Two widely used machines were compared and evaluated on two different fields in Eastern South Dakota as part of a regional precision farming project. This report describes the results from the Brookings County, SD field (Brookings field or site). The results for the Moody County, SD field (Moody field or site) were reported earlier (Malo et al., 2001).

The study objectives were:

1. Determine the relationships between two commercially available soil sensors (Veris 3100[®] and Geonics EM-38[®]).
2. Determine soil moisture impacts on soil sensor values.
3. Determine soil temperature impacts on soil sensor values.
4. Determine soil bulk density impacts on soil sensor values.

METHODS

During fall 2000, an experiment was done to compare two commercially available soil sensors and evaluate how soil properties impact the soil sensor readings. The field

studied was 160 acres (65 ha) and located in East Central South Dakota (Brookings County [44.229 °N, 96.652 °W]). The soils studied were Hapludolls, Calcudolls, Calciaquolls, and Endoaquolls. The soils formed in glacial till. Corn was raised in the field. The two soil sensors evaluated were Veris 3100[®] (Veris Technologies, Salina, Kansas) and the Geonics EM-38[®] (Geonics Ltd., Mississauga, Ontario, Canada). A cart was constructed and used to transport the EM-38[®] machine over the field at a height of eight in (20 cm) above the soil surface using the vertical configuration (0-100 cm soil depth). The Veris 3100[®] sensor went over the same area at the same time. The Veris 3100[®] unit gathered values from the shallow (VS), 0-1 ft [0-25 cm soil depth], and the deep (VD), 0-3 ft [0-90 cm soil depth], modes. Values were taken in late October.

At selected transects and landscape positions soils were sampled, morphologically described, and soil sensor readings were taken. Soil sensor values at selected sample locations are given in Table 1. At each selected sample location (17 sites) bulk density, soil moisture, soil temperatures, and morphologic information was measured. Bulk density values were determined using a three-inch (7.5 cm) long soil core with a 2-inch (5.1 cm) diameter from the center of each horizon and were based on field conditions. Soil temperatures were determined using a soil thermometer or an infrared thermometer. Soil temperatures were measured at the six-inch (15 cm), 12-inch (31 cm), 18-inch (46 cm), 24-inch (61 cm), and 30-inch (76 cm) depths immediately after the soil cores were pulled. After soil profiles were morphologically described, the separate horizons were bagged and soil moistures were determined. After soil samples were air-dried, the samples were sent to the University of Missouri for further detailed

soil characterization. Data were analyzed using Excel[®] and JMP[®] statistical packages. This paper reports the results from the field study and the soil sensor, soil moisture, bulk density, and soil temperature relationships.

RESULTS

Sensor Descriptive Statistics

Descriptive statistics for the EM-38[®] and Veris 3100[®] values are given in Table 2. The Veris 3100[®] Shallow had significantly lower mean sensor values when compared to Veris 3100[®] Deep or EM-38[®]. There was no significant difference in Veris 3100[®] Deep and EM-38[®] values. Both soil sensors (Veris 3100[®] Deep and EM-38[®]) evaluate the same soil area. The EM-38[®] had lower range, variance, and kurtosis values when compared to the two Veris 3100[®] measurements. The trends of these results were similar to those at the Moody site (Malo et al., 2001). The sensor mean, range, standard deviation, and maximum values were significantly lower in the Brookings field when compared to the Moody field. The Brookings field sensor values were more skewed and were more peaked, higher kurtosis values, than sensor values from the Moody field.

Soil Property Descriptive Statistics

Soil Moisture

Descriptive statistics for the studied soil properties are given in Table 3. At the time of sampling, the A horizon and the one-foot, 1F, average were significantly wetter (on a weight basis, Pw) than the other horizons or parts of the soil solum (Table 3). The trends of these results were similar to those in the Moody site (Malo et al., 2001).

Percent water content on a volume basis, Pv, showed a pattern similar to that found for Pw with significantly higher water contents in the A horizon and the 1F average when compared to the other depths and horizons studied. Soil moisture values were not skewed (values between -1 and 1). Kurtosis values were near 0 indicating a normal distribution (Table 3).

The soil moisture (both Pw and Pv) mean, range, standard deviation, and maximum values were significantly lower in the Brookings field than in the Moody field. The

Brookings field soil moisture values were more normal, kurtosis values near zero, than those at the Moody field (Malo et al., 2001).

Bulk Density (Bd)

Bulk density values increased significantly with increasing depth, with the C horizon having the highest values. These results were similar to those found in the Moody field (Malo et al., 2001) except for skewness. The Moody field values were skewed to the right (positive values) while the Brookings field values tended to be skewed to the left (negative values).

Soil Temperature

There was no significant difference in soil temperature with increasing soil depth on the date studied. The air temperatures were moderately cold (20-30 °F) the previous week and it was cloudy the two days prior to sampling. It was cloudy and cold (< 30 °F) on the day of sampling. The amount of residue cover on the soil in the Brookings field was significantly higher than found in the Moody field and that may have impacted soil temperatures. The soil temperature data was not skewed but the shape of the data distribution was flatter than normal (negative kurtosis values). These results were different from those found at the Moody site that was sampled one week earlier with much warmer conditions (Malo et al., 2001). The soil temperatures (mean, maximum, and minimum) at the Brookings field were significantly lower than those measured at the Moody field even though there was only seven days between sampling.

Sensor Comparisons

EM-38[®] values were significantly related to Veris 3100[®] Shallow and Veris 3100[®] Deep values (Table 4). Veris 3100[®] Shallow and Veris 3100[®] Deep were also significantly related to each other and had the highest adjusted R² values of all comparisons. There was no difference when Veris 3100[®] Shallow and EM-38[®] was compared to Veris 3100[®] Deep and EM-38[®]. These equations are able to predict soil sensor values within 4.5 to 5.1 mS m⁻¹. When compared to the Moody site (Malo et al., 2001), the EM-38[®] sensor at the Brookings site did a better job of relating to the Veris 3100[®] Shallow (adjusted R² values increased from 0.531 for the Moody field to 0.615 for the Brookings field) and a worse job

of relating to the Veris 3100[®] Deep (adjusted R^2 values decreased from 0.853 for the Moody field to 0.587 for the Brookings field). These differences may be due, in part, to soil parent material differences at the two sites. The Moody site has loess over glacial till while the Brookings site has glacial till parent material.

Correlation Results

The simple correlations between studied soil properties and soil sensor values are given in Table 5. The Brookings field had a moderate number of significant correlations between the soil properties studied. There were very few significant correlations for soil bulk density with other soil parameters measured while there were some significant correlations for soil moisture and soil temperature. Most significant correlations were found in layers other than the C horizon.

Soil sensor values were significantly positively correlated to Pw or Pv soil moisture in all horizons or layers except the C horizon and the EM-38[®] and Pv in the A horizon. The correlation coefficients were numerically similar when Pw and Pv soil moisture determinations were compared. These results were similar to the correlations found for the Moody field (Malo et al., 2001).

Soil sensors varied in their relationship to soil temperatures. The EM-38[®] did not correlate with soil temperatures at any depth studied while the Veris 3100[®] sensors were significantly positively correlated with soil temperatures at the 6- and 12-inch depths. These results were significantly different from those found in the Moody field where soil sensors and soil temperature were negatively correlated at all depths for all sensors (Malo et al., 2001).

The soil sensors studied were not correlated with soil bulk density except for the B horizon average bulk density (B Bd) with Veris 3100[®] Shallow (VS). These results were similar to those found at the Moody site (Malo et al., 2001).

Most of the significant correlations between soil temperature, ST, and soil moisture by weight, Pw, were found in the 1F layer and the A horizon. The correlations were all positive which was very different from those found in the Moody field where all the correlations

between Pw and ST were negative (Malo et al., 2001). The impact of climate and residue cover can be clearly seen in the comparison of these two sites. The Brookings site was subjected to cold, cloudy conditions the week prior to sampling and testing while the Moody site was subjected to warm, sunny conditions the week prior to and the day of sampling. The Brookings field had a dense cover of mature corn residue as compared to a sparse cover of mature soybean residue in the Moody field. Few correlations between ST and Pw were found in the B horizon and the 3-foot, 3F, zone. There were no significant correlations between ST and Pw in the C horizon.

There were only two significant correlations (both positive) between ST and percent moisture by volume, Pv, and those were at ST6 (soil temperature at the 6-inch depth) and ST12 with the 1F average Pv (Table 5). The Moody field had negative correlations between ST and Pv for all layers and ST depths studied (Malo et al., 2001). Possible reasons for these differences were discussed earlier.

There were only two significant correlations between soil temperature and bulk density (ST18, soil temperature at the 18-inch depth, and 1F Bd (1-foot average bulk density) and ST30 and 1F Bd). Soil moisture tests (Pw and Pv) were not significantly correlated with bulk density except for the B Bd and B Pv comparison where the relationship was positively correlated.

Soil Sensor Models

Based on the simple matrix correlation information stepwise multiple regression was used to examine the relationships between the soil properties studied and soil sensor values (Table 6). Equations using different combinations of soil properties were determined. Variables composed of parts of other variables were not included in the model if there was a significant correlation identified in Table 5.

The best multiple regression equations for single variables were Pw for the Veris 3100[®] Deep and EM-38[®] (adjusted $R^2 = 0.739$ and 0.884 , respectively) and Pv was best for the Veris 3100[®] Shallow (adjusted $R^2 = 0.830$). The lowest adjusted R^2 values for each sensor

were found with soil temperature and soil bulk density parameters.

When more than one type of parameter was added into the multiple regression equation, increased adjusted R^2 values were found, except for EM using bulk density and soil temperature. The best EM model included Pw and Bd, while the best VD model used Pv and ST. The best model for VS used Pw, Bd, and ST. These models were able to explain 43 to 93 % of the variability in sensor values and they are able to predict soil sensor values within 1.0 to 6.0 mS m^{-1} (Table 6). These results are similar to those found for the Moody field (Malo et al., 2001).

Soil Property Models Using Only Soil Sensor Data

Models were developed to predict soil properties using only soil sensor data. The models for soil moisture (Tables 7 and 8), bulk density, and soil temperature (Table 9) are given for the three soil moisture sensors studied.

Percent Moisture by Weight (Pw)

With the exception of the C horizon and the EM-38[®] sensor in the A horizon, models for Pw for each sensor had significant adjusted R^2 ranging from 0.234 to 0.482 (Table 7). The highest adjusted R^2 values were found with the B horizon for all sensors tested. All significant models were able to predict Pw within 1.5 to 2.7 %. For the significant models, the EM-38[®] sensor was able to predict, on average, Pw within 2.1 %, the Veris 3100[®] Shallow within 1.9 %, and the Veris 3100[®] Deep within 1.9 % for all soil layers studied. These results were comparable to those found in the Moody field even though the Moody field had a wider range of soil moisture values at the time of testing. When compared to the Moody field, the adjusted R^2 values for the Brookings field were lower, average adjusted $R^2 = 0.385$ versus 0.660 for Moody field (Malo et al, 2001). The average error was also lower at the Brookings site, 1.9 % versus 2.9 % for the Moody site, due to the reduced range of Pw values at the Brookings site.

Percent Water by Volume (Pv)

All significant Pv models for each sensor had significant adjusted R^2 ranging from 0.204 to 0.577 (Table 8). The highest adjusted R^2

values were found with the B horizon for each soil sensor tested. Significant models were able to predict Pv within 2.0 to 4.0 %. The EM-38[®] sensor was able to predict, on average, Pv within 3.2 %, the Veris 3100[®] Shallow within 3.0 %, and the Veris 3100[®] Deep within 2.7 % for all soil layers studied. When compared to the Moody field, the adjusted R^2 values for the Brookings field were lower, average adjusted $R^2 = 0.419$ versus 0.705 for Moody field (Malo et al, 2001). The average error was also lower at the Brookings site, 2.9 % versus 3.6 % for the Moody site, due to the reduced range of Pv values at the Brookings site.

Bulk Density (Bd)

There were no significant models found when soil sensors were used to predict soil bulk density in any layer or horizon studied. These results were similar to those found at the Moody site (Malo et al., 2001).

Soil Temperature (ST)

No significant models were found to predict soil temperature, ST, using the EM-38[®] or the Veris 3100[®] Shallow sensors. Significant models for ST6, ST12, and ST18 were found using VD. All the significant models for soil temperature (ST) had numerically low adjusted R^2 values (Table 9). The significant Veris 3100[®] Deep models were able to predict soil temperatures within 3.3 to 4.3 °F, with an average of 3.7 °F, for the date tested. These results were different from the Moody site where significant models were found for all sensors at all studied soil depths (Malo et al., 2001).

Soil Property Models Using Soil Sensor, ST6, and ST12 Data

Models were developed to predict soil properties using soil sensor and shallow soil temperature (ST6 and ST12) data. The models for soil moisture (Tables 10 and 11) and bulk density (Table 12) are given for the three soil moisture sensors studied. Only those parameters that are easily measured (soil temperature at 6- and 12-inch depths, EM-38[®], Veris 3100[®] Shallow, and Veris 3100[®] Deep) were used to develop the models included in Tables 10-12.

Percent Water by Weight (Pw)

All significant models for Pw for each sensor had moderate adjusted R^2 values (Table 10). The highest adjusted R^2 values were found in the 1F layer for all sensors, similar to Moody field findings (Malo, et al., 2001). No significant models including soil sensors were found for the C horizon. All models were able to predict Pw within 1.4 to 2.8 %. The significant models including the EM-38[®] and the Veris 3100[®] Shallow sensor were able to predict, on average, Pw within 1.9 % while the Veris 3100[®] Deep was able to predict within 2.1 % for all soil layers studied. When compared to the Moody field, the adjusted R^2 values for the Brookings field were lower, average adjusted $R^2 = 0.514$ versus 0.756 for the Moody field (Malo et al, 2001). The average model error was also lower at the Brookings site, 2.0 % versus 2.4 % at the Moody site, due to the reduced range of Pw values in the Brookings site.

Percent Water by Volume (Pv)

All significant Pv models for each sensor had moderate adjusted R^2 values (Table 11). The highest adjusted R^2 values were found in the B horizon average for both Veris 3100[®] sensors and in the 1F layer for the EM-38[®]. No significant models including soil sensors were found for the C horizon. All models were able to predict Pv within 2.0 to 3.5 %. The models including the EM-38[®] sensor were able to predict Pv, on average, within 3.0 % for all soil layers studied. The models including the Veris 3100[®] Shallow were able to predict Pv, on average, within 2.7 % while the Veris 3100[®] Deep was able to predict within 3.0 % for all soil layers studied. When compared to the Moody field, the adjusted R^2 values for the Brookings field were lower, average adjusted $R^2 = 0.436$ versus 0.781 for the Moody field (Malo et al, 2001). The average model error was also lower at the Brookings site, 2.9 % versus 3.1 % at the Moody site, due to the reduced range of Pv values in the Brookings site.

Bulk Density (Bd)

Soil sensors were not useful in predicting A horizon soil bulk density values (Table 12). Significant models were found that used each soil sensor to estimate soil bulk density for the B and for the three-foot average bulk density (3F Bd). A model for the 1F Bd layer was found that used VS and ST12. The significant

models were able to predict soil bulk density within 0.04 to 0.08 g cc⁻¹ with an average of 0.06 g cc⁻¹. Significant bulk density prediction models for only the A horizon or 1F layer were found at the Moody site (Malo et al., 2001).

Soil Property Models Using All Soil Sensor and Soil Property Data

Models were developed to predict soil properties using all soil sensor and studied soil property data. The models for soil moisture (Tables 13 and 14), bulk density (Tables 15a and 15b), and soil temperature (Tables 16a and 16b) are given for the three soil moisture sensors studied. All studied soil parameters (soil temperature, soil moisture, bulk density, EM-38[®], Veris 3100[®]Shallow, and Veris 3100[®] Deep) were used to develop the models included in Tables 13-16.

Percent Water by Weight (Pw)

All Pw models for each sensor had moderate to high adjusted R^2 values. The highest adjusted R^2 values were found in the 1F layer. All models were able to predict Pw within 1.0 to 1.9 % (Table 13). The models including the EM-38[®] sensor were able to predict, on average, Pw within 1.4 % for all soil layers studied. The models including the Veris 3100[®] Shallow were able to predict, on average, Pw within 1.3 % while the Veris 3100[®] Deep was able to predict within 1.4 % for all soil layers studied. When compared to Table 7 values (sensor only), these models in Table 13 were able to reduce the error term by approximately 30 %. When compared to the Moody field, the adjusted R^2 values for the Brookings field were lower, average adjusted $R^2 = 0.701$ versus 0.883 for the Moody field (Malo et al, 2001). The average model error was also slightly lower at the Brookings site, 1.4 % versus 1.6 % at the Moody site, due to the reduced range of Pw values at the Brookings site.

Percent Water by Volume (Pv)

All Pv models for each sensor had moderate to high adjusted R^2 values. The highest adjusted R^2 values were found in either the A horizon or 1F layer (Table 14). The models including the EM-38[®] sensor were able to predict, on average, Pv within 2.1 % for all soil layers studied. The models including the Veris 3100[®] Shallow were able to predict, on average, Pv within 2.1 % while the Veris 3100[®] Deep was able to predict within 2.0 % for all soil layers

studied. When compared to Table 8 values (sensor only), these models in Table 14 were able to reduce the error term by approximately 40 %. When compared to the Moody field, the adjusted R^2 values for the Brookings field were lower, average adjusted $R^2 = 0.735$ versus 0.876 for the Moody field (Malo et al, 2001). The average model error was also slightly lower at the Brookings site, 2.1 % versus 2.3 % at the Moody site, due to the reduced range of Pv values in the Brookings site.

Bulk Density (Bd)

When all soil parameters studied were included in model development for soil bulk density, the number of significant models increased dramatically when compared to the soil sensors alone (Table 15a and Table 15b). The highest adjusted R^2 values were found in the C horizon and 1F layer using Pw and in the 1F layer using Pv.

All models using Pw were able to predict Bd within 0.010 to 0.070 g cc⁻¹ for all layers studied (Table 15a). The models including the EM-38[®] sensor and Pw were able to predict, on average, Bd within 0.037 g cc⁻¹. The models including the Veris 3100[®] Shallow and Pw were able to predict, on average, Bd within 0.044 g cc⁻¹ while the Veris 3100[®] Deep was able to predict within 0.047 g cc⁻¹ for the soil layers studied. When compared to the Moody field, the adjusted R^2 values for the Brookings field models, excluding Pv, were lower, average adjusted $R^2 = 0.724$ versus 0.817 for the Moody field (Malo et al., 2001). The average Bd model (excluding Pv) error was higher at the Brookings site, 0.042 g cc⁻¹ versus 0.035 g cc⁻¹ at the Moody site.

All models using Pv were able to predict bulk density within 0.020 to 0.090 g cc⁻¹ for all layers studied (Table 15b). The models including the EM-38[®] sensor and Pv were able to predict, on average, Bd within 0.047 g cc⁻¹. The models including the Veris 3100[®] Shallow and Pw were able to predict, on average, Bd within 0.038 g cc⁻¹ while the Veris 3100[®] Deep was able to predict within 0.049 g cc⁻¹ for the soil layers studied. When compared to the Moody field, the adjusted R^2 values for the Brookings field models, excluding Pw, were the same, average adjusted $R^2 = 0.658$ versus 0.678 for the Moody field (Malo et al., 2001). The average Bd model (excluding Pw) error was the same for both sites at 0.047 g cc⁻¹.

Since there were no significant models in the sensor only analysis for Bd, no comparisons in error reduction due to inclusion of all studied soil parameters could be made.

Soil Temperature (ST)

All the models for ST for each sensor had numerically medium to high significant adjusted R^2 values (Table 16a and 16b). The highest adjusted R^2 values using Pw were found at ST12 and ST18 for all sensors tested (Table 16a). The highest adjusted R^2 values using Pv were found in ST18 for all sensors tested (Table 16b). All models were able to predict temperatures within 1.9 and 4.3 °F, with an average of 2.6 °F, for the date tested. The models including the EM-38[®] sensor and Pw or Pv were able to predict, on average, ST within 2.8 °F for all soil depths. The models including the Veris 3100[®] Shallow and Pw or Pv were able to predict ST, on average, within 2.4 °F while the Veris 3100[®] Deep was able to predict, on average, within 2.8 °F for all soil layers studied. When compared to Table 9 values (sensor only), these models in Tables 16a and 16b were able to reduce the error term by 25 %.

When compared to the Moody field, the adjusted R^2 values for the Brookings ST models excluding Pv were lower, average adjusted $R^2 = 0.614$ versus 0.834 for the Moody field (Malo et al., 2001). When compared to the Moody field, the adjusted R^2 values for the Brookings field ST models excluding Pw were lower, average adjusted $R^2 = 0.591$ versus 0.774 for Moody field (Malo et al., 2001). The average model error increased at the Brookings field, 2.6 °F versus 1.9 °F at the Moody field.

SUMMARY

The results of this preliminary study show that the EM-38[®] and the Veris 3100[®] soil sensors were strongly related to soil moisture contents (both percent water by weight and by volume) and to a lesser degree soil bulk density and soil temperature. Soil sensors alone can be used to predict soil moisture levels within 3 % (Pw or Pv) provided some ground truth in the field has been done. If other soil parameters are included in the model, then soil moisture predictions within 2 % (Pw or Pv) were possible for the soils studied. Differences in results were noted when the Brookings field

was compared to the Moody field. Climatic changes between sampling dates, residue cover, and soil parent material differences may have all contributed to the model differences found between the two sites. Further study is needed to verify the models and variables used in this report. Different soils and different times of the year need to be evaluated.

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