Investigating the Potential of Electromagnetic Induction for Mapping Multi-Depth Soil Moisture Variations in Southern Manitoba

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1. CONTEXT AND OBJECTIVES

This research aimed to explore the potential of electromagnetic induction as a valid soil moisture monitoring technique in a Canadian prairie watershed. Soil moisture (SM) information is important for many aspects of hydrology; however, current methods for collecting multi-depth SM data can be costly and non-representative, and understanding the spatial and temporal variability of SM remains challenging (Western et al., 1998; Reedy and Scanlon, 2003; Teuling and Troch, 2005; Vereecken et al., 2008; Grote et al., 2010). Alternatively, previous research has suggested that the apparent electrical conductivity (ECa) of a soil is often highly correlated to its soil water content and can be measured non-invasively through the use of electromagnetic induction meters (McNeill, 1980b; Reedy and Scanlon, 2003; Tromp-van Meerveld and McDonnell, 2009; Zhu et al., 2010).

Research Objectives:

i. Investigate the spatial and temporal variability of SM and ECa

ii. Examine the relationship between SM and ECa on a depth-average and depth-specific basis, over a range of wetness conditions

Studies encompassing these aspects, especially the depth-specific variability of SM and ECa, have not been attempted for a Canadian Prairie watershed.

2. STUDY SITE AND DATA COLLECTION

- ~0.3 ha plot in the South Tobacco Creek Watershed (southern Manitoba)
- 5 transects, 7 measurement points per transect (35 measurement points in total)
- SM and ECa data collected on four dates:
  - One "very dry" survey (Sept. 20/12)
  - Two "dry" surveys (Aug. 30/12, Sept. 11/12)
  - One "very wet" survey (May 15/13)

SM	ECa
• SM profiling probe with multi-depth sensors • SM measured on 0 to 100% saturation scale • Depth intervals of 0-30, 30-50, and >50 cm	• Geonics EM38 electromagnetic induction meter • ECa in mS/m • Measurements at 0, 20, and 40 cm above surface

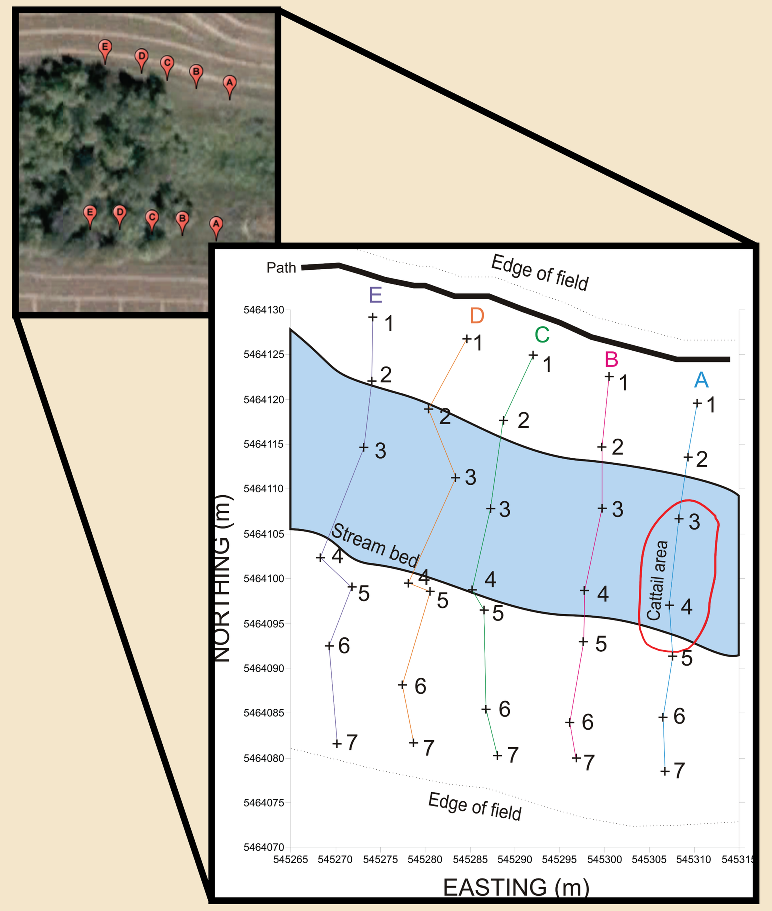

Figure 1. Aerial image of survey area (Google Earth, 2014) and schematic of survey setup. Blue area indicates "near stream zone."

3. SPATIAL AND TEMPORAL VARIABILITY OF SM AND ECa DATA

Data Analysis

i. Contour maps of SM and ECa (for each depth on each survey date) to visualize spatial patterns

ii. Variogram-derived correlation length (for each depth on each survey date) to quantify the smoothness or patchiness of the spatial patterns

Results and Discussion

- ECa contour maps (Figure 2) show increasing conductivity for wet conditions and high conductivity around the "near stream zone" and cattail area.
- SM contour maps (Figure 3) show consistent patterns between dry surveys, and high SM around the "near stream zone" (for the 30-50 cm depth interval) and cattail area.

➡ This suggests vegetation and topography (elevation decreases towards the cattails) act as major controls on SM and ECa distribution, an observation consistent with Grayson et al., 1997, Western et al., 2002, and Teuling and Troch, 2005.

- For both ECa and SM, correlation length increases for wet conditions, and this increase is more significant in the SM data.

➡ This indicates a higher spatial continuity of SM for increasingly wet conditions, which agrees with some previously published studies (e.g., Famiglietti et al., 1999; Hupet and Vanclooster, 2002) and contradicts others (e.g., Western et al., 1998; Zhu et al., 2010). Differences in study interpretations may be reconciled by differences in scale of survey and soil moisture state (Crow and Wood, 1999; Peters-Lidard and Pan, 2002; Teuling and Troch, 2005).

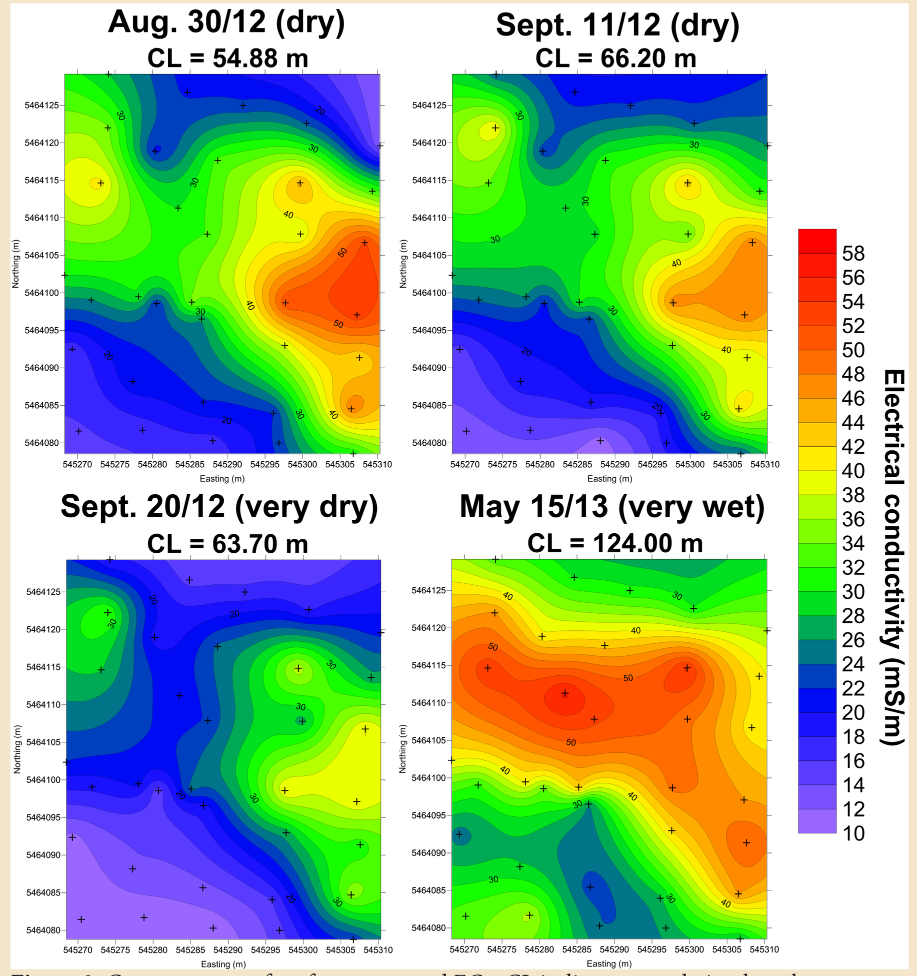

Figure 2. Contour maps of surface-measured ECa. CL indicates correlation length.

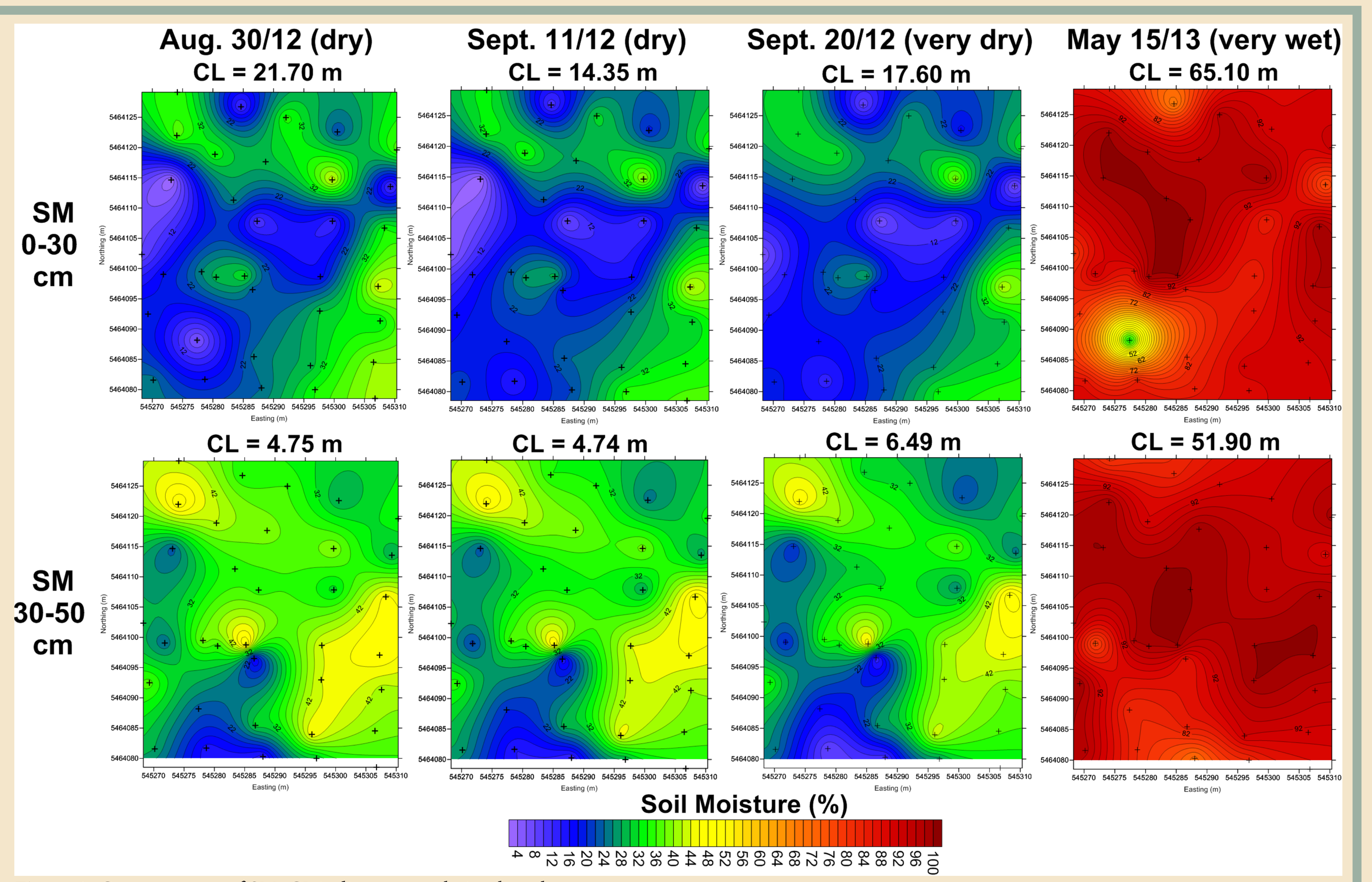

Figure 3. Contour maps of SM. CL indicates correlation length.

4. DEPTH-AVERAGED AND DEPTH-SPECIFIC RELATIONSHIP BETWEEN SM AND ECa

Data Analysis

i. **ECa pseudosection analysis**

Pseudosections were used to provide a simplistic representation of ECa with depth, for depth-specific comparison with SM (Figure 4).

- Relied on ECa measured at the soil surface and at 20 and 40 cm above the surface
- Each measurement was assigned a corresponding pseudodepth based on the response function of the EM38 for each measurement height (McNeill, 1980a):

$$R_H(z)=(4z+1)^{1/2}-2z$$

where $R_H(z)$ is the cumulative response function, which defines the relative contribution to ECa from all material below depth z

- $R_H(z)$ was set to one-third, thus resulting in pseudodepths of:
  - ECa_{40cm} ➡ 26 cm (to be compared to the 0-30cm SM depth range)
  - ECa_{20cm} ➡ 46 cm (to be compared to the 30-50cm SM depth range)
  - $ECa_{surface}$ ➡ 66 cm
- Above-surface measurements were corrected for the layer of air

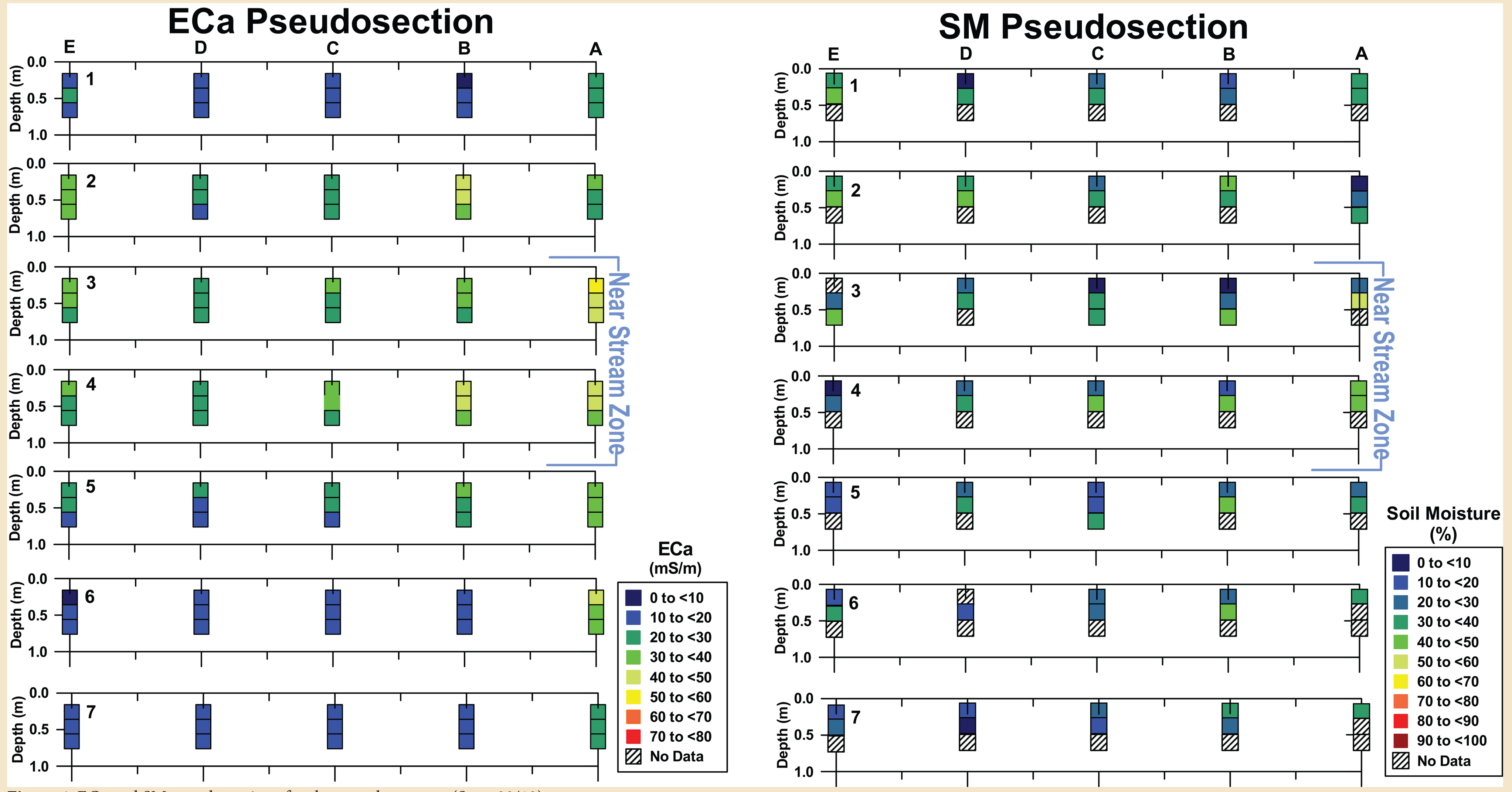

Figure 4. ECa and SM pseudosections for the very dry survey (Sept. 20/12).

ii. **Spearman rank correlation coefficients were computed for each survey date between:**

- Depth-averaged SM and surface-measured ECa
- Depth-specific SM and depth-specific ECa (derived from pseudosection analysis)

Table 1. Spearman rank correlation coefficients between ECa and SM values. Red indicates statistical significance at the 95% confidence limit. Green boxes highlight correlations with depth-averaged SM, and yellow boxes highlight the correlations between depth-specific SM and ECa.

	Aug. 30/12 (dry)				Sept. 11/12 (dry)			
	SM Depth-Averaged	SM 0-30 cm	SM 30-50 cm	SM >50 cm	SM Depth-Averaged	SM 0-30 cm	SM 30-50 cm	SM >50 cm
ECa 26 cm	0.43	0.19	0.33	0.80	0.46	0.07	0.47	0.67
ECa 46 cm	0.54	0.22	0.50	0.90	0.53	0.12	0.52	0.72
[1]ECa 66 cm	0.53	0.22	0.49	0.80	0.54	0.17	0.54	0.95
	Sept. 20/12 (very dry)				**May 15/13 (very wet)**			
	SM Depth-Averaged	SM 0-30 cm	SM 30-50 cm	SM >50 cm	SM Depth-Averaged	SM 0-30 cm	SM 30-50 cm	SM >50 cm
ECa 26 cm	0.61	0.28	0.51	0.90	0.70	0.66	0.56	0.87
ECa 46 cm	0.63	0.28	0.56	0.90	0.61	0.43	0.53	0.95
[1]ECa 66 cm	0.63	0.29	0.55	0.90	0.73	0.55	0.65	0.95

[1] Equivalent to surface-measured ECa.

Results and Discussion

- Correlation coefficients (Table 1) show moderate correlations between corresponding depth intervals of SM and ECa, but there is overlap with non-corresponding depth intervals.

➡ Each pseudodepth reading is still representative of an average conductivity and may still represent SM variations outside the given pseudodepth. This suggests that pseudosection analysis is too simplistic for representing depth-specific ECa.

- Correlations between depth-averaged SM and ECa are generally higher than correlations between depth-specific SM and ECa. Correlation coefficients for the very wet survey are also slightly higher than those for the dry surveys.

➡ This suggests that the EM38 is better at giving a representation of depth-averaged SM (as opposed to depth-specific SM).

➡ The relationship between SM and ECa is stronger during wet conditions.

5. DISCUSSION

- ECa cannot delineate small scale SM variations and is more representative of coarser resolution patterns, suggesting that the SM-ECa relationship is stronger over larger spatial scales (Kachanoski et al., 1990; Tromp-van Meerveld and McDonnell, 2009).
  - May be explained by a difference in measurement area: SM sensors have measurement sphere of 10 cm radius, whereas the EM38 has a lateral resolution of ~1 m.
- The EM38 could be used for fast and cost-effective mapping of general soil moisture patterns.
  - *e.g.,* ECa maps to identify locations of hydrological interest before SM testing.

6. CONCLUSIONS

- Spatial continuity of SM and ECa increases for increasingly wet conditions.
- ECa best represents an average SM with depth.
- ECa mapping could be used for detection of broad scale soil moisture variations.

Future Recommendations

- Using different sets of electromagnetic induction responses (including multiple dipole modes and multi-frequency responses) may allow for full geophysical inversions of ECa with depth, which may improve the characterization of the depth-specific relationship between SM and ECa.

7. REFERENCES

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