Comparison of Electrical and Thermal Conductivities for Soils From Five States

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Abstract: The arrangement of soil particles, particle size, mineralogy, solute concentration, and bulk density affects electrical (σ) and thermal (λ) conductivities, which are key properties for estimating soil physical states, subsurface water and energy balances, and land-atmosphere interactions. The purpose of this study was to compare how σ and λ change as a function of water content for soils under different vegetation and with different properties. Soil samples were collected from selected field sites in Idaho, Texas, Colorado, Iowa, and Ohio and packed into cylinders at a density of 1.2 Mg m^{-3} and then wetted to predetermined water contents (Θ) between 0.10 and 0.45 m^3 m^{-3}. A thermo–time domain reflectometer was used to determine σ and λ at each Θ at room temperature. Soil and vegetation-influenced differences within a state were only occasionally statistically significant; however, differences between states were highly significant for both σ and λ. The λ decreased as the amount of sorbed water (related to soil-specific surface area) increased. The λ increased more rapidly at low water contents than did σ, but σ increased more rapidly at high water contents. Changes in σ and λ with water content are related to the changing tortuosity of the solid plus liquid phases versus only the liquid phase (including sorbed water). This study contributes toward improved understanding of soil thermal and electrical conductivities over a range of soils.

Key words: Heat conductance, sorbed water content, electrical conductance.

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Electrical (σ) and thermal (λ) conductivities are key properties for estimating soil physical states, subsurface water and energy balances, and land-atmosphere interactions. Soil bulk σ measurements are affected by contact between soil and the measuring device or electrode because the flow of charge is through the liquid phase (and liquid sorbed to solids). The σ is often used as a surrogate measurement across fields and watersheds to differentiate soil and management boundaries, without theoretical analysis of the chemical and physical properties that are actually being measured (Carroll and Oliver, 2005; McCutcheon et al., 2006; Harvey and Morgan, 2009, among others). Many factors affect σ. If aggregates are large in relation to the electrode, contact is affected in partially wetted soil; therefore, aggregate size can influence σ measurements for certain water content ranges (Logsdon, 2006). In addition to soil structure, soil σ is increased by high levels of soil solution concentration (Shainberg et al., 1980), water content, temperature, and high charge clays (Logsdon and Laird, 2004; Hunt et al., 2006).

Soil λ occurs through both liquid and solid phases and to a lesser extent through the gaseous phase. It is not as sensitive to soil structure at the macroaggregate size range but rather is influenced by short-range properties (Hunt and Ewing, 2009). Short-range properties are mineral particle contact and associated water films, and microaggregates. Increased density increases λ at low- and mid-range water contents (Abu-Hamdeh and Reeder, 2000), at least, for sand (Horton and Wierenga, 1984). Increased salt levels decrease λ (Abu-Hamdeh and Reeder, 2000). Increased organic matter decreases λ for fine-textured soils (Gupta et al., 1977; Abu-Hamdeh and Reeder, 2000). Increased clay content decreases λ (Abu-Hamdeh and Reeder, 2000).

Bristow (2002) shows the theoretical shape of λ as a function of water content, Θ, for different textures and temperatures. First, there is a lag component in which λ changes little at low Θ. Then λ rapidly increases as Θ increases. At higher Θ, the slope of $\lambda(\Theta)$ lessens and becomes steady, increasing at lower temperatures and decreasing at higher temperatures.

The purpose of this study was to determine if soils from different states significantly influenced soil σ or λ across a range of water contents and to compare the rate of change as a function of water content for σ with that of λ across a range of water contents.

MATERIALS AND METHODS

Laboratory Analysis

The five locations are described by Logsdon et al. (2010) and in Tables 1 and 2. Pullman soil from Texas (Evett et al., 2005) has 0.48 and 0.39 g g^{-1} clay and silt fractions in the A horizon and 0.35 and 0.40 g g^{-1} clay and silt fractions in the carbonate portion of the Bk horizon; however, carbonates were 0.50 g g^{-1}. Field-scale mean particle size fractions for Colorado (McCutcheon et al., 2006) were 0.27 and 0.22 g g^{-1} clay and silt fractions and carbonates were 0.067 g g^{-1}, with a wide range of measured values. Idaho soils ranged from 0.23 to 0.69 g g^{-1} sand and 0.05 to 0.19 g g^{-1} clay (Western and Seyfried, 2005).

Undisturbed soil samples had been collected at surface or subsurface depths from different soils within a catena on a site within a state. When possible within each state, samples were collected from a different management or vegetation cover but the same soils. A few measurements were attempted on the undisturbed samples, but initial water content and density varied greatly. Some samples were too dense for safe insertion of the probe without needle deflection; therefore, the samples were air-dried and repacked before proceeding.

Thermal and electrical conductivities were measured in soil that had been packed into brass cylinder (54 mm diameter, 60 mm long). A subsample was oven dried to estimate initial soil water content, and water was misted on the soil to achieve 0.10 m^3 m^{-3} when packed to a bulk density of 1.2 Mg m^{-3}. One

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TABLE 1. Soil Characterization for the Sites From the Different States

State	Soil	Classification
Iowa	Galva	Fine-silty, mixed, superactive, mesic Typic Hapludoll
Iowa	Sac	Fine-silty, mixed, superactive, mesic Oxyaquic Hapludoll
Iowa	Primghar	Fine-silty, mixed, superactive, mesic Aquic Hapludoll
Idaho	Ola	Coarse-loamy, mixed, superactive, frigid Pachic Haploxeroll
Idaho	Kanlee	Fine-loamy, mixed, superactive, frigid Typic Argixerol
Idaho	Pit, uncertain	Coarse-loamy, mixed, superactive, frigid Ultic Haploxeroll
Colorado	Colby	Fine-silty, mixed, superactive, calcareous, mesic Aridic Ustorthent
Colorado	Wagonwheel	Coarse-silty, mixed, superactive, mesic Aridic Calciustept
Colorado	Kim	Fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthent
Ohio	Lordstown	Coarse-loamy, mixed, active, mesic Typic Dystrudept
Ohio	Muskingum	Fine-loamy, mixed, semiactive, mesic Typic Dystrudept
Ohio	Rayne	Fine-loamy, mixed, active, mesic Typic Hapludult
Texas	Pullman	Fine, mixed, superactive, thermic torrertic Paleustoll
Texas	Randall	Fine, smectitic, thermic Ustic Epiaquert
Texas	Mansker	Fine-loamy, carbonatic, thermic Calcidic Paleustoll

fourth of the cylinder was packed at a time, and then each layer was roughened with a spatula before packing the next layer. The intent was to measure at water contents between 0.10 and 0.45 m^{-3} m^{-3}, adding the water equivalent of 0.05 m^{-3} m^{-3} to the soil core without further disturbance at each increment. After the final measurements at the highest water content, the soil was oven dried. Actual water contents and bulk densities were back-calculated from measured soil masses at each soil water content level. The Ohio and Texas samples had some swelling, so the soil volume increased (effective bulk density decreased) as water content increased.

A thermo–time domain reflectometer (thermo-TDR) (Ren et al., 1999) was used to determine thermal properties (dual heat pulse procedure) and electrical conductivity. This is a three-(hollow) needle probe with 4-mm-long needles spaced approximately 6 mm apart. The outer needles contained chromel-constantan thermocouples. The middle needle was a heater made by inserting 38-gauge Nichrome 80 wire into the needle with resin encasing. The thermal analysis heated each sample for 6 sec, and the resistance was 533.13 Ω m^{-1}. A 12-V marine battery provided power. The three needles simultaneously served as the TDR probe. The TDR waveforms were collected by Win-TDR (Or et al., 2004) and saved for postmeasurement analysis. All measurements were made at room temperature.

Soil thermal properties were determined using the one-point method (Knight and Kluitenberg, 2004) and σ as described by Jones et al. (2002). The needle spacing was recalibrated frequently using the agar method (Campbell et al., 1991). Because the thermo-TDR has two measurements of thermal properties, these were averaged, except in a few cases when the two values were not in the same range. Then the more out-of-range value was not averaged with the other.

Sorbed water content was determined as described by Logsdon (2005). Briefly, the procedure for sorbed water was to place approximately 2 g of loose soil for each sample in a weigh dish placed in a vapor-tight dessicator over distilled water (~99% relative humidity) for 2 weeks, then over $MgNO_3$ (~54% relative humidity) for 2 weeks. Gravimetric water content was determined by weighing the soil sample, oven drying, and weighing again. Sorbed water content was determined for one or two subsamples for each sample.

Fitted Equations

The equation chosen to describe σ as a function of water content, $\sigma(\Theta)$, was (Ewing and Hunt, 2006):

$$\sigma(\Theta) = \sigma_s + a\sigma_b\left(\frac{\Theta - \Theta_c}{1 - \Theta_c}\right)^{\mu} \quad (1)$$

where Θ_c is the critical volume fraction for percolation, μ is 2.0 for three-dimensional systems, σ_b is the soil solution σ, and σ_s is the solid phase (i.e., sorbed water phase) σ. For these samples, the Θ_c content nearly always fits to zero, so for the three cases (out of 46), when it was different from zero, we set to zero. Setting Θ_c to zero would be realistic because σ_s was nonzero even at a low water content, and bulk σ would not go to zero (Ewing and Hunt, 2006). Therefore, the fitted parameters compared were σ_s and $a\sigma_b$. For the 46 samples, the significance probability (P) values ranged from 0.0001 to 0.014 with a mean of 0.0008.

TABLE 2. Vegetation Within the Sites at the Five States

State	Vegetation	Species	Reps
Iowa	Soybean in corn-soybean rotation	*Glycine max* (L.) Merr., *Zea mays* L.	2†
Iowa	Hardwood forest	Mix	2
Idaho	Burned regrown grass and forbs	Mix	1
Idaho	Not burned, shrubs	*Artemisia tridentata vaseyna* L., *Purshia tridentata* L.	1
Colorado	Fallow phase of wheat rotation	*Triticum aestivum* L.	2
Colorado	Grass rangeland	Mix	2
Ohio	Grassland	Mix	2
Texas	Rangeland	Mix	‡
Texas	Irrigated field	Mix	‡

†Number of samples for each vegetation-soil combination within a state.

‡For Pullman soil, there were two samples for the surface horizon and three for the subsurface horizon in the rangeland field and one subsurface sample in the irrigated field. There were two subsurface samples each for the Randall and Mansker soils but only in the rangeland field. Samples from all other states were taken from the soil surface.

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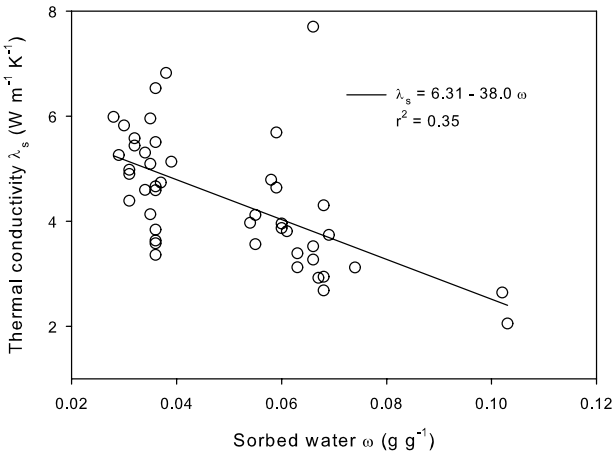

FIG. 1. The fitted solid phase thermal conductivity (λ_s) as a function of sorbed water (ω).

The following equation was chosen to describe λ as a function of water content, $\lambda(\Theta)$ (Lu et al., 2007):

$$\lambda(\Theta) = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \quad (2)$$

where

$$K_e = \exp\{a[1 - S_r^{(a-1.33)}]\} \quad (3)$$

$$S_r = \Theta/\Theta_s, \quad (4)$$

and

$$\lambda_{sat} = \lambda_s^{1-n}\,\lambda_w^{n} \quad (5)$$

where subscripts *sat* and *dry* refer to soil-water conditions with only soil and water or only soil and air, *n* is soil porosity, and λ_w for water is 0.596 W m^{-1} K^{-1} at room temperature. We modified this to determine the dry value as well:

$$\lambda_{dry} = \lambda_s^{1-n}\,\lambda_a^{n} \quad (6)$$

where λ_a for air is 0.025 W m^{-1} K^{-1} at room temperature (~22 °C). Therefore, the fitted parameters were λ_s and α. The α value is strongly affected by soil texture. Some of the fitted λ_s values were out of theoretical range, so the fitted λ_s values were used to determine λ_{sat}, which was then regressed with interpolated values at a water content of 0.45 m^3 m^{-3}:

$$\lambda_{sat} = 0.059 + 1.075\,\lambda_{.45} \quad r^2 = 0.72\,. \quad (7)$$

Then new λ_s values were back-calculated. The new λ_s values were used to determine λ_{sat} and λ_{dry}.

One difficulty with Eq.(2) is the omission of a lag component at low water contents (Bristow, 2002) when there is only a small change in λ as water content increases. Because the lowest water content in our study was 0.10 m^3 m^{-3}, only a few samples (from Colorado) showed this lag. The lag would be more apparent at lower water contents. Overall, the *P* values for the fit to Eq.(2) were all less than 0.0001 except one sample (out of 46) which was less than 0.0002.

Investigators developing equations describing λ as a function of water content often assume it would be easy to obtain measurements of dry samples (with no water). This may be fairly simple for sand, but soils with high surface area clays extract water out of the air at ambient relative humidity (i.e., during the time the sample is cooling to room temperature). Even drying to 105°C does not remove all sorbed water, but such drying can irreversibly fire some clay, thus changing their water sorption and conductive characteristics substantially. Whereas more water is removed at 190°C, this temperature will greatly alter clay and organic matter properties. Practically speaking, samples with high surface area clays will always have some water during the supposed "dry" measurement. Likewise, a near saturated "satiated" sample can be measured; however, cores leaking water (at free water pressure) and trapped air usually means there is some air even at "satiation." This explains our use of fitted values for wet and dry λ rather than attempting to measure them directly.

Minor variations in density and water content among the samples reduced the ability to compare actual values. Instead, fitted parameters from Eq.(1) and Eq.(2) were used to compare among the samples. The equations were fitted in SAS using the nonlinear Marquardt procedure. Then the fitted equations were used to calculate σ and λ values at the originally intended water contents: 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 m^3 m^{-3}. Analysis of variance with Tukey Honest significant difference test was used to determine significant differences among the states or within states. Differences were considered significant at $P = 0.05$.

TABLE 3. Variation of Thermal and Electrical Parameters by State

State	λ_s ‡ W m^{-1} K^{-1}	α ‡ —	λ_{wet} § W m^{-1} K^{-1}	λ_{dry} ¶ W m^{-1} K^{-1}	σ_s # S m^{-1}	$a\sigma_{sol}$ # S m^{-1}	ω g g^{-1}
Idaho	4.65 ab†	0.501a	1.49 ab	0.260 abc	0.0281 b	0.250 cd	0.033 c
Colorado	5.14 a	0.209 b	1.58 a	0.280 a	0.0359 a	0.276 bc	0.035 c
Ohio	5.04 a	0.423 a	1.56 ab	0.275 ab	0.0280 b	0.189 d	0.033 c
Iowa	4.24 ab	0.405 a	1.39 bc	0.247 bc	0.0211 c	0.321 ab	0.061 b
Texas	3.29 b	0.340 ab	1.25 c	0.224 c	0.0273 b	0.360 a	0.073 a

†Means in a column followed by the same letter were not significantly different at $P = 0.05$.
‡From Eq.(2).
§From Eq.(5).
¶From Eq.(6).
#From Eq.(1).

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TABLE 4. Variation of Mean Electrical Conductivity, σ (S m^{-1}), at Interpolated Water Contents (m^3 m^{-3}) by State

State	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
Idaho	0.031 b†	0.034 b	0.038 bc	0.044 b	0.051 b	0.058 b	0.068 b	0.079 c
Colorado	0.039 a	0.042 a	0.047 a	0.053 a	0.061 a	0.070 a	0.080 a	0.092 ab
Ohio	0.030 b	0.032 b	0.036 cd	0.040 b	0.045 c	0.051 c	0.058 c	0.066 d
Iowa	0.024 c	0.028 c	0.034 d	0.041 b	0.050 b	0.061 b	0.072 b	0.086 bc
Texas	0.031 b	0.035 b	0.042 b	0.050 a	0.060 b	0.071 a	0.085 a	0.100 a

†Means in a column followed by the same letter were not significantly different at $P = 0.05$.

To compare σ and λ at different water contents as a paired comparison (sample-by-sample) basis, first, a ratio was calculated as the change in conductivity between adjacent water contents divided by the total change in conductivity. They were paired by determining the ratio differences for electrical minus thermal conductivities:

$$\frac{\Delta(\sigma_i - \sigma_{i-1})}{\Delta(\sigma_{.45} - \sigma_{.1})} - \frac{\Delta(\lambda_i - \lambda_{i-1})}{\Delta(\lambda_{.45} - \lambda_{.1})} \quad (8)$$

Then 95% confidence interval of this difference was determined to assess statistical significance for each interval (Δ 0.05 m^3 m^{-3}). The confidence intervals that did not include zero were considered significant (Karlen and Colvin, 1992).

RESULTS AND DISCUSSION

There were differences among soils from the different states (long-range effects). Larger amounts of sorbed water, ω (g g^{-1}), are associated with a large surface area, which indicated less sand and more high-charge clays. The soil solid λ, λ_s, increases as the amount of quartz increases (Bristow, 2002). Quartz is generally associated with the sand fraction, so there was a weak inverse relation between λ_s and ω (Fig. 1, Table 3), as expected because ω would decrease as sand (quartz) content increased. The fitted soil solution σ, $a\sigma_b$, and λ_s were larger for Colorado, Idaho, and Texas soils, which might indicate that these soils contained some soluble salts (Tables 3 and 4). Perhaps high clay also increased $a\sigma_b$, as shown for high clay soils in Texas and Iowa. Ohio soils had lower clay and low soil solution concentration. The α value did not relate to soil texture as well as expected because high-sand Colorado soils had low α values, high-sand Ohio and Idaho soils had high α values, and high clay Iowa soils also had high α values. The fitted surface conductivity, σ_s, of the Colorado samples was high, although these samples did not have appreciable amounts of high-charge clay. This might indicate that the fitted σ_s included some contribution from σ_b. Iowa soils had the lowest fitted σ_s, although they had high amounts of high-charge clays.

Within-state differences were rarely significant. The α value was significantly less for soil under soybean (0.325) than for forest (0.485) in Iowa. The σ_s value was significantly greater for the soil under soybean (0.0235 S m^{-1}) than for forest (0.0187 S m^{-1}). Also, the ω content was significantly lower for the soil under soybean (0.057 g g^{-1}) than for forest (0.066 g g^{-1}). None of the other within-state vegetation differences were significant for the fitted parameters. A few within-state soil differences in ω showed significance. In Idaho, the Kanlee (0.034 g g^{-1}) and Pit (0.036 g g^{-1}) soils had significantly larger ω than the Ola (0.029 g g^{-1}) soil. In Ohio, the Lordstown (0.036 g g^{-1}) soil had significantly higher ω than the Rayne soil (0.031 g g^{-1}). In Texas, the Randall soil (0.102 g g^{-1}) had significantly larger ω than Pullman (0.067 g g^{-1}) or Mansker (0.067 g g^{-1}) soils.

Interpolated values of electrical conductivity, σ, revealed high values (Table 4) for Colorado soil throughout the water content range, as expected because of soluble salts. Values of σ were low for Ohio soils throughout the water content range because of low levels of salts and high-charge clays. The Texas soils showed high σ at high water contents because of interactions with high-charge clays. The Iowa soils also had high-charge clays but low salt levels, which resulted in intermediate values of σ. The high-charge clays might have reduced σ at low water contents, and led to intermediate values at high water contents. Idaho soils had intermediate values. The σ values for high water contents of the Texas soils (Table 4) were 30% smaller than the values measured for Pullman soil by Evett et al. (2005) using methods similar to Wraith (2002). On the other hand, σ values for Colorado soils (Table 4) were 33% larger than those determined by McCutcheon et al. (2006) for field-scale apparent σ at mid-range water contents. Values for Idaho soils (Table 4) were approximately 90% greater than field-scale apparent σ (Robinson et al., 2008).

The interpolated thermal conductivity, λ, values (Table 5) showed low λ for Colorado soil at low water contents and high λ at high water contents. High λ would be expected because of the higher amounts of sand and quartz. The soluble salts reduce λ (Abu-Hamdeh and Reeder, 2000) and could explain the lack of

TABLE 5. Variation of Mean Thermal Conductivity, λ (Wm^{-1}K^{-1}) at Interpolated Water Contents (m^3 m^{-3}) by State

State	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
Idaho	0.76 a†	0.95 a	1.09 a	1.20 a	1.28 a	1.34 a	1.39 ab	1.43 a
Color	0.55 c	0.82 b	1.02 a	1.17 a	1.28 a	1.37 a	1.44 a	1.49 a
Ohio	0.71 ab	0.93 a	1.10 a	1.22 a	1.31 a	1.39 a	1.45 ab	1.49 ab
Iowa	0.67 ab	0.86 ab	1.00 ab	1.10 ab	1.18 ab	1.24 ab	1.29 bc	1.32 bc
Texas	0.60 bc	0.78 b	0.91 b	1.00 b	1.07 b	1.12 b	1.16 c	1.19 c

†Means in a column followed by the same letter were not significantly different at $P = 0.05$.

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relation to the texture parameter α. The λ values were high for Idaho and Ohio soils throughout the water content range, as expected because of high levels of quartz. The λ values were low for Texas soils because of the high charge clays and to the soluble salts (Abu-Hamdeh and Reeder, 2000). The values for Texas soils between water contents of 0.1 and 0.3 match well values found by Evett (1994). Iowa soils had intermediate values of λ because there were low salt levels (tend to increase), which offset the lowering effect of the high-charge clays and low levels of quartz. Also, Iowa soils had higher amounts of organic matter, which can decrease λ (Gupta et al., 1977). Within-state differences for interpolated values were minor (not shown).

The σ increased slowly at low Θ, and with a greater slope at high Θ (Fig. 2A). By contrast, λ increased rapidly at low Θ, and with a smaller slope at high Θ (Fig. 2B). The paired comparison analysis (Fig. 3) showed that for Θ of 0.1 to 0.25 $m^3\ m^{-3}$, relative change in σ was significantly less than for λ; whereas from 0.25 to 0.45 $m^3\ m^{-3}$, the relative change in σ was significantly greater than for λ. This trend was expected because heat travels through both solid and liquid phases, with even a small Θ forming "pendular" linkages between the solid particles that increase conduction (Ewing and Horton, 2007; Hunt and Ewing, 2009). At high Θ, there would not be much more increase in λ because there would already be good connectivity and small tortuosity in the flow path. The conducting pathway for σ would largely be confined to the liquid phase (Ewing and Hunt, 2006; Hunt and Ewing, 2009), including liquid associated with solid colloidal particles, that is, clays and organic matter. The σ increased slowly at small Θ because most σ was associated with water sorbed on colloids with tortuous pathways between conducting regions. As Θ increased, tortuosity decreased, and additional solutes might have dissolved into the liquid phase, both of which led to a rapid increase in σ at high water contents.

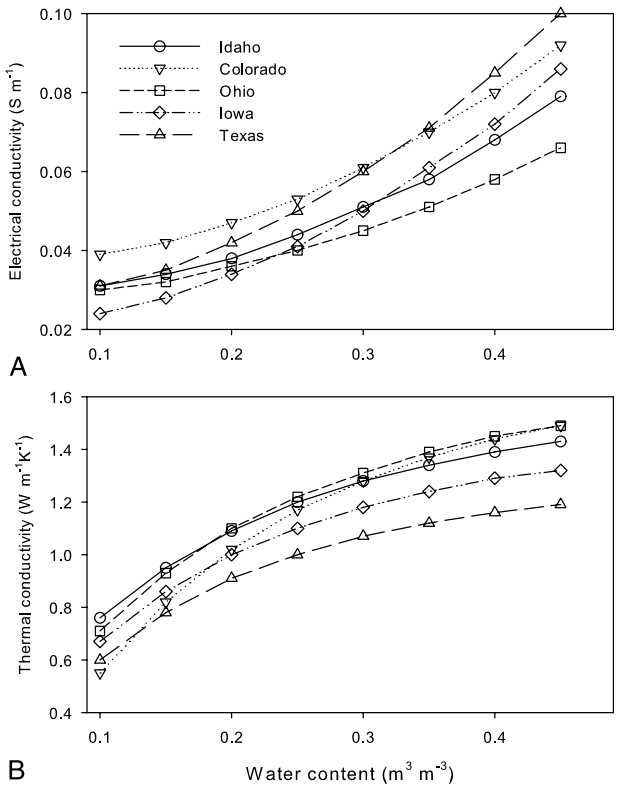

FIG. 2. Comparison of mean interpolated electrical conductivities (A) and thermal conductivities (B) as a function of water content.

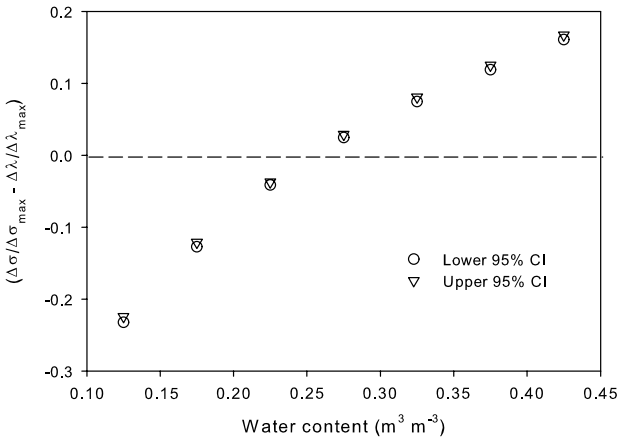

FIG. 3. The 95% confidence interval for the local slope of relative electrical conductivity (σ) minus the local slope of the thermal conductivity (λ). Negative indicated a steeper slope for λ than for σ, whereas a positive slope indicated a steeper slope for σ.

Because thermal conduction occurs through both liquid and solid phases, λ is more strongly related to air-filled porosity than to water content (Ochsner et al., 2001). There is a small thermal conduction through the air phase as well, but it is negligible compared with conduction through liquid and solid phase, except at temperatures higher than room temperature (Hopmans and Dane, 1986; Bristow, 2002) because of "latent heat transfer."

CONCLUSIONS

Overall, in this study, neither σ nor λ were very sensitive to vegetation-induced soil changes. Both conductivities were more sensitive to mineralogy and texture differences that showed up across states. Neither σ nor λ would be useful measurements to distinguish changes in local soil properties associated with land management. Instead, differences in soil electrical properties between states were more critical.

For all soil samples, the slope of $\lambda(\Theta)$ decreased as sorbed water content increased. Sorbed water could be directly related to a specific surface area if a uniform thickness of water film covered all surfaces. Higher sorbed water indicated higher amounts of high-surface area clays, which are known to decrease λ.

The slope of the relative σ increased significantly less than that for λ for water contents up to 0.25 $m^3\ m^{-3}$, beyond which the slope of the relative σ increased significantly more than for λ. The different rates of change were related to heat moving through both solid and liquid phases (and gaseous phase as temperature increases), but electrical charge moved through the liquid phase, either free liquid or along the hydrated solid surface.

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Mention of equipment manufacturer is for information only and does not constitute endorsement by the USDA-ARS nor exclusion of similar equipment by other manufacturers.

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