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# Comparing temperature correction models for soil electrical conductivity measurement

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**Abstract** There are various factors that affect soil electrical conductivity (EC) measurements, including soil texture, soil water content, cation exchange capacity (CEC) and others. Temperature is an important environmental variable, and different models can be used to correct for its effect on EC measurements and standardize the measurements to 25°C. It is relevant to analyze these models and to determine whether they are consistent with each other. Some models were wrongly cited. We found that the exponential model of Sheets and Hendrickx as corrected by Corwin and Lesch in 2005 performs the best. The ratio model also performs well between 3°C and 47°C.

**Keywords** Soil electrical conductivity (EC) · Temperature · Models

## Introduction

Many factors can affect soil electrical conductivity (EC) measurement, for example soil texture (clay, sand, silt), salinity, water content, organic matter and cation exchange capacity (CEC). Temperature is an important environmental factor that also affects EC (Brevik et al. 2004; Robinson et al. 2004; Sudduth et al. 2001). Electrical conductivity is usually cited as increasing at a rate of approximately 1.9% per °C increase in temperature (Corwin and Lesch 2005). The EC measurement is usually expressed at a reference temperature of 25°C ($EC_{25}$). The EC (i.e. bulk electrical conductivity $EC_a$ or water conductivity $EC_w$) measured at a particular temperature ($EC_T$ in °C) can be adjusted to a reference $EC_{25}$, using the following equation (U.S. Salinity Laboratory Staff 1954).

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$$\mathrm{EC}_{25} = f_{\mathrm{T}}\mathrm{EC}_{\mathrm{T}}, \tag{1}$$

where $f_{\mathrm{T}}$ is a temperature conversion factor (or temperature correction factor). The conversion factors are given in Table 1, which was originally published as Table 15 in the Agriculture Handbook No. 60 (U.S. Salinity Laboratory Staff 1954). The conversion factor is based on measurements of the electrical conductivity of soil saturation extracts and various salt solutions at different temperatures (Campbell et al. 1948). Although the table was derived for conductivity of the soil extract, the relationship appears to be the same for temperature dependence of the bulk soil electrical conductivity, $\mathrm{EC}_{\mathrm{a}}$ (Heimovaara et al. 1995; Persson and Berndtsson 1998).

Corwin and Lesch (2005) gave various models for the temperature conversion factor, either as polynomial equations (Stogryn 1971; Rhoades et al. 1999; Wraith and Or 1999), or as an exponential equation (Sheets and Hendrickx 1995). Besson et al. (2008) also introduced some temperature conversion models, but the work has some errors in the citation. It is relevant to analyze these models and to determine whether they are consistent with each other.

## Temperature correction models

### *The ratio model*

The commonly used relationship for correcting EC measurement to a standard 25°C is the ratio model (Hayashi 2004; Persson and Berndtsson 1998; Heimovaara et al. 1995; Sorensen and Glass 1987; Franson 1985; Barry et al. 2008; Besson et al. 2008; Keller and Frischknecht 1966)

$$\mathrm{EC}_{25} = \frac{\mathrm{EC}_{\mathrm{T}}}{1 + \delta(T - 25)}, \tag{2}$$

where $\mathrm{EC}_{25}$ is EC at a common temperature of 25°C, $\mathrm{EC}_{\mathrm{T}}$ is EC at a measured temperature $T$, and $\delta$ is the temperature slope compensation. The value commonly used for $\delta$ is $0.0191°\mathrm{C}^{-1}$, which is based on the EC and temperature relationship of 0.01 M KCl solution (Hayashi 2004; Huth and Poulton 2007). This value for $\delta$ is used to justify the commonly used maximum of an approximate 1.9% increase in EC per 1°C increase anywhere on the temperature scale. However, Eq. 2 is actually formulated for temperature changes up or down from 25°C. Groundwater textbooks frequently cite '2% increase in EC per °C increase of temperature', which equates to $\delta = 0.02$. Geophysicists commonly use $\delta = 0.025$ (Hayashi 2004; Besson et al. 2008; Keller and Frischknecht 1966). For soil data, Persson and Berndtsson (1998) found that $\delta = 0.023°\mathrm{C}^{-1}$ fitted their soil data best. Nevertheless, the commonly used $\delta$ of 0.0191 also fitted their data well. Heimovaara et al. (1995) found that the relationship of Eq. 2 with $\delta = 0.019°\mathrm{C}^{-1}$ worked well for eight soil cores. They also fitted Eq. 2 to the data in Table 1 and found that $\delta = 0.019°\mathrm{C}^{-1}$ was the optimum.

Hayashi (2004) examined the relationship between EC and the temperature of natural waters with different compositions and salinities. The author found that the temperature correction factor corresponding to 25°C ranged between 0.0175 and 0.0198.

**Table 1** Temperature factors ($f_T$) for correcting electrical conductivity data on soil extracts to the standard temperature of 25°C

$EC_{25} = EC_T \times f_T$

| °C | $f_T$ | °C | $f_T$ | °C | $f_T$ |
|---|---|---|---|---|---|
| 3.0 | 1.709 | 22.0 | 1.064 | 29. 0 | 0.925 |
| 4.0 | 1.660 | 22.2 | 1.060 | 29.2 | 0.921 |
| 5.0 | 1.613 | 22.4 | 1.055 | 29.4 | 0.918 |
| 6.0 | 1.569 | 22.6 | 1.051 | 29.6 | 0.914 |
| 7.0 | 1.528 | 22.8 | 1.047 | 29.8 | 0.911 |
| 8.0 | 1.488 | 23.0 | 1.043 | 30.0 | 0.907 |
| 9.0 | 1.448 | 23.2 | 1.038 | 30.2 | 0.904 |
| 10.0 | 1.411 | 23.4 | 1.034 | 30.4 | 0.901 |
| 11.0 | 1.375 | 23.6 | 1.029 | 30.6 | 0.897 |
| 12.0 | 1.341 | 23.8 | 1.025 | 30.8 | 0.894 |
| 13.0 | 1.309 | 24.0 | 1.020 | 31.0 | 0.890 |
| 14.0 | 1.277 | 24.2 | 1.016 | 31.2 | 0.887 |
| 15.0 | 1.247 | 24.4 | 1.012 | 31.4 | 0.884 |
| 16.0 | 1.218 | 24.6 | 1.008 | 31.6 | 0.880 |
| 17.0 | 1.189 | 24.8 | 1.004 | 31.8 | 0.877 |
| 18.0 | 1.163 | 25.0 | 1.000 | 32.0 | 0.873 |
| 18.2 | 1.157 | 25.2 | 0.996 | 32.2 | 0.870 |
| 18.4 | 1.152 | 25.4 | 0.992 | 32.4 | 0.867 |
| 18.6 | 1.147 | 25.6 | 0.988 | 32.6 | 0.864 |
| 18.8 | 1.142 | 25.8 | 0.983 | 32.8 | 0.861 |
| 19.0 | 1.136 | 26.0 | 0.979 | 33.0 | 0.858 |
| 19.2 | 1.131 | 26.2 | 0.975 | 34.0 | 0.843 |
| 19.4 | 1.127 | 26.4 | 0.971 | 35.0 | 0.829 |
| 19.6 | 1.122 | 26.6 | 0.967 | 36.0 | 0.815 |
| 19.8 | 1.117 | 26.8 | 0.964 | 37.0 | 0.801 |
| 20.0 | 1.112 | 27.0 | 0.960 | 38.0 | 0.788 |
| 20.2 | 1.107 | 27.2 | 0.956 | 39.0 | 0.775 |
| 20.4 | 1.102 | 27.4 | 0.953 | 40.0 | 0.763 |
| 20.6 | 1.097 | 27.6 | 0.950 | 41.0 | 0.750 |
| 20.8 | 1.092 | 27.8 | 0.947 | 42.0 | 0.739 |
| 21.0 | 21.0 | 28.0 | 0.943 | 43.0 | 0.727 |
| 21.2 | 21.2 | 28.2 | 0.940 | 44.0 | 0.716 |
| 21.4 | 21.4 | 28.4 | 0.936 | 45.0 | 0.705 |
| 21.6 | 21.6 | 28.6 | 0.932 | 46.0 | 0.694 |
| 21.8 | 21.8 | 28.8 | 0.929 | 47.0 | 0.683 |

Modified from U.S. Salinity Laboratory Staff (1954)

Scollar et al. (1990) gave a similar formula with $\delta = 0.022°\mathrm{C}^{-1}$ for the reference temperature at 20°C, whereas Dalliger (2006) used a $\delta = 0.025°\mathrm{C}^{-1}$ for the reference temperature at 20°C (Drnevich et al. 2008).

*Exponential models*

Corwin and Lesch (2005) gave an exponential equation for the temperature conversion factor from Sheets and Hendrickx (1995) as

$$f_T = 0.4470 + 1.4034e^{-T/26.815}. \tag{3}$$

However, when we checked the Sheets and Hendrickx's (1995) original paper, the equation was as follows

$$\mathrm{EC}_{25} = \mathrm{EC}_a \times \left[0.4470 + 1.4034e^{(T/26.815)}\right], \tag{4}$$

where $\mathrm{EC}_{25}$ is the standardized $\mathrm{EC}_a$ and $T$ is the soil temperature in °C. Sheets and Hendrickx's original equation was fitted to the data from the U.S. Salinity Laboratory Staff (1954) in conversion Table 1.

Comparing the plots (marked by ◆) created by the data from Table 1 with Corwin and Lesch's corrected equation (Eq. 3) and Sheets and Hendrickx's original equation (Eq. 4) (Fig. 1), it can be seen that Corwin and Lesch's (Eq. 3) is correct. This was clearly a publishing mistake, but one worth warning practitioners about.

Besson et al. (2008) quoted Slavich and Petterson (1990) as providing Eq. 3. However, the function is not found in that paper. Equation 3 is referred to as the corrected Sheets and Hendrickx's model in this paper.

Durlesser (1999) gave a similar formulation (Durlesser 1999; Auerswald, et al. 2001)

$$\mathrm{EC}_{25} = \mathrm{EC}_a \times \left(0.477 + 1.69 \times \exp^{-T/21}\right), \tag{5}$$

where $T$ is the measured temperature, $\mathrm{EC}_a$ is the electrical conductivity at $T$ °C.

Lück et al. (2005) gave another similar formulation

$$\mathrm{EC}_{25}/\mathrm{EC}_a = 0.36 + \exp^{\left(-\frac{T-12.5}{28.5}\right)}. \tag{6}$$

They said that the relationship corresponds well with that given by Eijkelkamp (2003) and Durlesser (1999). We checked the temperature correction data of Eijkelkamp and found it

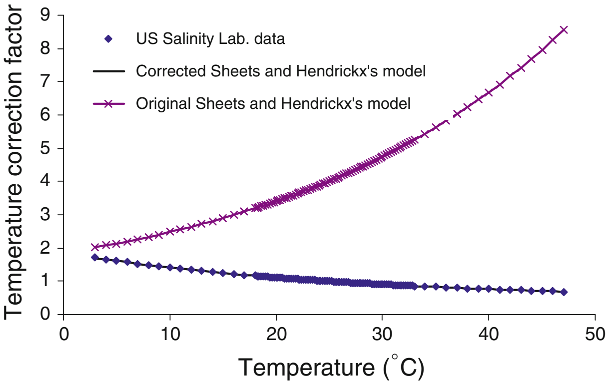


**Fig. 1** Sheets and Hendrickx's original model and Corwin and Lesch's corrected model compared with the data from Agriculture Handbook No. 60 (U.S. Salinity Laboratory Staff 1954)

was exactly the same as the U.S. Salinity Laboratory's correction factor (Table 1 in this paper).

Besson et al. (2008) quoted Wells (1978) as proposing a model with an exponential form

$$f_{\mathrm{T}} = e^{-\gamma(T_{\mathrm{ref}}-T_{\mathrm{m}})}, \tag{7}$$

where the coefficient $\gamma$ is equal to 0.02226, $T_{\mathrm{m}}$ is the measured temperature and $T_{\mathrm{ref}}$ is the reference temperature. If $T_{\mathrm{ref}}$ is 25°C, the temperature conversion function (Eq. 7) will become

$$f_{\mathrm{T}} = e^{-0.02226\times(25-T)}. \tag{8}$$

When we examined Wells's (1978) original paper, the following equation was found

$$\ln \mathrm{EC}_{T_2} = \ln \mathrm{EC}_{T_1} + \beta_1(T_2 - T_1) - \beta_2\left(T_2^2 - T_1^2\right), \tag{9}$$

where $\mathrm{EC}_{T_2}$ and $\mathrm{EC}_{T_1}$ are electrolytic conductivities at temperatures $T_2$ and $T_1$, respectively. For general use, $\beta_1$ is 0.0285 and $\beta_2$ is 0.000167. For the conversion reference temperature $T_2 = 25$°C, Wells's temperature conversion model will be

$$\mathrm{EC}_{25} = \mathrm{EC}_{\mathrm{T}} \times e^{0.0285\times(25-T)-0.000167\times(25^2-T^2)}. \tag{10}$$

A comparison of Wells's (1978) original formula (Eq. 10) and that cited by Besson et al. (2008) (Eq. 8) with data from Table 1 (Fig. 2) shows that Wells's original model corresponds well with the data and that cited by Besson et al. (2008) (Eq. 8) is incorrect. However, if the reciprocal of Eq. 8 is taken, we get Eq. 11. This is now consistent with the data in Table 1, but still does not perform as well as Wells's (1978) original model (Fig. 2).

$$\mathrm{EC}_{25} = \mathrm{EC}_{\mathrm{T}} \times e^{0.2226\times(25-T)}. \tag{11}$$

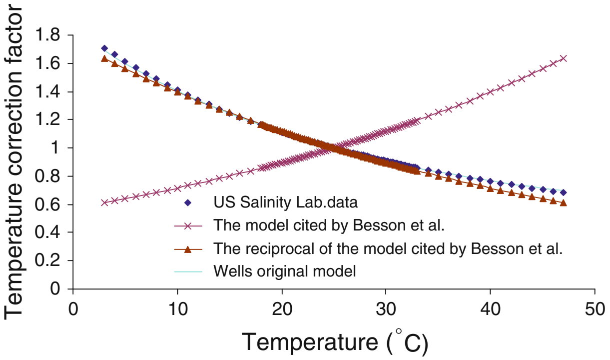


**Fig. 2** Wells (1978) original model, the model cited by Besson et al. (2008) and the reciprocal of the model cited by Besson et al. (2008), compared with the data from Agriculture Handbook No. 60 (U.S. Salinity Laboratory Staff 1954)

### *The power function model*

Besson et al. (2008) gave a new temperature conversion model, a power function which depends on only one parameter

$$f_{\mathrm{T}} = \left(\frac{T_{\mathrm{ref}}}{T_{\mathrm{m}}}\right)^{s}. \tag{12}$$

A constant value $s = 0.3$ is relevant for this empirical conversion model. If $T_{\mathrm{ref}}$ is equal to 25°C, this model can be rewritten as

$$f_{\mathrm{T}} = \left(\frac{25}{T}\right)^{0.3} \quad \text{or} \quad \mathrm{EC}_{25} = \mathrm{EC}_{\mathrm{T}}\left(\frac{25}{T}\right)^{0.3}. \tag{13}$$

### *The polynomial model*

The polynomial model by Rhoades et al. (1999) is given as

$$f_{\mathrm{T}} = 1 - 0.20346(T_a) + 0.03822(T_a^2) - 0.00555(T_a^3), \tag{14}$$

where $T_a = [-25°\mathrm{C}]/10$. This relationship was also derived from data provided by U.S. Salinity Laboratory Staff (1954), see Table 1. This model was referred to in Corwin and Lesch (2005) and Friedman (2005) as the more accurate temperature conversion factor based on a common soil solution composition.

However, in the paper by Friedman (2005) and by Besson et al. (2008), the model of Rhoades et al. (1999) is given as

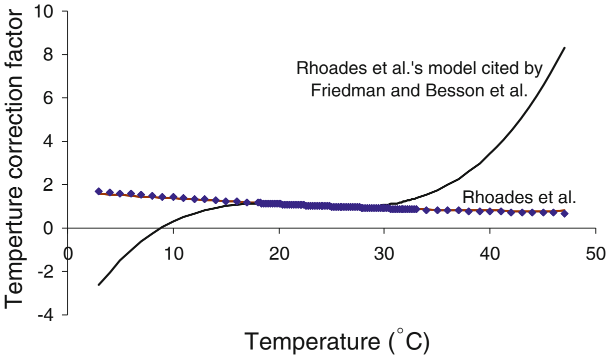
$$f_{\mathrm{T}} = 1 - 0.020346(T - 25) + 0.003822(T - 25)^2 + 0.000555(T - 25)^3. \tag{15}$$

If we substitute $T_a = [T - 25°\mathrm{C}]/10$ into Eq. 14, it becomes

$$f_{\mathrm{T}} = 1 - 0.020346(T - 25) + 0.0003822(T - 25)^2 - 0.00000555(T - 25)^3. \tag{16}$$

Comparing Eqs. 15 and 16 with data from Table 1 (Fig. 3), we can see that Friedman (2005) and Besson et al. (2008) cite an incorrect version of the Rhoades et al. (1999) model.

**Fig. 3** Rhoades et al.'s (1999) original model and the model cited by Friedman (2005) and Besson et al. (2008), compared with the data (*dots*) from Agriculture Handbook No. 60 (U.S. Salinity Laboratory Staff 1954)



### *Wraith and Or's model*

Other forms of polynomial referred to in Corwin and Lesch's paper (2005) include Stogryn (1971) and Wraith and Or (1999). In Wraith and Or's paper (1999), the electrical conductivity response of aqueous solutions is characterized as

$$\begin{aligned} &\mathrm{EC}_{\mathrm{w(T)}} = \mathrm{EC}_{\mathrm{w(25)}} \exp\left[-\Delta\left(2.033 \times 10^{-2} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2\right)\right], \\ &\mathrm{EC}_{\mathrm{w(T)}} \approx \mathrm{EC}_{\mathrm{w(25)}}[1 - 0.02\Delta] \end{aligned} \tag{17}$$

where $\mathrm{EC_w}$ is the electrical conductivity of water (dS $\mathrm{m}^{-1}$), $\Delta = 25 - T$ (°C). This simplified expression is most appropriate for temperatures near 25°C.

Wraith and Or's model (Eq. 17) is derived from Stogryn (1971) and Ulaby et al. (1986). In Stogryn's paper (1971), the conductivity for sea water was expressed as

$$\mathrm{EC}(T, S) = \mathrm{EC}(25, S) \exp(-\Delta\alpha), \tag{18}$$

where $T$ is the water temperature in °C, $S$ is the salinity in parts per thousand (‰) and $\Delta = 25 - T$. The $\alpha$ is a function of $T$ and $S$ such that

$$\begin{aligned} \alpha = {} & 2.033 \times 10^{-2} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 \\ & - S\left[1.849 \times 10^{-5} - 2.551 \times 10^{-7}\Delta + 2.551 \times 10^{-8}\Delta^2\right]. \end{aligned} \tag{19}$$

When salinity, $S$ is zero, the electrical conductivity of aqueous solutions can be expressed as Eq. 17.

The model of Stogryn (1971) was derived from Wely (1964) for seawater and the parameter $\alpha$ is defined as

$$\alpha = \frac{\log \mathrm{EC_s}(Cl, T) - \log \mathrm{EC_s}(Cl, 25)}{T - 25}. \tag{20}$$

The specific conductance of seawater $\mathrm{EC_s}$ is a function of the composition of the water, its temperature and pressure. At one atmosphere pressure, the specific conductance is a function of the two variables, chlorine concentration ($Cl$) and temperature ($T$). For any temperature, the relationship of $\alpha$ versus $Cl$ fits the following empirical expression (Wely 1964)

$$10^4\alpha = 88.3 + 0.55\tau + 0.0107\tau^2 - Cl(0.145 - 0.002\tau + 0.0002\tau^2), \tag{21}$$

where $\tau = 25 - T$.

The following equation can be derived from Eq. 20

$$\frac{\mathrm{EC_s}(Cl, T)}{\mathrm{EC_s}(Cl, 25)} = \exp(-\ln 10\alpha\tau). \tag{22}$$

Substituting the relationship of salinity $S$ with chlorine concentration ($Cl$) of S‰ = 1.80655Cl‰ (Wooster et al. 1969) into Eq. 21, and inserting the equation into Eq. 22, then Stogryn's model (1971) (Eqs. 18, 19) can be obtained.

Ulaby et al. (1986) cite Eqs. 18 and 19 in their book, which were derived by Wely (1964) and later modified by Stogryn (1971).

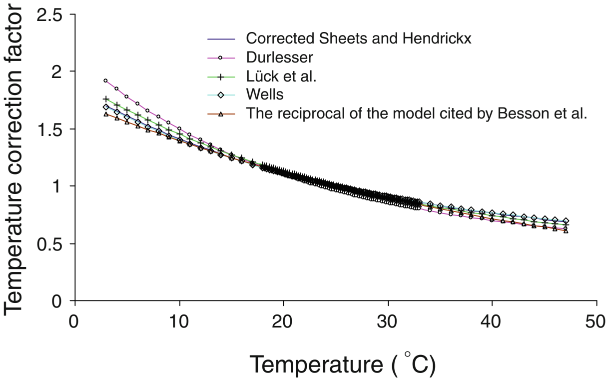


**Fig. 4** The comparison of all exponential models by the corrected Sheets and Hendrickx, Durlesser, Lück et al. Wells' original model and the reciprocal of the model cited by Besson et al.

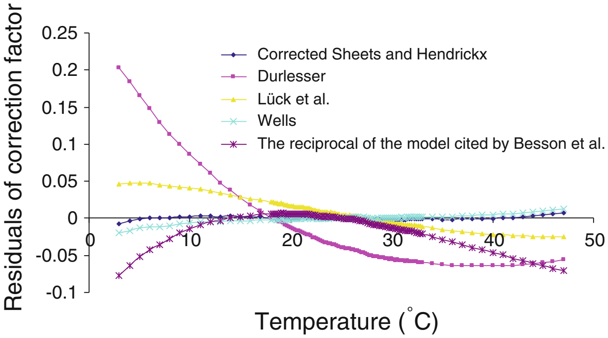


**Fig. 5** Residuals of all exponential models (Fig. 4) compared to the correction factor for soil extracts published by U.S. Salinity Laboratory Staff (1954)

## Comparison of the different temperature correction models

### *Comparison of exponential models*

First, we compare all exponential models, the corrected Sheets and Hendrickx (Corwin and Lesch 2005), Durlesser (1999) and Lück et al. (2005) models, Wells's original formula (1978) and the reciprocal of model (Eq. 11) cited in Besson et al. (2008).

Figure 4 shows the plot for all of the exponential models, and Fig. 5 shows the residuals of the models. Figure 4 shows that all of the exponential models are consistent, especially within the temperature range 15–35°C. However, careful inspection of the residuals with the correction table from the U.S. Salinity Laboratory (Table 1) in Fig. 5 reveals that the corrected Sheets and Hendrickx's model and Wells's original model have the smaller residual with an average error of 0.14% and 0.258%, respectively within the temperature range of 3–47°C. Durlesser's model has the largest average residual error of 4.85% because the equation developed by Durlesser (1999) is an empirical model for the temperature correction factor of specific soil types in Germany. The model of Lück et al. (2005) and the reciprocal of model cited by Besson et al. (2008) from Wells (1978) have an average error of 1.5%.

*Comparison of the exponential model with other temperature correction models*

Second, we compared the corrected Sheets and Hendrickx exponential model (Corwin and Lesch 2005) with other temperature correction models for EC measurements: the ratio model, the power function model of Besson et al. (2008), the polynomial model of Rhoades et al. (1999) and Wraith and Or's model (1999).

We modified the model from Wraith and Or (1999) so that it is in the same form as that of the models of Sheets and Hendrickx (1995) and Rhoades et al. (1999)

$$\mathrm{EC}_{\mathrm{w}(25)} = \mathrm{EC}_{\mathrm{w}(\mathrm{T})} \exp\left[-(T-25)(2.033\times10^{-2} - 1.266\times10^{-4}(T-25) + 2.464 \times10^{-6}(T-25)^2\right], \tag{23}$$

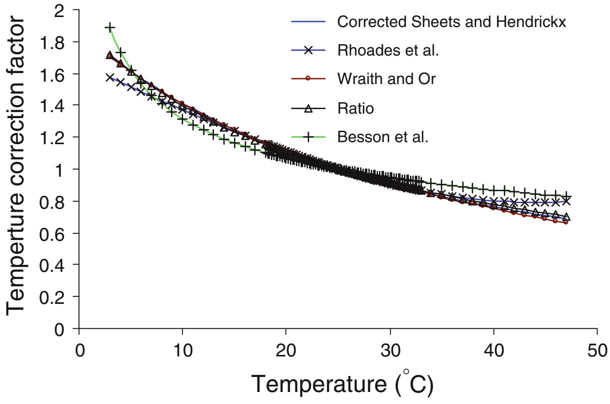


**Fig. 6** The comparison of models by the corrected Sheets and Hendrickx, Besson et al. Rhoades et al. Wraith and Or, and ratio models for temperature correction of EC measurement

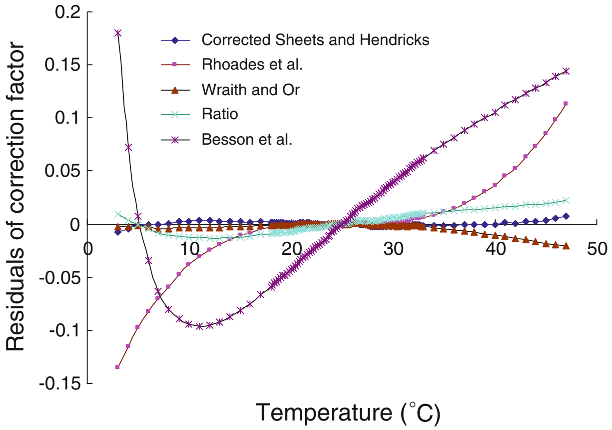


**Fig. 7** Residuals of various models (Fig. 6) compared to the correction factor for soil extracts published by U.S. Salinity Laboratory Staff (1954)

and for the simplified expression

$$\mathrm{EC}_{\mathrm{w}(25)} \approx \mathrm{EC}_{\mathrm{w(T)}} \times \frac{1}{1+0.02(T-25)}. \tag{24}$$

This is the same as the ratio model Eq. 2 with $\delta = 0.02°\mathrm{C}^{-1}$.

Figure 6 shows the plot for all of the models, and Fig. 7 shows the residuals of the models. The Besson et al. (2008) power function model is not as consistent as the other models. Again, the model of Besson et al. (2008) is an empirical conversion model describing the experimental data of electrical conductivity in specific undisturbed soil samples. It has a maximum residual error of 4.85% within the temperature arrange of 3–47°C (Fig. 7).

Other models are consistent, especially within the temperature range 10–40°C, for example the corrected Sheets and Hendrickx, Wraith and Or and ratio models (Fig. 6).

Careful inspection of the residuals with the correction table from the U.S. Salinity Laboratory (Table 1) in Fig. 7 reveals that most models, except for that provided in Besson et al. (2008), perform similarly within the range 20–30°C. The model of Rhoades et al. has the largest residuals outside the range 15–35°C (excluding Besson et al.). The model was originally designed to produce temperature correction coefficients between the range 15–35°C, and it was not supposed to be used outside the range 10–40°C (S.M. Lesch, personnel communication). The ratio model with $\delta = 0.019$ performs well within the temperature range of 3–47°C with an average error of 0.7%, however the model shows increasing error with increasing temperature above 40°C. Wraith and Or's model also performs well with an average error of 0.23% and also shows increasing error with increasing temperature above 40°C. The best performing model is the corrected Sheets and Hendrickx model (Corwin and Lesch 2005); it has the smallest residuals between 3–47°C and an average error of 0.14%.

## Conclusions

- We found some inconsistencies in the citation of previous equations for the effect of temperature on soil EC. Sheets and Hendricks's original formulation had a mistake. Rhoades's original equation is correct but it was mistakenly cited in Friedman (2005) and Besson et al. (2008). Besson et al. (2008) cite a model (Eqs. 7, 8) as originating from Wells (1978), which is incorrect. The reciprocal of the model in Besson et al. (2008) (Eq. 11) is consistent with other models.
- We found that the corrected exponential model of Sheets and Hendrickx (1995) (as correctly presented in Corwin and Lesch 2005) performs the best.
- The model of Rhoades et al. (1999) only works well within the 15–35°C range, for which it was originally designed.
- The simple ratio model works well within 3–47°C, as for the Wraith and Or (1999) model and Wells' original model (1978).
- However, the Lück et al. (2005) model and the reciprocal of the model cited in Besson et al. (2008) (Eq. 11) deviate from the standard value for most temperature ranges.
- The exponential model of Durrlesser (1999) and the power function model of Besson et al. (2008) are empirical models for experimental data from specific soil types.
- We suggest that practitioners use the corrected Sheets and Hendrickx or ratio models to correct $\mathrm{EC}_a$ readings, acquired within the 3–50°C range, to provide measurements referenced to 25°C ($\mathrm{EC}_{25}$).

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