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Systematic review and meta-analysis

Considerations on measurement frequency of electromagnetic sensors for soil water content determination

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ABSTRACT

Electromagnetic (EM) sensors are widely used to measure soil water content for different applications. The dielectric response of soil over the operational frequency of EM sensors in the megahertz to gigahertz range can be affected by a number of factors other than soil water content. It is therefore beneficial to examine the measurement frequency of sensors, for better understanding the sensor output (i.e., permittivity or circuit response), as well as its impact on water content determination. Previous investigations differed in measurement equipment, tested frequencies, and soil variables and hence found inconsistent conclusions regarding various EM sensors. In this paper, we try to provide comprehensive considerations on measurement frequency for EM sensing of soil water content, which could clarify sensor performance, selecting appropriate sensors, and designing new sensors.

1. Introduction

Soil water content is a primary factor that governs the mass and energy exchange at the air–soil interface. It also affects many other physical, chemical, and biological properties of soil. Consequently, it is of great interest to determine soil water content within many research and engineering disciplines, such as for applications in irrigation scheduling, hydrology, ecology, environmental science, geophysics, and geotechnical engineering.

Among the diverse techniques used to measure soil water content *in situ*, electromagnetic (EM) methods, based on sensing the soil dielectric properties, are the most popular since the seminal work of Topp et al. (1980). The EM signal responds to soil moisture because of the high permittivity of free water compared to the other constituents of soil (i.e., air and solid). Depending on the adopted measurement principle, the developed sensors generally fall into two categories of time-domain and frequency-domain devices (Robinson et a., 2003; Jones et al., 2005). A frequency-domain soil water content sensor typically measures the capacitance, impedance, or resonant frequency of the soil around the sensor electrodes. They often operate at a fixed measurement frequency in accordance with the signal source on their circuitry, although there are also solutions that involve broadband measurements (Pandey et al., 2013; González-Teruel et al., 2022). Time-domain devices, either time-domain-reflectometry (TDR) or −transmissometry (TDT), determine the soil water content from the travel time of the EM wave propagating along the sensor waveguides. The measurement frequency for time-domain methods is therefore not one single frequency, but a broad bandwidth signal which typically ranges between 0 to 1 GHz frequency (Heimovaara et al., 1996). Fig. 1 presents pictures of several common EM sensor models available on the market, which operate at frequencies from 20 MHz up to 1.5 GHz.

The accuracy of soil water content determination via EM sensors can be affected by a number of factors, including the sensor related variables (e.g., circuitry, probe geometry, measurement frequency, temperature, and installation) and soil properties (e.g., salinity, temperature, texture, specific surface area, particle shape, bound water, and phase configuration) (Friedman and Robinson, 2002; Jones and Or, 2002; Chen and Or, 2006). Among all these factors, measurement frequency is a key parameter for the sensor design. Previous work has evaluated the performance of different sensors with varying operational frequencies

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(Blonquist et al., 2005; Vaz et al., 2013) or identical sensor design operating at different frequencies (Kizito et al., 2008); results that are limited to specific sensor models and frequency ranges. A significant factor that makes the measurement frequency critical is the dielectric dispersion that occurs in many soils, i.e., the change of the dielectric properties as a function of frequency. The frequency-dependence of permittivity has been investigated using vector network analyzers and impedance analyzers (Campbell, 1990; Kelleners et al., 2005; Loewer et al., 2016; Chen and Or, 2006; Szypłowska et al., 2019; González-Teruel et al., 2020). Both sensor and soil contribute to the frequency dependance of dielectric measurements for soil water content determination. However, there is currently a dearth of comprehensive evaluations regarding the effects of measurement frequency on soil water content determination using EM sensors. This paper aims to address this critical gap by focusing on the major question: How do measurement frequency effects impact soil water content determination using EM sensors?

2. Fundamental theory

Dielectric permittivity (ε, F m^{-1}) is a measure of a material's ability to store electrical energy in an electric field. It is usually discussed in terms of relative permittivity (ε_r, unitless), which is the ratio of the material's permittivity to that of free space (ε_0, $= 8.854 \times 10^{-12}$ F m^{-1}):

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}\# \tag{1}$$

In practical applications, materials often exhibit both energy storage and energy dissipation characteristics when exposed to an electric field. This behavior is captured by the complex dielectric permittivity (ε_r*), which provides a comprehensive understanding of the material's electrical properties. The real part of the complex permittivity (ε_r') represents the material's capacity to store electrical energy, reflecting the alignment of molecules with the electric field. The imaginary part (ε_r''), also known as dielectric loss, accounts for the energy dissipated as heat due to molecular relaxation (ε_{relax}'') and electrical conductivity (σ_{dc}). Thus, ε_r* could be written as (Robinson et al., 2003):

$$\varepsilon_r^* = \varepsilon_r' - \varepsilon_r'' = \varepsilon_r' - j(\varepsilon_{relax}'' + \frac{\sigma_{dc}}{2\pi f \varepsilon_0})\# \tag{2}$$

where j is the imaginary unit and f is frequency.

The permittivity estimated by EM sensors is referred to as the apparent permittivity (K_a) of soil, which is a specific combination of ε_r' and ε_r'' influenced by the sensor's circuitry design (Jones et al., 2005). Soil volumetric water content (θ_v, cm^3 cm^{-3}) could be related to K_a using an empirical or mixing model, such as the widely used Topp et al. (1980) equation or other dielectric mixing models (van Dam et al., 2005).

3. Aspects of Consideration

3.1. Dielectric dispersion

Dielectric dispersion (from a frequency perspective) or relaxation (from a time perspective) refer to the frequency-dependent variation of a material's dielectric permittivity. It is a consequence of dielectric polarization when an electric field is applied. Specific polarization mechanisms can be found in soils (Levitskaya and Sternberg, 2019). A dielectric medium is dispersive if it suffers from relaxation within the bandwidth of the measuring instrument (Robinson et al., 2003). Air is nondispersive and liquid water can also be seen as effectively nondispersive with a high relaxation frequency (i.e., 11–30 GHz in the range of 5–45°C), well beyond the measurement frequencies of commercial EM sensors. While dry materials or wet materials with low surface area (e.g., quartz sand, and talc) exhibit little relaxation, as demonstrated in Fig. 2, materials with higher surface area and bound cations (e.g., sodium bentonite) may display significant dielectric dispersion as water content increases (Robinson et al., 2003). This suggests that in dispersive soils, EM sensors operating at different frequencies may yield inaccurate soil water content measurements if they rely on the widely used Topp equation (Topp et al., 1980), which was derived from TDR measurements. Since EM sensors may operate at different frequencies, specific calibration in dispersive soils is often critical, as their behavior deviates considerably from that of coarse- and medium-grained mineral soils. The dielectric behavior of bentonite (Fig. 2) was further interpreted in Kelleners et al. (2005), who suggested a minimum measurement frequency of above 500 MHz for EM sensors to avoid the more active dielectric relaxation region of the spectrum, i.e., below 500 MHz.

3.2. Soil salinity/electrical conductivity

The measurement of dielectric permittivity by EM sensors in soils with high salinity or electrical conductivity (EC) is significantly affected due to potential attenuation of the EM signal. Chen and Or (2006) measured the dielectric permittivity spectrum for Woodbridge sandy

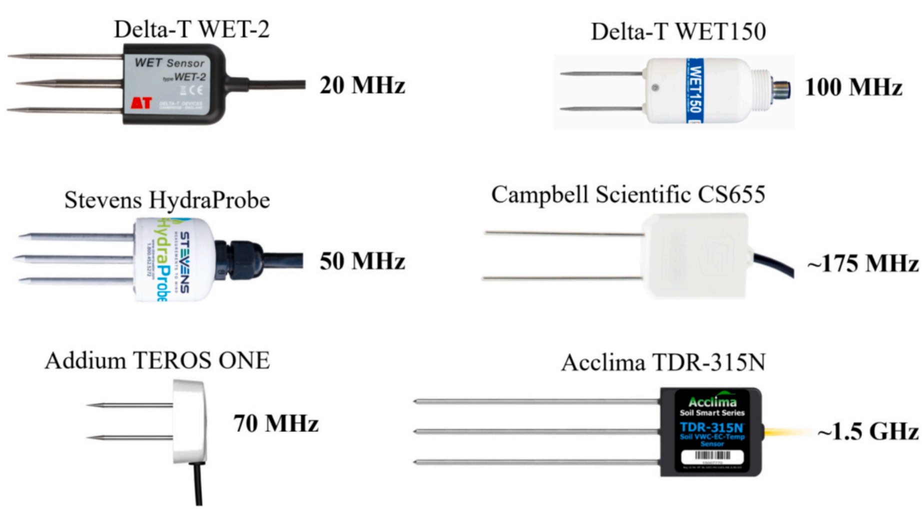

Fig. 1. Illustration of several comercially available EM sensors that operat at a range of frequencies from 20 MHz up to 1.5 GHz. The sensor models are (1) Delta-T WET-2, (2) Stevens HydraProbe, (3) Addium TEROS ONE, (4) Delta-T WET-150, (5) Campbell Scientific CS655, and (6) Acclima TDR-315 N. The operational frequencies for sensors −1, −2, −3 and −4 are documented in their manuals, sensor −5 in Kargas and Soulis (2019), and sensor −6 calculated as the 3-dB bandwidth of the step fuction with 150 ps 20 % to 80 % rise time (t_r), i.e., $f_{3dB} \approx 0.22/t_r$.

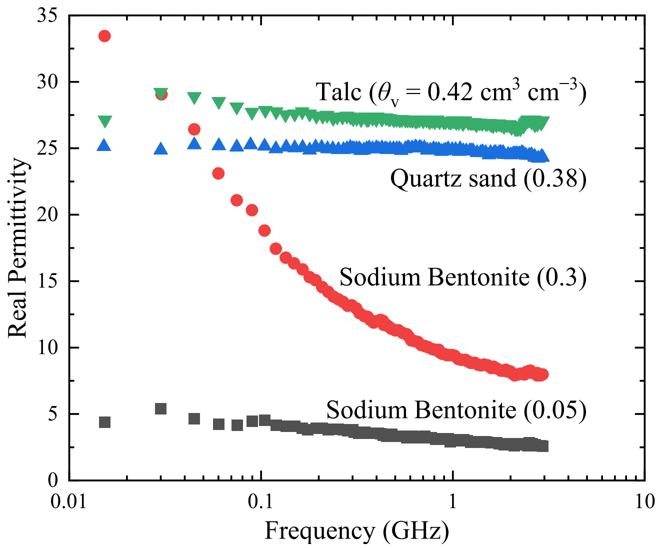

Fig. 2. Frequency dependance of the real permittivity (ε_r') for several soil minerals at different volumetric soil water contents measured with a vector network analyzer (
adapted from Jones et al., 2005).

loam soils at three different EC levels using a vector network analyzer (Fig. 3). Their results showed that EC significantly affects dielectric permittivity at relatively low frequencies, from kilohertz to 100 MHz, while the influence diminishes beyond 100 MHz. This implies that the EM sensors measuring at frequencies below 100 MHz may find applications in saline soils challenging without soil-specific calibration. Sheng et al. (2024) conducted an experimental evaluation of the effects of EC on permittivity determination using eight commercially available EM sensors. Their findings revealed that different sensors exhibit varying responses, which are not solely related to the measurement frequency. Other factors, such as sensor circuitry design and rod geometry, can also affect the susceptibility of EM sensors to electrically conducting soil conditions.

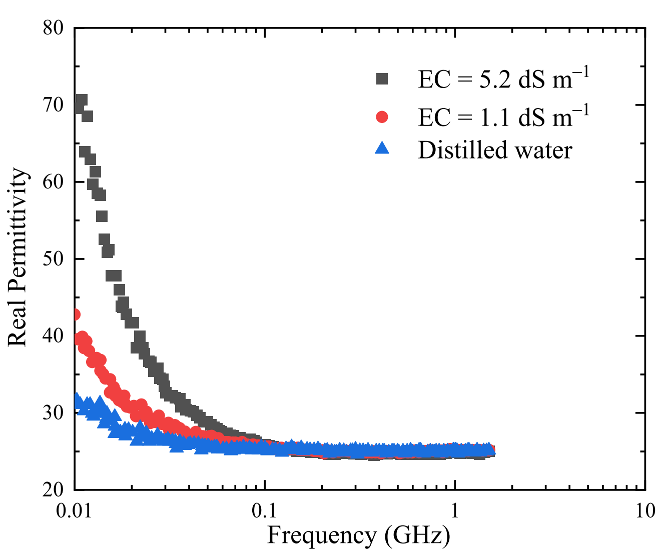

Fig. 3. The vector network analyzer measured real permittivity (ε_r') specturm for Woodbridge sandy loam saturated with three solutions of different electrical conductivity levels (
adapted from Chen and Or, 2006).

3.3. Soil texture

Similar to the soil salinity impacts on permittivity illustrated in Fig. 3, soil textural effects are also more pronounced at lower frequencies than at higher frequencies. Szypłowska et al. (2019) compared soil water content determinations at six different frequencies (i.e., between 20 and 3000 MHz) based on various calibration equations with real permittivity spectra from a novel transmission line sensor coupled with a vector network analyzer. Ten medium-textured soils were evaluated across a range of soil water content values in comparison. The resulting root mean square errors (*RMSEs*) for all ten soils combined is illustrated in Fig. 4, highlighting the roughly 0.01 cm^3 cm^{-3} *RMSE* water contents obtained within the several hundred MHz to the GHz frequency range. In contrast, the *RMSEs* associated with the 20 to 100 MHz frequency range of most commercial sensors, are associated with *RMSEs* of 0.02 to 0.03 cm^3 cm^{-3} for these medium-textured soils evaluated. We expect even larger errors could occur at these low frequencies if higher clay content soils were evaluated (Szypłowska et al., 2019). Soils with higher clay content enhance real permittivity more at these frequencies, making accurate calibration challenging. However, at higher frequencies (several hundred MHz and above), the impact of soil texture and salinity diminishes, resulting in more consistent and reliable dielectric permittivity readings across different soil types. This indicates that higher frequency measurements are less sensitive to variations in soil texture, thus providing accurate soil water content determination for a wider range of soil types.

3.4. Effective measurement frequency

Robinson et al. (2005) estimated the effective measurement frequency for TDR to be around 0.7–1 GHz in nondispersive soils and 100–200 MHz in dispersive clay soils, depending on probe design. Higher measurement frequency is beneficial for consistent soil water content determination yet varying effective frequencies due to soil texture are undesirable, suggesting the potential benefit of employing fixed-frequency sensor designs that operate at a higher frequency similar to TDR.

It needs to be noted that the measurement frequency for the broadband EM sensors can be affected by many factors, such as cable length,

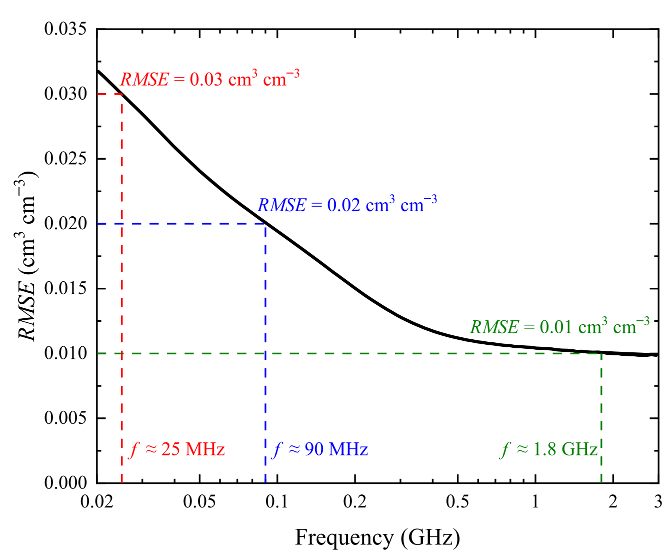

Fig. 4. Root mean square errors (RMSEs) of volumetric soil water content determined using a uniform calibration function for soils with varying textures across frequencies from 2 MHz to 3 GHz. The RMSE decreases as the frequency increases. The dotted lines indicate the minimum required measurement frequencies for RMSE levels of of 0.01, 0.02, and 0.03 cm^3 cm^{-3} (
adapted from Szypłowska et al., 2019).

connector quality, rod length, and the dielectric properties of the soil. High frequency components could be filtered out by components such as long coaxial cables, extended electrodes, or soils with higher permittivity. Several methods have been adopted to determine the maximal or effective frequency for travel time instruments (Or and Rasmussen, 1999; Topp et al., 2000; Robinson et al., 2005). This allows for comparison of time-domain sensors with other techniques working at fixed frequencies. Fig. 5 illustrates an example of finding the ‘maximal passable frequency’ by comparing the permittivity estimated from travel-time analysis to the permittivity spectrum (Jones et al., 2005).

3.5. Other considerations

Fig. 6 summarizes the various possible contributions to dielectric loss of heterogeneous aqueous systems proposed by Hasted (1973), where similar mechanisms may contribute to dielectric loss in wet porous media. This highlights the realm of frequencies in which each factor may exhibit more pronounced behaviors. Considering the additional factors that can influence the frequency dependence of the soil dielectric property we point to temperature, bound water, phase configuration, etc. Temperature has impacts on dielectric measurements of EM sensors from many different aspects, such as influencing soil EC (Chen and Or, 2006), the permittivity of water, and the transition between bound water and free ‘rotational’ water (Wraith and Or, 1999), in addition to the effects on the sensor circuitry. The water molecules in the soil can bind to cations and to the soil matrix. Because of the binding force, especially around cations, bound water is said to be irrotational and thus has little impact on the permittivity of soil compared to free water within an applied electric field. The relaxation frequency of bound water has been estimated to be below 150 MHz (Hilhorst et al., 2001) or in the range of 10–100 MHz (Robinson et al., 2003). The effects of bound water on dielectric measurements have been observed in Wraith and Or (1999) and Escorihuela et al. (2007). However, as Jones and Or (2002) point out, soil particle geometry and constituent phase (i.e., solid, water, air) configuration may also reduce and even exceed bulk permittivity reductions of porous media contributed by the influence of bound water, especially for media particle aspect ratios deviating by more than an order of magnitude from that of a sphere (Jones and Friedman, 2000). Improved methods for discriminating between effects from bound water versus those due to particle shape or phase configuration are needed (González-Teruel et al., 2020).

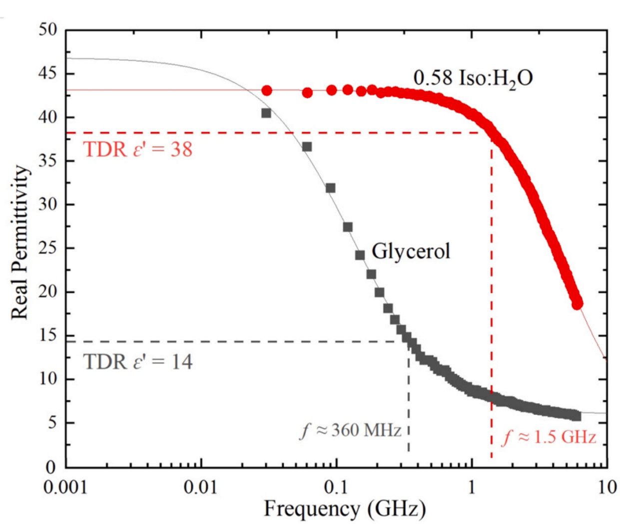

Fig. 5. Determination of the measurement frequency for time-domain reflectometry (TDR) by comparing the TDR-estimated permittivity (ε_r') to Cole-Cole modeled vector network analyzer data, yielding the effective measurement frequencies for TDR of 360 MHz in Glycerol versus 1.5 GHz in a 0.58 vol fraction of 2-Isopropoxyethanol in water (
adapted from Jones et al., 2005).

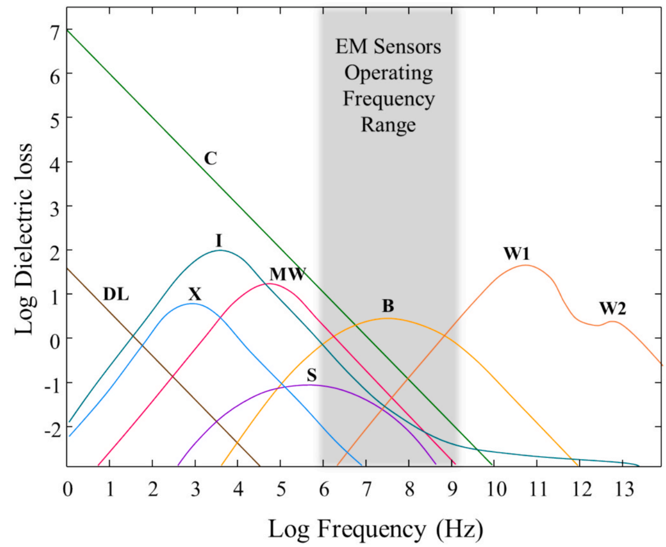

Fig. 6. Various mechanisms contributing to dielectric loss in wet porous media across a broad frequency spectrum. The mechanisms include: C, ionic conductivity; DL, charged double layer; X, crystal water relaxation; I, ice relaxation; MW, Maxwell-Wagner relaxation; S, surface conductivity; B, bound water relaxation; W1, primary free water relaxation; and W2, secondary free water relaxation. The shaded area indicates the operating frequency band for EM sensors (
adapted from Robinson et al., 2005; Hasted, 1973).

Table 1 lists several previous research studies that investigated the selection of measurement frequency for determining soil water content. The measuring instrument varies from certain EM sensor models to vector network analyzers, covering a frequency range of up to 3 GHz. These studies approached the influence of measurement frequency from different aspects (i.e., soil texture, EC, temperature, dielectric relaxation, and bound water) resulting in diverse suggested frequencies.

Table 1
List of previous studies that investigated the measurement frequency for EM sensing of soil water content.

Reference	Investigation Method and Suggested Measurement Frequency			
	Measuring Device	Tested Frequency Range	Variables Considered	Suggested Frequency
Campbell, 1990	Vecter network analyzer	1–50 MHz	Soil texture and temperature	50 MHz
Kelleners et al., 2005	Sentek EnviroSCAN probe, Tektronix TDR, and vector network analyzer	300 kHz – 3 GHz	Dielectric relaxation	> 500 MHz
Chen and Or, 2006	Vecter network analyzer	20 kHz – 1.5 GHz	Electrical conductivity and temperature	> 100 MHz
Escorihuela et al., 2007	Impedance probe and microwave remote sensing	100 MHz and 1.4 GHz	Bond water and temperature	> 500 MHz
Kizito et al., 2008	Decagon ECH_2O sensors	5–150 MHz	Soil texture, electrical conductivity, and temperature	70 MHz
Szypłowska et al., 2019	Vecter network analyzer	20 MHz – 3 GHz	Soil texture and electrical conductivity	> 250 MHz

Generally, high measurement frequencies are preferred to minimize the sensitivity of EM measurements to soil properties.

4. Summary

The frequency dependence of dielectric measurements has been shown to typically exhibit a reduced real permittivity as measurement frequency increases in lossy media, such as clayey and/or conductive soils that dissipate EM energy due to dielectric loss. As a key parameter of the sensor design, relating the sensor response to its measurement frequency would provide valuable insights (1) to interpret the sensor performance, (2) to assist in sensor selection for specific applications, and (3) to indicate direction for further sensor development. The soil properties considered above stem from different relaxation mechanisms of the dielectric loss for moist soil, including the Maxwell-Wagner effect, ionic conductivity, surface conductivity, and bound water relaxation. It would be ideal to develop standards that can be used to simulate all such relaxation mechanisms for improved characterization and evaluation of the many different EM sensors available today. These might include the combinations of dielectrically relaxing and electrically conducting liquids suggested by Jones et al. (2005).

Looking ahead, several key research directions emerge. First, systematic studies are needed to assess the trade-offs between measurement frequency, sensor response stability, and accuracy under varying soil textures, moisture levels, and salinity conditions. Second, multi-frequency or frequency-sweeping sensors could be explored to extract dielectric spectra and disentangle the effects of different loss mechanisms, improving estimation of both soil water content and salinity. Third, the development of standardized test materials and protocols simulating real-world soil dielectric behavior would enable meaningful cross-comparison of sensor technologies. Finally, with the increasing availability of compact, low-cost frequency-domain components, future work should focus on designing adaptive, field-deployable sensors with tunable frequencies and on developing modeling frameworks that link EM theory with observed sensor responses in heterogeneous soil environments towards improving our understanding of the underlying physical properties and processes.

CRediT authorship contribution statement

Wenyi Sheng: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Wenfeng Ni:** Visualization, Investigation, Data curation. **Juan D. González-Teruel:** Writing – review & editing, Methodology, Investigation. **Jinghui Xu:** Visualization, Investigation. **Scott B. Jones:** Writing – review & editing, Visualization, Supervision, Investigation, Conceptualization. **David A. Robinson:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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