A New Approach for In Situ Determination of Soil Bulk Density with the Thermo-TDR Technique

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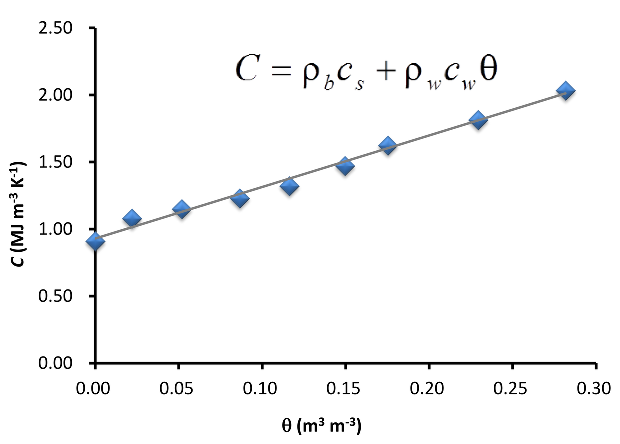
INTRODUCTION

- The thermo-TDR (time domain reflectometry) technique can be used to determine in-situ soil bulk density (ρ_b) based on the linear relationship between soil heat capacity (*C*) and soil water content (θ), which are measured with the heat pulse and TDR methods, respectively.



- A change in needle-to-needle spacing at probe insertion can affect the accuracy of *C* and lead to uncertainty in ρ_b estimates (Ren et al., 2003).
- However, soil thermal conductivity (λ) measurements from the heat pulse method are not affected by the changes in needle-to-needle spacing.
- The **objective** of this research is to develop a method to estimate ρ_b using measured λ data based on a model relating λ with soil particle size distribution (PSD), θ and ρ_b (Lu et al., 2014). Results obtained with standard and with improved sensors are compared.

THEORY

Estimating ρ_b using λ measurements ($\rho_{b\text{-}\lambda}$)

- Lu et al. (2014) introduced an equation that relates soil λ with θ and λ_{dry}. Two shape factors, α and β, along with λ_{dry}, are estimated from soil PSD and ρ_b.

$$\lambda = \lambda_{dry} + \exp(\beta - \theta^{-\alpha}) \quad [1]$$

$$\alpha = 0.67 f_{cl} + 0.24$$

$$\beta = 1.97 f_{sa} + 1.87\rho_b - 1.36 f_{sa}\rho_b - 0.95$$

$$\lambda_{dry} = -0.56\tau + 0.51$$

f_{cl}: clay fraction
f_{sa}: sand fraction
λ_{dry}: thermal conductivity of dry soils
τ: soil porosity

- Using λ and θ measurements from the thermo-TDR technique, we can obtain the shape factor for a specific soil from,

$$\beta = \ln(\lambda - \lambda_{dry}) + \theta^{-\alpha} \quad [2]$$

- Then ρ_b can be estimated by rearranging the β equation,

$$\rho_{b\text{-}\lambda} = \frac{\beta - 1.97 f_{sa} + 0.95}{1.87 - 1.36 f_{sa}} \quad [3]$$

Estimating ρ_b using *C* measurements ($\rho_{b\text{-}C}$)

$$\rho_{b\text{-}C} = \frac{C - \rho_w c_w \theta}{c_s} \quad [4]$$

ρ_w: density of water
c_w: specific heat of water
c_s: specific heat of soil solids

MATERIALS AND METHODS

- **Thermo-TDR Probe Design (Fig. 1)**
  - ✓ Standard: needle length, diameter, and spacing are 40 mm, 13 mm, and 6 mm, respectively. Tips are flat.
  - ✓ Improved: needle length, diameter, and spacing are 40 mm, 20 mm, and 8 mm, respectively. Tips are pointed.
- **Field Experiment**
  - ✓ Soil: silt loam, 17% sand and 21% clay
  - ✓ Four tillage treatments:
    - CK (moldboard plow without residue)
    - CT (moldboard plow with residue)
    - RT (rotary tillage)
    - NT (no tillage)
- **Measurements (Fig. 2)**
  - ✓ Depths: 5 and 15 cm
  - ✓ λ and C: heat pulse method
  - ✓ θ : TDR method
  - ✓ Gravimetric ρ_b: After the T-TDR measurements, soil cores are sampled near the probe locations

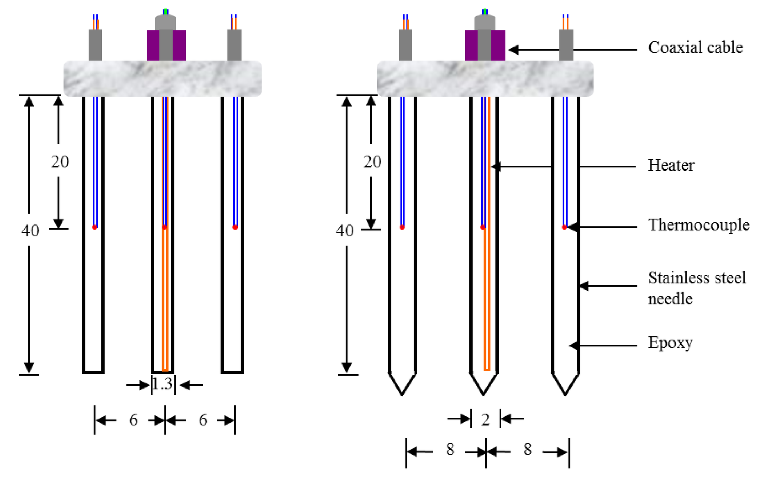


Fig 1. Schematic views of standard (left) and improved (right) thermo-TDR probes (Liu et al., 2008). Unit: mm.

Fig 2. Field installation of standard and improved thermo-TDR probes in the NT treatment. Cylinders are for soil cores.

RESULTS AND DISCUSSION

Gravimetric θ, ρ_b, and thermo-TDR Measured λ under Four Tillage Treatments

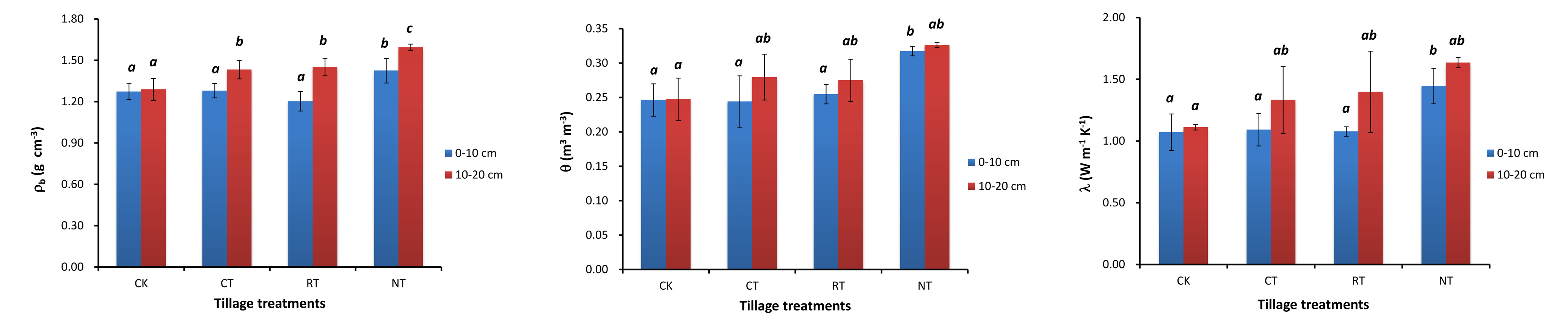


Fig 3. Gravimetric θ, ρ_b, and thermo-TDR measured λ for four tillage treatments. Within a specific layer, values followed by a different letter are significantly different among treatments at $p < 5\%$. Bars represent standard errors of the means.

- ✓ After harvesting the spring wheat, ρ_b, θ and λ showed variations in tilled layer due to different tillage operations.

Comparisons between thermo-TDR ρ_b and gravimetric ρ_b

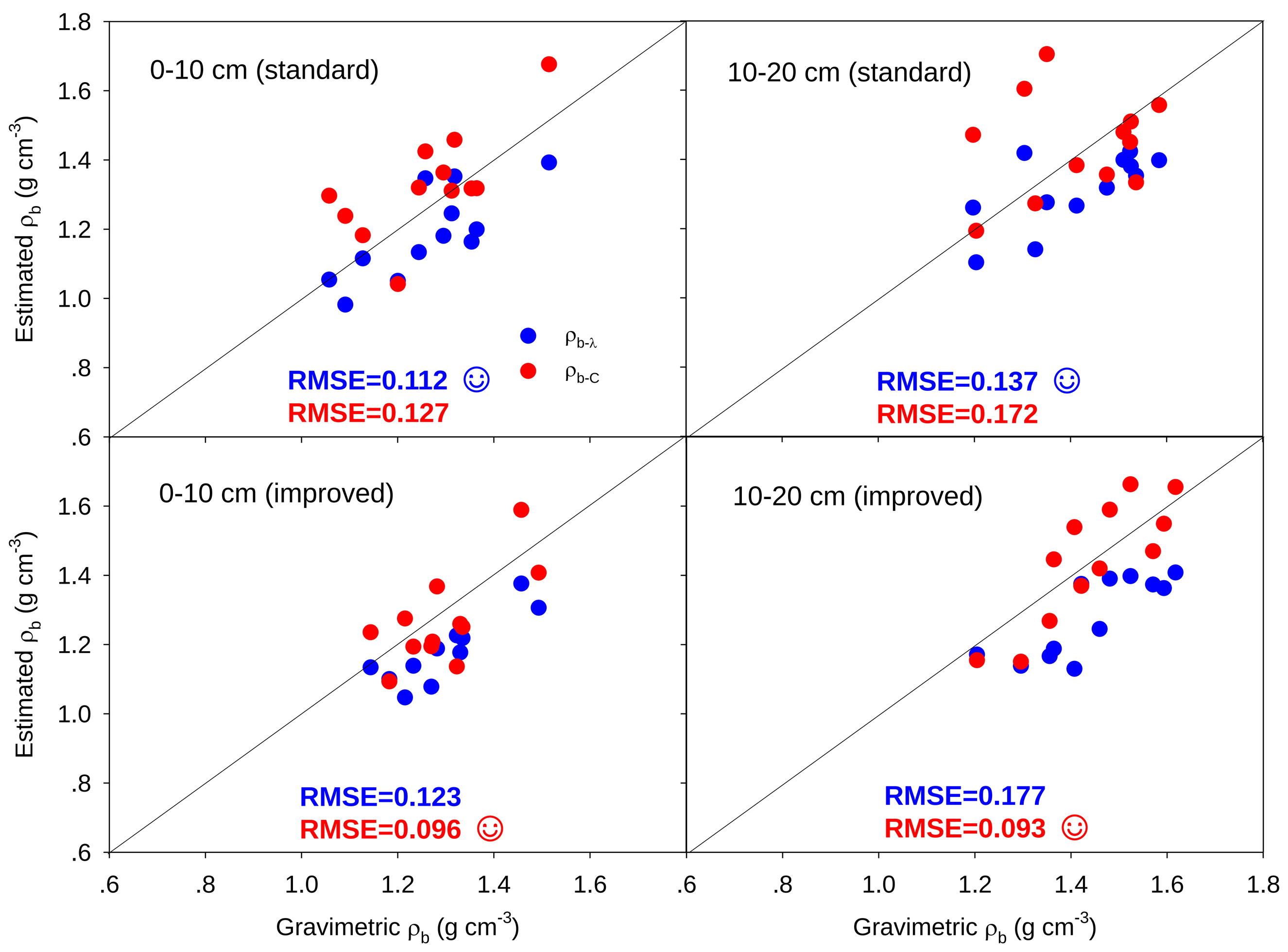


Fig.4 Comparison between the gravimetric and thermo-TDR ρ_b values in the 0-10 and 10-20 cm layers for four tillage treatments. The $\rho_{b\text{-}\lambda}$ (blue) and $\rho_{b\text{-}C}$ (red) are the ρ_b estimations using measured λ values and C values, respectively.

- ✓ The standard and improved probes both provide in-situ ρ_b with RMSE < 0.18 g cm^{-3}.
- ✓ With standard probes, $\rho_{b\text{-}\lambda}$ have smaller errors than $\rho_{b\text{-}C}$.
- ✓ With the improved probes, $\rho_{b\text{-}C}$ performs better than $\rho_{b\text{-}\lambda}$ with RMSE error < 0.10 g cm^{-3}. The possible explanations are:
  - The improved design is more robust, thus reduces the uncertainly in probe spacing changes, and obtains more accurate *C*.
  - The improved probes may have introduced additional errors, e.g., finite probe size and thermal properties.
  - When the accuracy of *C* is improved, the de Vries model performs superior to our empirical thermal conductivity model. However, ρ_b values from the thermal conductivity model are acceptable (errors are within 15%).

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