Determining Near-Surface Heat Flux Density Using Modeled Soil Thermal Conductivity

Xiaoyang Peng[1], Yili Lu[1], Joshua Heitman[2], Robert Horton[3], and Tusheng Ren[1]*

[1]Department of Soil & Water Sciences, China Agricultural University, Beijing, China 100193
[2]Soil Science Department, North Carolina State University, Raleigh, NC 27695
[3]Department of Agronomy, Iowa State University, Ames, IA 50011

Synergy in Science: Partnering for Solutions
ASA • CSSA • SSSA • ESA 2015 MEETING Nov. 15-18 | Minneapolis, MN

Background and Objectives

- The gradient method determines soil heat flux density (G) from the product of soil thermal conductivity (λ) and temperature (T) gradient at a soil depth below surface.

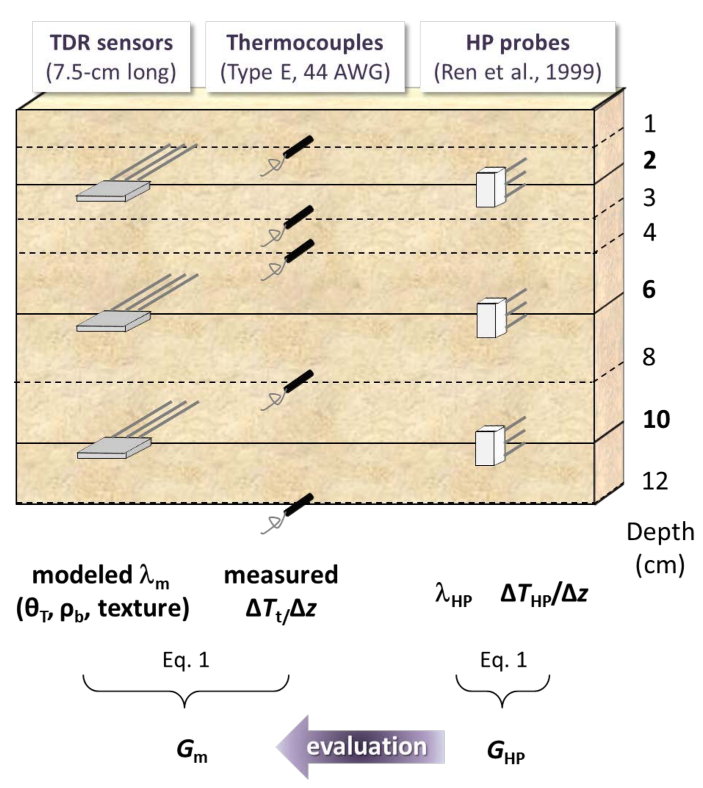
$$G = \lambda\,(dT / dz) \qquad [1]$$

- Heat-pulse (HP) probes have been used to measure λ. Its accuracy is influenced by soil-air interface, soil-probe contact resistance, and ambient temperature drift near surface.
- Thermal conductivity models can estimate λ with sufficient accuracy from information of soil texture, bulk density (ρ_b), and water content (θ).
- The **objectives** of this study are to evaluate:
  - ✓ the potential of estimating near-surface G using modeled thermal conductivity (λ_m) with the gradient method, and
  - ✓ the influences of θ and ρ_b on λ_m and G results.

Materials and Methods

- **Field site:** A bare sandy loam soil (79.8, 7.7, and 12.5% sand, silt, and clay contents, respectively) in the experimental farm of China Agricultural University.

Fig. 1. Sensor installation.



- **Measurements** (Fig. 1):
  - ✓ Field measurements lasted for 25 d (DOY 253-278);
  - ✓ G at 2, 6, and 10 cm were determined with two approaches: gradient method using measured λ_{HP} and gradient method using modeled λ_m.
- **Soil heat flux calculations** (Eq. 1, Fig. 1):
  - ✓ Using measured λ_{HP}

$$G_{HP} = -\lambda_{HP} \times (\Delta T_{HP}/\Delta z)$$

  - ✓ Using modeled λ_m from L07

$$G_{m\text{-}L07} = -\lambda_{m\text{-}L07} \times (\Delta T_t/\Delta z)$$

  - ✓ Using modeled λ_m from L14

$$G_{m\text{-}L14} = -\lambda_{m\text{-}L14} \times (\Delta T_t/\Delta z)$$

Parameter	Depth (cm)	Interval	Equipment/sensor
Bulk density (ρ_b)	0-5, 5-10	1.9 d	Ring samplers
Gravimetric water content (θ_m)	2, 6, 10	1.9 d	Layering sampler (Zhang et al., 2014)
TDR water content (θ_{TDR})	2, 6, 10	1 h	TDR 100 and 7.5-cm long TDR probe
Thermal conductivity (λ_{HP})	2, 6, 10	1 h	3-needle heat-pulse sensor
Temperature (T)	1, 3, 4, 8, 12	1 h	Thermocouple (T_t) and 3-needle heat-pulse sensor (T_{HP})

For heat-pulse λ_{HP} measurements: 1) ambient temperature drift was corrected (Jury and Bellantuoni, 1976); 2) late-time fitting scheme was used to fit the $\Delta T(t)$ curves (Lu et al., 2013).

- **The λ models**

L07 Model	L14 Model
$\lambda_{m\text{-}L07} = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry}$	$\lambda_{m\text{-}L14} = \lambda_{dry} + \exp(\beta - \theta^{-\alpha})$
$\lambda_{sat} = (\lambda_q^{f_{sa}} \lambda_o^{1-f_{sa}})^{1-n} \lambda_w^n$	$\lambda_{dry} = -0.56n + 0.51$
$\lambda_{dry} = -0.56n + 0.51$	$\alpha = 0.67 f_{cl} + 0.24$
$K_e = \exp\{\varepsilon[1 - (\theta/\theta_s)^{(\varepsilon - 1.33)}]\}$	$\beta = 1.97 f_{sa} + 1.87\rho_b - 1.36 f_{sa}\rho_b - 0.95$

f_{sa} and f_{cl}: sand and clay fraction, respectively
n: total porosity (1-ρ_b/2.65)
ε: texture dependent factor, 0.96 for coarse soils
a and b: shape factors of the λ(θ) curve

Three parameters, texture, ρ_b, and θ, are required for λ modeling.

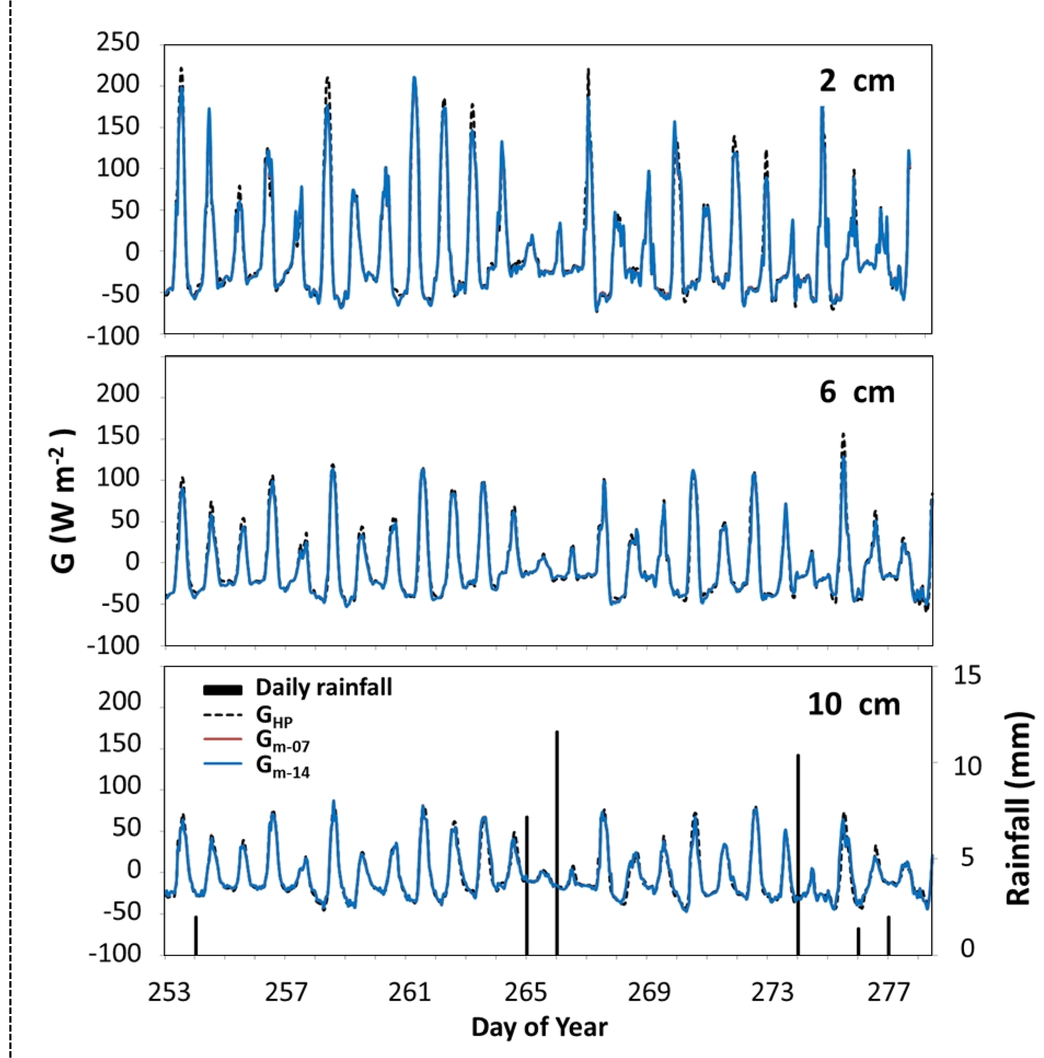


Fig. 2. Time series of G_m estimates using modeled λ_m against G_{HP} estimates using λ_{HP}. Daily rainfall is also shown in bars.

Table 1. RMSE of G_m estimates using modeled λ_m.

Depth (cm)	With $\Delta T_t/\Delta z$		With $\Delta T_{HP}/\Delta z$	
	L07	L14	L07	L14
2	9.1	8.9	6.6	5.7
6	5.8	5.7	1.8	1.6
10	5.8	5.9	1.3	1.3

Table 2. RMSE of modeled λ_m.

Depth (cm)	L07	L14
2	0.09	0.08
6	0.05	0.05
10	0.05	0.05

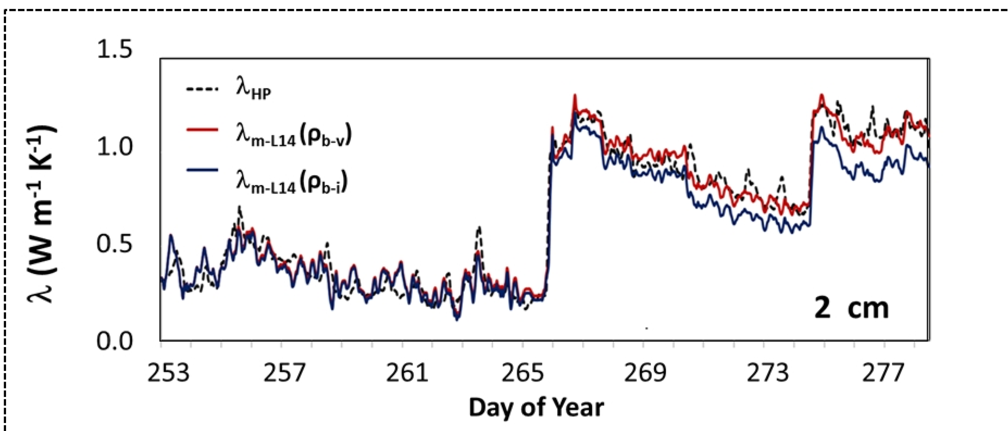


Fig. 3. Dynamics of λ_{HP} and modeled $\lambda_{m\text{-}L14}$ from dynamic $\rho_{b\text{-}v}$ values (every 1.9 d) and a fixed $\rho_{b\text{-}i}$ (measured on DOY 253) at 2 cm.

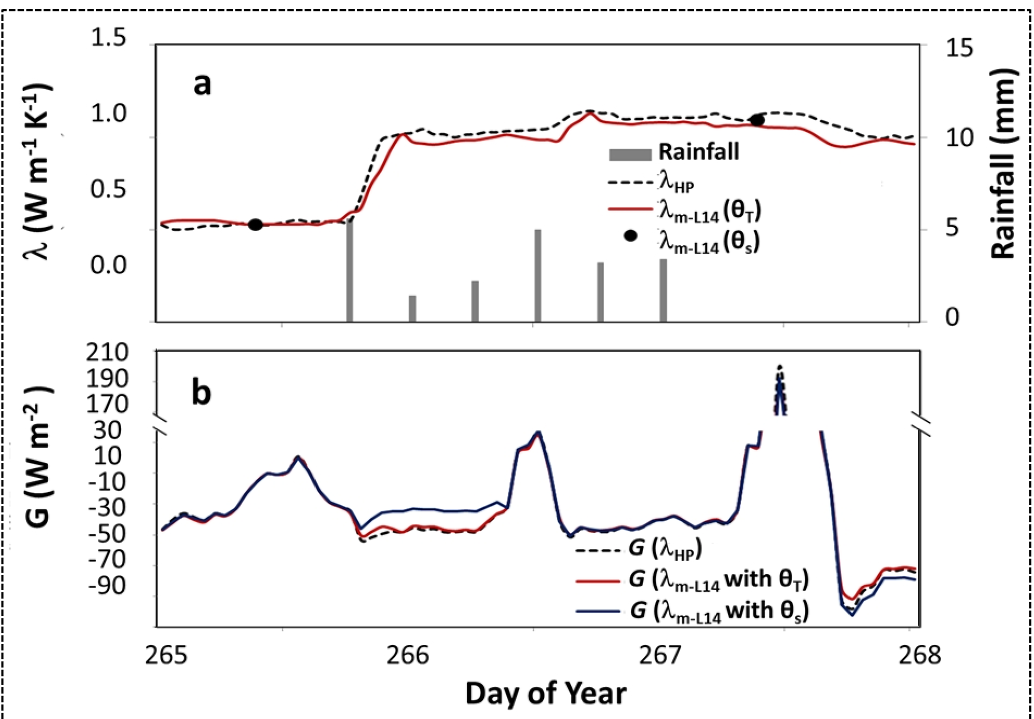


Fig. 4. a) Dynamics of λ_{HP} and modeled λ_m (with hourly θ_T and discrete θ_s) at 2 cm during DOY265-268; b) time series of G_{HP} and G_m estimated with $\lambda_m(\theta_T)$ and $\lambda_m(\theta_s)$. $\Delta T_{HP}/\Delta z$ was used with both λ_{HP} and λ_m for estimating G_{HP} and G_m. Rainfall is also shown in Fig. 4a as a total of every 6 h.

Results and Discussions

1. **Time series of G_m and G_{HP}**
   - **G_m and G_{HP} followed the same trend and showed similar responses to rainfall and diurnal solar radiation** (Fig. 2), with the magnitude of G decreasing with soil depth;
   - G_m and G_{HP} ranged from -70 to 210 W m^{-2} and -70 to 220 W m^{-2} at 2 cm, respectively;
   - G_m and G_{HP} reduced to -50 to 160 W m^{-2} at 6 cm, and to -50 to 130 W m^{-2} at 10 cm.
2. **Comparison of G_m and G_{HP}**
   - **G_m agreed well with G_{HP} at three depths** (with RMSE of 5.7-9.1 W m^{-2}, Table 1). The errors were attributed to the differences between $\Delta T_t/\Delta z$ & $\Delta T_{HP}/\Delta z$ and between λ_m & λ_{HP};
   - When using $\Delta T_{HP}/\Delta z$ with λ_m and λ_{HP} for estimating G (Eq. 1), G_m errors that caused by λ_m errors were in the range of 1.3-6.6 W m^{-2} (Table 1);
   - $G_{m\text{-}L07}$ and $G_{m\text{-}L14}$ estimates were in close agreement.
3. **Field performance of λ models** (Table 2)
   - λ_m estimates from the L07 and L14 models were in close agreement;
   - RMSEs of λ_m: 0.05-0.09 and 0.05-0.08 W m^{-1} K^{-1} for L07 and L14 models, respectively;
   - λ_m and λ_{HP} discrepancy was observed at 2 cm, producing larger G_m errors.
4. **Effect of ρ_b on λ modeling and G estimate**
   - ρ_b increased from 1.27 to 1.39 and 1.35 to 1.40 g cm^{-3} in 0-5 and 5-10 cm layers, respectively;
   - **Using dynamic ρ_b improved the model performance**. At 2 cm, for example,
     - ✓ With fixed $\rho_{b\text{-}i}$, $\lambda_{m\text{-}L14}$ deviated from λ_{HP} gradually (Fig. 3), with RMSE of 0.08 W m^{-1} K^{-1};
     - ✓ With dynamic $\rho_{b\text{-}v}$, $\lambda_{m\text{-}L14}$ agreed well with λ_{HP}, with RMSE of 0.05 W m^{-1} K^{-1}; Therefore,
     - ✓ Improved $\lambda_{m\text{-}L14}$ estimates using $\rho_{b\text{-}v}$ led to improved $G_{m\text{-}L14}$ (with RMSE decreased from 5.7 to 4.3 W m^{-2}).
   - At 6- and 10-cm depths, ρ_b varied slightly and had negligible effect on G_m data.
5. **Effect of θ on λ modeling and G estimate**
   - **The models** not only produced reliable λ estimates **with dynamic TDR θ_T**, but also **captured the abrupt changes in λ** (Fig. 4a) **and G** (Fig. 4b) **due to rainfall events**;
   - Using soil sampling θ_s, the models gave good estimates of λ and G at the specific measuring moment, but missed λ and G dynamics shortly after rainfalls (Fig. 4a, Fig. 4b).

Conclusions

1. For the gradient method, modeled λ_m can be used to produced reliable near-surface G;
2. Both Lu et al. (2007) and Lu et al. (2014) models performed well in estimating field λ_m;
3. Comparing with the gravimetric method, the TDR technique has the advantage of capturing the dynamics of θ_T, thus provides continuous λ_m and G_m shortly after rainfalls.
4. For near-surface layers (i.e., within 2 cm), it is necessary to include the temporal variations of ρ_b for estimating λ_m and G_m accurately.
5. With the modelling approach, one can estimate soil heat flux density G using existing measurements of soil water content, temperature, and bulk density, which eliminates the needs of measuring thermal conductivity with complicated equipment.

References

- Lu, S., Ren, T., Gong, Y., Horton, R., 2007. An improved model for predicting soil thermal conductivity from water content at room temperature. Soil Sci. Soc. Am. J. 71(1), 8–14.
- Lu, Y.L., Lu, S., Horton, R., Ren, T., 2014. An empirical model for estimating soil thermal conductivity from texture, water content, and bulk density. Soil Sci. Soc. Am. J. 78:1859–1868.

Correspondence
Xiaoyang Peng: xypeng@cau.edu.cn
Tusheng Ren: tsren@cau.edu.cn

Acknowledgements
National Science Foundation of China (41271238)
High End Foreign Expert Program of China (GDT20141100002)