

Proceeding Paper

An Improved Hapke Model to Characterize the Variation of Soil Moisture Content [†]

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Abstract: Hapke model has been widely used in the field of soil remote sensing. However, the latest development of the Hapke model (i.e., Hapke-HSR model) adopted a simple hypothesis to consider the influence of soil moisture content (SMC), which brought great difficulties to SMC parameter inversion. This paper presents a method to improve Hapke model using the improved multilayer radiative transfer model of soil reflectance (MARMIT-2), which can effectively improve the ability of Hapke-HSR model to characterize the variation of SMC. Finally, we use soil database to comprehensively verify the ability of the improved Hapke model. The results show that the improved Hapke can effectively characterize the spectral characteristics of soil and show higher fitting accuracy (RMSE = 0.009) compared with the Hapke-HSR model (RMSE = 0.031), especially at high SMC ($\geq 30\%$). Therefore, the improved Hapke model can better understand soil physical properties, and improve the inversion accuracy of soil-vegetation physical parameters, which can be used to enhance agricultural water use efficiency.

Keywords: Hapke model; soil hyperspectral reflectance; soil moisture content

1. Introduction

Soil plays an important role in agriculture, and hydrology system. There are many factors that affect its directionality and spectral characteristics under natural conditions [1], such as soil moisture content (SMC), surface roughness, and organic matter content, etc. The SMC as a key variable on the Earth's surface, controls many surface processes, such as evapotranspiration, and energy budgets [2]. The SMC can directly reflect the dry and wet state of the surface and obtain irrigation conditions in agricultural areas [3]. It is of great scientific significance for water resources assessment, drought and flood monitoring. Therefore, it is of great value to study the reflection characteristics of soil for a better understanding of its physical properties.

The Hapke model has been widely-used in the field of quantitative remote sensing. Recently, we systematically evaluated the performance of the Hapke model in characterizing soil reflectance characteristics [4]. However, there were still the following problems in the characterization of soil spectral reflectance characteristics. The Hapke model adopted a simple hypothesis to consider the influence of SMC on the soil spectral reflectance. In this study, aiming at this problem of the Hapke model, we proposed an approach to improve the Hapke-HSR model using the improved multilayer radiative transfer model of soil reflectance (MARMIT-2) [5]. Finally, we use soil database to comprehensively verify the ability of the improved Hapke model. Therefore, this paper provides key theoretical basis and technical support for soil radiative transfer modeling, which is of great scientific significance for soil and vegetation related parameters inversion.

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2. Materials and Models

2.1. Materials

To better verify the accuracy of the improved Hapke model, we used Bab16 database collected by Dupiau et al (2022) [5], which were obtained using the ASD FieldSpec spectroradiometer. The Bab16 database provided the soil component of each sample, which was mainly composed of organic matter, calcium carbonate, and organic carbon. etc. This database provided dry and wet soil spectral reflectance, which included 106 spectra in the 0.4-2.4 μm range with a spectral resolution of 0.001 μm . The Bab16 database provided a key data source for validating the improved Hapke model to characterize the variation characteristics of SMC.

2.2. Improvement of the Hapke model

The Hapke model assumes that the dry soil is a semi-infinite horizontal surface which contains irregular absorbing particles [6], and the Hapke model formulas can be expressed as:

$$R_d(\theta_s, \theta_v, \varphi, \lambda) = \frac{\omega}{4 \cos \theta_s + \cos \theta_v} \{ [P(g, g') (1 + B(g))] + H(\cos \theta_s) H(\cos \theta_v) - 1 \} \quad (1)$$

where $R_d(\theta_s, \theta_v, \varphi, \lambda)$ is the dry soil reflectance, ω is the single scattering albedo, $P(g, g')$ is the scattering phase function. $B(g)$ is the function of hot spot height and width (Ding et al., 2022).

The Hapke model is extended to the field of soil hyperspectral modeling (i.e., Hapke-HSR model), which has been systematically verified in previous paper [4]. The formulas between single scattering albedo and wavelength can be expressed as:

$$\omega = 1 - \frac{4\pi M \chi_{soil}}{\lambda} \quad (2)$$

We fitted the soil spectrum into two parts by assuming that the χ_{soil} parameter doesn't vary greatly with wavelength. The formulas can be expressed as follows:

$$\omega_1 = 1 - \frac{1}{A_0 \lambda + A_1} \quad (3)$$

$$\omega_2 = 1 - \frac{1}{A_2 \lambda + A_3} + \Delta d \quad (4)$$

where Δd is the offset between the two spectra, A_i ($i = 0, 1, 2, 3$) are the spectral fitting parameters.

To consider the effect of SMC in the Hapke-HSR model in previous study, the equivalent water thickness is assumed to correspond to the variation of dry soil to wet soil [7]. The model formula is as follows:

$$R_w(\theta_s, \theta_v, \varphi, \lambda) = R_d(\theta_s, \theta_v, \varphi, \lambda) \times e^{-\alpha_{water} f} \quad (5)$$

where α_{water} represents the absorption coefficient of water, and $R_w(\theta_s, \theta_v, \varphi)$ represents the reflectance of the wet soil.

In this study, we used the improved multilayer radiative transfer model of soil reflectance (MARMIT-2) model to consider the effect of SMC on soil spectral reflectance. The reflectance of wet soil is expressed as:

$$R_{mod}(\theta_s, \theta_v, \varphi, \lambda) = \varepsilon R_w(\theta_s, \theta_v, \varphi, \lambda) + (1 - \varepsilon) R_d(\theta_s, \theta_v, \varphi, \lambda) \quad (6)$$

where $R_d(\theta_s, \theta_v, \varphi, \lambda)$ is the spectral reflectance of dry soil simulated by the Hapke-HSR model, $R_w(\theta_s, \theta_v, \varphi, \lambda)$ is the spectral reflectance of completely wet soil, ε is the proportion of wet soil.

3. Results

3.1. Validating the Improved Hapke Model to Characterize Soil Spectral Reflectance Characteristics

Figure 1 shows the Hapke-HSR and improved Hapke models fit the effect of the typical measured soil spectral reflectance at SMC = 0%, 10.7%, 21.1%, 30.8% and 45.5%. The spectral reflectance of soil decreases obviously with the increase of SMC, especially in the near-infrared band, while the effect of SMC is relatively small in the visible light region. The fitting results of the Hapke-HSR and improved Hapke models can well capture the variation of soil spectral reflectance with the increase of SMC, and show a high consistency with the measured soil spectral reflectance. However, the improved Hapke model fitting the measured spectral reflectance is much better than the Hapke-HSR model, especially at SMC \geq 30%. The simulated spectral reflectance by the Hapke-HSR model underestimated the measured spectral reflectance at wavelengths around 1.9 μm . Table 1 shows the Hapke-HSR and improved Hapke models fit soil spectral reflectance parameters and statistical results. The accuracy of the Hapke-HSR model decreases with the increase of SMC. At SMC \geq 30%, the RMSE values of the Hapke model are greater than 0.02, while that of the improved Hapke model are less than 0.01. These results shows that the improved Hapke model effectively considers the influence of SMC, which has high accuracy in characterizing the spectral reflectance characteristics of soil compared with the Hapke-HSR model.

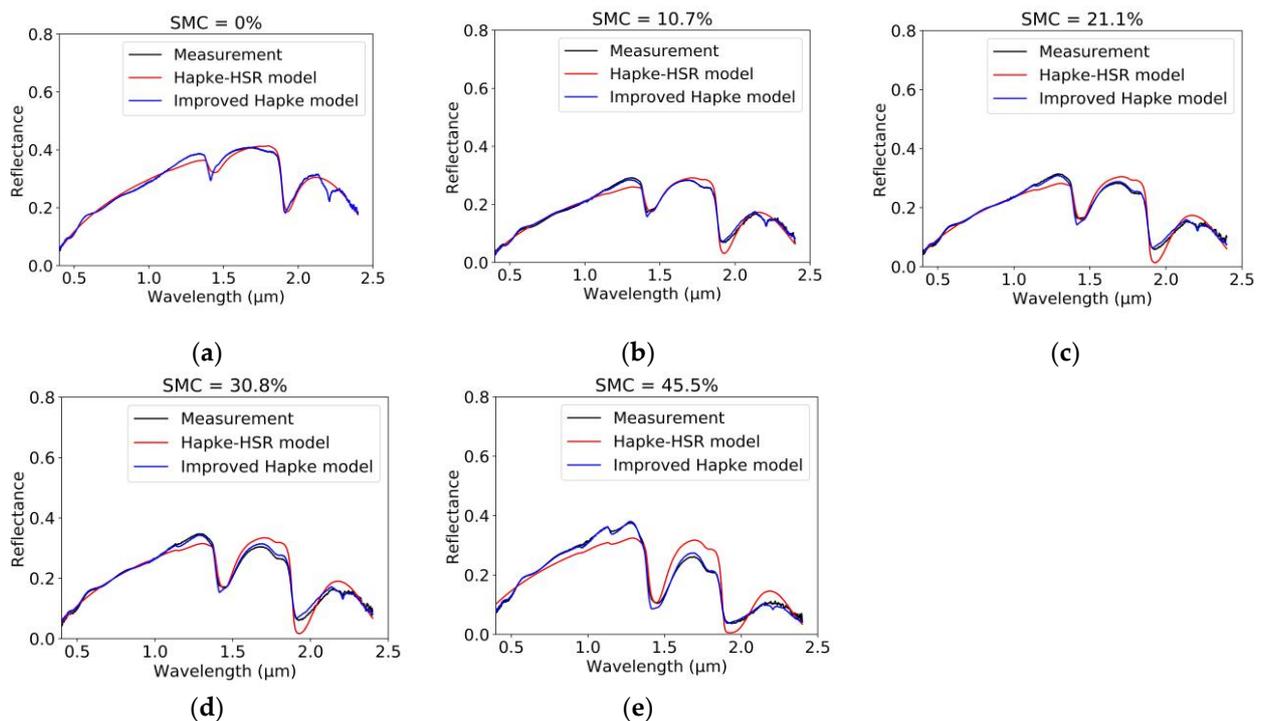


Figure 1. The Hapke-HSR and improved Hapke models fit the measured spectral reflectance of soil at soil moisture content (SMC) =0% (a), 10.7% (b), 21.1% (c), 30.8% (d) and 45.5% (e).

Table 1. The Hapke-HSR and improved Hapke models fit soil spectral reflectance parameters and statistical results.

Models	SMC (%)	b	M/f	δ / A_0	L/A ₁	ϵ / A_2	A ₃	R ²	RMSE	bias
Hapke-HSR	0.0	1.4	0.6	2.447	0.180	-4.150	12.010	0.974	0.014	0.000
	10.7	0.0	1.6	2.685	0.091	-5.119	14.339	0.960	0.015	-0.002
	21.1	0.0	2.2	3.144	-0.023	-5.618	15.939	0.941	0.020	0.000
	30.8	0.2	2.4	3.544	-0.173	-6.051	17.081	0.936	0.023	0.003
	45.5	1.0	4.0	2.377	0.439	-4.292	12.350	0.884	0.037	0.004
Improved Hapke	0.0	2.0	0.30	0.000	0.00	0.0	--	1.000	0.001	0.000
	10.7	1.3	0.38	0.001	0.02	0.3	--	0.994	0.006	0.000
	21.1	2.4	0.27	0.009	0.03	0.4	--	0.992	0.007	0.000
	30.8	3.0	0.24	0.002	0.03	0.4	--	0.990	0.009	0.002
	45.5	5.8	0.17	0.002	0.05	0.6	--	0.993	0.009	-0.002

3.2. Validating the Improved Hapke Model for High SMC

In this section, the Hapke-HSR and improved Hapke models show high fitting accuracy at SMC = 0-30%, while Hapke-HSR model needs to be further improved at SMC ≥ 30% (e.g., Figure 1). Therefore, this paper focused on comparing the fitting results of these two models at SMC ≥ 30% in the following work. Figure 2 shows the overall results of Hapke-HSR and improved Hapke models fitting all measured spectral reflectance at SMC ≥ 30%. These two models showed a high correlation with the measured spectral reflectance (R² > 0.96), and the overall RMSE values of these two models were in the range of 0.009-0.031. However, the accuracy of the improved Hapke model in fitting the measured spectral reflectance is significantly better than that of the Hapke-HSR model. The overall RMSE value is reduced by 0.022, and the MRE value is reduced by 3.314% compared with the Hapke-HSR model. In addition, the improved Hapke model is more effective in fitting measured soil spectral reflectance for high soil reflectance. These results indicate that the improved Hapke model can more effectively characterize soil reflectance characteristics, especially in high SMC conditions.

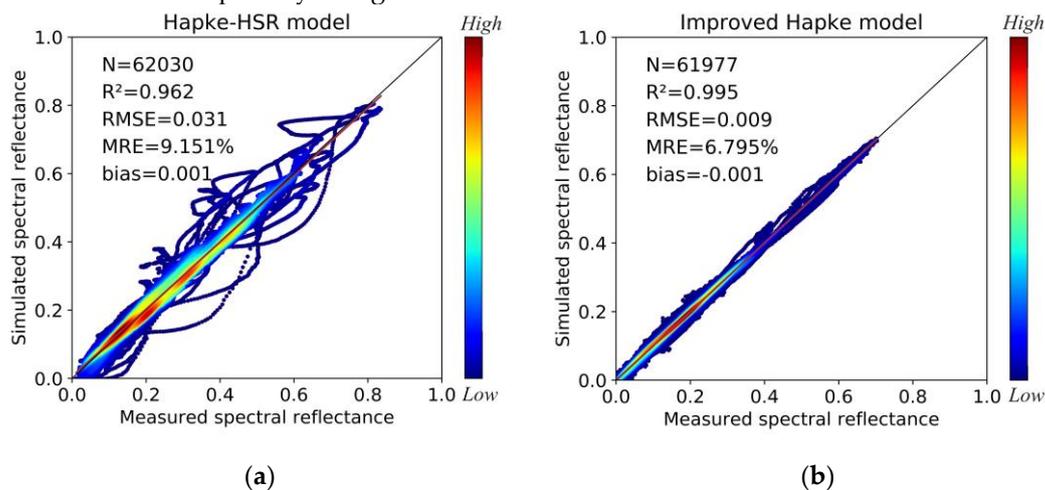


Figure 2. Compare the density scatter plot of the simulated spectral reflectance by the Hapke-HSR (a) and improved Hapke (b) models with the measured spectral reflectance.

4. Conclusions

Soil radiative transfer modeling is an important process to understand the characteristics of soil surface reflectance. This study focuses on the problems of the Hapke-HSR

model in characterizing soil reflection characteristics, and proposes an approach to improve the Hapke model. This approach can effectively solve the problem of the Hapke-HSR model in characterizing the variation of SMC. Finally, we used soil database to comprehensively verify the ability of the improved Hapke model to characterize soil spectral reflectance characteristics. The validation results show that the Hapke-HSR and improved Hapke models show high accuracy in characterizing the characteristics of soil spectral reflectance. However, the improved Hapke model has a very obvious improvement in accuracy ($R^2 = 0.995$ and $RMSE = 0.009$) compared with the Hapke-HSR ($R^2 = 0.962$ and $RMSE = 0.031$), especially at $SMC \geq 30\%$. Therefore, this paper is of great scientific significance for soil and vegetation related parameters inversion, construction of crop irrigation index system, and realization of precision agricultural irrigation.

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Data Availability Statement: The data can be obtained from the first author on request.

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Conflicts of Interest: The authors declare no conflict of interest.

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