environmental sciences proceedings

MDPI

Proceeding Paper

Improved Hapke Model to Characterize Soil Moisture Content Variation †

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† Presented at The 5th International Electronic Conference on Remote Sensing, 7–21 November 2023; Available online: https://ecrs2023.sciforum.net/.

Abstract: The 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 the soil moisture content (SMC), which brought great difficulties to SMC parameter inversion. This paper presents a method to improve the Hapke model using the improved multilayer radiative transfer model of soil reflectance (MARMIT-2), which can effectively improve the ability of the Hapke-HSR model to characterize the variation in the SMC. Finally, we used the 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 a higher fitting accuracy (RMSE = 0.009) compared with the Hapke-HSR model (RMSE = 0.031), especially at a high SMC (≥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

Citation: Ding, A.; Ma, H.; Zhao, P.; Ren, S.; Xu, K.; Jiang, H. Improved Hapke Model to Characterize Soil Moisture Content Variation. *Environ. Sci. Proc.* **2024**, *29*, 76. https://doi.org/10.3390/ECRS2023-16859

Academic Editor: Dmitry Efremenko

Published: 6 February 2024

1. Introduction

Soil plays an important role in agriculture and hydrology systems. There are many factors that affect its directionality and spectral characteristics under natural conditions [1], such as the soil moisture content (SMC), surface roughness, organic matter content, etc. The SMC, as a key variable of 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, and 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 is 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 the 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 used the soil database to comprehensively verify the ability of the improved Hapke model. Therefore, this paper provides a key theoretical basis and technical support for soil radiative transfer modeling, which is of great scientific significance for soil- and vegetation-related parameter inversion.

2. Materials and Models

2.1. Materials

To better verify the accuracy of the improved Hapke model, we used the Bab16 database collected by Dupiau et al. (2022) [5], which was 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 the SMC.

2.2. Improvement of the Hapke Model

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

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

where R_d (θ_s, θ_v, φ, λ) is the dry soil reflectance, ω is the single-scattering albedo, $P(g, g')$ is the scattering phase function, and $B(g)$ is the function of the hot spot height and width [4].

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 fit the soil spectrum into two parts by assuming that the χ_{soil} parameter does not 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, and A_i (i = 0, 1, 2, 3) is the spectral fitting parameters.

To consider the effect of the SMC in the Hapke-HSR model in the 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:

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

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

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

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

where R_d (θ_s, θ_v, φ, λ) is the spectral reflectance of dry soil simulated by the Hapke-HSR model, R_w (θ_s, θ_v, φ, λ) is the spectral reflectance of completely wet soil, and ε is the proportion of the 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 of the effect of the typically measured soil spectral reflectance at SMCs = 0%, 10.7%, 21.1%, 30.8%, and 45.5%. The spectral reflectance of soil decreased obviously with the increase in the SMC, especially in the near-infrared band, while the effect of the SMC was relatively small in the visible light region. The fitting results of the Hapke-HSR and improved Hapke models can capture the variation in soil spectral reflectance with the increase in the SMC well, and showed a high, consistency with the measured soil spectral reflectance. However, the improved Hapke model fitting the measured spectral reflectance was much better than the Hapke-HSR model, especially at an 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 of soil spectral reflectance parameters and statistical results. The accuracy of the Hapke-HSR model decreased with the increase in the SMC. At an SMC $\geq$ 30%, the RMSE values of the Hapke model were greater than 0.02, while that of the improved Hapke model were less than 0.01. These results show that the improved Hapke model effectively considered the influence of the SMC, demonstrating a high accuracy in characterizing the spectral reflectance characteristics of soil compared with the Hapke-HSR model.

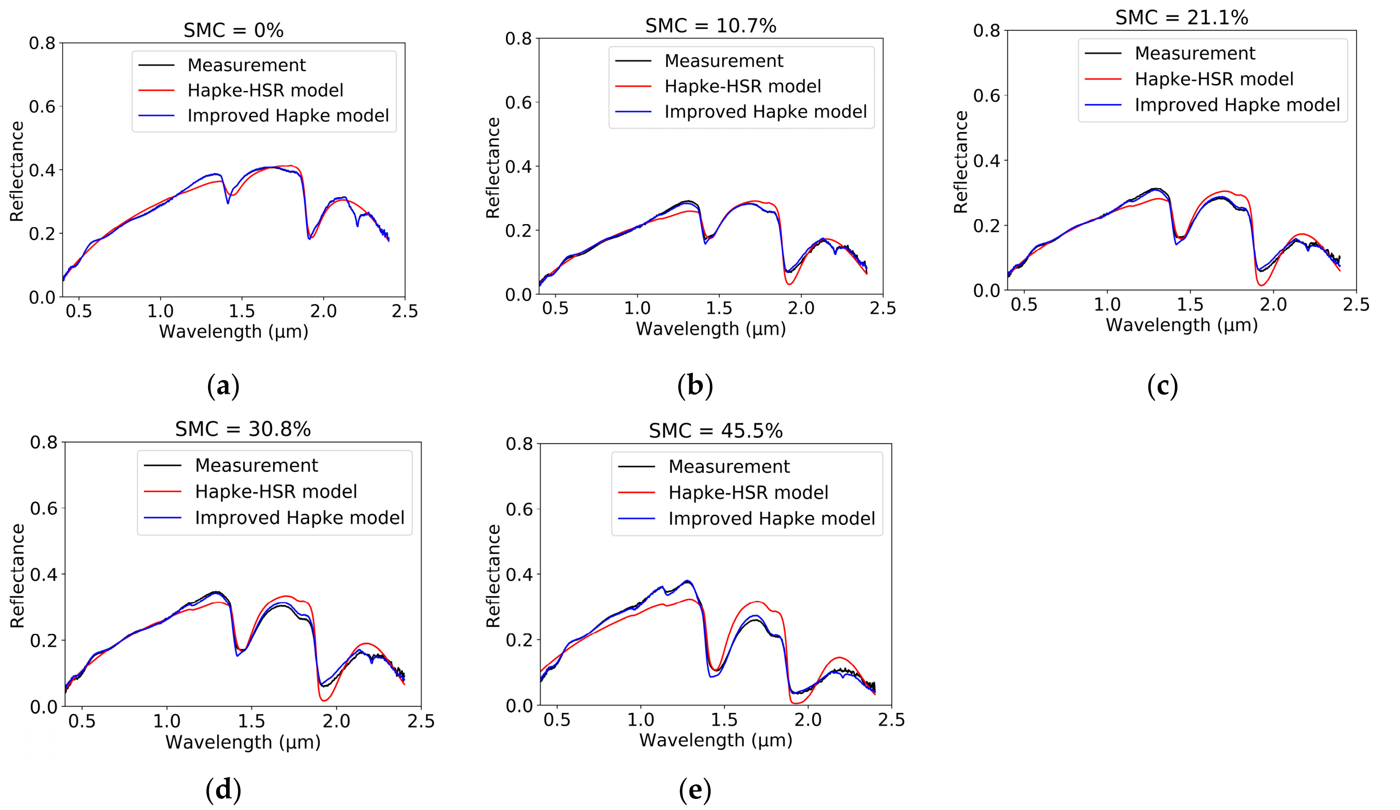

Figure 1. The Hapke-HSR and improved Hapke models' fit of the measured spectral reflectance of soil at the soil moisture content (SMC) = 0% (**a**), 10.7% (**b**), 21.1% (**c**), 30.8%, (**d**) and 45.5% (**e**).

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

Model	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 a High SMC

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

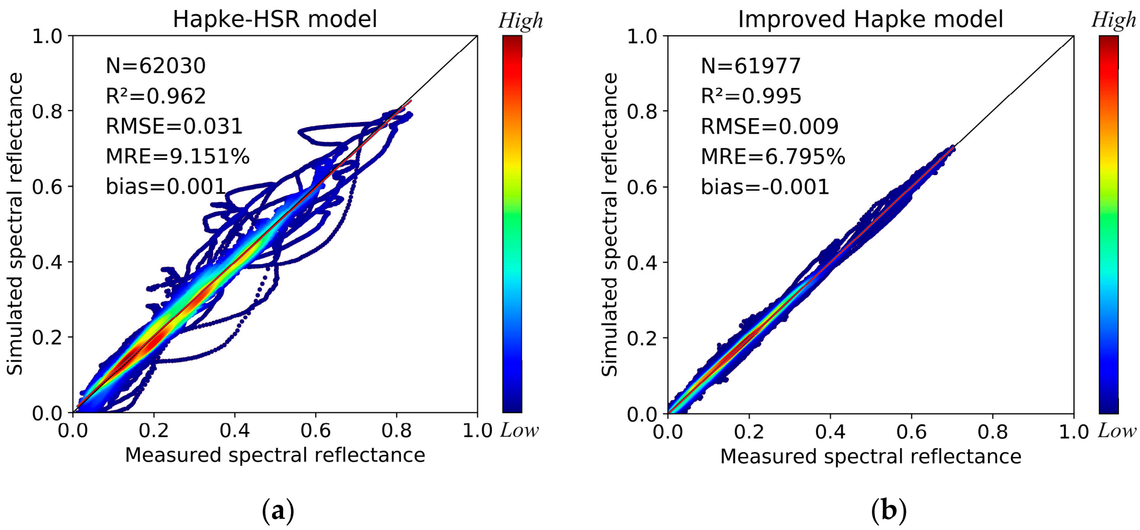

Figure 2. Comparison of the density scatter plot of the simulated spectral reflectance by the Hapke-HSR (**a**) and improved Hapke (**b**) models with the measured spectral reflectance.

4. Conclusions

Soil radiative transfer modeling is an important process to understand the characteristics of soil surface reflectance. This study focused on the problems of the Hapke-HSR model in characterizing soil reflection characteristics and proposed an approach to improve the Hapke model. This approach can effectively solve the problem of the Hapke-HSR model in characterizing the variation in the SMC. Finally, we used the 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 model (R^2 = 0.962 and RMSE = 0.031), especially at an SMC $\geq$ 30%. Therefore, this paper is of great scientific significance for soil- and vegetation-related parameter inversion, construction of a crop irrigation index system, and realization of precision agricultural irrigation.

Author Contributions: Conceptualization, A.D. and H.M.; methodology, A.D. and P.Z; validation, A.D., K.X. and S.R.; formal analysis, A.D.; investigation, A.D. and H.J.; resources, A.D. and H.M.; writing—original draft preparation, A.D.; writing—review and editing, A.D., H.M., P.Z., S.R., K.X. and H.J; funding acquisition, A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This study was partially supported by the National Natural Science Foundation of China (no. 42301363), Anhui Provincial Natural Science Foundation (no. 2308085QD118), and Fundamental Research Funds for the Central Universities (no. JZ2023HGQA0148).

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

Acknowledgments: We are grateful to Dupiau et al. for sharing the code of the MARMIT-2 model and soil database.

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

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