From Controlled Laboratory Spectra to Outdoor Hyperspectral Imagery: Assessing the Transferability of Soil Moisture Models

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Hyperspectral imaging offers a non-contact and spatially explicit approach for estimating soil moisture by exploiting moisture-induced variations in soil spectral reflectance. However, most calibration models are developed under controlled laboratory conditions, and their applicability to outdoor hyperspectral imagery remains uncertain. Variations in illumination, viewing geometry, soil-surface roughness, moisture heterogeneity, shadowing, and vegetation cover may alter the measured spectral response and substantially reduce model transferability. This study integrates controlled laboratory experiments with outdoor hyperspectral observations to assess whether soil moisture–spectral relationships established under laboratory conditions remain consistent under realistic environmental conditions.

Laboratory hyperspectral measurements were first acquired across multiple gravimetric soil moisture levels using a hyperspectral camera (400-1100 nm). These controlled observations were used to establish a reference relationship between soil moisture and spectral response. Distinct moisture-dependent variations were observed, particularly in the red-edge and near-infrared regions. A pronounced transition in spectral behavior occurred near the soil saturation threshold, beyond which the optical response was increasingly dominated by free water. The laboratory measurements therefore provided a controlled spectral baseline for subsequent evaluation under outdoor conditions.

Outdoor experiments were then designed to reproduce the laboratory moisture gradient under progressively more complex environmental conditions. A divided soil sandbox was used to generate spatial moisture gradients ranging from relatively dry to near-saturated conditions. Additional hyperspectral observations were collected during natural drying and under vegetation-cover treatments ranging from 0% to 100%. White- and dark-reference calibration was performed before each image acquisition, and in situ soil moisture measurements were used as reference labels. Comparison of laboratory and outdoor measurements at comparable moisture levels revealed substantial spectral shifts associated with differences in illumination intensity, viewing geometry, soil-surface roughness, ambient reflections, spatially nonuniform moisture conditions, and soil–vegetation spectral mixing.

Preliminary soil moisture estimation was conducted using a one-dimensional convolutional neural network, a long short-term memory network, partial least-squares regression, and a three-dimensional convolutional neural network. The spectral-level models achieved coefficients of determination of 0.78, 0.73, and 0.71, respectively, whereas the spatial–spectral three-dimensional convolutional model achieved an R^2 of 0.54. The lower performance of the image-cube-level model highlights the challenges introduced by spatial heterogeneity, limited region-level labels, shadow contamination, and mixed soil–vegetation pixels in outdoor imagery.

These findings indicate that laboratory hyperspectral measurements provide a robust basis for characterizing soil moisture–spectral relationships, but that direct application of laboratory-derived models to outdoor imagery is constrained by a substantial domain shift. The combined laboratory and outdoor experiments establish a systematic framework for quantifying cross-environment spectral variability and provide a foundation for the future development of domain-adaptation and weakly supervised learning approaches for robust soil moisture estimation under realistic field conditions.

Keywords: Hyperspectral imaging; Soil moisture estimation; Laboratory-to-field transfer; Domain shift; Spectral variability; Spatial–spectral modeling.