Machine Learning-Based Root Zone Soil Moisture Estimation from UAV Hyperspectral Imagery

Sanaz Shafian[1], **Milad Vahidi**[1], **William Hunter Frame**[1]

[1]School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Main Body

Accurate estimation of root-zone soil moisture is critical for precision irrigation, crop productivity, and sustainable water management. Conventional in situ measurements provide reliable observations but are labor-intensive and cannot adequately characterize spatial variability across agricultural fields. This study evaluated the potential of drone-based hyperspectral imagery integrated with Principal Component Analysis (PCA) and machine learning to estimate soil moisture at 10 cm and 30 cm depths in irrigated and non-irrigated corn fields.

Field experiments were conducted during the 2023 growing season at the Virginia Tech Tidewater Agricultural Research and Extension Center (TAREC), Virginia, USA. The experimental site consisted of 104 corn plots divided into irrigated and non-irrigated treatments. UAV flights were performed on seven dates using a Resonon Pika-L hyperspectral sensor (400–1100 nm) mounted on a DJI Matrice 600 platform. Simultaneously, soil moisture measurements at 10 cm and 30 cm depths were collected using PR2 Profile probes. Hyperspectral images were radiometrically corrected, georeferenced, mosaicked, and processed to extract canopy reflectance. PCA was applied to reduce dimensionality and identify the most informative spectral features prior to model development.

Support Vector Regression (SVR), Random Forest (RF), Gradient Boosting (XGBoost), and Artificial Neural Network (ANN) models were trained and evaluated using cross-validation. PCA substantially reduced data dimensionality while preserving the spectral information most closely associated with soil moisture variation, improving computational efficiency and model robustness.

Among all evaluated algorithms, the ANN consistently produced the highest prediction accuracy for estimating soil moisture at both depths. The strongest relationships between canopy reflectance and soil moisture occurred in non-irrigated treatments, where water stress increased spectral sensitivity. Estimation accuracy was generally higher at 30 cm during periods of increased root activity, indicating that canopy spectral responses reflected deeper root-zone water availability under drought conditions. The PCA analysis further identified informative wavelength regions associated with soil moisture variability, demonstrating the value of hyperspectral sensing for feature selection.

The proposed framework demonstrates that combining drone-based hyperspectral imaging, PCA-driven feature extraction, and deep learning provides an accurate, non-destructive approach for monitoring root-zone soil moisture. This methodology offers significant potential for precision irrigation scheduling, water-use optimization, and next-generation decision support systems for sustainable crop production.