TerraFormer: A Multimodal Latent World Model for Soil Dynamics

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Soil degradation affects over 1.7 billion people globally, yet long-term prediction of soil evolution remains fundamentally challenging because soil emerges from complex interactions among climate, geography, and internal processes. Existing approaches treat soil as isolated variables to predict or rule-based systems to approximate, rather than a dynamic state evolving under environmental forcing. This study introduces TerraFormer, the first multimodal soil world model that represents soil not as a static map for prediction, but as a latent dynamic system for simulation. TerraFormer compresses soil, climate, and geographic data into a compact latent state using a variational autoencoder with a transformer-based encoder, then models how that state evolves autoregressively under climate forcing before decoding future states back into soil variables. Trained on large-scale geospatial datasets (OpenLandMap, GLDAS, ERA5), TerraFormer significantly outperforms LSTM baselines across 38 variables, improving mean R^2 from 0.79 to 0.93, reducing prediction variance (s: 0.13 ? 0.11), and maintaining high spatial fidelity (SSIM > 0.9). These results demonstrate that modeling soil as a latent dynamical system yields more accurate and stable multi-step forecasts up to 12 months in advance. This work makes three key contributions: (i) reframing soil modeling from static prediction to latent-state simulation, (ii) introducing a unified multimodal framework integrating soil, climate, and geographic data, and (iii) demonstrating improved accuracy and stability over traditional sequence models. TerraFormer enables scenario simulation and digital soil twins for agriculture, climate adaptation, and environmental management.

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