Permafrost Soil Carbon Stock Estimation using a Multimodal Geospatial Foundation Model, 3D-ABC

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Permafrost ecosystems are experiencing warming at an accelerated rate relative to the global average, affecting hydrological processes, permafrost stability, vegetation patterns, and nutrient cycling. Permafrost soils hold a globally significant carbon reservoir accumulated over millennia due to slow microbial decomposition in cold, oxygen-limited environments. However, permafrost soil carbon stock estimates are highly uncertain due to landscape variability and limited data coverage across Arctic and Boreal zones. Machine learning has demonstrated capability in predicting permafrost soil carbon stocks based on environmental covariates. However, many machine learning models often struggle in regions with sparse training data or with conditions that significantly differ from training distributions. Novel methodologies are thus required to refine permafrost carbon stock assessments—essential for understanding greenhouse gas dynamics and informing policy in a rapidly changing climate. Recent advancements in foundation models offer a promising approach by integrating extensive geospatial datasets to enhance carbon stock estimations.

The 3D Above and Below Ground Carbon Stocks (3D-ABC) foundation model, developed within the Helmholtz Foundation Model Initiative, seeks to produce detailed permafrost carbon stock maps as a key application. 3D-ABC employs an adaptive AI framework designed for multimodal data integration and diverse predictive tasks. 3D-ABC leverages high-performance computing resources, including the JUWELS Booster and the upcoming JUPITER supercomputer at the Jülich Supercomputing Centre, consisting of a multimodal input processor, a foundation model encoder, an adaptive fusion neck, and task-specific prediction heads. The model is pretrained using a masked autoencoder to enable self-supervised learning on multimodal data before fine-tuning with labeled datasets for specific downstream tasks. Pretraining data sources include the Harmonized Landsat and Sentinel-2 dataset (HLS), TanDEM-X Interferometric SAR coherence data, ECMWF ERA5-Land climate reanalysis data, the Copernicus Global Elevation Model (GLO-30), and NASA's GEDI and ICESat lidar data.

Fine-tuning datasets for the permafrost soil carbon mapping task will include labeled soil carbon profile data from the Northern Circumpolar Soil Carbon database, the World Soil Information System Snapshot 2023, the International Soil Carbon Network database, the Northern Pedon database, and a new harmonized soil profile reference database, called the Circum-Arctic Soil Permafrost Region (CASPeR) database. Additionally, environmental covariates derived from remote sensing, climate models, and topographic datasets will be incorporated. 3D-ABC aims to generate high-resolution (30–100 meter) permafrost soil carbon maps, validated with in-situ measurements and evaluated against existing geospatial carbon stock products.

By integrating massive amounts of multimodal data and an advanced computational infrastructure, 3D-ABC has potential to significantly reduce uncertainties in permafrost carbon stock estimates. The outcomes aim to enhance understanding of Arctic and Boreal ecosystems, provide critical insights into carbon fluxes, support climate modeling efforts, and contribute to policy-making decisions.

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