Forest canopy height mapping at global scale by fusing Sentinel-2 and GEDI

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Mapping forest structure at global scale is an important component in understanding the Earth's carbon cycle. Several new space missions have been developed to support this goal by measuring forest structure predictive of biomass and carbon stock. Furthermore, forest structure characterizes habitats and is thus key for biodiversity conservation. NASA's Global Ecosystem Dynamics Investigation is one of these missions, which is the first space-based LIDAR designed to measure forest structure (Dubayah et al., 2020). Despite atmospheric noise, the on-orbit full waveforms measured by GEDI are predictive of canopy top height (Lang et al., 2022b). Ultimately, these sparse waveforms and derived canopy height metrics will be used to produce global biomass products with 1-km resolution (Dubayah et al., 2020).

Nevertheless, there is a need for high spatial and temporal resolution maps to make informed localized decisions and to improve carbon emission estimates caused by deforestation. Here we present our probabilistic deep learning approach to estimate wall-to-wall canopy height maps from ESA's optical Sentinel-2 images with a 10 m ground sampling distance (Lang et al., 2022a). A deep ensemble of fully convolutional neural networks is trained to regress canopy top height using sparse GEDI reference data (Lang et al., 2022b). Not only does this approach extend our previous work (Lang et al., 2019, 2021; Becker et al., 2021) from country-level modelling to a global scale, it also yields the predictive uncertainty of the final canopy height estimates. In other words, the model estimates the variance of its predictions indicating in which cases the predictions are less trustworthy.

To enable such a globally trained model to adjust for regional conditions, the geographical coordinates are used as additional inputs to the Sentinel-2 bands. Furthermore, canopy height follows a long-tail distribution, i.e. tall trees are very rare. Thus, a new balancing strategy is developed to reduce the underestimation of tall canopies while preserving the calibration of the predictive uncertainty estimates.

The model performance is evaluated globally on held-out GEDI reference data from randomly selected Sentinel-2 tiles, corresponding to 100 km x 100 km regions. In addition, the resulting maps are compared to dense canopy top height maps (RH98) derived from NASA's LVIS airborne LIDAR campaigns (AfriSAR, ABoVE/GEDI). On the held-out data the model achieves an RMSE of 6.0 m and a ME of 1.3 m, which indicates a slight overestimation w.r.t. GEDI reference heights. The final, dense predictions are in good agreement with the LVIS derived RH98 and yield an RMSE of 8.8 m and a ME of 0.2 m. Both the usage of geo-coordinates and the balancing strategy reduce the saturation of high canopies. Furthermore, the predictive uncertainty estimates are empirically well calibrated, i.e. the predictive variances correspond to the expected squared errors.

To conclude, the developed methodology makes it possible to produce high-resolution canopy height maps from Sentinel-2 at global scale. How such a model, trained within the GEDI coverage between 51.6° North and South, generalizes to regions north of 51.6° latitude remains to be evaluated with additional reference data.

References

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