A Vertical Vegetation Structure Model of Europe

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Abstract

Vertical vegetation structure data has the potential to reveal nuanced ecosystem response to climate change and disturbances such as from wildfires, droughts, deforestation, and forest degradation. However, existing global-scale studies mainly focus on canopy top height or simplified single descriptors of vertical structure at low spatial resolution. Here, we address this gap by integrating full-waveform lidar observations from the Global Ecosystem Dynamics Investigation (GEDI) and Sentinel-2 optical images into a wall-to-wall vertical structure model (VSM). The model provides a dense map of estimated relative height profiles at 10 meter resolution for Europe. We see great potential in the presented vertical structure model for advancing science and environmental resource management.

1 Introduction

Intact vegetation ecosystems provide a central basis for human and animal life [35] by regulating the climate at local and global scales, regulating the hydrological cycle, and conserving biodiversity. They can reduce the destructive impact of severe weather events and climate change [22], for example, by lowering the risk of soil erosion and land-slides, or by acting as a buffer against hurricanes, storm surges, or avalanches. Even so, pristine ecosystems are globally under immense pressure due to human exploitation of natural resources [37] often associated with the production of commodities such as palm oil, cocoa, soybeans, and cattle [14, 17].

With $\approx$85% of Europe's forested areas being actively managed, often as monocultures with mainly a single or only a few tree species, there are great challenges, but also opportunities ahead to strengthen their climate resilience [11]. These monocultures are vulnerable to extended periods of drought and heat waves, which can lead to vast losses, as for example seen in Germany, where large areas were emergency logged to prevent the further spread of bark beetle pest [32]. In addition, remaining natural ecosystems are fragmented and located in proximity to land with high human activity, such as agriculture or urban areas. This proximity can cause ”edge effects" with substantial impacts on ecosystem services even across land use boundaries [34].

Even formally protected areas are impacted by human activities [19]. The urgency of addressing the global challenges of adapting to a changing climate and avoiding biodiversity collapse [15] have led to several international environmental initiatives to preserve the remaining intact ecosystems and to reverse degraded habitats to a natural state. Examples include the UN Decade on Ecosystem Restoration [25] and the Kunming-Montreal Global Biodiversity Framework [1]. A specific target of the latter known as the “30 by 30" commitment aims to protect 30% of the world's land, ocean, and freshwater areas by the year 2030 [1]. Furthermore, in May 2023 the European Union (EU) enacted the EU Deforestation Regulation [13] to limit deforestation caused by the major agricultural commodities sold in the EU.

A crucial step towards implementing such global conservation targets on land is to quantify the conservational value of vegetation ecosystems to guide resources towards protecting the most valuable

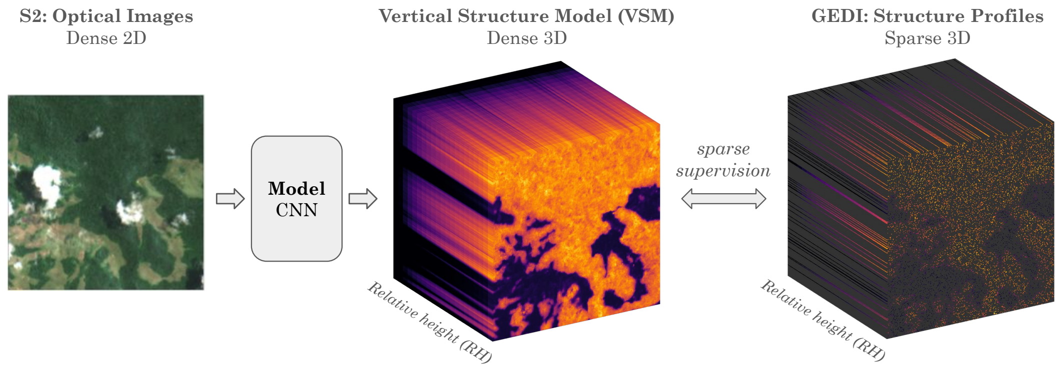

Figure 1: Illustration of our approach. Sentinel-2 satellite images are used as a *dense 2D* input to a convolutional neural network (CNN) trained with *sparse 3D* supervision of GEDI vertical profiles. The output is a *dense 3D* Vertical Structure Model (VSM) with a 10m ground sampling distance.

ecosystems [29, 31, 16, 26]. Quantifying this conservational value is challenging as we need to account for a multitude of criteria including carbon stocks [5], biodiversity [36], and the naturalness of ecosystems [3]. Conservation and afforestation of degraded forest ecosystems is discussed as mechanisms to capture carbon from the atmosphere, but high uncertainties of estimated carbon stock potentials remain a challenge [24]. Furthermore, monitoring ecosystem functions is crucial to understand how ecosystems respond to anthropogenic drivers and a changing climate [23].

Vertical vegetation structure is an essential variable [12] that allows to quantify aboveground carbon stocks, biodiversity, and the naturalness of ecosystems [7, 4, 21, 26]. In addition, vegetation structure properties dominate the explanation of the variation of ecosystem functioning [23]. Vertical vegetation structure has been studied to quantify the effectiveness of protected areas [19, 8, 2, 20], but to better understand human drivers influencing three-dimensional forest structure and to facilitate the effective management of protected areas, improved vegetation structure data is needed that is globally consistent, timely, and provide high spatial resolution [19].

Here, we present a globally applicable approach to model the full vertical structure profile of vegetation by combining data from two different space missions: Sentinel-2 satellite images and GEDI space borne lidar profiles. Our approach advances state-of-the-art that are limited to single statistics as proxies for the vertical distribution of biomass (like canopy top height [30, 18, 27] or entropy [4]). We extend the established concept of *canopy height models (CHM)*, i.e., the 2.5D raster data of vegetation height above ground, to the concept of *vertical structure models (VSM)* to represent the full 3D structure of terrestrial ecosystems, capturing both horizontal *and* vertical variation (see illustration in Fig. 1).

We use our developed model to compute annual VSMs for Europe (i.e. countries belonging to the EU, EFTA, and UK). These VSMs are three-dimensional data cubes covering the entire landmass, representing the vertical structure distribution at 10 meter spatial resolution. This data advances the availability of global structure data in spatial coverage, as well as spatial and temporal resolution. While our VSM also provides canopy top heights advancing or matching the accuracy of state-of-the-art, our approach provides full vertical profiles and thus structure variations in the understory that are more sensitive to small canopy gaps.

2 Combining Sentinel-2 optical images and GEDI spaceborne lidar

There is no single satellite sensor that can provide dense global vertical vegetation structure data. While dedicated laser scanner instruments like the Global Ecosystem Dynamics Investigation (GEDI) have advanced the availability of sparse global-scale vertical structure measurements [6], the derived map products that aggregate these sparse measurements fall short in terms of spatial resolution (1 km), global coverage beyond 51.6° N & S, and are not designed for monitoring over time [4]. On the other hand, optical satellite missions like Sentinel-2 or Landsat provide global coverage at spatial resolutions up to 10 m with revisit times of five days, but cannot provide a direct measurement of vertical structure. Modeling vegetation parameters using both types of sensors promises to overcome the limitations of each sensor alone and the progress of artificial intelligence and modern computer vision methods has led to advanced canopy height products [18, 27]. Nevertheless, the state-of-the-art remains limited by capturing only few statistics of the structure.

Our methodology combines dense 2D satellite imagery from Sentinel-2 and sparse 3D GEDI LiDAR footprints to produce high-resolution dense 3D vertical structure models for Europe (see Fig. 1). We train a convolutional neural network (CNN) to predict the GEDI vertical profile for each Sentinel-2 pixel using sparse supervision and a quantile regression loss.

GEDI lidar data provide sparse height measurements for different canopy layers. We use Relative Height (RH) from the L2A product as reference data. For each GEDI shot, we obtain 101 RH metrics (RH0–RH100) describing the vertical structure of the 3D structure within a 25m footprint. Each RH value represents the height above the ground at which a specific percentage of the total laser energy is returned. In this study, we only retained footprints with a sensitivity value greater than 0.95, following [4], to ensure reliable ground returns in dense canopy cover. Additional quality flags provided in the L2A product were used to remove invalid or low-quality data. To capture vegetation structure under leaf-on conditions, we further restricted the dataset to footprints acquired during the growing season, derived from NPP VIIRS Global Land Surface Phenology product [39].

Sentinel-2. Previous studies on canopy top height mapping [30, 18, 28, 33] have demonstrated that predictive representations can be learned from optical satellite imagery to estimate vegetation height. Building on previous findings in [18], we used 12 optical bands from Sentinel-2 L2A data as input for vegetation structure modeling. To ensure temporal consistency with the GEDI observations, only Sentinel-2 images acquired during the growing season were used. A strict patch-level cloud coverage filter was applied to get a high quality dataset.

Auxiliary data. ESA WorldCover 2021 land cover map [38] was used for multitask learning. The ESA land cover information provides surface type context that helps the model distinguish vegetated from non-vegetated surfaces. Including this land cover mapping task enables the model to learn broader land surface characteristics, thereby reducing unrealistic vertical vegetation profile predictions in regions beyond the GEDI range. Besides, the land cover prediction can enhance the explainability of the model. We also use the slope information derived from the Copernicus DEM [9] to only optimize the RH regression on terrain with $<15°$ slope (threshold following [27]). Steep terrain can lead to a distorted GEDI waveform and yield unreliable vertical profile estimates. However, we optimize the land cover as an auxiliary task in all terrain conditions.

3 Experiments and results

Experimental setup. We sampled a total of 300 million GEDI shots uniformly across the global landmass. After quality filtering and pairing with cloud-free Sentinel-2 image patches, we ended up with a total of 179 million data points. At each location, we sampled a 15×15 pixel patch from the closest, cloud-free Sentinel-2 image within the growing season of that year. To train and evaluate our model, we followed prior work [18] and splited the data by Sentinel-2 tiles that correspond to approximately 100km$\times$100km. Therefore, we held out 12.6 % of randomly selected tiles for testing (i.e. 1392 tiles, with 52 in Europe). We trained our model for 2,234,400 iterations with batch size 4096 using the Adam optimizer.

Deployment and VSM computation. To compute an annual VSM for the year 2020, we sampled up to 20 images with the lowest cloud cover within the growing season for every Sentinel-2 tile. We used a ”late" median aggregation strategy following [18]. Hence, each image was processed to predict a date-specific VSM, that was filtered to remove cloudy pixels and pixels with predicted snow and urban landcover before aggregating the individual predictions to a median composite (see Fig. 2).

Evaluation. The RH10, RH25, RH50 and RH98 predictions for Europe are shown in Fig. 2 (top). There are no border artifacts within individual Sentinel-2 tiles, however, deploying the model across adjacent Sentinel-2 tiles remains challenging, as predictions from different dates can lead to tilling artifacts.

We evaluated all RH metrics on the 52 hold-out test tiles in Europe and visualize the residual distribution for each RH (Fig. 2 bottom). While all RH have a low bias, we observe that the variation of residuals increases towards both RH0 and RH100, having the lowest variation around RH35. The

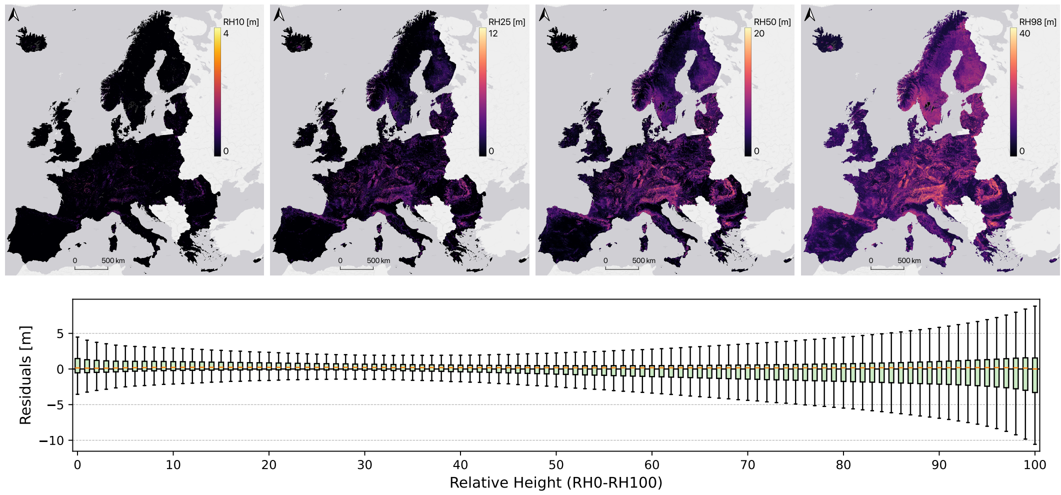

Figure 2: Vertical structure model of Europe. Top: Maps of key metrics RH10, RH25, RH50, RH98. Note, while lower RH metrics can be negative mainly for bare ground landcover, we only visualize positive values. Bottom: Residual error per RH metric on hold-out GEDI data. Boxplots show the median, quartiles and the 5th and 95th percentile for RH0–RH100.

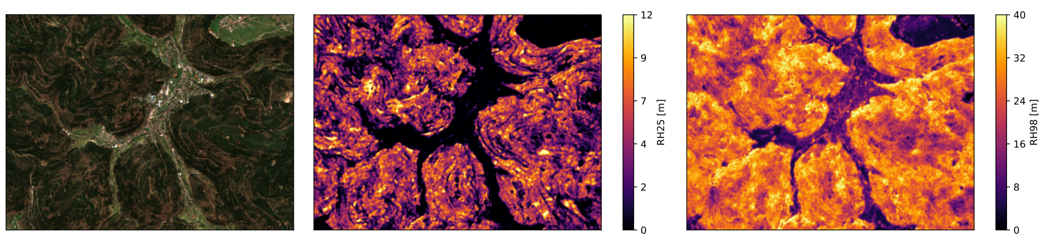

Figure 3: Comparison of RH25 and RH98 in capturing small structures like canopy gaps. Left: Input Sentinel-2 image. Middle: Predicted RH25. Right: Predicted RH98

bias for RH95, RH98, and RH100 compares well with previous studies [30, 18, 27]. An example is provided showing the qualitative differences between predictions for different RH values (Fig. 3).

4 Discussion and conclusions

Our VHM provides additional information not captured by an CHM. The VSM makes full use of the information contained in the GEDI profile measurements. While our estimates of lower RH metrics capture the understory structure, these are dominantly sensitive to small canopy gaps that are closed by the canopy top height proxies (i.e., >RH95) because of GEDI's 25m footprint (Fig. 3). Our model relies on texture structure in Sentinel-2 optical images and cannot "see through" closed canopies. Thus, there is great potential to complement our VSM with SAR data, such as, for example, the ESA BIOMASS mission [10].

The monitoring of resources become more and more important under the changing climate. Beyond forests' importance for biodiversity conservation and carbon storage, Europe is especially relying on several direct ecosystem services in all climate zones. Intact forest ecosystems regulate the local climate which can dampen extended heatwaves in the South and in alpine regions, forests act as protection against avalanches or landslides. However, both intact forest ecosystems and managed forests are under stress. With the changing climate, insects like the bark beetle spread quickly, leading to loss of a large number of trees. European forest management needs to cope with these stress factors by finding new strategies to diversify our forests and make them resilient under the changing climate. We envision that our VSM will be beneficial for monitoring and proactive management, also to reduce the risk of wildfires by identifying fuel material in the understory.

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