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Seasonal flooding provides limitations and opportunities for ecosystem carbon accounting from space

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1. Accurate measurements of ecosystem flooding reduce uncertainty in carbon accounting

Flooding controls wetland carbon cycling and hinders accurate measurements of ecosystem structure from remotely sensed data. In wetlands, flood frequency and duration is critical to controlling carbon cycling, but high canopy cover can obscure fluctuations in inundation and increase uncertainty in measurements of ecosystem structure. Here we provide an overview of the challenges of recording accurate tree height measurements under flood conditions and the role that new digital technologies can play in characterizing sub-canopy inundation and reducing measurement uncertainty. Subsequently, we highlight the opportunities that spaceborne sensors can now provide for understanding the hydrological processes that control wetland ecosystem carbon cycling. We demonstrate this at a number of globally important high-carbon locations where changes in flooding regime impact ecosystem classification and measurement.

Credible, accurate and reliable monitoring of stocks and changes in forest structure are critical for achieving international goals and national commitments to forest conservation, management, climate change and sustainable development [1, 2]. Achieving this requires accurate measurements of tree height, which is used as a predictor of biomass [3] and informs the subsequent retrieval of carbon stocks, structure, function and biodiversity [4]. Estimating forest structure, however, is problematic in tidally and seasonally flooded forests where tree height estimates vary relative to sub-canopy tidal/flooding conditions. Diurnal flooding can impact tree height estimates by several meters a day while seasonal flood events in excess of 20 m [5] drive uncertainties in forest height estimation over longer-term observation periods.

Simultaneously, flooding defines the distribution and extent of wetlands, which are both the world's largest natural source of methane emissions and the most important source of uncertainty in the global methane budget [6]. Within wetlands, inundation period directly drives carbon cycling and both the sequestration of organic carbon and the emission of methane [7]. Increased flooding frequency and period increases methane emissions, driven by the presence and duration of waterlogged soils and subsequent anoxic conditions. These conditions are controlled by flood duration, type (tidal, riverine, pluvial), chemistry (saline, brackish or fresh) and depth. A lack of measurements on sub-canopy flood dynamics, particularly in remote tropical forested areas, increases uncertainty in estimates of forested wetland methane fluxes. Wetlands are highly vulnerable to changes in climate and subsequent precipitation and inundation, with droughts severely limiting carbon sequestration through decreasing the accumulation of peat soils, as seen in the Congo Basin [8]. Conversely, extreme flooding can cause die-off and subsequent peat collapse, as in the mangroves of the Florida Everglades [9]. Therefore, knowledge of sub-canopy inundation period and frequency is key for regional and global carbon models, particularly when reporting a country's Greenhouse Gas emissions and Nationally Determined Contributions under the UNFCCC Paris Climate Agreement. Here we highlight that spaceborne instruments can now consistently observe flood levels in forested wetland ecosystems, providing critical information on environmental processes where the greatest measurement uncertainty resides.

2. New approaches for measuring 3D ecosystem structure from space

Understanding the relationship between ecosystem structure (e.g. tree height) and ecosystem processes (e.g. carbon cycling) requires a network of locally sampled field and inventory plots. Traditionally, this has involved aggregation of *in-situ* field surveys, which are the cornerstone of model calibration and uncertainty estimation [10]. Major limitations in our ability to scale these data have been the lack of consistent data collection methods between surveys and an inability to sample many locations. Light detection and ranging (lidar) instruments are recognized as among the most reliable technologies for mapping the three-dimensional structure of ecosystem topography and composition [11, 12] and while they have excelled at regional, site and footprint scales they have not been able to provide the geographic coverage needed to derive global scale information with low uncertainty [13]. However, we are now entering an era where consistently collected lidar data is readily available.

Currently, two spaceborne systems are able to sample ecosystem characteristics with near-global coverage. The first is NASA's Global Ecosystem Dynamics Investigation (GEDI), a multi-beam lidar that records eight transects of vertical structure using 25 m footprints. Operating from the International Space Station between December 2018–March 2023, GEDI directly measures canopy structure using a footprint size on the order of conventional forest plot sizes and pixel resolution of moderate-resolution remote sensing data commonly used to map forest cover [13]. A second spaceborne lidar instrument, ICESat-2 (Ice, Cloud and land Elevation Satellite 2; [14]), is a satellite platform carrying a photon counting laser. Since 2018 ICESat-2 has collected data of Earth's surface in a configuration of 6 transects (3 pairs in a strong/weak energy ratio of 4:1) of 11 m footprints, every 70 cm along the satellite trajectory [15]. The ICESat-2 land and vegetation data product (ATL08) provides estimates of terrestrial ground and canopy height elevations [16]. A purpose of these two satellites is to link observations with *in-situ* measurements to derive robust models of global forest structure.

3. Ecosystem flooding impacts reliable tree height estimation

Lidar instruments excel at deriving reliable tree height estimates with low uncertainty, on the assumption that ground elevation is static and does not vary through time. This assumption cannot be guaranteed within forested floodplains where the detected ground elevation changes with flood depth. A large area of Earth's forested land is affected by this phenomenon, including the world's largest and most commonly studied tropical forest, the Amazon. The Amazon and its large tributaries experience seasonal flood waves of 10–15 m and approximately 10% of the Amazon basin is impacted by regular seasonal flooding [17]. Seasonal flooding also occurs across other major flooded forests such as the Pantanal Wetland, Brazil, the Everglades, USA, and the Cuvette Centrale of the Congo Basin, spanning the Democratic Republic of Congo and Republic of Congo. Since biomass correlates with forest height, any flood-induced underestimation of tree height directly affects biomass estimation. Considering the large geographic extent of seasonally flooded forests globally, the potential implications of this for global biomass mapping efforts are substantial and could ultimately result in a systematic underestimation of forest carbon stocks with imprecise levels of uncertainty.

Figure 1 highlights how sub-canopy flooding impacts tree height estimates in the floodplain forests of the Juruá River, a high-sediment, 'whitewater' tributary of the Amazon River. Approximately half of the Juruá floodplain forest is composed of flats and depressions inundated from 3 to 10 months per year with seasonal water depths up to 7.5 m. The remaining half is situated on higher ground and experiences flood depths less than 3 m. By comparing GEDI elevation estimates acquired during high-water and low-water stages, GEDI RH98 indicates an overestimation of ground elevation under flood conditions by 4.7 $\pm$ 4.9 m (mean $\pm$ sd; figure 1(c), translating to an underestimation of canopy height by 3.6 $\pm$ 7.4 m (mean $\pm$ sd) (figure 1(c)). Subsequent GEDI aboveground biomass (AGB) estimates at high water are 47.9 $\pm$ 120.8 t ha^{-1} (mean $\pm$ sd) lower than those from measurements acquired under decreased flood depth. As seasonal flood depths can reach several meters and persist for several months (figure 1(d)), GEDI-based canopy heights and subsequent AGB estimates over these floodplain forests can be heavily impacted and warrants further investigation.

4. Opportunities for understanding ecosystem function

The majority of ecosystem carbon is stored in soils and not in forests and other AGB. The retrieval of sub-canopy flooding provides novel opportunities to deepen and improve our understanding of hydrology and its control on carbon cycling. This need is

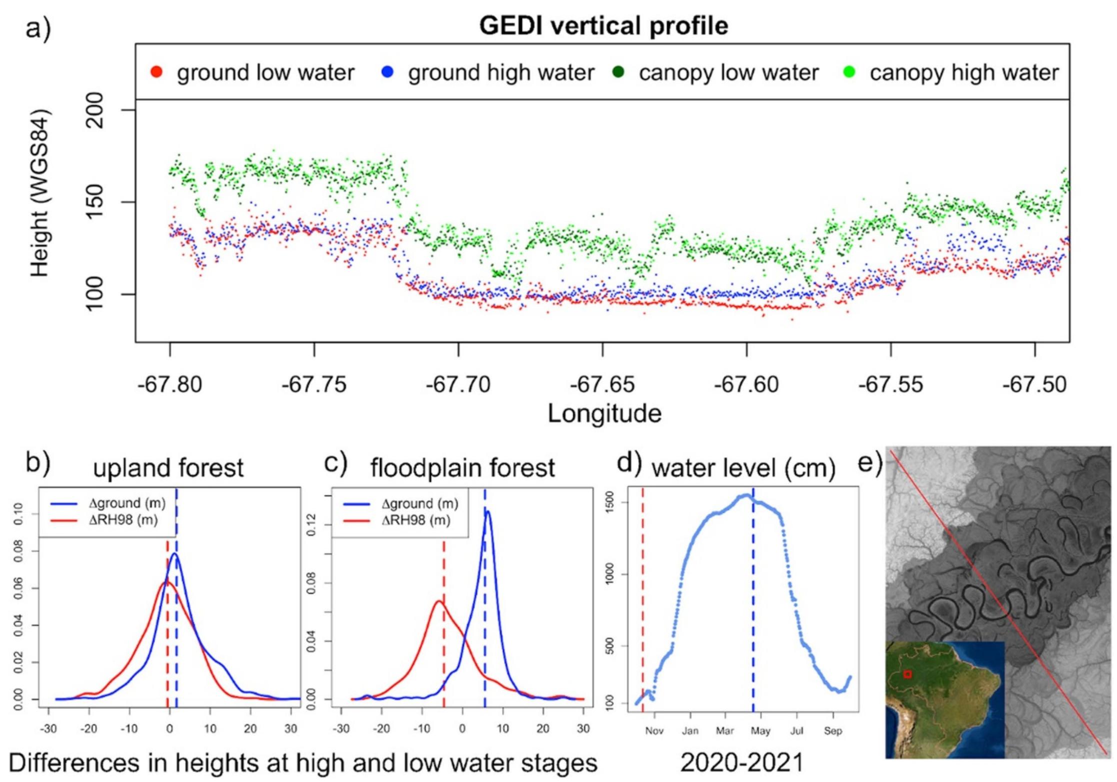

Figure 1. Vertical profiles of GEDI L2A data (a) acquired at low water (12 October 2020) and at high water (18 April 2021) over the Juruá River floodplain in the Amazon (red line in figure (e)). The distance between the two parallel GEDI tracks is ca. 90 m. The floodplain forest is located approximately between longitude −67.7° and −67.5°. Over upland forest ground and canopy heights at high and low waters are similar (b). An overestimation of terrain height due to sub-canopy flooding leads to an underestimation of tree height for floodplain forests (c). Dashed lines in (b) and (c) indicate median value. Based on river gauging data (Gavião station, Brazilian National Water Agency: www.snirh.gov.br/hidroweb) water level ranges by 14 m (d). Dashed lines in (d) show acquisition days of GEDI data at low (red) and high (blue) water.

particularly pertinent in Blue Carbon ecosystems (e.g. mangroves), freshwater forests, and other forested wetlands where carbon fluxes between the land, ocean and atmosphere are both driven and constrained by the presence of water [8, 18].

ICESat–2 ATL08 repeat-track data are capable of observing fluctuating inundation levels at the same location. Figure 2 provides examples of different types of flooded ecosystems where changes in the detected ground elevation are a consequence of different flood depths between two dates. Figure 2(A) shows an ICESat–2 ATL08 ground track (GT1R) over the Amazon, Brazil. From two separately acquired tracks (23 April 2019–19 July 2021) a difference between the median detected ground elevations was measured at 1.8 m (mean: 51.69 ± 1.29 m, mean: 50.03 ± 1.98 m). Similarly, a difference of 1.45 m (mean: 1.34 ± 0.59 m, mean: 0.08 ± 0.64 m) in median surface elevation was observed between two ICESat-2 ground tracks (7 April 2019–31 December 2021; GT3L) over the mangrove forests of the Niger Delta, Nigeria (figure 2(B)). Here, channels that segment the region are observed to overflow and flood the forest floor. Finally, figure 2(C) demonstrates a 0.61 m difference in median surface elevation (mean: 4.43 ± 1.47 m, mean: 4.97 ± 1.22 m) for a forested raised peat dome accompanied by a flooded surface at higher latitudes, from two ground track profiles (22 June 2019–17 September 2021; GT2R) over Sebangau National Park, Borneo.

The presence of water is critical to ecosystem function in wetland ecosystems and these new space-borne technologies provide an avenue of opportunity to monitor inundation extent and duration. The ability to model and monitor important ecosystems, which are traditionally difficult to sample *in-situ*, would benefit existing approaches to measuring peat dome presence and subsidence [19, 20] and will be an important advancement in monitoring the health of ecosystems at the forefront of climate change impacts. Currently, approximately 15,000 repeat tracks are available globally (1387 per cycle), with more expected as ICESat-2 continues to collect data. No other remote sensing instrument is capable of determining the spatial distribution and depth of inundation in these systems, at high spatial resolution, despite its importance for determining carbon sequestration and emissions. In each of these examples,

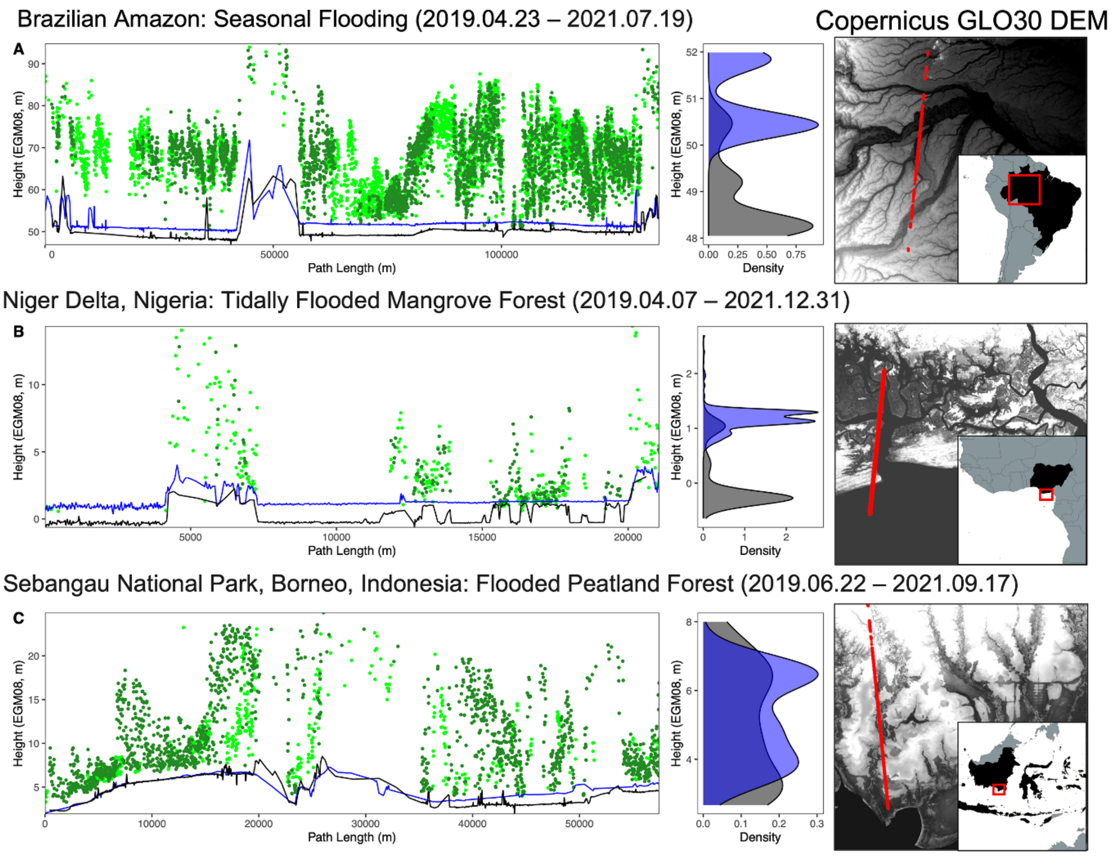

Figure 2. Detection of sub-canopy ground elevations as a consequence of changing water levels. (A) Amazon, Brazil, demonstrating a 1.45 m change in water levels with seasonal flooding. (B) Niger Delta Mangrove Forest, Nigeria, with tidal inundation detected beneath the canopy. (C) A peat dome in Sebangau National Park, Borneo, where raised water levels are visible on the right side of the dome.

the difference between high and low water directly controls the detected ground elevations, even when changes in water level are modest. A time-series of changing water levels will allow the full construction of daily and seasonal flood dynamics and potentially allow the modeling and estimation of peat dome size and depth from space.

5. The future of flooded ecosystem monitoring from space

New spaceborne lidar systems have initiated an era of modeling and monitoring ecosystem structure and hydrology from space. It is important that we account for the uncertainty in our models and acknowledge the sources of uncertainty in lidar observations. Here, we demonstrate that the presence of water, both seasonal and short-term, directly impacts our estimations of forest structure and biomass. However, we recognize and herald the ability of spaceborne lidar to ameliorate flood-related uncertainty. The ability to detect sub-canopy changes in water levels, remotely and at the global scale, is unprecedented and provides information on an elusive parameter, accompanied by a suite of opportunities, to enhance our understanding of the linkages between ecosystem carbon and hydrology. We are within a golden age of spaceborne instrumentation for monitoring Earth's dynamic processes and lidar data fusion with existing (e.g. Sentinel-1) and forthcoming sensors (e.g. NASA/ISRO NISAR, NASA SWOT, ESA BIOMASS) will be the most effective tool in increasing our understanding of both biomass allocation and hydrological processes. Expected products from new missions will require independent calibration and validation, with lidar capable of providing this critical role. In order to exploit these opportunities, both wide area coverage and repeat-track lidar samples are required and we encourage both systems to consider observing architectures that are able to fill in gaps in undersampled areas while also accounting for the value of repeat-track data for time-series monitoring.

Fundamentally, we highlight the scientific contribution of spaceborne lidar instruments for furthering our understanding of our dynamic planet at a critical point in humanity's effort to respond to our changing climate. The challenges of this are many and multi-faceted, but spaceborne lidar is recognized as an indispensable tool that aids our understanding and informs our action.

Data availability statement

No new data were created or analysed in this study.

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References

[1] Hansen A J *et al* 2021 *Conserv. Lett.* **14** e12822
[2] Linser S and Lier M 2020 *Sustainability* **12** 2898
[3] Duncanson L *et al* 2022 *Remote Sens. Environ.* **270** 112845
[4] Pereira H M *et al* 2013 *Science* **339** 277–8
[5] Espinoza J-C, Marengo J A, Schongart J and Jimenez J C 2022 *Weather Clim. Extremes* **35** 100406
[6] Saunois M *et al* 2020 *Earth Syst. Sci. Data* **12** 1561–623
[7] Hondula K L, Jones C N and Palmer M A 2021 *Environ. Res. Lett.* **16** 84016
[8] Garcin Y *et al* 2022 *Nature* **612** 277–82
[9] Lagomasino D, Fatoyinbo T, Castañeda-Moya E, Cook B D, Montesano P M, Neigh C S R, Corp L A, Ott L E, Chavez S and Morton D C 2021 *Nat. Commun.* **12** 1–8
[10] Duncanson L *et al* 2019 *Surv. Geophys.* **40** 979–99
[11] Sun M, Cui L, Park J, García M, Zhou Y, Silva C A, He L, Zhang H and Zhao K 2022 *Forests* **13** 1686
[12] Musthafa M and Singh G 2022 *Front. For. Glob. Change* **5** 822704
[13] Dubayah R *et al* 2020 *Sci. Remote Sens.* **1** 100002
[14] Markus T *et al* 2017 *Remote Sens. Environ.* **190** 260–73
[15] Magruder L A, Brunt K M and Alonzo M 2020 *Remote Sens.* **12** 3653
[16] Neuenschwander A and Pitts K 2019 *Remote Sens. Environ.* **221** 247–59
[17] Fleischmann A S *et al* 2022 *Remote Sens. Environ.* **278** 113099
[18] Negandhi K, Edwards G, Kelleway J J, Howard D, Safari D and Saintilan N 2019 *Sci. Rep.* **9** 1–9
[19] Hoyt A M, Chaussard E, Seppalainen S S and Harvey C F 2020 *Nat. Geosci.* **13** 435–40
[20] Umarhadi D A, Avtar R, Widyatmanti W, Johnson B A, Yunus A P, Khedher K M and Singh G 2021 *Land Degrad. Dev.* **32** 4779–94