Integrating Multi-Scale Remote Sensing and Ground-Sampling to Map Seagrass Blue Carbon Stocks in Phu Quoc Island, Vietnam

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Abstract *Seagrass meadows are pivotal "blue carbon" ecosystems, yet the extensive meadows surrounding Phu Quoc island, a crucial national asset for Vietnam, remain poorly quantified. This study provides the first spatially explicit, high-resolution assessment of seagrass distribution and its associated organic carbon stocks for this vital ecosystem. Ultra-high-resolution multispectral UAV imagery was collected and classified into benthic habitats using a Random Forest machine learning algorithm, achieving an overall accuracy of 83.75%. The high-resolution habitat map was then downscaled to a 10-meter grid to produce a seagrass density map, categorizing the meadow into bare, sparse, moderate, and dense patches. In-situ ground surveys and laboratory analysis of biomass and sediment cores provided mean carbon stock values for each density class. By extrapolating these values across the density map, we generated a spatially explicit model of carbon storage. The results reveal a strong carbon gradient, with dense seagrass meadows storing over seven times more carbon (328.6 MgC.ha^{-1}) than bare sediments (43.7 MgC.ha^{-1}). This research establishes a critical baseline for blue carbon accounting in Vietnam and provides an essential, data-driven tool for targeted marine spatial planning, supporting national climate strategies and the Sustainable Development Goals.*

Keywords: Biomass, Blue carbon, Multi-scale analysis, Climate change mitigation, UAV, machine learning

Introduction

Seagrass meadows are among the most productive and valuable ecosystems on Earth, acting as the “green lungs” of our coastal seas. These underwater flowering plants provide a suite of critical ecosystem services, including serving as nursery grounds for commercially important fisheries, stabilizing sediments to mitigate coastal erosion, and cycling nutrients (Stankovic et al., 2021). Critically, they are powerhouse "blue carbon" ecosystems. Despite occupying less than 0.2% of the global ocean floor, seagrasses are responsible for 10-18% of the total carbon burial in the ocean, sequestering carbon at rates up to 35 times faster than tropical rainforests (Fourqurean et al., 2012; Duarte et al., 2005). This makes their protection and restoration essential nature-based solutions for climate change mitigation.

The ASEAN region is a global hotspot for blue carbon, hosting a third of the world's seagrass meadows (UNEP, 2020). Vietnam, with its extensive coastline, is a key part of this, historically supporting vast seagrass beds. However, these vital habitats are under severe threat. Over the last two decades, Vietnam has lost an estimated 45-50% of its seagrass area, with the national extent declining from over 36,000 hectares to approximately 17,000 hectares (Vo et al., 2020). This degradation, driven primarily by coastal development, aquaculture expansion, and pollution, not only diminishes biodiversity and coastal resilience but also risks releasing significant quantities of stored carbon back into the atmosphere (Pendleton et al., 2012).

Amidst this national decline, the extensive seagrass meadow surrounding Phu Quoc island, estimated at 9,600 hectares, stands out as a critical remnant and a nationally significant blue carbon asset. Despite its importance, this ecosystem remains poorly quantified. There is a pressing lack of spatially explicit, high-resolution data on the seagrass biomass and, most importantly, the organic carbon locked within its sediments. This data gap hinders effective conservation planning, precludes the inclusion of seagrass in national carbon inventories, and limits opportunities for leveraging blue carbon finance mechanisms.

This study aims to address this critical knowledge gap by providing the first robust, landscape-scale assessment of seagrass biomass and sediment organic carbon stocks for Phu Quoc island. By integrating ultra-high-resolution UAV imagery with broad-coverage satellite data and targeted in-situ sampling, we generate detailed maps of seagrass distribution and its associated carbon stocks. The results establish a fundamental scientific baseline for monitoring and managing this vital ecosystem, providing data-driven insights to support Vietnam's conservation policies and its commitments to the Sustainable Development Goals, particularly SDG 13 (Climate Action) and SDG 14 (Life Below Water).

Methodology

a. Study site

The study was conducted in the coastal waters of Phu Quoc Island, An Giang Province, Vietnam. Field surveys and sample collection took place at Bai Bon (BB), selected for their known seagrass distribution, accessibility, and representation of the region's coastal habitats. The fieldwork was carried out in two phases during August 2025.

Bai Bon (10°18'27"N, 104°4'40"E) is an expansive intertidal flat that extends over a kilometer from the shore. The substrate is predominantly muddy, with water depths reaching up to two meters at high tide. The area is characterized by a diverse seagrass community, with dominant species including *Enhalus acoroides* and *Cymodocea rotundata*. Other species such as *Thalassia hemprichii, Halodule uninervis,* and *Halophila ovalis* are also present.

The site is subject to significant anthropogenic pressures. The shoreline and intertidal zone are dotted with houses built over the water, which may discharge waste directly into the sea. The area is a hub of local economic activity, including aquaculture of fish and mollusks, and extensive use of fish traps, particularly within dense seagrass patches. Frequent boat traffic for fishing and transportation has resulted in visible scarring on the seagrass beds.

b. Sediment sampling and Biomass sampling and analysis

Sediment Sampling

Sediment samples were collected following standardized blue carbon protocols to ensure consistency and prevent contamination. At each predetermined sampling site, the precise GPS coordinates and water depth were recorded. A PVC core sampler (6cm diameter) was driven vertically into the sediment to a target depth of 100 cm. Upon retrieval, the core was measured, and the PVC tube was capped at both ends and sealed with waterproof tape to maintain the integrity of the sample. Each core was meticulously labeled with a unique identifier, GPS coordinates, water depth, core length, date, and collector information. The samples were then transported in cool, insulated containers for subsequent laboratory analysis of carbon stock.

Figure 1 Preparing and inserting PVC corer to collect sediment cores

Biomass Sampling

Seagrass biomass sampling was conducted in accordance with global seagrass monitoring guidelines to assess productivity and species composition. At each sampling point, a 50 × 50 cm quadrat was placed on the benthos, and the GPS location and water depth were recorded. All seagrass shoots within the quadrat were counted and identified by species to determine shoot density.

Figure 2 Biomass sample harvesting and sample washing

For biomass analysis, all plant material from a randomly selected 25 × 25 cm sub-quadrat was carefully harvested. This included excavating the complete plant, including above-ground shoots and below-ground roots and rhizomes. Excess sediment was gently shaken off underwater before the sample was placed in a pre-labeled bag. Samples were immediately stored in a cool box with ice packs for transport to the laboratory, where they were rinsed, sorted by species, and prepared for biomass and carbon analysis.

c. UAV images

UAV Image Acquisition

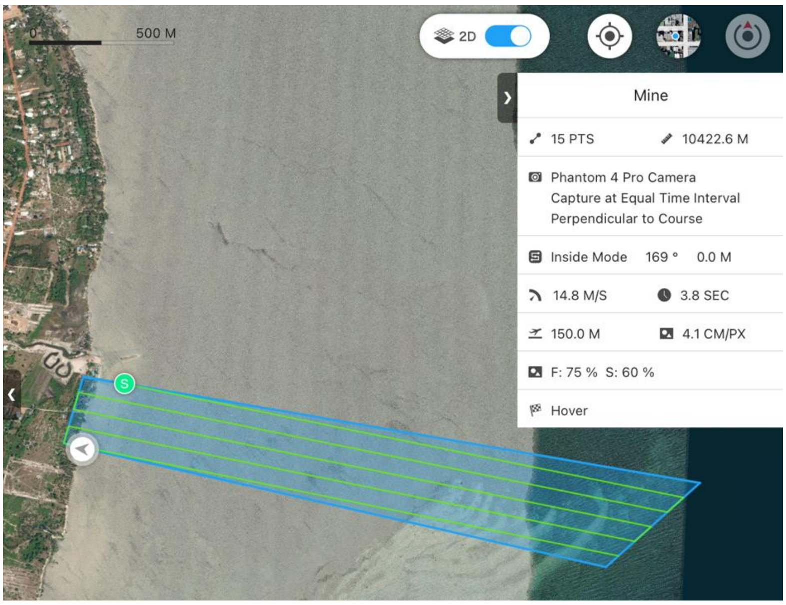

Figure 3 Flight path of Bai Bon, at 150m altitude

High-resolution aerial imagery was acquired using a DJI Phantom 4 Pro drone equipped with a 20-megapixel camera. To ensure maximum visibility of the submerged seagrass beds and minimize signal attenuation from the water column, all survey flights were conducted during low tide. Flight altitudes were varied between 10 meters and 150 meters to capture data at multiple scales, allowing for both detailed species-level analysis and broader landscape-scale mapping. To ensure high spatial accuracy in the final map products, Ground Control Points (GCPs) were established and measured throughout the survey areas.

Photogrammetric Processing

The collected UAV images were processed using Structure-from-Motion (SfM) photogrammetry software (Agisoft PhotoScan) to generate spatially accurate orthomosaics and Digital Elevation Models (DEMs). The workflow involved aligning the images by matching common features to create a sparse point cloud. This model was then georeferenced and optimized using the field-collected GCPs to ensure high geometric accuracy.

Following optimization, a dense 3D point cloud was generated, capturing detailed information on the seagrass canopy and substrate. From this dense cloud, a final high-resolution orthomosaic and a DEM were exported for each site. The resulting orthomosaics had a ground resolution ranging from 0.23 cm/pixel to 3.3 cm/pixel, providing a detailed basis for subsequent habitat classification.

Data Processing and Carbon Stock Mapping

The data processing workflow was executed within the Google Earth Engine platform to integrate the high-resolution UAV imagery with field-based carbon measurements.

1. **UAV Image Classification:** The high-resolution UAV orthomosaic from 150m altitude was first classified into three primary benthic habitat classes: seagrass, sand, and others. This was achieved using a supervised Random Forest machine learning algorithm, which was trained on manually digitized polygons representative of each class. The number of training points for seagrass, sand and others class were 133, 105 and 33 respectively. Out of those 271 points, 70% (191 points) were used to train the classifier, while 30% (80 points) were used for validation.
2. **Seagrass Density Mapping:** The resulting high-resolution habitat map was then downscaled to a 10-meter resolution to align with the Sentinel-2 satellite grid. This process calculated the percentage of seagrass cover within each 10-meter pixel. Based on these percentage values, a seagrass density map was created by categorizing each

pixel into one of four classes: bare (0% cover), sparse (0-33% cover), moderate (33-67% cover), or dense (>67% cover).

3. **Carbon Stock Extrapolation:** In the final step, the seagrass density map was used to create spatially explicit maps of carbon stocks. The average carbon stock values for soil, biomass (Organic Carbon Content), and total carbon—derived from the laboratory analysis of the field samples—were assigned to each corresponding density class on the map. This procedure generated the final carbon stock maps for the surveyed area.

Results and Discussion

a. Seagrass Biomass and Sediment Organic Carbon Stocks

Total organic carbon stock (TOC) in soil and biomass cores showed a clear gradient with seagrass density. The overall mean was 159.1 ± 61.6 $MgC.ha^{-1}$, with biomass pools (117.3 $MgC.ha^{-1}$) contributing nearly three times more than soil carbon (41.7 $MgC.ha^{-1}$) (Table 1).

Dense seagrass meadows exhibited the highest total carbon stock (328.6 $MgC.ha^{-1}$), driven primarily by their substantial biomass contribution (280.0 $MgC.ha^{-1}$) alongside soil reserves (48.7 $MgC.ha^{-1}$). Moderate-density meadows stored considerable amounts as well (163.9 $MgC.ha^{-1}$), whereas sparse meadows contained lower stocks (100.2 $MgC.ha^{-1}$). Bare sediments held only 43.7 $MgC.ha^{-1}$, reflecting the absence of biomass input (Table 1).

Table 1. Total Organic Carbon Stock in Soil and Biomass Cores Across Seagrass Density Levels at Bai Bon and Bai Vong, Phu Quoc, Viet Nam.

Seagrass density	Soil Carbon stock ($MgC.ha^{-1}$)	OCC (AG+BG) ($MgC.ha^{-1}$)	Total Organic Carbon ($MgC.ha^{-1}$)
Bare	43.672	0	43.672
Sparse	36.544	63.640	100.184
Moderate	38.127	125.746	163.873
Dense	48.655	279.986	328.641
AVE	41.749	117.343	159.092
SE	2.763	59.984	61.618

b. UAV image

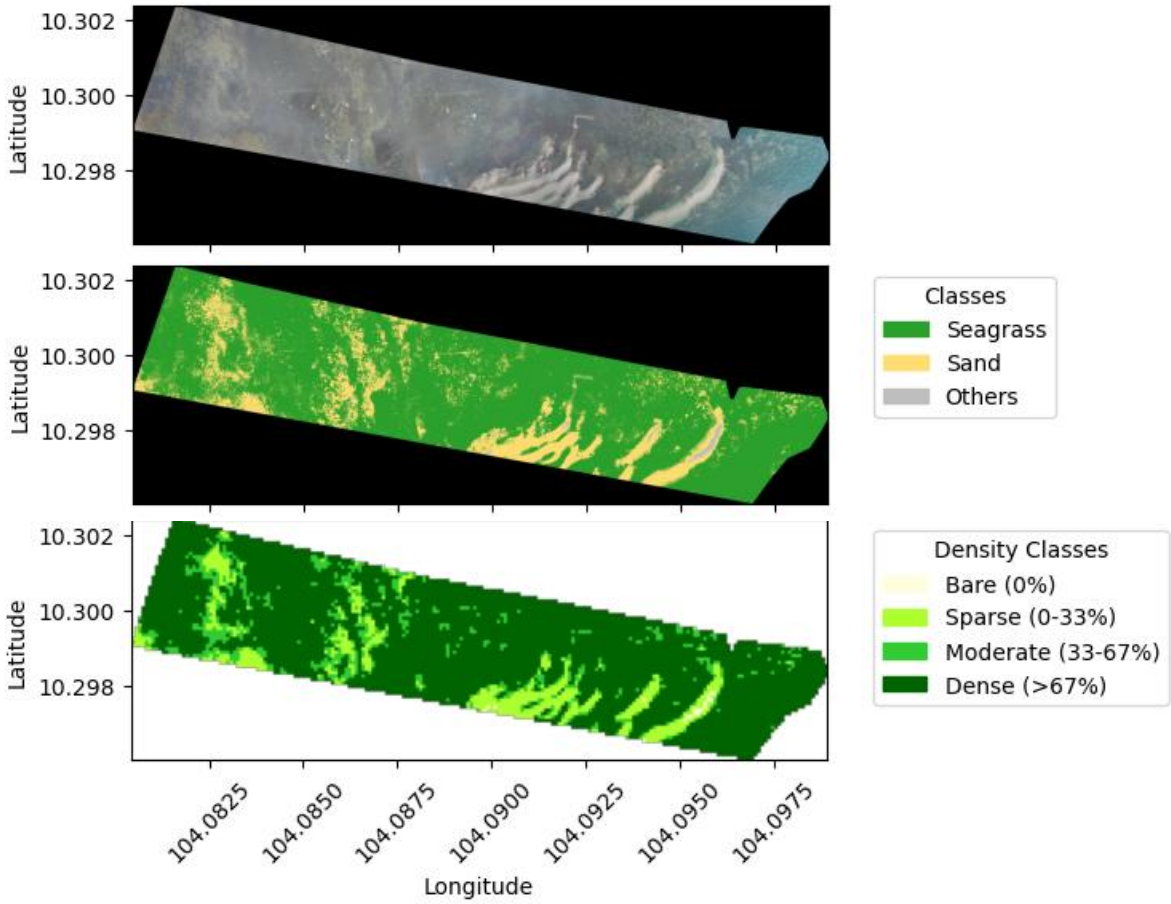

Figure 4: UAV orthomosaic (top), classified image (middle) and downsampled density classes (bottom)

Table 1: Confusion matrix for UAV classification

Actual Class	Predicted class			Row Total	Producer's Accuracy	Consumer's Accuracy
	Seagrass	Sand	Others			
Seagrass	31	6	0	37	83.78%	81.58%
Sand	7	28	0	35	80.00%	82.35%
Others	0	0	8	8	100.00%	100.00%
Column Total	16	19	20	84		

The supervised Random Forest classifier demonstrated a high level of performance in differentiating the primary benthic habitats from the high-resolution UAV imagery. The classification achieved an **overall accuracy of 83.75%** and a **Kappa coefficient of 0.72**. A

Kappa value in this range indicates substantial agreement between the classified map and the validation data, confirming that the model's performance is significantly better than random chance and is robust for this type of environmental application.

An analysis of the individual class accuracies reveals specific strengths and limitations of the model. The "Others" class was classified with perfect accuracy (100% for both producer's and consumer's accuracy), suggesting that its spectral signature was highly distinct from both seagrass and sand.

The primary classes of interest, Seagrass and Sand, were also classified with good accuracy. The producer's accuracy for Seagrass was 83.78%, indicating that the model successfully identified the vast majority of true seagrass areas. Similarly, the producer's accuracy for Sand was 80.00%. The consumer's accuracies for Seagrass (81.58%) and Sand (82.35%) were also strong, instilling confidence that the habitats labeled on the final map are correct more than four out of five times.

The confusion matrix highlights that the principal source of classification error was the spectral similarity between the Seagrass and Sand classes. A small percentage of seagrass pixels were misclassified as sand, and vice versa. This is a common and expected challenge in the remote sensing of submerged aquatic vegetation. The spectral signal of sparse seagrass growing on a bright, sandy substrate can be very similar to that of pure sand, particularly under varying water depths and turbidity levels. Despite this inherent spectral confusion, the classifier's ability to distinguish between these two critical classes with over 80% accuracy is a strong result, providing a reliable foundation for the subsequent downscaling and carbon stock estimation.

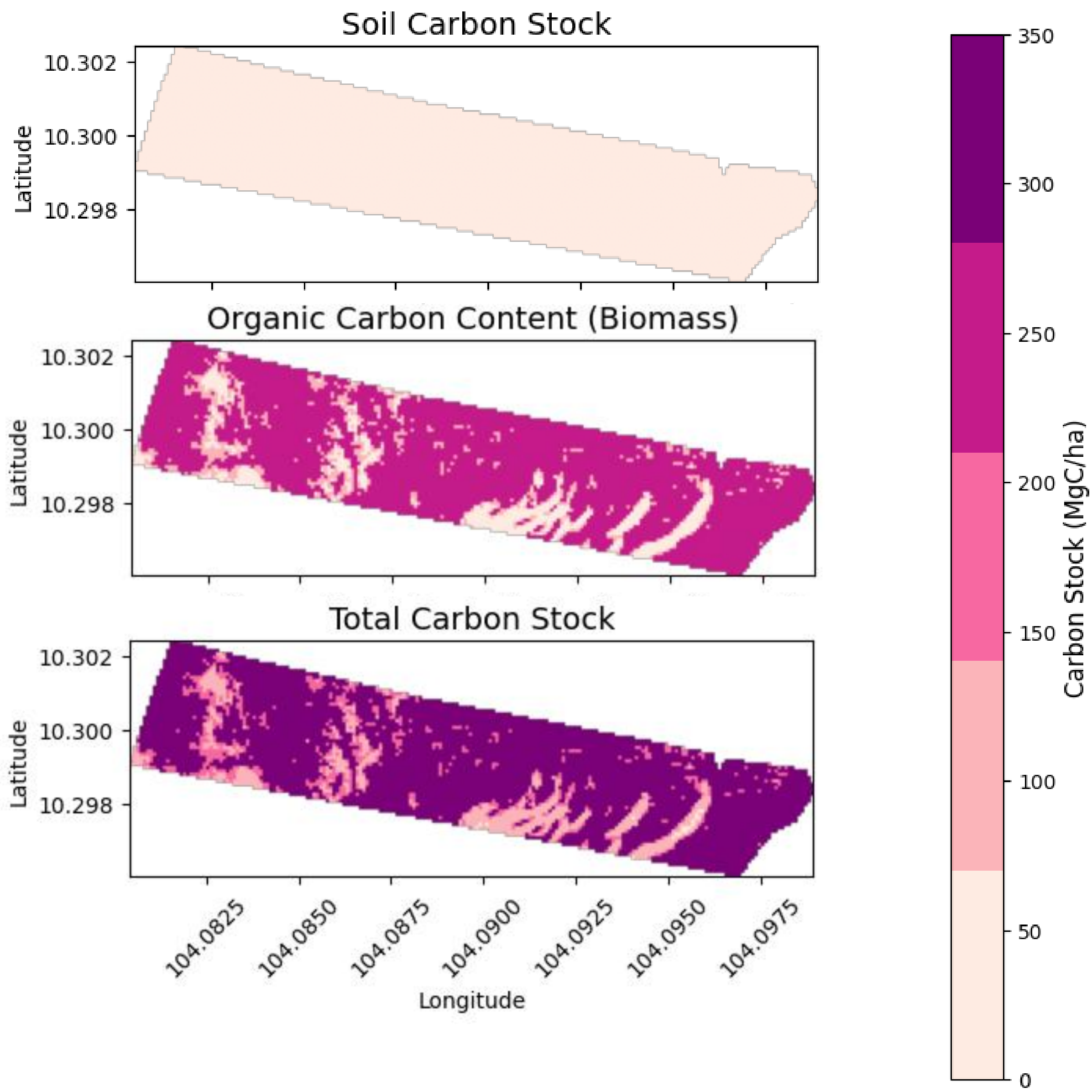

Figure 5: Carbon stock in soil, biomass and total carbon stock

The integration of the seagrass density map with field-based measurements produced a spatially explicit model of the total organic carbon (TOC) stock across the study area (Figure 2). The results reveal a landscape of highly variable carbon storage, directly correlated with the density of the seagrass meadows.

The total carbon stock stored within the mapped area shows a clear gradient, with dense seagrass meadows acting as significant carbon hotspots. These dense patches store an estimated **328.6 MgC.ha^{-1}**, a value more than seven times greater than the **43.7 MgC.ha^{-1}** held in bare sediments. Moderate-density meadows also represent a substantial reservoir, holding **163.9 MgC.ha^{-1}**, while sparse meadows contain **100.2 MgC.ha^{-1}**.

The importance of this spatially explicit approach cannot be overstated. A single, non-spatial average for the entire ecosystem would obscure this critical variability and misrepresent the true distribution of the carbon resource. The resulting map provides a powerful visual tool, moving beyond a simple inventory to identify the precise locations of high-value carbon sinks. This detailed spatial information is fundamental for effective marine spatial planning, allowing conservation efforts to be strategically targeted towards protecting the most vital carbon-rich areas of the seagrass ecosystem.

Conclusion

This study successfully demonstrates the power of an integrated, multi-scale remote sensing approach to provide the first spatially explicit quantification of seagrass distribution and blue carbon stocks for the nationally significant meadows of Phu Quoc, Vietnam. By leveraging the detail of ultra-high-resolution UAV imagery to train a broader analysis of satellite data, we developed a robust and accurate methodology for mapping these vital submerged ecosystems at a landscape scale.

The results revealed a highly heterogeneous distribution of carbon storage, directly linked to seagrass density. Dense seagrass meadows were identified as critical carbon hotspots, storing over seven times more organic carbon (328.6 MgC.ha^{-1}) than bare sediments (43.7 MgC.ha^{-1}). This finding underscores the immense value of intact, healthy seagrass ecosystems for climate change mitigation and highlights the inadequacy of using non-spatial averages for carbon accounting. The creation of these detailed carbon maps provides an indispensable tool for marine spatial planning, enabling policymakers and conservation managers to prioritize the protection of the most valuable carbon sinks from anthropogenic pressures.

Ultimately, this research establishes a critical scientific baseline for monitoring, reporting, and verification (MRV) of blue carbon in Vietnam. The data provides the foundational evidence required to incorporate seagrass ecosystems into national climate strategies, such as Nationally Determined Contributions (NDCs), and opens pathways for leveraging blue carbon finance mechanisms. By translating complex ecosystem functions into quantifiable data, this work provides the urgent, data-driven insights needed to inform robust conservation policies and safeguard the invaluable climate and biodiversity benefits of Phu Quoc's coastal habitats.

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