3D imaging insights into forests and coral reefs

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ABSTRACT:

Forests and coral reefs are structurally complex ecosystems threatened by climate change. *In situ* 3D imaging measurements provide unprecedented, quantitative and detailed structural information that allows testing of hypotheses relating form to function. This affords new insights into both individual organisms and their relationship to their surroundings and neighbours.

The importance of structural measurements

Corals and trees form the building blocks of their respective ecosystems. The structural complexity of forests and coral reefs plays an important role in the biodiversity, productivity and functionality of these ecosystems [1]. Corals and trees have been hypothesised to follow similar architectural growth rules that shape their structures [2]. Structure and function are linked: organisms have evolved under constraints of nutrients, light, water or space limitations and competition, and reproduction strategies, Box 1. Understanding 3D structure will assist in making links between structure and function that are needed to develop a general theory of ecosystem assembly and function [3].

New *in situ* 3D structural measurements from terrestrial LiDAR and Structure-from-Motion (SfM) analysis of digital photography enable precise, accurate and comprehensive structural measurements. These measurements have already provided unique insights into forests and coral reef ecosystems [3,4], but it is only now that analytical processing methods are sufficiently mature to assist in understanding functional-structural relationships by testing hypotheses relating form and function. Critically, these improved measurement approaches will allow more accurately defined baseline mapping and quantitative monitoring. When combined with traditional ecological and physiological knowledge, along with airborne or satellite remote sensing, such *in situ* observations can revolutionise how we monitor and manage forest and coral reef ecosystems in a changing climate.

In situ monitoring of 3D ecosystem structure

Before the 1980s, the structure of ecosystems was often represented qualitatively and often only in 2D, e.g. via the hand-drawn architectural models of trees and corals [2]. Representing inherently 3D structural properties in 1D or 2D can help simplify analysis, but also implies a loss of information of the ecosystem that may be vital for a proper understanding of key ecological services [1]. Attempts to collect detailed 3D data were often invasive, such as the felling of trees or the use of chain-and-tape methods in coral reefs.

Non-invasive *in situ* 3D imaging technologies either use direct measurements using LiDAR (Light Detection and Ranging, also called laser scanning) or through indirect Structure-from-Motion measurements derived from overlapping images (figure 1). SfM has existed since the late 1970s, but advances in data collection via drones, autonomous underwater vehicles and even handheld cameras have driven software developments, processing speed and robustness to extract 3D information from the images [5,6]. LiDAR and SfM sensors have become significantly cheaper, democratizing access to data. Further advancements in systematic surveys methods have removed the need for high-end navigation and controls, enabling precise georeferencing and site revisits for monitoring [7]. This resulted in new applications, such as quantifying precise loss of ecosystems or habitat by acute disturbance events. New developments in terrestrial LiDAR techniques in the last decade have led to new advances for the *in situ* measurement of individual tree and forest structure, Figure 1. Whereas the initial focus was on complementing and improving forest inventories [8], it is only now that we see the use of 3D architecture as model-input to understand e.g. wind damage in forests [9]. However, the relative novelty of such detailed 3D structural data means there is a long way to go to understand how best to unlock their full potential or make reliable comparisons at multiple sites [10]. Bottlenecks include reliable extraction of small structural elements (e.g. tips of tree branches), automation and robustness of methods and reliable point cloud classification. LiDAR applications for subsea fine-scale structural assessments of coral reefs are limited so far because of power requirements (water attenuates the LiDAR signal) and scattering from particles in the water (more data noise).

Ecosystem structure and climate change

Three-dimensional *in situ* information from forests and coral reefs could play a key role in understanding how ecosystems are changing. First, basic structural measurements of a tree or a coral colony are often used to quantify presence and provide population and demographic parameters. Second, aggregated structural measurements provide a topological understanding of structure, which relates to their functioning. Third, the structure of trees and corals directly relates to habitat suitability and interactions with other species [4].

Ecosystem structure and climate are closely linked: changes in climate lead directly to physical changes in ecosystem structure and vice versa. For example, the 2010 Amazon drought event lead to 2.2 Pg carbon committed emissions due to increased tree mortality, as well as subsequent impacts on forest composition and resilience [11]. Large trees are more vulnerable to droughts [12], but currently also have the largest uncertainties associated with their biomass estimates [8], making it difficult to define optimal climate mitigation actions. Similarly, ocean warming has caused global-scale bleaching and catastrophic mortality in corals.

The way forward

Extreme climate events are impacting forests and coral reefs. The complementarity between fine-scale 3D *in situ* data and measurements over larger areas will be a catalyst for advancing our understanding of ecosystem functioning. *In situ* measurements provide the finest detail, but generally lack the spatial coverage that is required to understand ecosystem functioning: linking “smaller-area-higher-detail” with “larger-area-lower-detail” data will assist in understanding local ecosystem processes regionally and globally.

3D data at regional scales, primarily from airborne LiDAR, are often already available but limited due to low temporal frequency and uncertain *in situ* data. These regional datasets are often commissioned by national mapping or environmental agencies for purposes other than forest or coral reef monitoring, but can provide wall-to-wall spatial coverage (albeit aggregated over the data acquisition time). Increased public availability of these data will help to rapidly upscale our understanding of vulnerable ecosystems. Some countries already make such data available, but often with limited or no metadata or quality information.

A range of new purpose-built space missions just launched or planned will estimate the structure and carbon of forests at global scales, and new initiatives aim to create global coral reefs maps that can serve as baseline maps to monitor short-term changes. The success of these missions will be directly related to ground calibration in which advancements in 3D monitoring will be important. To successfully combine observations across scale domains, a quality assessment framework will be essential. Measurement uncertainty will propagate through the upscaling chain from individuals to communities to global datasets. To understand the uncertainty of satellite estimates of aboveground biomass, for example, requires quantified uncertainty of carbon storage at tree level, as well as how these individual uncertainties aggregate at plot and continental scales. The recognition of terrestrial laser scanning for measuring detailed 3D vegetation structure in the most recent IPCC national greenhouse gas reporting guidelines is a step in the right direction for reaching international standards on quantified uncertainties.

Most of the processing methods for fine-scale 3D data are modified from methods that were originally designed for less spatially explicit data. A key question that remains is: are we using algorithms that are fit-for-purpose to exploit the full potential of these *in situ* data? Data measurement has matured significantly over the years, but active restoration approaches require a close integration between management practices and research. The relative low-cost and ease of data acquisition will allow further analysis of structure-function relationships with detailed 4D data, with time being the 4^{th} dimension. Such approaches will improve our knowledge of forest growth dynamics or coral reef recovery by combining detailed structural metrics with ecosystem models.

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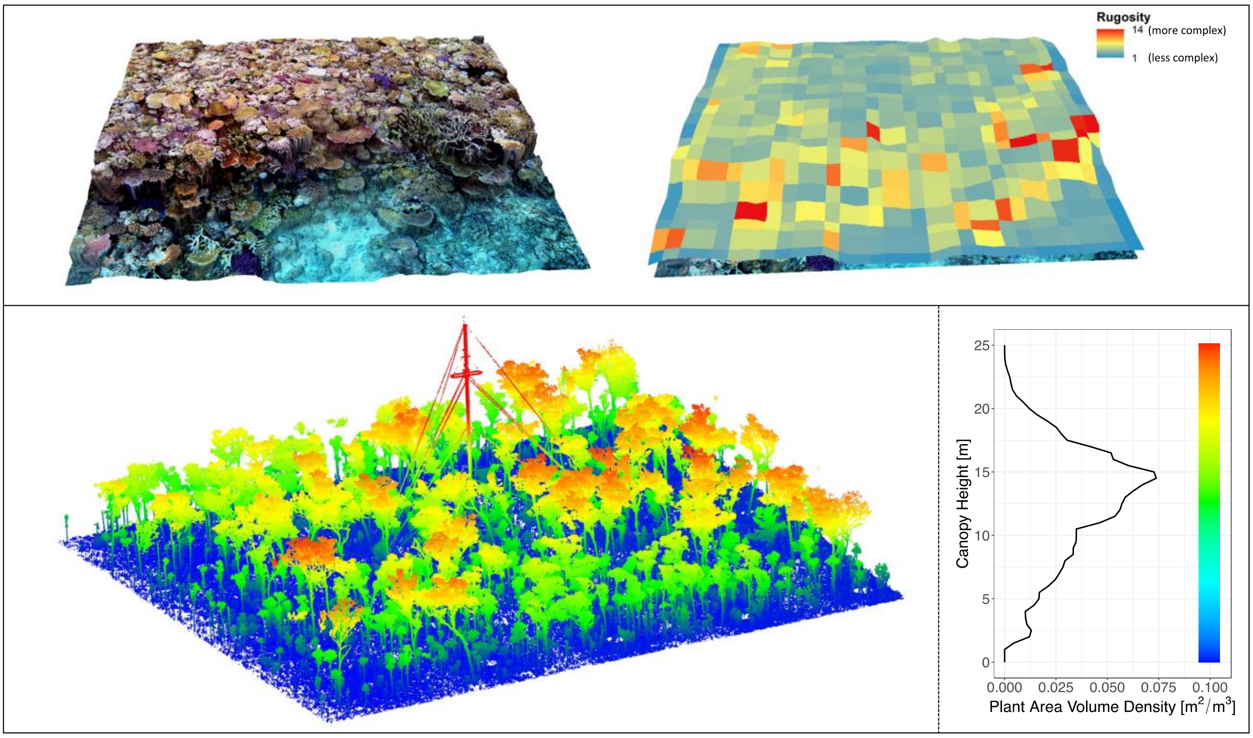
Box 1: Definition of structural measurements.

Structure is the spatial arrangement of the basic components of a system. Within this context, structural measurements refer to both individuals (trees and corals), as well as their aggregated communities of forest and coral reef ecosystems. Structural measurements for trees include: tree height, canopy width, diameter at breast height, leaf and branch angle distribution and all aspects of biomass. These measurements can be made for individual trees as well as aggregate or average measurements at plot level. Structural measurements for corals include both colony height and width, while change in height per unit horizontal segment is termed rugosity or roughness. Rugosity is widely accepted as a measure of habitat complexity [1]. Structural parameters of forests and coral reefs are used in their baseline inventory and taxonomic mapping, and for regular field-based monitoring. The main advantages of terrestrial LiDAR and Structure-from-Motion measurements over traditional *in situ* manual measurements are their increased accuracy, precision, certainty, repeatability and traceability. Traceability is defined as the chain of steps taken from raw data to derived structural metric. This is an important process in establishing reliable baseline scenarios of structure with quantified uncertainties that are required to quantify structural change over time.

Figure 1: New in situ 3D technologies provide unprecedented insights into the place of individual trees and corals in forests and reefs.

(top) Left panel: A 3D render of Lagoon Reef, far northern Great Barrier Reef, Australia, derived from Structure-from-Motion algorithms applied to overlapping hand-held camera images collected in the field [5]. Right panel: Deriving quantitative structural measurements from in situ 3D data. Rugosity, or relative variation in height per unit distance (in 0.25 m pixels) of Lagoon Reef, far northern Great Barrier Reef, Australia.

(bottom) 3D complexity of a 1 hectare tropical savanna in Litchfield (Northern Territory, Australia) captured using terrestrial LiDAR. Left panel: The colours represent canopy height (blue = 0 m, red ≥ 25 m). Right panel: Derived plant area volume density as a function of canopy height (in 1 m height bins). This structural metric tells us how the volume of leaf and branch material is distributed with height in the canopy.


Rugosity
14 (more complex)
1 (less complex)
Canopy Height [m]
25
20
15
10
5
0
0.000
0.025
0.050
0.075
0.100
Plant Area Volume Density [m2/m3]