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Going 3D – the changing landscape of forest structural complexity

By Alice Rosen and Tommaso Jucker, 21 August 2026

REVISED MANUSCRIPT

Forests with complex three-dimensional (3D) structures – with variation in the height, size, and arrangement of trees, branches, and leaves – are home to a large proportion of the world's biodiversity. They also capture and store substantial amounts of carbon from the atmosphere, making them a key ally in the fight against climate change. Despite their global importance, forests are facing severe climate-related threats (including fires, drought, and disease) and are being cleared at alarming rates due to logging for timber and agricultural expansion. These disturbances dramatically alter the 3D structure of forests, impacting their ability to safeguard biodiversity and provide valuable ecosystem services. To understand and predict the true impact of these changes, it is crucial that we develop new approaches to accurately measure the 3D structure of forest canopies. Traditional, ground-based methods struggle with this, attempting to describe structural complexity from oversimplified features of trees. However, with recent advances in Light Detection and Ranging (LiDAR) technology, we can measure complex forest ecosystems in 3D over vast areas. This technology is changing the way we understand structural complexity and what it means for the health of our ecosystems. As these methods continue to improve – becoming more robust and generalisable – they will help us better

understand, conserve, and restore our globally important forests.

{1}Why complexity matters

{2}As trees grow, jostle for space in the canopy and eventually die, they give rise to incredibly complex three-dimensional (3D) forest structures that have fascinated ecologists for decades [C.G. Jones et al., 1994]. In structurally complex forests, vegetation is typically distributed across multiple layers, with trees of different sizes and shapes interspersed with gaps. This variety of structures provides a wide range of niches for organisms living in and below the canopy, helping more species to coexist [J.A. Walter et al., 2021; S. Gámez and N.C. Harris, 2022; K.E. Kovalenko et al., 2012; G.A. Langellotto and R.F. Denno, 2004]. Structurally complex forests can also support greater plant growth and carbon storage [C.M. Gough et al., 2019]. It is unsurprising, therefore, that forest structural complexity is increasingly seen as an important feature of these ecosystems that we should aim to protect and enhance [W.D. Simonson et al., 2014].

{3}A forest's 3D structure is shaped by the pool of tree species that grow in a given region, as well as differences in their ecological strategies. Forests with a diverse mix of tree species generally have a more complex structure than ones that are species-poor [D.C. Zemp et al., 2019; J. Juchheim et al., 2019]. Trees with complementary crown shapes are able to pack their crowns into the available space more efficiently [T. Jucker et al., 2015; H. Pretzsch, 2014]. Light-demanding species extend their crowns to the very top of the canopy, whilst trees that are more tolerant of shade fill the remaining space lower down. Overall, this creates a complex, multi-layered structure that captures more light [J. Sapijanskas et al., 2014; J.W. Atkins et al., 2018], which can boost plant growth and the accumulation of carbon [M. Dalponte et al., 2019]. This also creates more favourable microclimatic conditions in the understorey for new seedlings to grow, protecting them from extreme changes in temperature and humidity found outside the forest canopy [T. Jucker et al., 2018].

{4}Natural disturbances such as storms, fire and drought also play a key role in shaping the 3D structure of forests [T. Jucker, 2022]. Gaps created after treefalls spark new growth in the understorey and preserve a diversity of species with different ecological strategies [A. Muscolo et al., 2014; J. Zhu et al., 2014]. However, the increase in human-driven disturbances – including climate change, intensive logging and agricultural expansion – are fundamentally altering the structure of the world's forests, threatening their ability to store carbon and safeguard biodiversity [T. Newbold et al., 2015; A.P. Williams and J.T. Abatzoglou, 2016; D.T. Milodowski et al., 2021]. This has led to growing interest in developing ways to measure and track changes in forest structural complexity over time and space in order to guide conservation and restoration efforts [D.C. Zemp et al., 2019; N. Camarretta et al., 2020; D.R.A. Almeida et al., 2019; C. Penone et al., 2019]. But to do this we first need to agree on what we mean by '*structural complexity*', and that is easier said than done.

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{6}Figure 1. Cross-section of a ground-based LiDAR point cloud from a tropical forest in Sabah, Malaysian Borneo. Points are coloured to distinguish individual trees, revealing the diversity of tree sizes, crown shapes, and positions within the forest. Multiple canopy layers are interspersed with gaps that allow light to penetrate to the dense understory below. Together, these features illustrate the forest's complex three-dimensional structure. Image created by Toby Jackson, University of Bristol.

{7}Defining and measuring structural complexity – not so simple

{8}Structural complexity describes many different components, which inherently makes it difficult to define. A useful starting point is the '*diversity, density, size, and arrangement of structural elements, as well as the spatial scales over which they occur*' [M. Tokeshi and S. Arakaki, 2012]. Put simply, complexity depends on how much vegetation there is, but also on how varied it is in size and how it is arranged in space. Because this definition brings together several different features, no single measure is likely to neatly capture every aspect of complexity [A. Rosen et al., 2024]. This has resulted in a multitude of ways to measuring structural complexity, and some confusion over how they should be interpreted and compared. At present, there is no widely accepted framework for measuring forest 3D structure. Adding to this confusion, numerous terms – including '*habitat architecture*', '*structural heterogeneity*' and '*structural diversity*' – are often used interchangeably as synonyms of structural complexity [C. McElhinny et al., 2005].

{9}To measure the structural complexity of forests, ecologists have traditionally relied on ground-based measurements requiring little more than a tape measure. These measurements typically describe individual features of forest structure, such as tree trunk diameter or tree

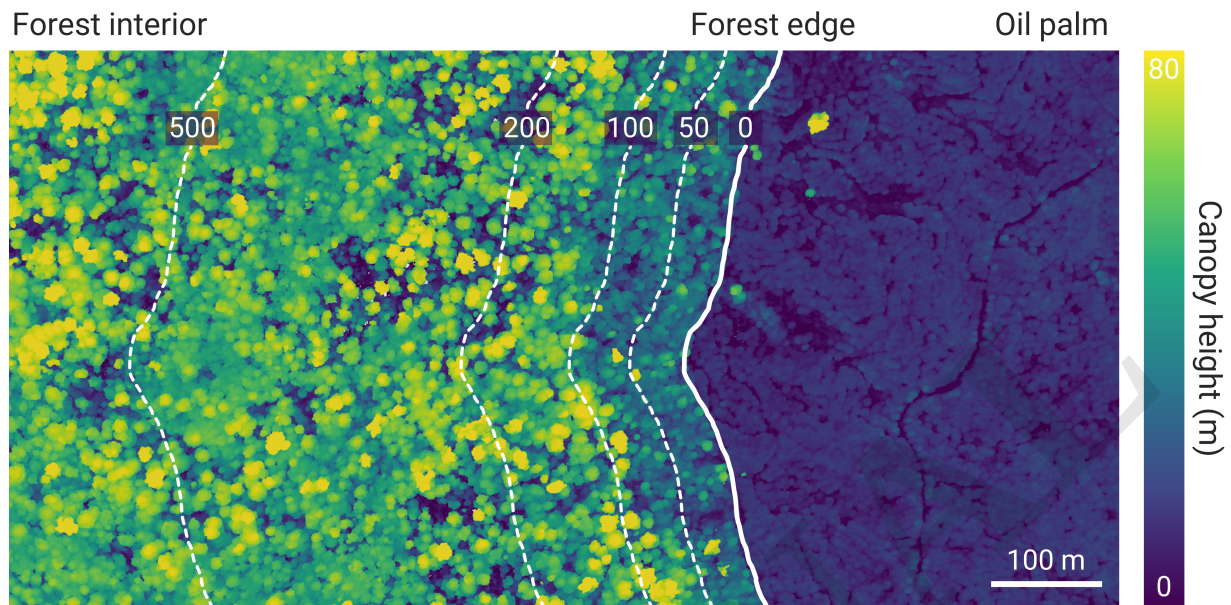
height, rather than capturing complexity across multiple dimensions. A number of efforts have been made to combine these traditional measures of forest structure into a framework for quantifying structural complexity. Some methods focus on the horizontal arrangement of trees [P.J. Clark and F.C. Evans, 1954; K. Földner, 1995]; others are concerned with the density and distribution of leaves in the canopy; and others focus instead on the vertical structure of forests [R.H. MacArthur and J.W. MacArthur, 1961] or the diversity of their structural elements [N.L. Lexerød and T. Eid, 2006]. But all of these approaches share the same fundamental limitation: they reduce something that is inherently three-dimensional to a set of simplified ground-based measurements [E.R. Lines et al., 2022].

{10} **Capturing forest structure in 3D – a remote sensing revolution**

{11} One increasingly popular solution to the challenge of measuring forest 3D structure has been to turn to remote sensing technologies such as Light Detection and Ranging (LiDAR) [N. Camarretta et al., 2020; K.C. Cushman et al., 2026]. LiDAR scanners work by shooting hundreds of thousands of laser pulses per second towards the canopy and then measuring the time it takes for each of those pulses to return to the sensor. The result is an incredibly detailed 3D ‘point cloud’: a collection of points showing where leaves, branches, tree trunks and the ground occur in 3D space. LiDAR sensors can be mounted on a range of platforms, allowing forest structure to be measured at different scales and from different viewpoints. Operated from the ground, LiDAR can be used to generate highly detailed 3D models of individual trees, right down to the level of fine branches and leaves [K. Calders et al., 2020]. Mounted on aircraft such as an aeroplane, helicopter or drone, LiDAR allows us to capture the 3D structure of forest canopies across entire landscapes in a way that would simply be impossible from the ground [T. Jucker et al., 2018; E.R. Lines et al., 2022] (Figure 1). And with NASA’s Global Ecosystem Dynamics Investigation (GEDI) – a satellite-mounted LiDAR sensor – we are now starting to build high-resolution global maps of forest canopy structure from space [F.D. Schneider et al., 2020].

{12} This LiDAR data revolution is driving growing interest in the study of forest structural complexity. We can now measure familiar features of forest structure over vastly greater areas thanks to this technology. For instance, foliage height diversity (FHD), which describes how foliage is distributed vertically through the canopy, has been used by ecologists for decades but can now be mapped from space using GEDI [H. Tang et al., 2019]. A growing number of open-source tools are also making it easier to extract ecologically meaningful information from 3D point clouds [J.W. Atkins et al., 2022]. As a result, we are building a picture of how and why structural complexity varies across different forest ecosystems [M. Ehbrecht et al., 2021]. Equipped with this knowledge, we can begin to identify priority areas for conservation [M. Ehbrecht et al., 2021] and develop management practices that help to restore the structural complexity of degraded forests [N. Camarretta et al., 2020; C. Penone et al., 2019].

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{14}Figure 2. Example of a 3D canopy height model derived from airborne LiDAR data acquired across a tropical forest landscape in Sabah, Malaysian Borneo. The colour gradient reflects the height of the canopy, ranging from tall forests in yellow to short vegetation and bare ground in blue. Going from left to right, the map shows a sharp transition zone from an old-growth tropical rainforest – where emergent trees exceed 80 m in height – to an oil palm plantation with its characteristic short and uniform canopy. A decrease in forest canopy height is clearly visible in the first 100 m from the boundary of the oil palm plantation. These edge effects can extend hundreds of metres into the forest interior and are linked to increased rates of tree mortality driven by warmer, drier and windier conditions in these transition zones.

{15}But all of this brings into sharp focus the need to think carefully about how we define and measure structural complexity [L.H.L. Loke and R.A. Chisholm, 2022]. In one sense, we are no longer constrained by what is practical to measure, allowing us to focus on features that tell us more directly about how forests function, store carbon, and support biodiversity (including canopy layering, variation in canopy height, and the size and distribution of gaps [E.R. Lines et al., 2022]). At the same time, the growing number of metrics, methods, and definitions makes it difficult to compare and interpret findings from different studies. Similar challenges apply to the LiDAR data themselves. Although their availability has expanded enormously in recent years, LiDAR data remain unevenly distributed around the world and are often collected and processed in different ways. Recent initiatives such as the Global Canopy Atlas are beginning to address this by bringing together thousands of airborne LiDAR surveys and transforming them into standardised, analysis-ready maps of canopy structure [F.J. Fischer et al., 2025].

{16}Laying the foundations for the future of habitat complexity research

{17}Recent advances in LiDAR technology mean that we can now measure the 3D structure of

forests at spatial scales and resolutions that were unthinkable just two decades ago. As interest in habitat complexity research and access to LiDAR data continue to grow, we need to think carefully about how best to use this wealth of new information. In particular, we should strive to develop robust, clearly defined and generalisable methods that are straightforward to interpret and allow structural complexity to be compared across ecosystem types. There is unlikely to be a one-size-fits-all approach, but we should aim to identify measures that improve our understanding of how ecosystems function and how they support biodiversity. This could be a promising step towards identifying areas of high conservation value, measuring the impacts of habitat disturbance, and improving how we restore ecosystems following major disturbances.

{18}Bibliography

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