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Review

Co-developing an international TLS network for the 3D ecological understanding of global trees: System architecture, remote sensing models, and functional prospects

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A B S T R A C T

Trees are spread worldwide, as the watchmen that experience the intricate ecological effects caused by various environmental factors. In order to better understand such effects, it is preferential to achieve finely and fully mapped global trees and their environments. For this task, aerial and satellite-based remote sensing (RS) methods have been developed. However, a critical branch regarding the apparent forms of trees has significantly fallen behind due to the technical deficiency found within their global-scale surveying methods. Now, terrestrial laser scanning (TLS), a state-of-the-art RS technology, is useful for the *in situ* three-dimensional (3D) mapping of trees and their environments. Thus, we proposed co-developing an international TLS network as a macroscale ecotechnology to increase the 3D ecological understanding of global trees. First, we generated the system architecture and tested the available RS models to deepen its ground stakes. Then, we verified the ecotechnology regarding the identification of its theoretical feasibility, a review of its technical preparations, and a case testification based on a prototype we designed. Next, we conducted its functional prospects by previewing its scientific and technical potentials and its functional extensibility. Finally, we summarized its technical and scientific challenges, which can be used as the cutting points to promote the improvement of this technology in future studies. Overall, with the implication of establishing a novel cornerstone-sense ecotechnology, the co-development of an international TLS network can revolutionize the 3D ecological understanding of global trees and create new fields of research from 3D global tree structural ecology to 3D macroecology.

1. Introduction

Trees, the Earth's watchmen, show distinctive forms caused by various environmental factors [1]. During their growth phase into relatively large-sized individual trees with the ecological imprints, they have experienced the varying decadal-, centennial-, or even millennial-scale effects in terrestrial processes [2]. For exploring the complicated mechanisms of their ecological drives, people have increasingly aspired detailed investigations of trees that are best distributed as extensively as possible [3] and their data fine-analyses [4]. Furthermore, the ecological understanding of individual trees on a large scale has been stressed for comprehensively unveiling the complex natural secrets.

1.1. *Ecological understanding of trees: global-oriented trend*

Among the “large” scales, a prominent one is the “global” scale. The global-oriented trend of tree ecological understanding has been growing along with increases in global sciences such as global ecology [1]. As scientists indicated [5], more coordinated global-scale efforts are required to supply the knowledge, share the information, and add the conservation capacity for reducing the loss of tree species within biodiversity hotspots. In order to achieve such goals, various maps of global trees have been generated in terms of species diversity [6]. Such map-based derivations can

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reflect a large variety of global environmental changes and, in turn, the ecological effects of these changes on global trees [7], including ecosystem phenology [8] to tree pollination [9]. A study of global trees and their changes can further show the performance of individual trees on ecological effects from different terrestrial processes [1]. For example, Tejedor et al. posed and validated a global-oriented perspective on the climate-driven growth synchrony of neighboring trees [10], and Manzanedo et al. collected evidence on the unprecedented rise in growth synchrony from global-scale tree ring records [11]. Such knowledge facilitates formulating the global-scale guidelines for sustainable applications of non-native trees in order to avoid tree invasions and mitigate their negative impacts [12].

These scientific potentials created significant attention concerning global trees. Kendal et al. compared the climatic niches of the urban and native tree populations worldwide [13]. Bastin et al. assessed the effect of global tree restoration and stressed its efficacy for the mitigation of climate change [14]. Han and Singh reviewed the causative mechanisms and the modeling methods for forecasting tree mortality under global warming [15]. Along with these endeavors, Adams and Pfautsch urged the relevant fields to regard the challenges that involve global trees and their changes [16]. Hartmann et al. examined the patterns and trends of global tree mortality [17]. Ratnam et al. proposed planting a trillion trees globally as a nature-adaptive solution plan as well as a reasonable political measure to solve our sustainability-related challenges [18]. These contributions have significant implications and demonstrate the significance of the ecological understanding of global trees.

1.2. Ecological understanding of trees: structure-underlined trend

Another trend in the ecological understanding of trees has been regarding their structures, as reflected by the representative studies on the ecological effect of tree crown structure influenced by the lichen communities [19]. Quantitative morphometry of tree branching structures has long been emphasized [20], due to its wide-spectrum roles. For instance, a novel study on tree structures in human-disturbed littoral forests suggested that some incentives can be developed to leverage global and local conservation demands [21]. Furthermore, the significance of tree structure studies using a three-dimensional (3D) mode, has been utilized to see forest stands and even forest systems composed of heterogeneous trees as stand-scale resource distributions emerge from the structures of the individual trees [22]. For predicting the pan-tropical forest structures, the largest-sized trees have been used as the intermedia between ground and airborne observations [23]. Therefore, the aggregated structures of trees, namely, the structures of tree populations [24] and tree communities [25], that involve their ecological patterns such as small trees that often form a ring structure around large trees [26], their ecological attributions such as mammalian predation [27], their ecological effects such as influences on understory compositions [28], and their ecological functions such as tsunami mitigations [29] have yet to be brought into mainstream research.

The scientific focus has recently been reduced to the tree level, with its fine-scale forms used to probe its ecological causes, such as selective logging [30], and its ecological effects, such as their varying impacts on macrolichen *Letharia vulpina* [31]. Tree structures are an ecological influence on regional and global differences in their diverse environmental and climatical feedback [32]. Collectively, tree communities, single trees, and their structures have been emphasized more in their relevant domains. This structure-underlined trend enables people to retrieve many relatively hard-to-measure attributes of trees from their visible forms [33].

1.3. Towards a 3D ecological understanding of global trees

Literature reviews revealed the global-oriented and structure-underlined trends in the ecological understanding of trees. The trends further merged into cutting-edge research that included a 3D ecological understanding of global trees. This emerging trend stemmed from the characterization of the structures of the trees globally and facilitated a change from a more comprehensive understanding of the elementary ecological function units to a better record-keeping method used to track the Earth's carbon cycles [3]. This trend has long been reflected in the field of global tree assessment [34] as well as the relevant disciplines. For example, the complicated links between forest growth and their corresponding normalized difference vegetation indices were investigated on a global scale [35]. To finish these tasks, new methods such as terrestrial laser scanning (TLS)-bridged co-prediction of tree-level multifarious stem structural parameters based on Worldview-2 panchromatic images [36] have been designed. Next, new remotely sensed tree crown cover-based indicators have been proposed to monitor global sustainability and environmental initiatives [37]. Additionally, the allometric equations that are applied to characterize tree structures have been enhanced and merged the remotely sensed imagery into the global forest monitoring programs [38]. In summary, fully mapping and characterizing the structures of global trees and their variations is in high demand to better explore their relevant global ecological sciences, such as macroecology [32] and global carbon cycles [3].

The tendency to promote the 3D ecological understanding of global trees may provide a foundational reconstruction to give new perspectives to many relevant fields, as illustrated in Fig. 1, which includes tree photosynthesis to boundary layer biometeorology. Studies on topics such as ecosystem evolution [39] and vegetation structural ecology [40] are restricted to the shortcomings of measuring tree samples and mapping tree structures. The proposed 3D ecological understanding of the global tree concept addresses these gaps in principle, with the primary research question being how to implement this concept into practice.

1.4. Underlying bottleneck: 3D mapping of global trees and their environments

However, establishing 3D mapping into common practice is challenging, since both the traditional practice and the current programs used to map trees and the intercontinental distances that restrict people from surveying the structural details of global trees [41]. Although a series of endeavors that are aimed at studying global trees have been made [42–47], the 3D mapping of tree structures and their dynamics across the globe have been a fundamental bottleneck. This issue has created a core branch of global ecology based on their apparent forms that lag far behind [48]. To deal with this issue, a few strategies have been attempted to map and study global trees. Selecting and measuring a volume-appropriate body of typical forest plots worldwide were utilized to derive tree diversities [49] and assess forest plantations [50]. Global meta-analysis and model simulations were used to reveal the ecological effects of the scattered trees regarding biodiversity conservation [51] and the response of forest structure to climate change [52]. Remote sensing (RS) has been used to collect global tree information [53]. After adopting this method, new insights on the structural ecology of global trees were generated.

However, the progress that has been made by these few endeavors are far actually supporting the 3D understanding of global trees [41]. Until now, *in situ* surveying techniques that can measure the full forms of trees individually cannot efficiently cover the Earth, while satellite-based RS approaches can only derive limited

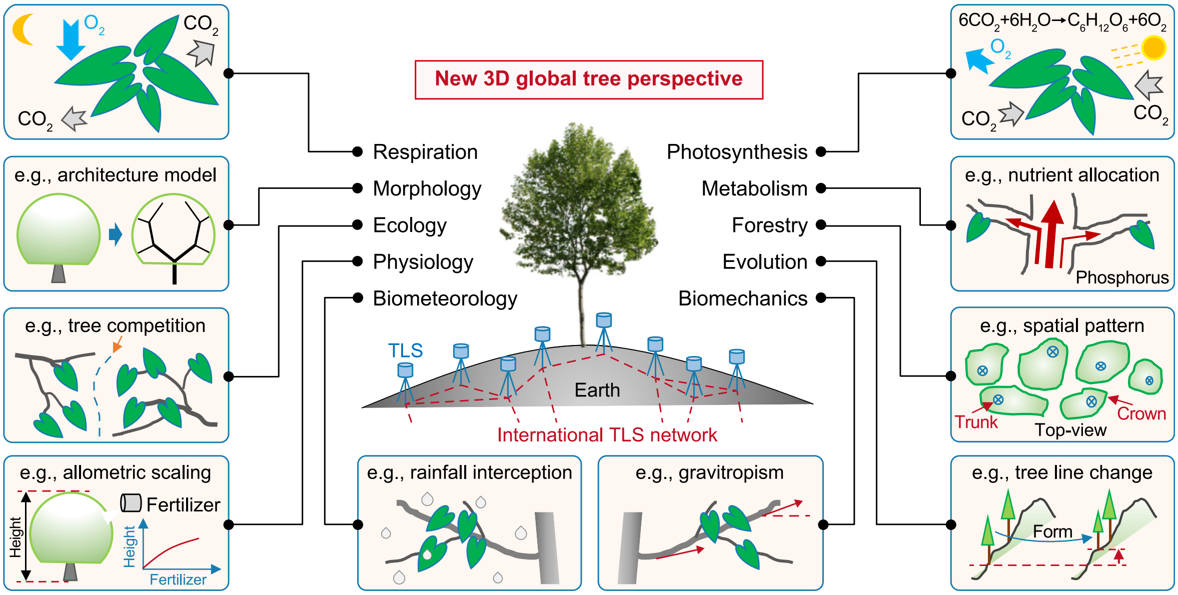

Fig. 1. Schematic diagram of the construction an international TLS network used to measure the 3D structures of global trees and its newly derived 3D perspectives on the basic disciplines relevant to global trees, ranging from ecology to biometeorology.

feature parameters needed to characterize their 3D structures [53]. This challenging dilemma, will persist, although scientists have already predicted that satellites have the ability to map every tree on Earth [53]. The reason is that this prospect [53] still needs a definition of its “upper limit” — the near future RS technologies can help people to “see every tree” but not “see the structure of every tree”, let alone “see the 3D structure of every tree”. The underlying bottleneck is that over an extended period of time, it is challenging to predict tree mapping solution plans to efficiently measure the structures of global trees and their local environments, especially when their smaller-size organs grow in a 3D manner. This study is dedicated to devising a macroscale ecotechnology to achieve the goal of a 3D ecological understanding of global trees.

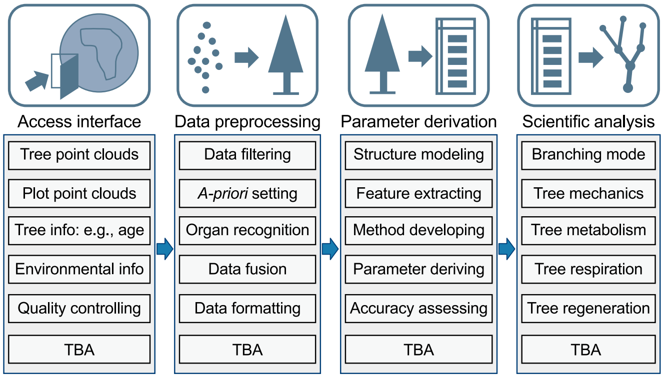

Fig. 2. Schematic system architecture diagram designed for the proposed international TLS network, and the four sequential functional modules range from access interface, data preprocessing, parameter derivation, and scientific analysis, with their individual functional units.

2. Scheme: Co-developing an international TLS network

Achieving the given scientific goal relies on first accomplishing the goal of fine-scale 3D tree structure mapping. TLS is becoming a viable technical solution [54], and its data has been widely validated to fulfill its processes, such as classifying tree species [55] and deriving tree structural attributes [56]. TLS has been created for an operational program for the inventory of forest structures at the plot scale level [57]. In light of these technical strengths and the earlier conceptual blueprints, such as organizing the global network of plots for the censoring of species diversities in tropical forests [58], we proposed to co-develop an international TLS network, that is schematically displayed in Fig. 1. This scheme is equivalent to the creation of the cornerstone in order to boost the 3D ecological understanding of global trees.

2.1. System architecture

For the management of the proposed international TLS network and the analyses of its collected data, we tentatively proposed the TLS system architecture. As listed in Fig. 2, its major functional modules contain the primary procedures of data processing needed to support the TLS network, covering the access interface, data preprocessing, parameter deriving, to scientific analysis. The first functional module involves uniformly uploading tree- and plot-related point clouds, tree information such as species and age, environmental information such as topography, and controlling data quality. Through this access interface, users can share their TLS data and use it in a uniform format worldwide. The second functional module executes data filtering, *a-priori* setting, tree organ recognition, data fusion, and output formatting. This step can ensure that all TLS data collected by the TLS network is consistently available for future applications. The third functional module deals with operating tree structure modeling, variable extraction, method development, parameter retrival, and accuracy assessment. This module serves as the core program that derives the 3D feature parameters for reliably characterizing the global tree attributes. The last functional module focuses on how to conduct scientific analyses regarding the modes of branching, mechanics, metabolism, respiration, and regeneration of trees. This step aims at achieving the ultimate goal of this study. Using all the above-listed implemented routines, the 3D ecological understanding of global trees and their variations can be readily accomplished.

The system architecture of the proposed network is planned to be functionally extendable, as indicated by the to-be-added (TBA) functional units in Fig. 2. This purposeful pre-setting facilitates the future adjustment and enhancement of the functionality of the system architecture. This mode allows operators to efficiently configure the functional modules and carry out the specific functions of the resulting assemblies. For this purpose, the backend of the systems architecture is far more than the functional units that are shown in Fig. 2. The TBA units may involve the functions that can compare and choose the programs voluntarily supplied by different study groups around the world. The functions that can validate and balance the results are derived based on distinct methods, and the functions that make real-time updates of the systems architecture and all procedures need to be run automatically. Overall, the system architecture can be effectively improved in order to support the operation of the proposed TLS network and achieve the goals of this study.

2.2. RS models

Transforming the designed system architecture of the proposed international network to an operable system is met with the complexity and challenges of TLS scanning trees in various scenarios. As illustrated in Fig. 3, the representations of the targets in the TLS-collected point cloud of an object tree (red-colored) and its local growth environment (blue-colored) are incomplete, due to the phenomena of laser beam occlusions [59]. To solve such issues, the representative RS models support the major aspects in the 3D ecological understanding of individual trees. They are overviewed to guide the adoption of the appropriate trees needed for deepening the ground stakes of the proposed international TLS network.

The schematic diagrams of the RS models are listed in Fig. 4. As shown in Fig. 4a, the geometrical representation model for deriving the biophysical feature parameters of stems and branches, such as the cylinder-based geometrical model for deriving the diameter at the breast height (DBH) and the content of the biomass [60]. Such geometrical models also comprise circles, cones, and truncated cones. Fig. 4b presents the point cloud voxelization model for estimating the biophysical feature parameters of tree crowns, such as the voxel size model for estimating the tree leaf area index (LAI) and crown volume [61]. The settings of voxelization sizes can vary with the specific derivations of different feature parameter scenarios. Fig. 4c shows the convex hull model for characterizing the physiological feature parameters of trees, such as the triangle net-represented convex hull model used to predict their photosynthesis

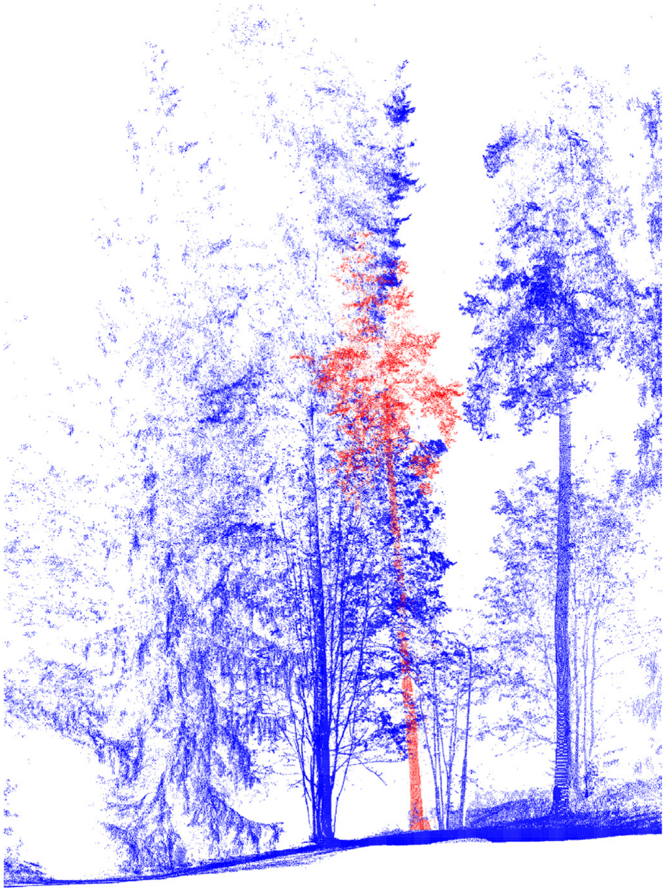

Fig. 3. Illustration of the TLS-collected point cloud of an individual tree (red-colored) and its local growth environment (blue-colored) as its niche reconstruction. The aggregation of which the proposed international TLS network can support the 3D ecological understanding of global trees.

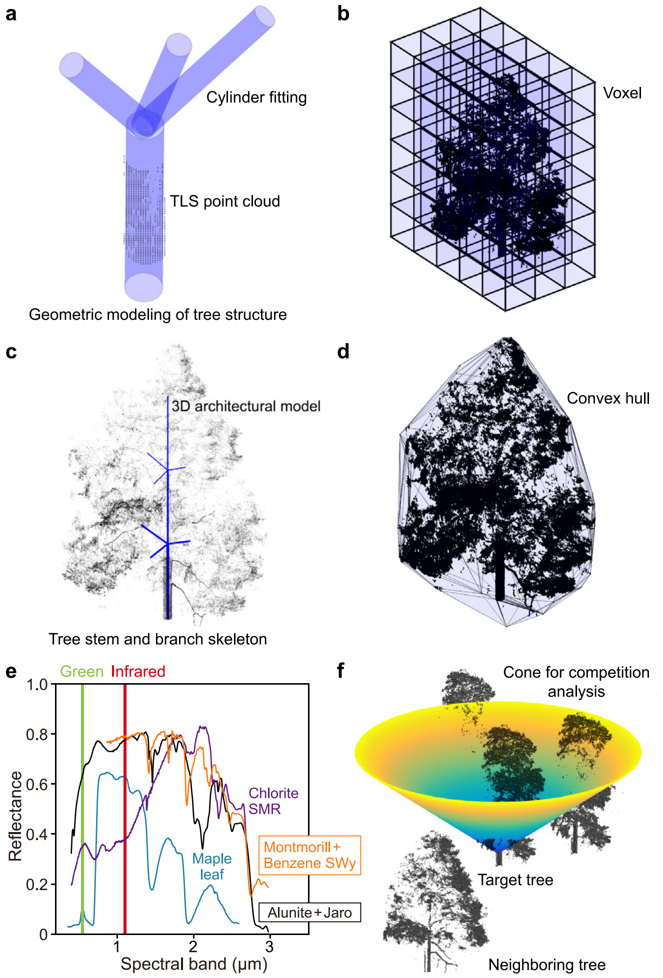

Fig. 4. Schematic diagram of the TLS-based RS models commonly used to enhance the 3D ecological understanding of individual trees: **a**, the geometrical representation model for deriving the biophysical feature parameters of stems and branches such as DBH and biomass [60]; **b**, the point cloud voxelization model for estimating the biophysical feature parameters of tree canopies such as LAI and crown volume [61]; **c**, the convex hull model for predicting the biophysiological feature parameters of trees such as photosynthesis and respiration capacity [62]; **d**, the plant architecture model for characterizing the growth structural feature parameters of trees such as branching habits [40]; **e**, the spectral signature model for retrieving the biochemical feature parameters of trees such as nitrogen and water content [63]; **f**, the cone space searching model for disclosing the interactive ecological effects between the target and its neighboring trees as well as between the target tree and its local environment such as competition and facilitation [64].

and respiration capacities [62]. Fig. 4d illustrates the plant architecture model used to estimate the growth structural feature parameters of trees, such as the Hallé architecture model for deriving branching habits [40]. Fig. 4e lists the spectral signature model used to retrieve the biochemical feature parameters of trees, such as the standard spectral data in published libraries for the quantity retrieval of nitrogen and water content [63]. Fig. 4f displays the bottom-up cone space searching model used to expose the interactive ecological effects between the target and its neighboring trees and between the target tree and its local environment, such as the competition effect between trees [64]. As for the facilitation effect between trees, the bottom-down cone space searching model works. Our proposed international TLS network will develop a more powerful capacity using all of the proposed models.

3. Scheme verification

3.1. Theoretical feasibility

The proposed ecotechnology can be validated first through theoretical feasibility. In addition to the worldwide availability of various commercial TLS systems and their common applications in forest inventory [57], theoretical feasibility can realize the comparison of the performance of TLS, airborne laser scanning (ALS), and satellite-based laser scanning (SLS), in terms of the principal functional indices such as sampling density and spatial coverage [65]. As illustrated in Fig. 5, the typical 3D local tree structural ecology (TSE) branch studies the 3D structural ecology of local-area trees at a tree level. Neither ALS nor SLS can measure trees' fine structure and, therefore, is unavailable to support the local 3D TSE. Instead, they are primarily available to support 3D regional tree community structural ecology (TCSE), which investigates the 3D structural ecology of regional trees at the community level [56]. The 3D global forest canopy structural ecology (FCSE) focuses on the 3D structural ecology of global trees at the canopy level. Moreover, state-of-the-art SLS systems such as NASA's Global Ecosystem Dynamics Investigation (GEDI) [41] are still theoretically available for 3D global TCSE. However, TLS and its regional and global networks are available for 3D local, 3D regional, and 3D global TSE. TLS can also be applied over long time intervals. The proposed network will be a kernel cornerstone of 3D training data collection in assisting satellite RS in achieving “satellite-based 3D mapping of every tree on Earth” [53]. This comparison reveals that the proposed international TLS network is unavailable for 3D mapping every individual tree across the globe; however, it can produce a reasonable solution plan in order to get closer to the goal of the 3D ecological understanding of global trees.

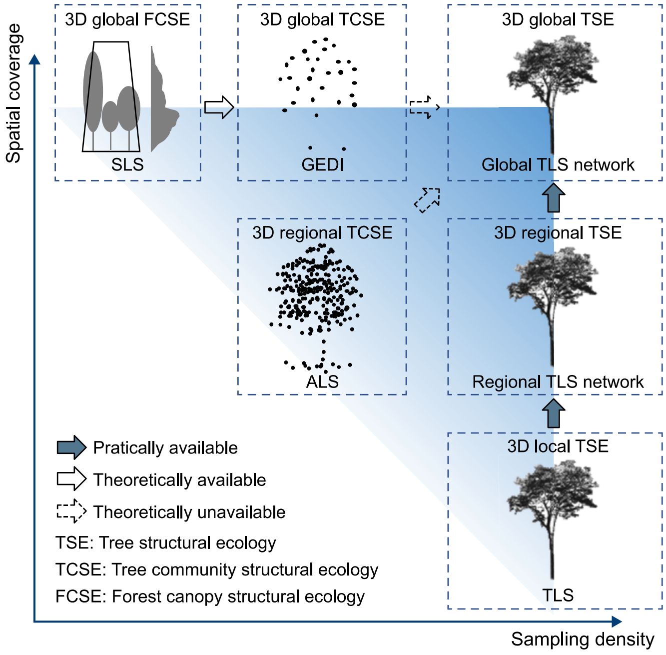

Fig. 5. Schematic diagram that clarifies the co-development potential of an international TLS network on the 3D ecological understanding of global trees, via conducting a comparison of the functions of TLS, ALS, and SLS on the goal task in terms of the representative sampling density and spatial coverage performance indices.

3.2. Technical preparations

The ecotechnology proposal is also rooted in existing technical preparations, which can be absorbed into the program of co-developing the related international TLS network needed to accomplish the task. Such technical preparations cover all aspects of TLS tree structure mapping, as listed in Table 1. Specifically, numerous TLS-based methods have been developed to produce a massive variety of tree structural feature parameters, such as tree height [66], tree volume [69], stem position [67], DBH [60], stem diameter [72], stem volume [73], stem taper [74], branching structure [76], branching angle [77], branch bending [78], branch volume [79], leaf angle distribution [80], effective leaf area [81], leaf area density [82], LAI [83], crown width [84], crown base height [85], crown projection area [86], crown volume [61], plant area index [87], plant area density [88], plant extinction coefficient [89], crown gap size [90], crown gap fraction [91], directional crown gap fraction [92], canopy cover [71], canopy gap fraction [93], and canopy clumping index [94]. The derived tree structural feature parameters can retrieve other tree attributes such as woody materials [70] and aboveground biomass [68,75]. The related methods can be adapted or even directly assimilated to fundamentally back up the functional realization of the proposed international TLS network.

3.3. Case testification

The feasibility of developing the proposed TLS network can be case tested in practice. Based on the experiments and results in Ref. [68], we took the related mapping scenarios and built a simple international TLS network prototype, and derived the performance diversity on the aboveground biomass estimations for large tropical trees at three distant study sites (Peru, Indonesia, and Guyana), as shown in Fig. 6. Moreover, a global-sense comparison is almost impossible based on the traditional forest inventory approaches. Additionally, both the surmisable advantages as previewed above and our case comparison pointed out the technical potentials of the proposed international TLS network. The technical potentials may generate new schemes for the 3D understanding of global trees and may further reveal relevant and new scientific knowledge.

Collectively, co-developing an international TLS network for the 3D understanding of global trees is theoretically viable. First, designing a TLS network can abide by the practices of selecting and setting forest plots in previous studies on global trees [49,50]. Second, its data processing can assimilate the TLS-based algorithms already validated for deriving various tree information, including tree species classification [55] to aboveground biomass retrieval [75]. Third, the collected data and derived results can be fused with the mature global databases of both plant traits and their environmental information records [95]. For example, a variety of tree structural feature parameters, beyond the often-used tree height, can better predict tree mortality risks during droughts [48], guiding extending the applicability of the existing solutions of 3D tree

Table 1
Exemplification of the categorical richness of feature parameters that are effectively derived from the TLS data within previous studies used to characterize the different aspects of the tree structure. This suggests the strong potential of TLS that can cause a radical change in the basic scheme of 3D tree structure mapping at a fine scale.

Feature parameter	Feature type	Tree species or forest types	Reference
Tree height	Tree	Broadleaves (*Quercus robur*)	[66]
Position	Tree	Scots pine (*Pinus sylvestris*); Norway spruce (*Picea abies*); Birch (*Betula* spp.)	[67]
Aboveground biomass	Tree	Tropical forest with multiple species	[68]
Volume	Tree	Rosea (*Eucalyptus leucoxylon*); Mallee (*Eucalyptus macrocarpa*); Ironbark gum (Eucalyptus tricarpa)	[69]
Woody material	Tree	Douglas fir (*Pseudotsuga menziesii*); Western hemlock (*Tsuga heterophylla*)	[70]
Canopy cover	Tree	Field sites with oak trees and shrubs, Luton, UK	[71]
Diameter at breast height (DBH)	Stem	Coniferous forest; Deciduous forest	[60]
Stem diameter	Stem	Beech (*Fagus sylvatica* L.); Douglas fir (*Pseudotsuga menziesii*)	[72]
Stem volume	Stem	Scots pine (*Pinus sylvestris* L.); Norway spruce (*Picea abies* L.); Birch (*Betula* L. spp.)	[73]
Stem taper	Stem	Scots pine (*Pinus sylvestris* L.); Norway spruce (*Picea abies* L.)	[74]
Biomass	Stem branch	Scots pine (*Pinus sylvestris* L.); Norway spruce (*Picea abies* L.)	[75]
Branching structure	Branch	Douglas fir (*Pseudotsuga menziesii*); Western red cedar (*Thuja plicata*); Western hemlock (*Tsuga heterophylla*)	[76]
Branch angle	Branch	Norway spruces (*Picea abies L. Karst.*); European beech (*Fagus sylvatica* L.)	[77]
Branch bending	Branch	Black locust (*Robinia pseudoacacia* L.); Small-leaved lime (*Tilia cordata Mill.*)	[78]
Branch volume	Branch	Wild cherry (*Prunus avium*); Sycamore maple (*Acer pseudoplatanus*); English oak (*Quercus robur*); European ash (*Fraxinus excelsior*)	[79]
Leaf angle distribution	Leaf	Pine (*Pinus elliotti* var. *densa*)	[80]
Effective leaf area	Leaf	Douglas fir (*Pseudotsuga menziesii*)	[81]
Leaf area density	Leaf	Apple tree (*Malus communis* L. 'Red Chief' and 'Golden'); Pear tree (*Pyrus communis* L. 'Conference' and 'Blanquilla'); Vine (*Vitis vinifera* L. 'Cabernet Sauvignon' and 'Merlot')	[82]
Leaf area index (LAI)	Leaf	Shea tree (*Vitellaria paradoxa*)	[83]
Crown width	Crown	Loblolly pine (*Pinus taeda, L.*);	[84]
Crown base height	Crown	Red Pine (*Pinus densiflora*); Korean Pine (*Pinus koraiensis);* Japanese Larch (*Larix leptolepis*); Oak (*Quercus* spp.)	[85]
Crown projection area	Crown	Oliver (*Erythrophleum fordii*); Pine (*Pinus massoniana*)	[86]
Crown volume	Crown	Olive (*Olea europaea* L.)	[61]
Plant area index	Crown	European lime (*Tilia cordata*)	[87]
Plant area density	Crown	Japanese larch (*Larix kaempferi Sarg.*)	[88]
Extinction coefficient	Crown	Masson pine (*Pinus Massoniana Lamb.*)	[89]
Gap size	Crown	Holm oak (*Quercus ilex, L.*)	[90]
Gap fraction	Crown	Cork oak (*Quercus suber* L.)	[91]
Directional gap fraction	Crown	Mountain pine (*Pinus mugo*); Stone pine (*Pinus cembra*)	[92]
Canopy gap fraction	Crown	Birch (*Betula* spp.)	[93]
Clumping index	Crown	Magnolia Lily tree (*Magnolia denudata*)	[94]

structural ecology [48,52] to global trees and their subsequent changes. Finally, the 3D ecological understanding of global trees can approach a more “practically available” goal and allows for the comprehensive structural analyses using the TLS network-collected data that was used as the ground-truth sample for training, Furthermore, the proposed TLS network can help fundamentally fulfill the 3D ecological understanding of global trees applying large-cover RS data [53] that was used as the up-scaling media.

4. Functional prospects

The demand for the 3D ecological understanding of global trees is why we decided to construct the proposed international TLS network; however, the thematic design cannot reveal all of its potentials. Moreover, to inspire more scientists to put more effort into expanding its application range, our discussions as follows focus on briefly decoding the theoretically latent capacities of the international TLS network from the technical, scientific, and individually functional-extending perspectives.

4.1. Technical potential

The proposed international TLS network can provide a common platform for researchers to readily participate in the relevant global

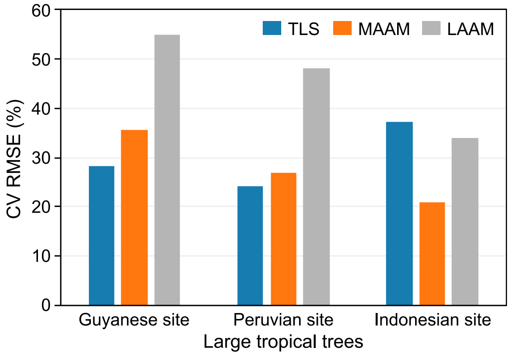

Fig. 6. Boxplot of the accuracies (in terms of the coefficient of variation of the root mean square error, labelled as CV RMSE) of the aboveground biomass estimations based on the TLS-based approach (as TLS) and pantropical allometric models (most accurate allometric model, as MAAM, and least accurate allometric model, as LAAM) for the large tropical trees at three distant study sites (Peru, Indonesia, and Guyana) [68]. The integration of the TLS systems at the three sites used as a simple international TLS network can preliminarily validate our proposed solution plan for 3D mapping and the ecological understanding of global trees.

studies that, traditionally, are challenging by uploading their data collections, downloading their global datasets, and sharing their findings. Specifically, the network can provide the data for reconstructing the growth scenes of global trees, enabling researchers to feel that they are actually standing amongst the trees. The network-recorded plots can serve as the ground-truth data for large-area RS training and testing of the related forests, facilitating the examination of global trees more thoroughly. Next, the network can help enhance method coordination, with the newly developed methods validated based on its collected common data. Finally, the network can support the cross-checking of the derivations from different research groups that focus on the same topics and is core for eliminating the false ecological inferences involving global trees.

4.2. Scientific potential

The scientific potential of the proposed international TLS network bringing's about revolutionary views on global trees in view of 3D structural ecology. The first interest in studying global trees is their differences under diverse growing conditions and what causes these differences. The data accumulation of the proposed TLS network can support the 3D reexamining of the structural ecological secrets of global trees, such as whether the global importance of large-diameter trees [33], how tree structure-climate interactions [52] operate across the globe, and whether the biodiversity situations of trees growing in different environments [49,51] is consistent with their structural diversities. Analyses of the data collected by the TLS network can reshape the methodological frameworks into the 3D resolution of global trees' ecological modes, such as the global patterns of microclimate ecology [96] of trees globally. Furthermore, the proposed TLS network can potentially upgrade the 3D studies on the long-stressed global tree structure-relevant ecological topics such as global carbon cycles [3] and global biodiversity conservation [51]. Additionally, with the already validated contributions to the TLS-based tree structural ecology (Table 2), the proposed TLS network can project a totally new field of 3D global tree structural ecology. The ecological potentials of the proposed international TLS network will keep expanding along with its future development and applications, far beyond the cases reviewed in this study.

The proposed TLS network can support the extension of the explorations on global trees from their 3D structural ecology to their 3D structural science. This brings new 3D insights into the global importance of large-diameter trees [33], outside the ecological range. The perspective changes to biological or even life sciences further shed light on the secrets of how tree structure is determined by resource allocation [110], with underlying metabolic mechanisms revealed. However, the applicability of the proposed TLS network can be extended beyond global trees to other kinds of global plants. This extension is of great significance for the 3D understanding of global vegetation [95], including comprehensively keeping track of the Earth's carbon cycle components [3] and the Earth in a 3D sense. The scientific potentials of the proposed TLS network will keep expanding along with its future development and applications that are far beyond the scope of this study, as reviewed in this work. Overall, the ecotechnology of internationally co-developing a global TLS network is of fundamental importance for the basic advancement and promotion of the 3D ecological understanding of global trees to create new fields of 3D global tree structural ecology.

4.3. Functional extensibility

The potential of the proposed international TLS network can be functionally extended, regarding its diversified RS manners, through the introduction of various kinds of 3D mapping technologies. As illustrated in Fig. 7, drone-based and backpack laser scanning can help resolve the coverage inefficiencies as well as the TLS perspective singularity used for 3D forest plot mapping. The other modes of 3D mapping technologies, such as the structures obtained from the motion approach in close-range photogrammetry [113] can collect the structural-heterogenous attributes of trees. Furthermore, the representative larger-cover RS technologies, such as airborne light detection and ranging (LiDAR) [114] and satellite imaging [115] listed in Table 3, can elevate the traditional plot-based 3D ecological understanding of global trees into an up-to-date stand-based 3D ecological understanding of global trees, that helps arrive to the real sense 3D ecological understanding of global trees.

Combining the data collected by the proposed TLS network with airborne LiDAR point clouds or satellite imagery is complicated; however, such fusions of heterogeneous data can help to figure out the 3D biophysical, biochemical, biophysiological, and ecological characteristics of global trees, as revealed by the cases in Table 3. The principle in the related fusions of the heterogeneous datasets is illustrated in Fig. 7, with the scale-related gap identified. The proposed international TLS network can serve as the tree crown-scale interlink for filling this long-standing gap between the commonly-operated leaf-scale and canopy-scale tree structural retrievals based on the RS models such as PRecision Oscillation and SPECTrum experiment (PROSPECT) [111] and Forest LIGHT interaction (FLIGHT) [112], respectively. Applications of such RS models can further increase the 3D ecological understanding of global trees.

Overall, the 3D global tree structural ecology potentially derived from the proposed TLS network can fundamentally support the range upgrade of fields such as forestry, biodiversity, botany, geomorphology, geophysics, urban science, and environmental science. Additionally, with the heterogenous RS measures and the enhanced RS modeling strategies, such 3D global-oriented functional extensions may create breakthroughs within these fields. This can predict the corresponding disciplines that may transition from the conventional modes to 3D global stages, including 3D global forestry to 3D global plant structural science.

5. Challenges

The following task of realizing the conceived international TLS network systems architecture is challenging. The challenges of the

Table 2
Exemplification of the potential of TLS on advancing 3D tree structural ecology, based on its already-boosted applications that examines a range of subjects involving tree structures. The integration of such structural feature parameters can fully characterize the entire 3D forms of trees and the ecological causes and influences of their reproduction and evolution, respectively.

Structural ecological effect	TLS-derived feature parameter	Tree species or forest types	Reference
Metabolic scaling	Branch radius scaling ratio; Branch length scaling ratio; Architecture-based metabolic scaling rate	*Eperua grandiflora*; *Ormosia coutinhoi*; *Eperua falcata*	[62]
Life history strategies	Tree height; DBH; Height of the lowest foliage; Crown width of its long side; the short side of the crown width	*Cyclobalanopsis multinervis*; *Rhododendron stamineum*; *Fagus lucida*; *Cyclobalanopsis gracilis*; *Sassafras tzumu*	[97]
Wind resistance	Fundamental frequency; Critical wind speed	*Fraxinus excelsior*; *Acer pseudoplatanus*; *Betula* spp., *Quercus* spp.	[98]
Forest regeneration	Tree height; Diameter at breast height (DBH)	*Picea abies* L. *H. Karst*; *Abies alba Mill.*; *Pinus sylvestris*; *Larix decidua Mill.*	[99]
Fire-induced change to vegetation physiognomy and biomass	Tree height; Canopy cover; Aboveground carbon storage	*Colophospermum mopane*; *Acacia nigrescens*; *Sclerocarya bierra*; *Dichrostachys cinerra*; *Terminalia sericea*	[100]
Forest structural diversity	Plant Area Volume Density (PAVD); Canopy height; Canopy gap; Canopy openness	Coffee forest; Silvopasture	[101]
Long-term abandonment of forest management strongly impacting tree morphology and wood volume allocation pattern	Diameter at breast height; Tree height; Total wood volume; Total branch number; Height-to-diameter ratio; Merchantable wood volume; Volume of fine woody material; Crown base height; Crown volume; Crown projection area; Crown surface area; Crown ratio; Crown length; Crown openness; Taper; Taper top height; Volume of branch-free trunk; Mean branch length sum; Mean maximum branch order; Mean branch number 1st order; Mean branch number 2nd order; Branch volume 1st order; Branch volume 2nd order; Branch length 1st order; Branch length 2nd order; Crown length-width ratio; Crown roughness	*Fagus sylvatica* L.	[102]
Branch architecture	Branch length; Branch diameter; Branch order; Tree volume	*Eperua grandiflora*; *Ormosia coutinhoi*; *Eperua falcata*	[103]
Diversity of vegetation elements	Apparent reflectance; Normalized difference index value (NDI); Dimensionality metrics at multiple scales	Temperate mixed forest; Eucalyptus; Urban forest plantation; Agriculture	[104]
Stem growth mode	Stem volume at an annual resolution	*Picea abies*; *Abies alba*	[105]
Below-canopy bat trait relationships with forest structure	Vegetation density (Stem density; Mean maximum density; Max maximum density; Mean height of maximum density; Max height of maximum density;	*Austronomus australis*; *Saccolaimus flaviventris*; *Mormopterus ridei*; *Mormopterus planiceps*; *Mormopterus* spp.; *Chalinolobus gouldii*;	[106]

Table 2 (*continued*)

Structural ecological effect	TLS-derived feature parameter	Tree species or forest types	Reference
	Lower-storey density) Canopy cover (Cover 1–2.5 m; Cover 2.5–10 m; Cover 10–20 m; Cover 20–30 m; Cover above 30 m; Cover 1 m to the max height; Maximum height) Vegetation height (Maximum height; Mean height) Vegetation gap space (Total gap volume; Maximum gap volume) Structural variability (Density variability; Variability in the height of maximum density; Height variability)	*Scotorepens balstoni*; *Scotorepens greyii*; *Vespadelus darlingtoni*; *Vespadelus vulturnus*; *Chalinolobus morio*; *Vespadelus regulus*; *Nyctophilus geoffroyi*; *Nyctophilus gouldi*; *Nyctophilus* spp.	
Directional growth space occupation	DBH; Height; Mean crown projection area derived from two-dimensional; Relative height within crown with maximum projection area; Crown diameter; Biomass	*Picea abies* [*L.*] *Karst.*; *Fagus sylvatica* L.	[78]
3D distribution of water content in leaves	Backscatter intensity	*Tolmiea menziesii*; *Hydrangea arborescens*; *Rhododendron* sp.; *Codiaeum variegatum*; *Photinia fraseri*; *Schefflera arboricola*; *Ficus benjamina*; *Zamioculcas zamiifolia*	[63]
Tree geometry and allometry	Basal area (cross-sectional area at breast height); Girth at 1.3 m; Diameter above buttress (DAB); Height of DAB measurement; Buttress volume; Buttress form factor	*Koompassia excelsa Fabaceae*; *Ficus robusta Moraceae*; *Celtis rigescens Cannabaceae*; *Ficus albipila Moraceae*; *Shorea leprosula Dipterocarpaceae*; *Sterculia urceolata Sterculiaceae*; *Sterculia urceolata Sterculiaceae*; *Sterculia foetida Sterculiaceae*; *Ceiba pentandra Bombacaceae*; *Bombax ceiba Bombacaceae*; *Bombax valetonii Bombacaceae*; *Bombax valetonii*	[107]
Canopy morphology and leaf angle distribution	Foliage profile; LAI; Leaf Angle Distribution (LAD)	*Pinus elliotti* var. *densa*; *Bursera sim-aruba*; *Celtis laevigata*; *Coccoloba div-ersifolia*; *Eugenia axi-llaris*; *Taxodium* spp.; *Rhizophora mangle*; *Avicennia germinans*	[80]
Forest spring phenology	Vertical plant profiles	*Quercus* spp.; *Betula* spp.; *Sambucus nigra*; *Sorbus aucuparia*; *Prunus* spp.; *Amelanchier* spp.; *Ilex aquifolium.*	[93]
Tree root system growth mode	Root system volume;	*Picea abies* L.	[108]

(*continued on next page*)

Table 2 (*continued*)

Structural ecological effect	TLS-derived feature parameter	Tree species or forest types	Reference
	Stump diameter; Root breakpoint diameter; Linear root length; Cumulative percentage; Root fraction counts		
Leaf area distribution	Leaf area in an individual tree; LAD profile; Tree LAI;	*Vitellaria paradoxa*	[83]
Solar-induced chlorophyll fluorescence	Multi-scale clumping at branch and canopy level	*Betula* L. spp.; *Picea abies* L.	[109]

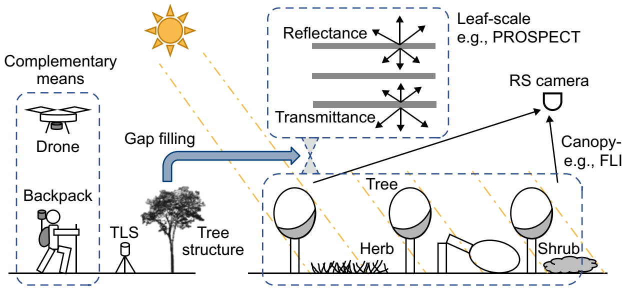

Fig. 7. Schematic diagram reflecting the potential of the proposed international TLS network on expanding the coverages of the traditional RS modes used in the 3D characterization of global trees that serves as the tree crown-scale interlink for filling the long-standing technical gap between the leaf-scale and the forest canopy-scale tree structure information retrievals via the RS PROSPECT [111] and FLIGHT [112] models, respectively.

system involve different technical and scientific issues; however, if the challenges can be resolved, it can advance the field more rapidly.

5.1. Technical challenges

During the development of the proposed international TLS network, various technical issues emerged during the process of realizing its functional modules, with each being composed of specific functional units (Fig. 2). Along with the crafting and coordinating of such functional units from their initial design the representative technical challenges can be pre-determined as follows.

For the first functional access interface module, its technical implementation involves data upload to quality control, intending to support the following steps in order to make consistent global derivations. This goal, however, also means higher requirements in realizing the system's concrete functions. Uploading TLS data may result in the common problem of data inconsistency, often caused by different laser scanning modes or discrepant ranging principles. In the case of mobile laser scanning, the data needs to be converted into the same format as the TLS data [125]. Next, a representative challenge is isolating the trees from the point clouds at high speeds and on sufficient scales. This process may result in the issues of making accurate registration of the individual TLS point clouds rapidly and automatically, creating issues in automating the extraction and processing of individual trees from such large point clouds [126]. Increasing interests in these applications drive the rapid development of full automation [127], which has yet to pose a challenge during the first procedure.

For the second functional data preprocessing, the technical operations range from data filtering to formatting. Their integrated function ensures the stable derivation of various tree structure feature parameters during the next step. The background processing, which is typically invisible to users, must handle many issues in unifying the multifarious uploaded datasets. For example, in the case of tree organ recognition functional units, extracting its high-order branching is typical in the canopy occlusion effect during laser scanning, with point density becoming lower in the tree canopy [59]. Furthermore, the divergence of a laser beam leads to a larger pulse footprint with an increasing range. This effectively restricts the characterization and details of the branch tips and leaves [128]. These adverse factors mean smaller objects on the top of the crown cannot be resolved. This directly affects the way reconstruction methods follow the tree's branching structure;

Table 3
Exemplification of the previous endeavors on expanding the functional coverage of TLS via combining various airborne and satellite-based RS solutions for the 3D ecological understanding of trees on regional and global scales. This suggests that the potential of TLS can elucidate the thrives of 3D global tree structural ecology and 3D macroecology.

TLS parameter	Global-oriented cover expansion data type	Reference
Position	QuickBird satellite imagery;	[114]
Tree height	Airborne LiDAR point clouds;	
Health condition	Airborne ProSpectTIR hyperspectral imagery;	
Tree species	IKONOS and WorldView-2 satellite imagery	
Tree cover	Landsat satellite TM & ETM + imagery	[116]
LAI	Landsat satellite TM imagery	[117]
Biomass	ALOS satellite PALSAR L-band SAR data	[118]
Biomass/carbon	Airborne LiteMapper 5600 waveform-digitizing LiDAR data	[119]
Stem volume	ALOS-2 satellite PALSAR-2 L-band SAR data & Sentinel-1 satellite L-band SAR data	[120]
Height of tree crown	Airborne RIEGL LMS-Q1560 LiDAR data & WorldView-3 satellite stereo imagery	[121]
Forest structure	Multi-modal data from PlanetScope, Sentinel-2, Landsat-7, Sentinel-1, and ALOS-2 PALSAR-2 satellites	[122]
Fire severity indices	Landsat satellite multi-temporal imagery	[123]
Surface moisture index (SurfMI)	Sentinel-1/-2 and Landsat-8 satellite data with high spatial and temporal resolutions	[124]
Stem structure variable (SSV)	WorldView-2 panchromatic imagery	[36]
LAI	MODIS, CLYCLOPES, GLOBCARBON, and GEOV1 satellite products	[115]

therefore, resulting in the diminished accuracy of the 3D quantitative structure model (QSM) [129], particularly with increasing height.

For the third parameter derivation functional module, the procedures range from structure modeling to parameter retrieving, finally ensuring their performance during accuracy assessment. This module is the core circle of the plotted system architecture, is essential, and guarantees its effectiveness; however, it is challenging. The task of structure modeling and its functional unit is far from mature; however, various QSM algorithms have been developed [129]. The performance of the QSM methods depends on the quality of the aimed point cloud data, and quantifying the uncertainties of the QSM results remains challenging. For instance, the QSM cylinder fitting method may fail for the buttressed trees in tropical forests [54]. In addition, feature modeling and algorithm development are generally the primary problems in the general RS domain. These tasks have not been implemented in this research direction.

For the fourth scientific analysis functional module, the related technical tasks are the supporting cornerstones and are more intricate due to the diversity of scientific explorations. As illustrated in Fig. 2, future studies comprising tree architecture to tree regeneration may generate many technical challenges. Branching architecture is an area where TLS has the potential to make new contributions [56]; however, the recognition of branches, from major ones to tiny tips accurately, is still an unanswered research question. Such bottlenecks will happen when exploring scientific research on tree mechanics, metabolism, respiration, and seed dispersal, all having far-reaching significance.

5.2. Scientific challenges

Even if the proposed TLS network can supply accurate and precise global tree feature parameters, its data collection is far from fully supporting the scientific explorations of the causes and processes that have left various ecological imprints on their appearances [56]. For such unclear scientific subjects (as illustrated in Fig. 2) involving the structures of global trees, mastering their disciplinary contexts and conducting frontier analyses are necessary for working through the proposed international TLS network-collected datasets in order to realize their 3D scientific understanding.

Within the scientific analysis functional module, the first functional unit must focus on tree-branching architecture. Its 3D TLS characterization is the foundation that supports subsequent tree structure-related scientific explorations. It has the potential to reflect a different situation that diverges from the results of traditional mapping technologies [54]. This means that new-generation methods and theories must be discovered to explain the discoveries [130]. For instance, trees often present asymmetric branching modes and in theory non-optimal external branching networks [131]. Tree branching angles tend to show little correlation with path fraction or conservatism within species and appear as an independent feature parameter used to describe tree architecture. The proposed TLS network means more diverse branching architectures of single trees can be observed. Decoding these architectures from the trunks to the branch tips robustly and quantitatively needs to be studied in the near future. Architecture forms that cause such features as light capture maximization and shading of competitors by maximizing vertical heights, crown areas, and spatial arrangements between crowns [132] also needs to be further explored.

The second functional unit can be regarded as tree biomechanics and maintains the biomechanical safety that is a core factor for controlling the architecture; thus, limiting the height and growth of stocks [133] of global trees. Another key factor impacting a tree's architecture is wind damage. Many empirical and mechanistic modeling methods have been designed to characterize wind damage interactions [134]. However, whether the existing methods work for different tree species, especially for broadleaf trees, remains a topic of debate. Given that trees with large first-order branches have multiplex significant sway modes [135], a more detailed understanding and description of their architectures is required to reveal their complex dynamic response to wind forces. Additionally, how trees dissipate wind energy [136] through their 3D structures needs to be further explored. Collectively, such research on global trees and their local growth environments promise new biomechanistic insights into the underlying issues of tree structural ecology; however, the corresponding TLS-based studies will not be easy.

The third unit considers tree metabolism. Tree architecture also depends on the inner determinants of metabolism and metabolic scaling being decided by potential resource uptake and availability [137]. Specifically, resources, such as light and nutrients, are the driving forces of branching in the form of light competition within the canopy [138]. Thus, the principle of maximizing the efficiency of resource distribution to and between the centers of metabolic activity can be adopted in the TLS-based studies of the tree structure. However, identifying the theoretical guidance does not mean that the specific studies are simple. The reason is that the inherent link between a tree's architecture and metabolism has been relatively unclear so far, compared to the first two functional units, meaning numerous challenges in handling the related heterogeneous data processing.

The fourth unit concentrates on tree respiration. The metabolism process of a tree is accompanied by respiration; thus, a tree's respiration is a key factor that interacts with its branching form. Specifically, more than half of the carbon assimilated by photosynthesis in trees is used for autotrophic respiration and is unavailable for biomass production [139]. The variation in the autotrophic respiration of trees is important in deciding an ecosystem's carbon balance [140] and canopy structure. A series of physiological assumptions have been adopted to characterize the scaling modes; however, a central source of uncertainty lies in the accurate assessment of the canopy surface area of a tree. This is where TLS can re-test the existing allometric assumptions and provide new insights. Additionally, there are challenges in measuring the respiration of all tree organs that arise from the restriction of TLS in mapping the complex tree branching structures.

The fifth aspect investigates tree reproduction. Apart from collecting resources and competition for the light needed to maintain metabolism and respiration, a critical functional role of a tree's architecture is seed dispersal and reproduction. For seed dispersal, tree architecture is vital for optimizing the operation strategies, e.g., good tree architecture exposes seeds to the wind using branches that extend far from the main tree stems [141]. However, as indicated by Ref. [56]; few studies have shown the relationships between tree forms and seed dispersal. Furthermore, this is area needs to be further explored with the new availability of TLS data; however, will be met with many challenges.

Given that the diversity of scientific explorations is limitless, the fourth supporting system module (Fig. 2) needs to be more open in future developments as well as the applications of its functional units, e.g., open and rapid absorption of the programs focused on solving the novel scientific analyses from different research groups. Furthermore, enriching the TBA functional units may be able to fully reconstruct a series of technical workflows, giving rise to new series of technical challenges. Such reasonable prospects of the potential technical and scientific issues, can enlighten new directions in order to effectively develop the proposed international TLS network.

6. Summary

The ecotechnological plan of co-developing an international TLS network is vital in solving the long bottleneck that has been created during the mapping of the individual; therefore, creating a revolution in the 3D ecological understanding of global trees. We devised the TLS network system architecture and verified its validity using the confirmation of its theoretical feasibility, our review of its technical preparations, and our case testification of its practicability. While its development may meet numerous scientific and technical challenges, its establishment will be implicative. Furthermore, once the system has been established, it will support the 3D ecological understanding of global trees and facilitate scientists to reexamine the existing theories regarding why trees show the forms and how trees show their form changes; thus, further developing new theories in a more general sense [142]. This innovation can upgrade the related fields regarding tree structural, metabolic, respiration, biomechanical, and evolutionary sciences, and their reconstructions. Furthermore, the contributions can promote the ecological understanding of global ecosystems [127], which are now of significant importance in macroecology [32], and the advanced 3D mode. Overall, this proposed macroscale ecotechnology co-developed as an international TLS network at the level of planning theoretical frameworks beyond the level of developing concrete algorithms has the potential to produce massive algorithm developments that can create many new fields of scientific research from 3D global tree structural ecology to 3D macroecology.

CRediT authorship contribution statement

Lin Yi: Conceptualization, Methodology, Writing - Original draft preparation. **Sagi Filin:** Conceptualization, Writing - Reviewing and Editing. **Roland Billen:** Writing - Reviewing and Editing. **Nobuya Mizoue:** Writing - Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this work.

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