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REMOTE SENSING (J SUAREZ, SECTION EDITOR)

Trends and Developments in the Realm of Virtual Forest Visualization

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Abstract

Purpose of the Review We aim to present virtual forest visualization in an accessible manner to help a broad audience understand this concept along with spatial data integration to create digital environments that closely replicate real-world forests. Such efforts are motivated by a multitude of reasons, from creating a virtual science laboratory to guiding real-world applications. The digital reconstruction of forests is an evolving field in forestry, with close connections to computer science and data science. The key considerations in visualization are also explained in detail which are crucial part of visualization like Input and output data along with challenges and constraints.
Findings Recent advancements in digital sensing technologies have improved forest visualizations considerably. Data from techniques such as LiDAR and photogrammetry, along with other forest information, have facilitated the creation of highly detailed and accurate virtual forest models. These technologies not only capture the geometric structure of forests, but also enable the interactive exploration of different layers, from the canopy to the forest floor. The integration of these methods with Geographic Information Systems (GIS) and various user interfaces has further enhanced the spatial accuracy and contextual relevance of virtual forests. A major breakthrough in forest visualization is the incorporation of Extended Reality (XR) technologies, including Augmented (AR), Virtual (VR), and Mixed Reality (MR). These tools enable users to experience forest environments in a fully immersive way, without the need for physical presence. Given that some forests are prohibitively difficult to reach and navigate, and that some experiences can be greatly enriched by overlaying virtual elements onto the real world, XR experiences offer a valuable alternative to traditional data visualization approaches. Additionally, we also present four case studies to showcase the applications of visualization in the European forest context which can be applicable in the global context.
Summary We examine key trends, developments, and challenges according to the global research in the use of 2D and 3D visualization for virtual forest experiences and present selected case studies. We describe the potential of virtual forest visualization for applications in forest management, conservation, education, and research. We also present an opportunity to utilize and develop further the scope of visualization using these latest technologies in forestry globally.

Keywords Augmented reality · Computer graphics · Mixed reality · 3D modeling, virtual reality

Introduction

Forests cover approximately 30% of the global land area [1]. They support biodiversity while also providing multiple essential ecosystem services, including provisioning (e.g., timber, protection), regulating (e.g., carbon storage), supporting (e.g., nutrient cycles), and cultural (e.g., recreation) services [2]. The ability of forests to fix carbon from the atmosphere [3] means that they are a key component of the global carbon cycle. However, biodiversity and forests' capacity to provide ecosystem services is limited, due to high rates of deforestation and forest degradation [4, 5], increases in the occurrence of disturbances [6–9], and other climate-change-induced impacts, such as more frequent and intensive droughts [10, 11]. The related environmental and socio-economic consequences are immense [12, 13],

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Extended author information available on the last page of the article creating uncertainties for forest owners by complicating risk assessments and forest planning [14]. Recent policies, such as the EU Green Deal [15], recognize the role of forest functions and give a strong impulse to incentivize the provision of multiple ecosystem services [16]. Management methods that differ from traditional rotational ones are being implemented [17], and new approaches are being developed further [9, 18–20]. The aim of these approaches is to reduce the risk of climate change impacts by enhancing the adaptive capacity of forests [18], by fostering diversity of tree species and structures [21, 22].

Even though the adaption of forests to climate change has started, there are challenges in its implementation [18], which can be explained by the rapid speed at which climate change is occurring. In this context, forest visualization may prove beneficial. It facilitates a deep and interactive understanding of forest functioning, biodiversity, and the relationships among plant and animal species, even without physical presence in the forest. Through virtual representations, humans can gain a clear comprehension of complex ecological processes and forest dynamics [23]. For forest managers and policymakers alike, visualization tools can aid decision-making by offering insights into the potential impacts of various forest management strategies for forest development, biodiversity, and ecosystem services, such as carbon storage. Virtual simulations can be used to predict the outcomes of interventions, such as selective logging versus clear-cutting or reforestation, thereby supporting the development of sustainable forest management practices. Visualization makes it possible to assess simulated trajectories from predictive models that simulate future forest conditions under different scenarios in a much more comprehensive way. These models can anticipate how forests may evolve in response to environmental changes, such as rising temperatures or changing human activities, thereby guiding conservation and restoration efforts.

Visualization has emerged as a powerful tool for experiencing forests virtually as a forest digital model, offering great potential to enhance our understanding of and interaction with forest environments [24]. This approach allows individuals to step into a virtual representation of a forest, providing a unique opportunity to explore these ecosystems in ways that were previously not possible. The capacity to create highly realistic and immersive virtual forests has increased immensely, presenting new opportunities for both scientific research and public engagement. Forest digital twin models are very useful to create simulations like wildfire detection and rate of spread [25]. By offering an interactive experience, these virtual forests provide a deep and intuitive understanding of forest functions, forests' interactions with other ecosystems, and their vital role in sustaining global biodiversity and climate stability. Furthermore, virtual forests have the potential to engage a wider audience, including students, educators, policymakers, and the general public. For those who may lack access to physical forests or the opportunity to study them in-depth, these virtual experiences serve as an educational and immersive tool, fostering greater awareness and appreciation of forest ecosystems. As these technologies continue to evolve, they promise even more dynamic and enriching ways to explore forests, facilitating better-informed decision-making and encouraging collective action towards conservation and sustainability [26].

By creating accessible and engaging experiences, virtual forests have the potential to raise awareness about critical environmental issues affecting forests, such as deforestation, climate change, and biodiversity loss [27, 28]. These virtual environments allow users to immerse themselves in dynamic, interactive simulations that showcase ongoing processes within forests. By visualizing the delicate balance of ecosystems and the impacts of human activities, virtual forests can simplify complex ecological concepts and make them more tangible for a wide audience. These immersive experiences not only foster a deep understanding of the challenges forests face, through first-person experiences virtually, but also offer a powerful platform for conveying the urgency of conservation efforts, as the emotional impact of first-hand experience lasts longer than analytical visualizations [29]. Users can see for themselves, e.g., how deforestation contributes to habitat loss, how climate change alters forest health, and how the decline in biodiversity threatens ecological stability [30].

Virtual forests can be defined at various levels of complexity and detail, i.e., a small part of a tree, the complete tree, groups of trees, or forest stands, including all vegetation and other living beings. At the most fundamental level, visualizing individual tree stems helps us to assess basic structural attributes [31] and the health of an individual tree. In the representation of an individual tree stem, simple data, such as tree height and Diameter at Breast Height (DBH), can provide an initial overview of tree dynamics. By expanding to the stem-level, branch-level, and leaf-level, visualization introduces more detailed information about the complete structure of a tree. Additional canopy parameters, such as size, volume, Leaf Area Index (LAI), Canopy Projection Area (CPA), and biomass can be extracted from the remote sensing data and shown on-demand, in as much detail as requested by the user. Such detailed visualizations are essential for understanding a tree's growth patterns and how it adapts to environmental conditions [32]. From this fundamental visualization of an individual tree, one can expand the level of complexity to simulate entire forest ecosystems according to the user's goals, assuming that the necessary datasets are available.

Besides different levels of detail and complexity, the spatial or non-spatial data visualization of forests can be applied across various spatial scales from small scale [33] to large scale [34]. For example, at the plot scale, detailed representations of individual trees and their immediate surroundings enable localized studies of species interactions, biodiversity, and microhabitats [35]. At the regional scale, a representation can focus on the integration of multiple plots into a cohesive overview of forest structure and dynamics [36]. At the country scale, visualizations aggregate data from diverse regions, offering insights into national forest resources, conservation needs, and policies [37]. The computational demands of forest visualizations are typically so high that dedicated game engines (e.g., Unity) are required for the rendering of the data. Different software and programming languages can be used to bridge the gap between geographic data and game engines to transform the forest landscape into a user-interactive visualization that features higher realism, efficiency, and navigation from the individual tree to forest stand to landscape scale compared with classical visualization techniques [38].

The efficiency of forest resource management can be improved through digital visualizations of the current state of forests. Using various modeling and simulation approaches, characteristic morphological changes of the forest can be analyzed. One goal for digital, interactive forest modeling is to virtually make the results of simulations that predict future forest conditions accessible to end users by integrating predictive forest inventory models with machine learning [39, 40]. To date, however, there has been limited research on virtual forests as a scientific topic, which provides us with an opportunity to explore this domain and understand the current trends in virtual forest technology [41–44].

State of the Art

In this section, we review the current state of the art in Computer Graphics (CG), Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR) and Extended Reality (XR) and explain these concepts in the context of visualization, observation, analysis, and interaction with and in forests. In simple terms, AR adds digital content such as 2D or 3D objects into real-world scenarios; VR provides a complete immersive environment for the user; and MR combines AR and VR, allowing the user to interact with the digital objects while maintaining access to both virtual and real worlds [44]. Throughout the literature, sometimes AR, VR, and MR are collectively referred as XR. The development of sophisticated visualization techniques, such as 3D modeling, AR, and VR [44, 45], has enabled the creation of detailed and life-like simulations of individual trees of smaller and larger forest stands. These technologies allow users to navigate through virtual landscapes, observe the growth of and changes to trees and plants over time, and witness the effects of environmental factors like climate change, disease, or human activities [36]. A representation of the virtual forest pipeline, comprising the various input data sources, intermediate steps, and output visualization forms, is shown in Fig. 1.

Single-screen vs. multi-screen setups – Computer Graphics (CG)

The field of Computer Graphics, known as CG, focuses on generating, manipulating, and displaying visual content using digital technology. It encompasses the creation and representation of images, animations, and visual simulations through computational processes [46]. CG encompasses

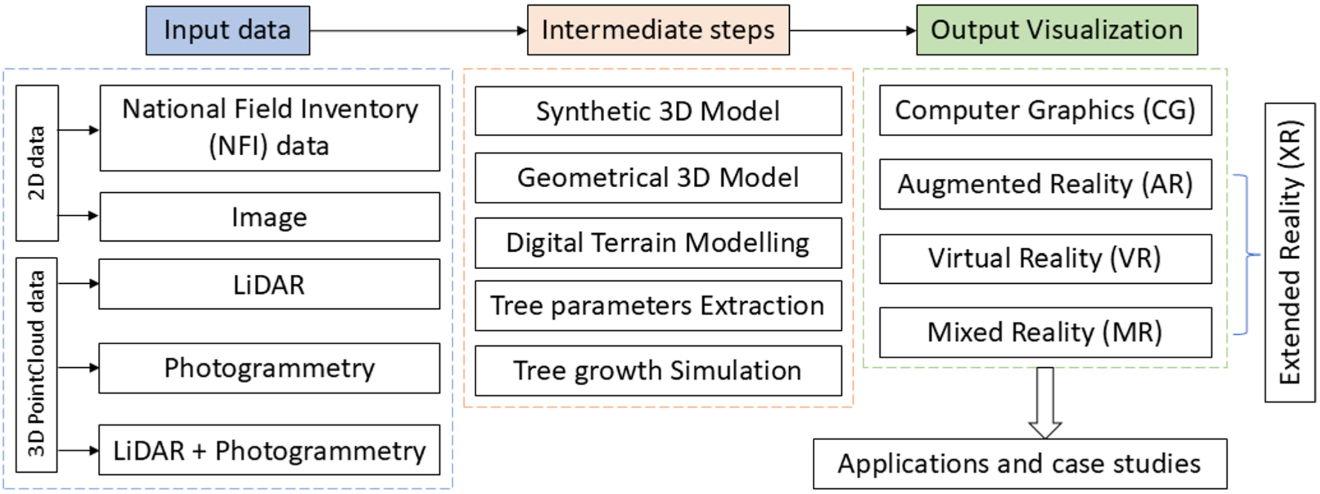

Fig. 1 Overview of the virtual forest pipeline

a range of techniques and technologies used to create 2D and 3D images, animations, and visual effects across various applications, including video games, simulations, VR, and graphic design. In forestry, virtual visualization of forest data on a single screen or multiple screens can greatly enhance the analysis and understanding of complex ecosystems. By utilizing advanced CG, researchers, forest managers, and conservationists can gain deep insights into forest structure, dynamics, and spatial relationships.

When forest data are displayed on a single screen, users can explore and interact with a digital representation of the forest in a compact and accessible format. This approach enables detailed examination of specific topics, such as identifying tree species, assessing forest health, or monitoring changes over time. However, a single-screen setup may limit the scope of visualization, particularly for large or complex datasets that require a broader spatial context. Expanding the visualization to three screens creates a more immersive experience, enabling users to view different angles or perspectives of the forest simultaneously. This setup is especially beneficial for comparing multiple data layers or visualizing the forest in 3D, where separate screens can display different aspects such as canopy cover, topography, or vegetation density. The increased field of view enhances the understanding of spatial relationships and structural complexity within the forest. Finally, when forest data are visualized across more than three screens, the experience becomes even more immersive and dynamic. Such a multi-screen setup can extend across on all the walls of an entire room or a large display wall, offering a panoramic view of the forest landscape. This approach provides an expansive and detailed perspective, potentially improving data interpretation and analysis [47]. Each configuration offers unique advantages, allowing users to tailor their visualization approach to the specific needs of their analysis, whether they are conducting detailed studies of individual trees or assessing the overall health and biodiversity of an entire forest. These visualization techniques offer opportunities to better understand the complexity of forest environments, supporting improved management and conservation.

Augmented Reality (AR)

Augmented reality (AR) is a technology that overlays digital information, such as images, sounds, or other data, onto the real world, enhancing the user's immersive and interactive perception of their environment (e.g [48]).,. This is typically achieved through devices such as smartphones, tablets, or AR glasses, allowing users to interact with both the physical and virtual elements simultaneously. Visualizing forests using AR can be powerful for enhancing the understanding and management of forest ecosystems, e.g., virtual trees can be shown in-situ in their spatial context, and digital replicas of trees, tree patches, or forests can be shown more realistically for scientific exploration or communication. This technology can be used to visualize tree growth and plan tree planting lines, assess forest health, demarcate forest boundaries [49], or explore biodiversity, all in real-time while navigating the physical landscape. Additionally, it can facilitate automated forest inventories [50], for example, by assisting in the collection of data on key forest species [51], trees [52], and wood parameters [53].

Visualizing forests using AR can transform how we interact with and understand forest environments. AR technology superimposes digital information, such as 3D models of trees, topographic maps, or species data, directly onto the physical forest landscape, creating an interactive and immersive experience. This allows users to explore the forest in real-time while gaining insights into various ecological aspects, such as tree species distribution, canopy structure, and environmental conditions. AR can also enhance decision-making by enabling foresters to visualize the impacts of management practices and timber harvesting operations (e.g [54])., in a more realistic manner than is possible with traditional visualization solutions, by examining activities such as logging, wood stacking, or reforestation before their implementation. For this reason, early research involved exploring the use of AR-enabled head-up displays for operators of forestry machines, to provide additional information for making informed decisions in situ [55–57]. Moreover, AR can be an educational tool, making complex forest data easily accessible to students, researchers, and the public. By integrating digital content with the real-world environment, AR offers a dynamic and powerful way to visualize and engage with forests, leading to better management, conservation, and learning outcomes.

The COST Action "Augmented Reality in Forestry" (ARiF) (https://arif-cost.eu/), a pan-European interdisciplin ary research network, has identified a number of application areas where AR technology can be useful in forestry. These include but are not limited to navigation and mapping tasks, forest management and conservation, pest and disease identification, public engagement and education, timber trade and wood processing, and natural disaster management.

Despite the vast potential of AR technology to optimize a number of processes, from disaster management to forest inventories, to stakeholder communication and decision-making, a recent interview study of forestry professionals and AR experts [50] acknowledged a number of socio-technical barriers to its wide adoption and use in the field, e.g., high acquisition costs, limited durability of the hardware, and suboptimal user experiences in situ. They also discussed opportunities for addressing these limitations and recommended developing bespoke AR applications tailored to the needs of field workers, using multimodal interfaces (e.g., voice) and modular visualization modes to increase usability and reduce overall cognitive load. Figure 2 represents a user interacting with AR device.

Virtual Reality (VR)

Virtual reality (VR) offers a potentially transformative way to explore and interact with forest ecosystems in a fully immersive digital environment. With VR technology, detailed, three-dimensional simulations of forests can be created, allowing users to "walk" in the forest through various terrain types, to observe tree species, and to examine ecological processes from multiple perspectives without physically being there. Based on the related work that demonstrates the powerful impact of VR on people, specifically on feelings of presence, emotions, and memory [58–60], such immersive experiences are particularly valuable for forest management, research, and education. Specifically, they enable users to visualize the effects of different management strategies, to study forest dynamics over time, and to engage in realistic simulations of environmental conditions. The benefits of VR in visualizing forests have been examined earlier [61], e.g., for forest management communication and operational forestry [62, 63]. VR and other forms of Extended Reality (XR) can also facilitate remote learning and collaboration, allowing students, researchers, and professionals to explore forests and conduct virtual fieldwork from anywhere in the world [64, 65]. In some senses a virtual laboratory can be created, that can be used for studying how forests are affected by climate change [66]. Given the prior work that provided a life-like representation of the forest and a first-person experience, possibly with an emotional connection, it is evident that VR can enhance understanding, decision-making, and conservation efforts, making it a powerful tool for advancing forestry practices and environmental education. VR even offers therapeutic potential, as walking in a virtual forest has been shown to provide stress reduction [67]. Figure 3 depicts a user interacting with different VR device.

Mixed Reality (MR)

The term Mixed Reality (MR), as it is used in contemporary literature, does not have a single definition [68]. In many publications, the terms AR and MR are used interchangeably. However, in earlier studies the term MR was

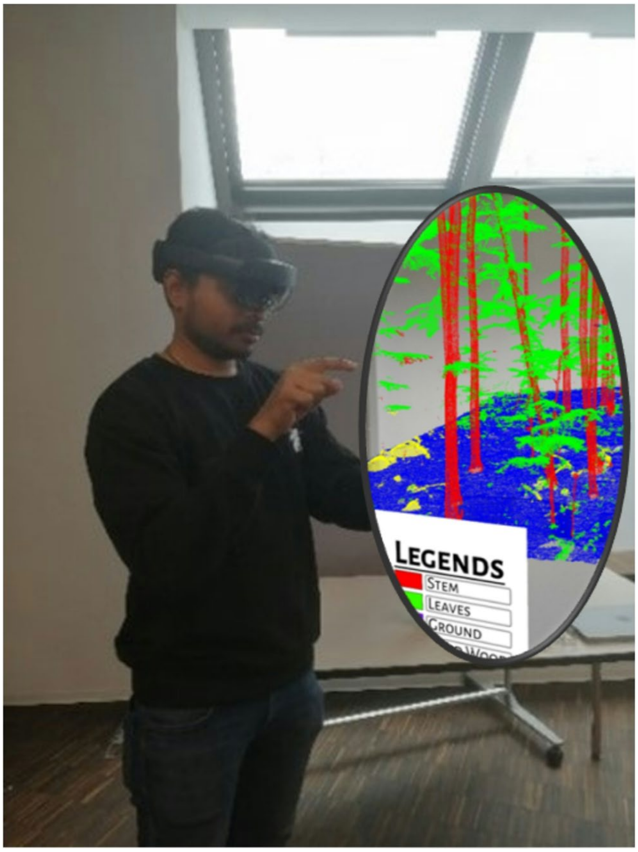

Fig. 2 A user interacting with an Augmented Reality (AR) device (Microsoft Hololens) (image credit: Kushwaha/WSL)

Fig. 3 A user interacting with a Virtual Reality (VR) device (Meta Quest Pro) (image credit: Kushwaha/WSL)

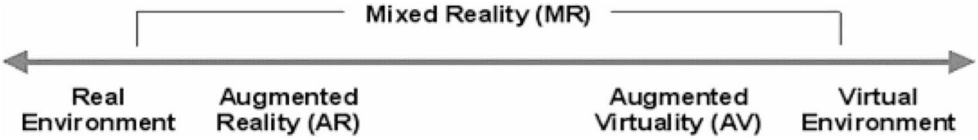

Fig. 4 The degree of mixture between real and virtual objects. The real environment and the virtual environment represent the two ends of this continuum, while Mixed Reality (MR) occupies the middle section and contains both Augmented Reality (AR) and Augmented Virtuality (AV) [58, 69]

used to express all things that are between real and virtual, following the concept introduced by the seminal paper [69]. In taxonomy MR is a superset, and AR is a form of MR (Fig. 4).

In contemporary times, especially because of how Microsoft Hololens uses the term MR, the term has evolved such that an XR system that contains spatial computing would be called MR. Spatial computing (in the world of XR research) means that the device would use computer vision and machine learning to compute the visible environment, and thus the virtual objects could be spatially referenced to the scene [58, 70]. In such a scene, the device "knows" where the surfaces begin and end, and potentially even identifies the objects as, e.g., tables, chairs, people, or an individual person. Being able to interpret the scene makes it possible to add virtual objects in meaningful ways, and not only as floating information anywhere in the field of view of the user. If the latter is the case, then one can still call this AR, because it augments the reality but does not fully mix the physical and virtual to blend them into a seamless experience. In the forestry-related context of this paper, we use the definition of [62], in which MR is in agreement with the contemporary definition above (i.e., with spatial computing), mixing AR and VR by enabling users to interact with the real world and the virtual world simultaneously. As AR, it does not try to immerse users or to separate them from the real world. Using MR in forestry has immense potential for simulation and training in the physical world, e.g., forest fires could be simulated in situ without endangering anything, consequences of various interventions could be examined against the reality in the field, and relevant factual information could be examined directly in the relevant context [44]. Figure 5 represents the visualization of a forest plot in CG, AR and VR.

The immersive experience has become quite intrusive when virtual visualizations are combined with other factors such as sound, scent, body movements, wind effects, water effects, etc [71, 72]. Inducing sounds of nature has shown physiological stress recovery [73] and anxiety reduction [74] in people. There is an effective and qualitative psychophysiological response when the users experience soundscape perception along with visualization [75]. There are immersive experiences which include olfactory stimulus-based attractors which are basically meant for users to navigate with the help of scent and sound reflexes [76, 77]. There is still significant scope for development in XR applications in forestry, alongside increasing interest in systems developed to assist users. In the following section we present a few case studies which provide more clarity of the various applications of visualization in forestry.

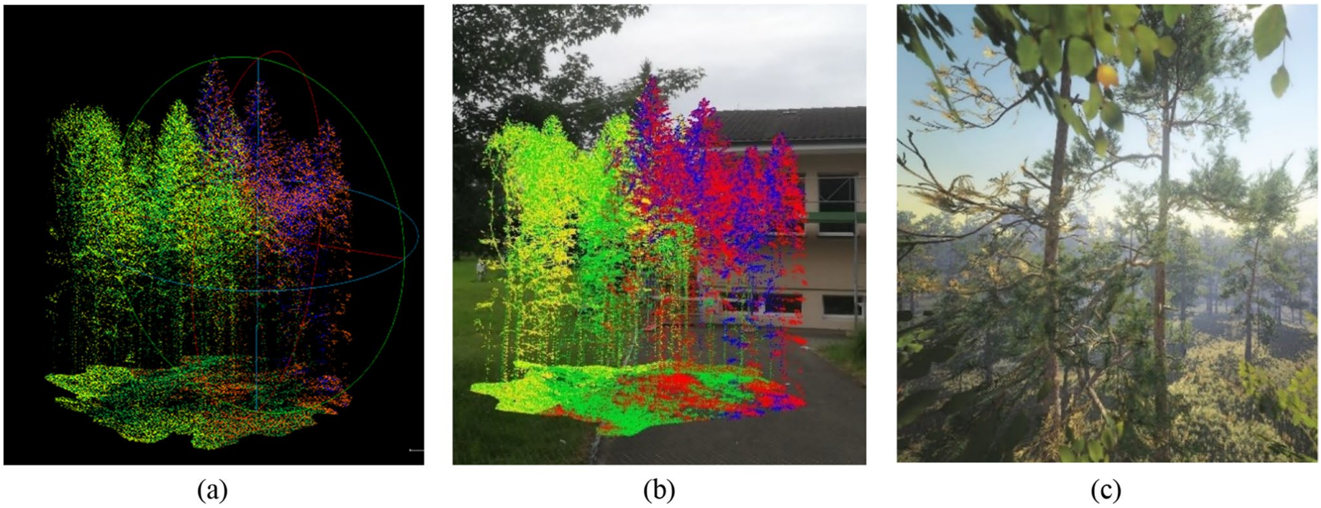

Fig. 5 Visual illustration of a forest plot using (**a**) computer Graphics (CG) (image credit: Kushwaha/WSL), (**b**) Augmented Reality (AR) (image credit: Kushwaha/WSL), and (**c**) Virtual Reality (VR) (image credit: Weber 2022)

Fig. 6 Screenshot from a virtual forest application with mesh-based trees, described in [36] (image credit: Holm/WSL)

Applications of Forest Visualization

Use Case 1: Immersive Experience for an end-user

Virtual forests can take on different forms and meanings, depending on the intended use. If we consider small forest owners as an example, virtual forests can be defined as realistic 3D representations of their forests, with a digital twin that accurately captures, for example, the tree positions, stems, crowns, and regeneration. The virtual forest generated through 3D reconstruction could include color information to enhance the visualization experience, and it could allow the user to walk through the forest area through an immersive experience. Similarly, virtual forests can be seen as the fusion of data and model-driven representations of how a forest would grow and evolve under different management strategies. In this case, the virtual forest can feature either color point clouds or textured mesh-based trees that accurately reflect realistic tree growth parameters (Fig. 6). The tree representations should be based on actual forest plots, and the tree growth parameters should be derived from field inventories or tree growth simulators. This approach is both data- and model-driven, as it combines real-world data with simulations to create a realistic representation of the forest.

Use Case 2: Videogrammetry for Virtual Forest Visualization

One potential avenue for sharing information about forests with the public is through immersive 3D videos (see Fig. 7) which can be captured using fisheye lenses [78] or multiple rigged cameras [79]. Such videos can give viewers a fully immersive experience, allowing them to explore the forest area in detail. This technology is particularly easy to apply on a larger scale, as data are easy to acquire and process due to the equipment's robustness and low cost. Additionally, the Level of Detail (LOD) captured in such videos can be quite high, providing viewers with a realistic representation of the forest's current state. While these videos do not necessarily provide actual 3D information, they can be viewed within the virtual reality framework, creating a sense of realism that is difficult to achieve with other media types. Overall, immersive 3D videos have the potential to be an effective tool for sharing information about forests with the wider public.

Use Case 3: Mixed Reality (MR) for Forest Management Training and decision-making

Marteloscopes are designated forest plots, often 100 m × 100 m, used to instruct forest management practices. Within each marteloscope, individual trees are assigned unique identifiers, and their morphological, ecological, and economic parameters—such as species, diameter, timber quality, and habitat value—are systematically recorded through field measurements. This comprehensive dataset from a marteloscope facilitates user engagement in forest management exercises, including thinning decisions and timber-quality assessments. Such exercises are essential components of forest management training, as they integrate ecological and economic knowledge with practical decision-making skills. Traditionally, these exercises have been executed using pen-and-paper methods and, more recently, mobile

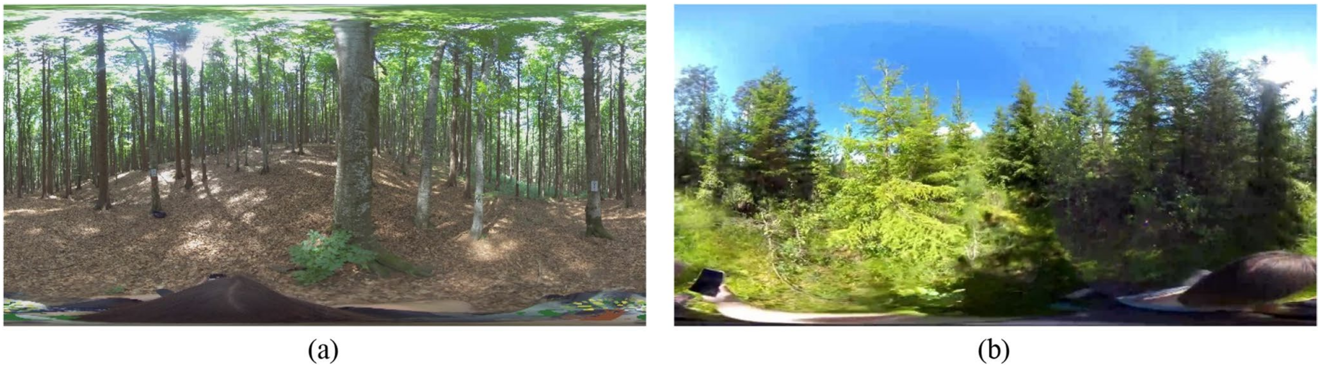
(a) (b)

Fig. 7 Screenshots from immersive 3D videos captured in the forest (image credit: Hristova/WSL) applications such as I+software. However, this reliance on 2D-based visualization presents challenges for individuals who may struggle to interpret 2D data within a 3D forest context. In addition, many assessments are contingent on subjective observations, which can introduce inconsistencies in the data. For instance, the ability to identify ecological features, such as bird nests, tree cavities or fungi, may vary among individuals, and assessments of timber quality may differ based on the evaluator's experience, resulting in variability in the data, which can be further used for forest decision-making. The 3D reconstruction of a marteloscope, combined with the overlaying of MR technology onto the real-world environment, presents a potential solution to these challenges. By linking 2D data directly to the corresponding tree stems, users can visualize habitat trees with enhanced clarity and accurately identify ecological features such as cavities, bird nests, or fungi along the tree stem. From an economic perspective, MR technology could facilitate the segmentation of tree stems with virtual cylindrical sections that represent distinct timber quality grades, thereby enabling users to more precisely assess the economic value of each tree component. This approach promises to enhance the precision and consistency of forest management decisions. Figure 8 shows an instructor training a student on MR technology in a real forest scenario in the marteloscope.

Use Case 4: Current and Future Scenario Visualization at the Landscape Level

The main objective of visualization applied to dynamic forest modeling is to show spatially explicit changes through time at the stand or landscape level, i.e., to represent the results from complicated simulations that are difficult to grasp based on 2D graphs. As described by [80], this coupling is meaningful not only for scientists but also for stakeholders who are not involved in forest modeling. For the former, good visualization can quickly show oddities in model behavior, which may help to detect errors quickly (in the input data or in how some processes are implemented in the model, including the detection of programming errors). For the latter, good visualization can better show how the forests and the landscape may change under certain drivers (e.g., climate change, different management strategies) without having to navigate through complex graphs and tables of data. Following the subdivision into these two groups, here called "modelers" and "model users", a visualization tool with two view modes can be used. The first one, called the "scientific view" (Fig. 9), is simplified considerably and easy to interpret (e.g., cones are conifers, spheres are broadleaved trees, and size is proportional to biomass). The second mode is more general. It requires higher computational effort, but the results look much more realistic. Thus, it is called the "realistic mode' (Fig. 10). The visualization tool has been used to visualize outputs from two models: the first one, ForClim [81], works at the stand level, and the second one, LandClim [82], works at the landscape scale. Figures 9 and 10 show examples of LandClim simulation outputs of the same area in the two viewing modes.

Fig. 8 An instructor training a student about Mixed Reality (MR) technology in the Swiss forest (image credit: FoI/ETH)

Key Considerations

Input Data

Various data types are used to comprehensively understand and visualize forests and their structure. These data types can be categorized into spatial and non-spatial attribute data, which both play a crucial role in forest visualization and analysis [83]. Spatial data refer to information tied to specific geographic coordinate locations, such as satellite or aerial imagery, GIS maps, and spatial coordinates. This type of data helps visualize aspects such as the forest's structure, distribution of species, and changes in forest cover over time. On the other hand, non-spatial data encompass attributes not directly linked to a specific geographic coordinate location, such as total species counts, growth rates, climate data, and other in situ measurements that contribute to a profound understanding of forest dynamics. When spatial and non-spatial attribute data are combined, they can provide a comprehensive overview, offering both qualitative and quantitative insights into forest ecosystems. This integration facilitates accurate monitoring, management, and conservation strategies, ensuring that forest resources are preserved and sustainably used [84].

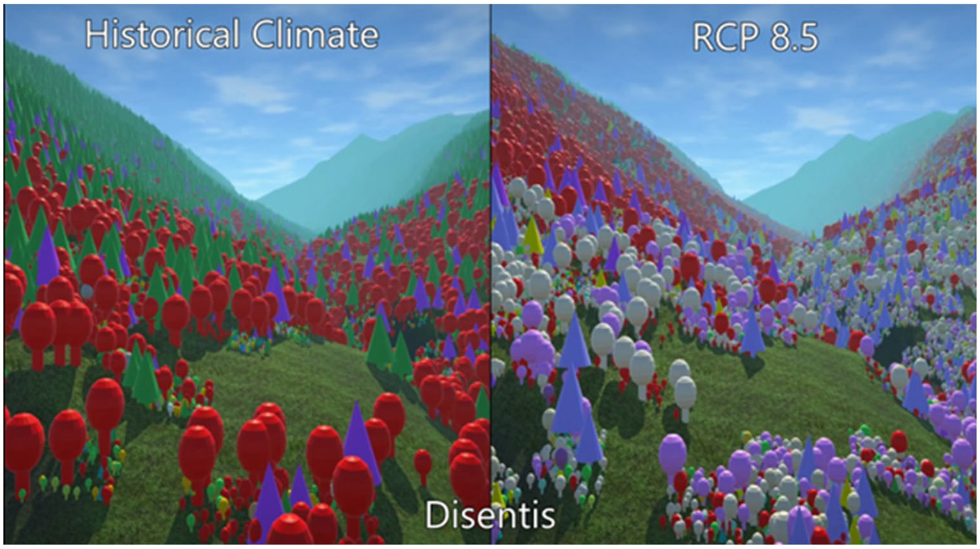

Fig. 9 Visualization of LandClim output in scientific mode. Cone-shaped trees represent conifers, and spherical trees represent broadleaf trees. Different colors refer to different species (image credit: Hands/ETH)

National Forest Inventory (NFI) Data

National Forest Inventory (NFI) is a program that conducts systematic sample inventories by collecting and analyzing data from its own country's forests and provides valuable information for efficient forest management [85]. NFI data encompass a wide range of measurements, including information on forest area, number of trees, growing stock, harvesting, and biodiversity. NFI data are collected on forest plots with a pre-defined size, e.g., 500 m^2. In these forest plots, tree features such as DBH and tree height are measured for an average of 13 trees, corresponding to certain DBH criteria [86]. In an interpretation area, stand attributes, such as the developmental stage, are estimated by forest engineers. NFI data have been widely used as a reliable reference for research studies [87]. This emphasizes the importance of field data as a benchmark. At the same time, it is important to acknowledge the significant challenges encountered during field campaigns. Field measurements are often expensive, labor-intensive, and time-consuming. Therefore, NFI surveys may not be suitable for large forest areas. Additionally, field measurements are only conducted for trees starting from 12 cm in DBH, excluding young saplings and regeneration.

Image Data (2D)

A simple photogrammetric image captured from a digital sensor is a form of image data that provides a visual representation of the forest. This image typically consists of RGB (Red, Green, and Blue) channels, which combine to create a realistic color photograph that can be used to visualize the forest from a specific vantage point. The perspective of this image can vary, depending on whether it is taken from an aerial viewpoint, such as from a drone or satellite, or a terrestrial viewpoint, such as from ground level or a nearby

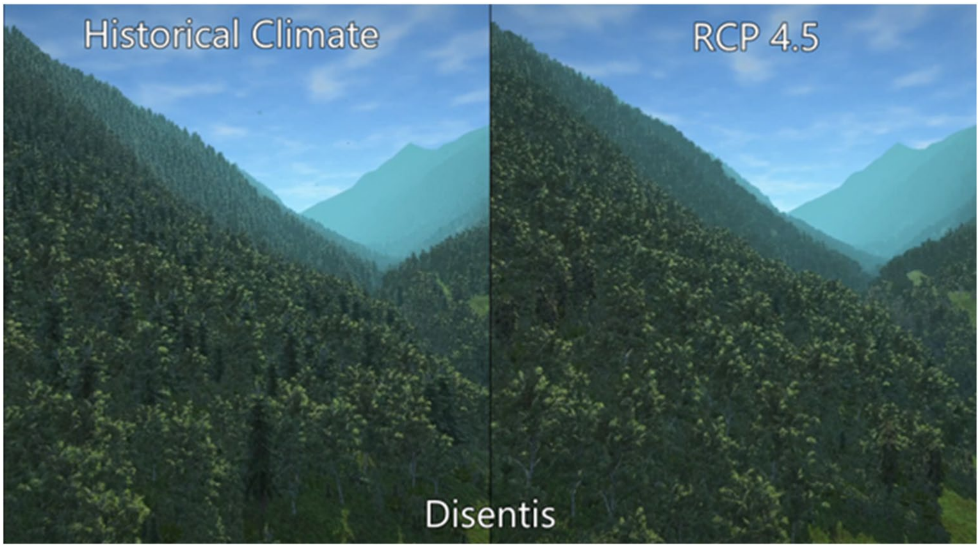

Fig. 10 Visualization of LandClim output in realistic mode. The shapes of different tree species are visible, but harder to appreciate. The visualization is more realistic (image credit: Hands/ETH)

structure. While a single photogrammetric image offers a valuable overview of the forest, enabling a basic visual assessment of its general structure and composition. The primary drawback is that this image only captures the forest from one specific angle at a particular moment in time and space, providing a limited, two-dimensional perspective. As a result, it fails to effectively represent the complex, three-dimensional nature of the forest, including variations in canopy height, density, and the spatial distribution of different tree species. It lacks the depth and detail needed for thorough analysis and decision-making in forest management.

Point Cloud Data (3D)

Point cloud data consists of a collection of points that map the geometry of a scene. Such data can be obtained from several advanced technologies, such as photogrammetry and LiDAR. Point cloud data generated through these technologies can vary in density, capturing different forest elements with varying levels of detail. Depending on factors such as the type of sensor, the platform used (e.g., airborne, terrestrial), the direction of the scanner, and the exposure of the forest stand, point clouds can have varying qualities at different levels, including the ground, tree stems, branches, leaves, or canopy. Photogrammetry is used for 3D reconstruction from various digital images; these sensors are often low-cost, lightweight, and easy to handle [88]. Photogrammetry employs collinearity and coplanarity constraints coupled with Multi-View Stereo (MVS) to create a dense 3D point cloud from 2D images [44]. It has been used for forestry purposes, especially due to its low-cost nature [89]. As photogrammetry is a passive optical technique, the light conditions have a major impact on the overall quality of the 3D reconstruction. This is in contrast to active systems, such as LiDAR and radar. Furthermore, different mathematical models may be employed, such as fish-eye, action, and spherical (360-degree) cameras. A common drawback of affordable spherical and action cameras is their low resolution, which may heavily impact the quality of the point cloud that is generated. Other factors influencing the 3D reconstruction using photogrammetry are image overlap and camera calibration (which may be cumbersome for spherical cameras). Furthermore, extracting and matching key features from images may be limited in the forest, due to heterogeneity and occlusion [31].

LiDAR technology works on the concept of measuring Time-of-Flight (ToF) of each reflection from the objects when shot with multiple laser beams. Terrestrial LiDAR is often expensive, involves heavy equipment that is impractical for complex forest conditions, such as steep slopes and dense undergrowth, and requires expert knowledge. However, new types of LiDAR, such as mobile laser scanners [86] and solid-state LiDAR systems [90], have shown promising results in forestry applications. Compared with photogrammetry, LiDAR is not influenced by light changes in the forest, due to the fact that the laser is an active sensor. LiDAR technology is considered as a high standard for point cloud generation in forestry due to its various advantages, notably point cloud density and positional accuracy. Yet, LiDAR point cloud data provide limited textural information on forest features compared with the photo-realistic results obtained from photogrammetry.

LiDAR and photogrammetric point cloud data both have limitations and advantages. Photogrammetric point cloud data, generated from multiple images, are particularly rich in RGB information, providing detailed color information that enhances the visual representation of the forest. Conversely, LiDAR-generated point cloud data excel in capturing accurate geometric information. LiDAR measures the distance from the sensors to objects, involving either a ToF or phase-shift computation, resulting in precise, geometrically rich data. However, LiDAR typically lacks the rich RGB color information that photogrammetry provides, which can limit the visual appeal and interpretability of the resulting 3D model. By combining the high geometric accuracy of LiDAR with the rich RGB information from photogrammetry, one can create a more accurate 3D model and realistic virtual forest scenarios, that not only represents the forest's structure with great precision but also includes detailed color information. This integration results in a more comprehensive and visually accurate representation of the forest, enabling better visualization, analysis, and decision-making in fields such as forest management, conservation, and ecological research [35]. These additional data types can be integrated to create completer and more accurate pictures of the forest, enabling better understanding and informed actions.

Simulated Datasets

Current 2D simulations of the leaves or texture of the tree bark are based on the illumination factor and species information. There are algorithms which can be used to develop generic tree models for visualization in forest landscape [91]. Simulated datasets can be in the form of 2D image or 3D mesh or point clouds [92]. Detailed 3D visualization of trees often relies on collecting LiDAR data within forested areas. This process can be time-consuming, which limits the amount of scanned data that can be gathered. As a result, simulating large amounts of 3D tree data can be advantageous for creating more extensive datasets with minimal manual effort. 3D tree simulators have primarily been designed to augment datasets for training Deep Learning (DL) models. Several state-of-the-art approaches focus on generating synthetic tree data. For instance, Bryson et al.

Table 1 The table presents a generic overview of various input data along with their acquisition mode, resolution, cost and ease of use

Input data	Acquisition	Resolution	Cost	Ease of use
NFI	In-Field	High (ground truth)	Moderate	Expert knowledge
Image (2D)	Remote Sensing	Low to High	Moderate	Easy acquisition and expertise needed in processing and analysis
Point cloud (3D)	Remote Sensing	Low to High	High	Experience needed for acquisition and expertise need in processing and analysis
Simulated (2D & 3D)	In-lab synthesis	Approximated	Low	Initial knowledge and coding needed. Saves lot of time without field work.

*Note: These parameters vary depending on the sensor and platform

[93] have created an artificial dataset tailored for training DL models that target stem and crown classification. However, their method can also be employed to generate virtual trees for visualization purposes. Additionally, Dobbs et al. [94] propose a supervised tool for generating and labeling a wide range of tree types, with the goal of learning to produce the skeleton of an input tree. Furthermore, Hristova et al. [95] introduce an unsupervised method for generating several main tree species around Europe. Their approach facilitates the creation of various shapes of a given tree species, ultimately aiming to showcase species diversity in virtual forests. Thus, simulated data saves considerable time as the datasets are prepared on the computers and do not require field work Table 1.

Output Data Visualization

The most effective way to visualize a forest is through virtual 3D models. They provide a more accurate and detailed representation of the forest's structure, enabling better analysis and understanding of its various components. Further, it helps in visualization, simulations, and representation for any decision-making and forest management. Point cloud data are a particularly valuable source for creating these 3D models. In representing output data, the question of the Level of Detail (LoD) is an important notion. While LoD may mean different things in different domains, in a formal manner, it usually refers to a standardized way of representing 3D data, as defined in the CityGML standard [96]. Within this standard, the question of LoD for trees and vegetation is an ongoing research topic [62, 97]. In forestry, different scales of LOD can refer to landscape level, forest stand level, tree level, stem, branch, leaves, nodes level.

Challenges and Constraints

Obtaining accurate and comprehensive data for creating 3D visualizations of forests presents several difficulties. Current data collection methods, such as remote sensing and field measurements, have limitations that need to be addressed to improve data accuracy and coverage. When collecting data for forest 3D visualizations, challenges may arise due to factors such as forest type, density, and undergrowth. For example, incomplete terrestrial data collection, caused by limitations in digital sensors, can result in a lack of information for the upper part of the canopy. To improve data completeness and coverage, a combination of ground-based and aerial data collection methods can be employed, although this approach has its own challenges [98]. One such challenge is occlusions, which are common in forest environments. The highly unstructured nature of forests can make data collection complex, leading to incomplete point clouds and visualizations.

Software

Many open-source and commercial software products exist for working with photogrammetry, LiDAR, and 3D mesh data. Photogrammetric and LiDAR point cloud processing is often performed using proprietary software, which can be expensive, especially for more accurate products. The quality of point cloud creation and the resulting visualizations may depend on the algorithms built into the software and the parameters used during data processing. The software is designed with user-friendly interfaces for easier access and navigation. Interdevice communication also depends on how compatible the software is with other devices.

Hardware

Hardware configuration is a key factor to consider in basically any 3D visualization effort. One of the primary limitations in creating photogrammetric point clouds or processing LiDAR point cloud is the availability of resources. A powerful Graphics Processing Unit (GPU) is essential for the fast and efficient construction of point clouds. In addition, the amount of Random Access Memory (RAM) available is crucial for ensuring robust computation. In programs like Agisoft Metashape, insufficient RAM memory can lead to memory swapping, which can slow down the computation process by up to ten times. Memory swapping typically occurs during tasks such as frame orientation and dense point creation, especially when processing numerous high-resolution photos (for example, more than 10,000 4 K video frames). The hardware requirements for visualizing forestry simulations can be similarly demanding. Maintaining a high frame rate [Frames Per Second (FPS)] is crucial for ensuring the usability of any visualization tool. FPS values below 30 make the tool difficult to use and unresponsive. During the development of Use Case 4 (Sect. 3.4), computational limitations were persistent. Visualizing forests at the landscape scale is technically challenging due to the sheer number of individual stems. Although the memory footprint of such a forest is relatively small, the CPU and GPU requirements for achieving high frame rates increase rapidly with the total number of trees. For instance, the development hardware for the realistic mode consists of an AMD Ryzen 7 5800X paired with an NVIDIA 4070. A landscape like the one shown in Surselva, Switzerland (a small section of which is shown in Figs. 9 and 10), can contain tens of millions of trees, each requiring rendering using a complex 3D model with greater polygons. Distant objects can be rendered as billboards—textured planes designed to imitate the full 3D model from a distance—to reduce the overall load on the GPU. Even with this simplification, frame rates often remain in the low 30 s, even on this high-end hardware. The scientific mode of landscape visualization was designed to be more usable for a broad range of researchers.

Often, forest modelers prioritize CPU speed over GPU power due to the inherent CPU demands of running complex ecological simulations. Ecological models are rarely designed to leverage the inherent parallelism of a dedicated GPU. As a result, it is more advantageous for them to use a mode with a significantly smaller number of polygons (tens rather than thousands) per tree, which can operate on the general integrated GPUs present in many systems. For instance, a 12th-generation Intel i7 CPU can provide frame rates in the range of 20–30 FPS when the Surselva landscape is viewed in this mode. The tradeoff is that this view is primarily useful to researchers, so a dedicated GPU is almost always needed for outreach purposes.

Data Standards and Inter Device Synchronization

Standardization of datasets plays a crucial role in inter-device communication and synchronization [99]. There are many efforts being made to improve the standard of the datasets in which they are being shared. Different commercial software has its own proprietary formats of the datasets. But in situations where datasets from different devices need to be integrated it is very important that all of them refer to the same standards. Similarly, when there is need to integrate multiple devices, it is also very important that the output format from one device is in the standard of the readable format of the other device. There are efforts like Open Geospatial Consortium (OGC) being made to standardize the multiple datasets across various sources and platforms.

Conclusion

From the literature review and in-depth analysis of various case studies, we have observed that visualization through a virtual environment adds lots of value for the user. By integrating both data and model-driven approaches, virtual forests can offer forest owners and decision-makers valuable insights into how their forests may grow and change over time. These insights can help us to make decisions about forest management strategies, such as thinning or harvesting, or about protection against diseases, on the forest's growth and regeneration. Forest visualization can be used to better understand and manage the forests in the current stage, or over the short and long term. By leveraging the capabilities of 2D and 3D data representation, it is possible to gain valuable insights into the health and condition of forested areas and to take proactive steps towards ensuring their sustainable management and preservation. Furthermore, 2D and 3D visualization offers a range of possibilities in the field of forestry studies. These technological advancements allows both researchers and practitioners to evaluate forest parameter features, such as forest attractiveness and the need for management strategies, in a more detailed, realistic, and comprehensive manner. Moreover, researchers and practitioners can assess the quality of the forest edge without actually visiting the forest, saving time and resources. Overall, virtual forest visualization presents an exciting opportunity to advance the field and better understand forest ecosystems.

Future Scope

Many algorithms can be developed using highly detailed input data for various forest management tasks. These include visualization of regenerated or harvested areas, as well as real-time detection of individual trees and their attributes, such as DBH, height, and species. Currently, only a limited number of tree species models exist. However, with proper training, more AI-generated species models could be developed to provide more accurate information and serve as the basis for determining other forest-relevant parameters (e.g., biomass volume, assortments, monetary value). Both current and future technologies can integrate these tasks seamlessly for end users. For example, current or historic data can be combined with real-time drone or other sensor data to improve the efficiency of forest management decisions. Additionally, more real-time interactions and immersive visualizations can be incorporated to enhance user experience and decision making. ○

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    - ○ Shows the importance of individual tree data throughout a larger landscape. Presented the design and implementation of a system for producing, storing, distributing, querying, and viewing individual tree data, both in a web browser and in a game engine-mediated interactive 3D visualization.

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Declarations

Competing interests The authors declare no competing interests.

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