Empirical Data Meets Immersive Design

Lessons learned from 3D modelling a biodiversity intervention site for virtual reality

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3D models of urban biodiversity emerge as innovative tools to foster biodiversity awareness, engage stakeholders, and support adaptive urban planning. However, 3D visualisations of urban biodiversity are still rarely in a meaningful level of accuracy for communicating biodiversity values, due to challenges related to empirical data collection and species 3D modelling. We present insights gained from the 3D modelling of a biodiversity intervention site in Tartu, Estonia, for virtual reality. To attain high model fidelity, empirical data collection should be planned carefully, considering the aimed spatial resolution of model accuracy, the shortcomings of available data sources and performance limitations. Secondly, the shortage of taxonomically accurate species 3D models in correct age versions and Levels of Detail still complicate ensuring consistency across visual elements, unless modellers use methods of 3D model creation from data. The findings also underscore the importance of defining goals and target audiences for communication, to determine how to prioritise data accuracy and design elements. However, successful model implementation may foster species knowledge and support conservation, promoting pro-environmental attitudes for a more sustainable future.

Keywords: *3D Modelling, Urban Biodiversity, Virtual Reality, VR, Immersive Design, Empirical Data*

INTRODUCTION

The accelerated decline in biodiversity driven by anthropogenic pressures, also known as the Holocene extinction (Turvey, 2009) takes its toll on urban biodiversity, causing far-reaching consequences such as the disruption of essential ecosystem services (Jansson, 2013). Biodiverse green spaces in cities also support recreation, physical health and mental well-being. Counteracting biodiversity loss within cities requires innovative tools to foster awareness, engage stakeholders, and support adaptive urbanplanning (Bulkeley, Kok and Xie, 2021). One such tool can be highly realistic 3D models of urban biodiversity. Realistic 3D models support collecting feedback from urban stakeholders by making plans more understandable (Eilola et al, 2023). 3D models of biodiversity can enhance environmental awareness by providing immersive learning experiences through virtual reality (VR) and augmented reality (AR), fostering deeper understanding and advocacy for biodiversity (Harrington et al, 2022; Höftberger et al, 2023) and its conservation. Consequently, integrating biodiversity into urban 3D models is becoming

increasingly relevant for urban planning and stakeholder engagement.

3D visualisations of urban biodiversity are however still rarely in the level of accuracy that would be meaningful for communicating biodiversity values. In 3D city models and urban digital twins, modelling of plant individuals is often still restricted to large woody plants, such as trees, and arranged plantations, leaving e.g. spontaneous herbaceous vegetation classified as 'grass' (Feng, Liu and Gong, 2015; Fernández-Alvarado et al, 2022; Li et al, 2025). Outside of the urban realm, there has been an increase in biotic environment-related extended reality (XR) solutions on the topics of sustainability and conservation (Cosio et al, 2023), but only a few examples (e.g. Harrington, 2020; Harrington et al, 2021; Chandler et al, 2022) have 3D modelled biodiversity based on empirical data beyond woody plants.

The shortage of models of biodiversity in virtual reality is likely due to the fact that unlike 3D visualisations built for computer games (Wills, 2002), 3D models built for reality-based communication purposes need to attain high model fidelity – the truthfulness and accuracy of the data that the model is based on – to the represented site, which can be challenging for their creators. Attaining high information fidelity requires mapping biodiversity over wider spatial scales with either fieldwork, the usage of proxy measures for diversity (Vihervaara et al, 2017), or high-resolution remote sensing data (Biljecki and Ito 2021; Finizio et al, 2024) coupled with AI-based models for species identification (Wang and Gamon, 2019; Finizio et al, 2024; Gillespie, Ruffley and Exposito-Alonso, 2024). Attaining high visual and audio fidelity – the truthfulness and realism of the sensory experience conveyed by the modelled elements – (Harrington, 2023; Lindquist et al, 2020) may also be complicated e.g. by the difficulty of locating either species 3D models and audio files that match the collected empirical data and suit the computational limitations of the modelling environment, or a method of model construction from data (e.g. Fol et al, 2024; Singh and Kaunert, 2025).

In this paper, we present insights gained from the 3D modelling of a biodiversity intervention site in Tartu, Estonia, for virtual reality. Our findings highlight key considerations for biodiversity data collection and model development that teams should consider when creating immersive representations of biodiversity-rich sites in virtual reality.

THE JAAMAMÕISA STREAM INTERVENTION SITE MODEL

Jaamamõisa stream (58°23'03.2"N 26°44'59.1"E) is a 3 km long waterway in Tartu, Southern Estonia, forming a green corridor from a nearby nature reserve towards Tartu city centre. The stream is bordered by a biodiversity-rich riverbank meadow, home to a wide variety of herbaceous plants, as well as new a construction area. The area is a target intervention site for the urbanLIFEcircles project, which aims to establish a connected network of biodiversity-rich green areas in Tartu (Võsaste, 2025). The city's intention is to extend the biodiversity-rich areas of the Jaamamõisa stream beyond the riverbank meadow via several interventions, designed to enhance ecological connectivity and habitat diversity while improving accessibility and public engagement. Additionally, the project aims at enhancing digital accessibility to biodiversity by creating virtual nature trails of the city.

As the Jaamamõisa stream intervention site is a popular recreational area for the local population, a 3D model-based immersive biodiversity game was envisioned as a tool for communicating intervention goals. The model was agreed to visualise the present and anticipated future biodiversity of the intervention site – particularly herbaceous plant diversity – alongside the planned interventions and their underlying goals and rationales. Given the focus especially on the herbaceous vegetation diversity,

it was agreed to model the site as it is in summer without seasonal variations.

Scene modelling

To present the site model in a realistic manner, QGIS was used to preprocess geographical real-world data, which was subsequently exported to Unity. As Unity does not directly support geographic coordinate systems, all data were transformed into Unity internal coordinate system with the centre of the target area at origo. Terrains with a combined size of 4 km^2 were created from grayscale heightmaps and textured with orthophotos. The terrain was split into 13 tiles, with a central tile of 1 km^2 representing the detailed target area, while surrounding background tiles measured 0,25 km^2 each. To enhance visual realism, detail texture layers were applied to the centre tiles, compensating for the insufficient resolution of the orthophotos at street level viewing. In addition to the terrain, a simplified city model was imported and optimised in Blender (blender.org). An imaginary walking trail was designed to guide players from one intervention to another. Intervention signs were modelled in Blender, scripted with interactivity in Unity and equipped with an activation button, to allow players to see changes in the model before and after the intervention. Additional information signs were distributed across the trail to communicate information about biodiversity. An advanced physics-based VR interaction Unity asset was implemented for player character control.

Further, a plant identification tool (Figure 1) was also developed and implemented to support interactive learning within the virtual environment. A time-of-day system was implemented to allow the player to explore the virtual world even at night. The User interface was developed to be compatible primarily with a specific model of a VR headset (Meta Quest 3) and with standard PC monitors.

Herbaceous vegetation modelling

Herbaceous plant modelling of the Jaamamõisa stream started with the inventory of the pre-intervention herbaceous vegetation at the site

Figure 1: A plant identification tool allows game users to study different species of the biodiversity-rich meadow

during summers 2023 and 2024. Key areas of the intervention site were divided into two sections, i.e. into the intensively managed Southern part and a more Northern flower meadow. For both sections, experts compiled lists of observed herbaceous plant species, estimated relative species coverages (%) and average vegetation heights (cm) of herbaceous plants using 1x1 m^2 plant study squares (one square per section in 2023 and three squares per section in 2024). The intention was to interpolate plant densities between the study squares to create gradients of vegetation across the studied sections. However, due to the detailed topographic gradients and the presence of the stream at the intervention site, the visual placement of plants to the model following this method did not turn out realistic, given the observed spatial patterns of plant assemblages in the area. Therefore, site vegetation was re-inventoried, and polygons of visually distinct areas of homogeneous vegetation were delineated, each with a species list, vegetation cover (%) and average herbaceous vegetation height (cm).

Herbaceous plants were self-modelled in the project to attain an as a coherent look across the models as possible. As many of the sighted herbaceous species as possible were photographed against a grey background, resulting in 70 photographed species. Apart from very common species, plants were photographed on site, without removing them from the soil. Whereas some recent examples have used hand-created low-polygon 3D models based on photographs (Harrington et al, 2021; Chandler et al, 2022), 2D presentation was chosen for this project, due to computational limitations caused by large numbers and rather small sizes of herbaceous plant species at the site. Subsequently, plant photographs were rendered into 2D billboards with transparent backgrounds. As plants were photographed over a two-month period, some plants appear in the scene in slightly different seasonal forms.

The use of 2D billboards posed a challenge in aligning the plant cover measurements recorded by the fieldworkers with billboard placement densities in the virtual model. Plant densities applied through Unity's painting tools were calibrated to visually correspond with the empirical coverages of plants. An additional problem was caused by the different maintenance regimes across the intervention site, due to which individuals of the same species appeared as low-cut and fully-grown versions at different parts of the intervention site. Since Unity did not provide tools for plant cutting, the available options for incorporating species models with varying vegetation heights were either to duplicate the plant models and algorithmically trim them to the desired heights, or to use different texture UV maps for each height variation. However, both approaches result in additional computational cost due to model duplication.

Considering the high numbers of herbaceous plants, it is common not to model each plant individually. However, the usage of 1-3 billboards per plant species and instancing technology calls for computational methods that create variation between individuals, e.g. small height variations, rotation, tilt angle, to avoid scenes from looking repetitive. Additionally, the multiplication of only a few individual plant models can bias the outlook of a meadow from its empirical outlook, if the photographed individuals are even slightly atypical to the species in terms of their size, shape or colour. Additionally, post-process colour grading, which is typically used in games for artistic style, can affect whether the modelled herbaceous species will match their real-life counterparts.

Herbaceous plants typically appear in spatially aggregated patterns, which are determined by an array of ecological factors for different species (Lara-Romero et al, 2015; Perret et al, 2022). Correct plant aggregation patterns are important for attaining a realistic feel for a virtual natural scene (Chandler et al, 2022; Holm and Schweier,

2024). Therefore, aggregation patterns of herbaceous species required careful balancing in order to attain a realistic result even beyond the spatial scale of delineated homogeneous plant assemblages created by fieldworkers. Some game engine assets offer algorithmic tools for element distribution across space (Harrington, 2023) based on e.g. topographic or soil variables. However, in this project, plant aggregation patterns were created by hand due to the complexity of the placement rules required for a potential algorithm. Site photographs were used as reference to achieve the most realistic plant placement (Figure 2).

Woody plant modelling

While urban tree modelling from point clouds is becoming mainstream (e.g. Münzinger, Prechtel and Behnisch, 2022; Chen et al, 2024), robust solutions for projecting the growth of point-cloud derived tree shapes in a species-specific manner are still lacking (Holm and Schweier, 2024). Therefore, trees of the sites were modelled using representative models of trees of same age, without trying to model trees by individual branch structures. Tree locations, species, heights (m), canopy widths (m) and Diameter Breast Heights (DBH; cm) were derived as a shapefile from the City of Tartu. For the northernmost parts of the intervention site, where GIS data on tree locations was unavailable, drone images were used for tree placement. Matching tree models were either created algorithmically (Fabritius et al, 2023), or models were purchased from the Unity Asset Store that matched as closely as possible with the tree species and tree dimensions in the empirical data.

The lack of a coherent library of taxonomically and regionally correct plant models with suitable licenses and growth age series complicated the creation of coherent-looking sceneries. Purchasing models from different sources resulted in different paint tones and different used modelling techniques, styles (e.g. realistic vs stylised or cartoon-like) and level of detail (LoD), which could easily have created a collage-like visual appearance for the trees. Some of the visual issues were corrected by hand before model

Figure 2: Detailed topographic variations and the presence of a stream create fine-scale spatial patterns for herbaceous vegetation. The digital nature trail is equipped with information signs

placement to site, e.g. the low-polygon algorithmic trees were modified in Blender to include more roundness and detail. Algorithmic tree models were also enhanced with self-built shaders simulating shadows and wind movement for more realistic feel in a virtual reality environment. Some tree species' models were replaced by either a closely related species or a model of another species with the same general outlook due to the lack of a combination of the taxonomically correct species in the correct heights, for the prediction of tree growth into the future to represent the post intervention site.

Animal modelling

Animal observations of the site were available in the PlutoF database (Abarenkov et al, 2010), which holds both systematic observations from expert field surveys and citizen science data. For the presentation of animal observations, four methods were considered: information signs of animal observations, static and mobile animal 3D models, ambient sounds and positioned sounds. The use of animal observation data raised questions of how to filter observations based on age, frequency and time of year to choose species to include in the 3D model. Eventually, modelled animal species were selected by city experts based on representativeness to the site and model availability. Species densities were decided visually.

The use of purchased animal 3D models resulted in similar challenges as in the case of woody plants with the limited availability and licencing restrictions of taxonomically accurate digital assets. Furthermore, existing models varied in terms of level of detail, visual quality and modelling style. Further, smaller animals, such as insects and spiders, were difficult to model and visualise without being obscured from view. To address this issue, we positioned e.g. spiders in their original size on informational panels where they are more visible to users. However, during user testing of the VR environment, most participants did not notice the small animals.

Animal 3D models with dynamic animations could further enhance 3D model realism by simulating natural behaviours such as movement and interaction with the environment. Birds in flight or insects crawling across surfaces add a layer of dynamism that static models cannot achieve. Unfortunately, to date, animated models of animals that behave in a natural way are limited. Additionally, these animations require careful optimisation to ensure smooth performance within computationally constrained environments like VR. The integration of moving animals into their virtual habitats introduced additional complexity. For instance, birds might be depicted flying between trees or insects pollinating flowers, requiring precise coordination between animal animations and plant placement. Animal reactions to human presence were considered but not modelled.

Soundscapes have emerged as a highly effective tool for enhancing the perception of animal biodiversity. Realistic audio representations of local fauna by geolocation significantly increase users' perceived biodiversity richness (Lindquist et al, 2020) and support a multimodal, multisensory immersive embodied experience (Harrington, 2023). For this project, sounds recorded at the intervention site were processed and integrated as 2D ambient sounds. An alternative approach to implementing sound would be to have individual objects, such as birds, emit 3D (positional) audio.

Intervention modelling

The planned biodiversity interventions for the site included the placement of submerged and on-the-ground dead wood, to enhance habitat diversity for aquatic and specialist species. Additionally, sections of flat banks, stones, floodplain ponds, aquatic plants and a small wetland were introduced to the stream to increase aquatic habitat diversity. The removal of

a dam in the upper course of the stream aimed at facilitating species movement and biomass flow. A bridge was added to access the flower meadow, while the introduction of bushes and trees was intended to increase overall species diversity on the site.

City experts planned biodiversity interventions in terms of their locations and described how the scene would appear before, immediately after, and at two later stages (one month or year, depending on the type of intervention, and 2-5 years) post intervention. Additionally, experts provided details on the objectives of each intervention and contributed descriptive texts to support model communication via intervention signs. The purpose of this timeline was to elicit a more detailed quantitative and qualitative understanding on the experts' assumptions regarding long-term effects of interventions on both site appearance and biodiversity. This included factors such as moss growth on dead wood, increases in e.g. insect densities within the newly established aquatic ecosystem, and tree growth throughout the years.

3D model objects needed for intervention modelling (stones, dead wood, bridge) were purchased from the Unity Asset Store. Interventions with terrain changes were particularly challenging to implement, as they required activation of an additional 1 km^2 centre tile to visualise the intervention scenario terrain with separately placed herbaceous vegetation, which had long loading times during intervention activation. As also some interventions, e.g. terrain changes, were not easily noticeable from the walking trail, interventions were slightly exaggerated to make them more visible to model users.

BALANCING MODEL AUTHENTICITY, PERFORMANCE AND COMMUNICATION GOALS

This study demonstrates the potential of 3D modelling and immersive VR as tools to communicate urban biodiversity, using the Jaamamõisa stream site in Tartu, Estonia, as a case study. The findings underscore the importance of defining clear goals and target audiences to balance data accuracy with design elements. For instance, audiences with varying levels of species literacy are likely to perceive a 3D model of site biodiversity differently, and appreciate different model details (Hooykaas et al, 2019). To ensure informed engagement with biodiversity data in educational and interactive contexts, it is important to consider how to communicate the sources and assumptions behind predictive and analytical models. At best, successful model implementation may foster species knowledge and support biodiversity conservation, ultimately promoting pro-environmental attitudes for a more sustainable future (Härtel et al, 2024).

To attain high model fidelity, empirical data collection should be planned considering the aimed resolution of model spatial accuracy, the shortcomings of each available data source and performance limitations. For instance, the usage of LiDAR or 360° photography would allow highest accuracy in data collection, but for performance reasons, the modelled 3D objects may still need to be converted to low-polygon 3D models, to balance visual fidelity and model performance (Chandler et al, 2022; Holm and Schweier, 2024). When modelling herbaceous vegetation, data collection should match the targeted spatial resolution and extent of the site 3D model. A meaningful spatial resolution for empirical data collection may depend on the modelled ecosystem and the typical aggregation patterns of its main flora (Perret et al, 2022). The plan for plant placement may contain hierarchical levels of data classification, e.g. the definition of visually uniform vegetation areas as polygons,

and within them, estimation of plant densities (Harrington et al, 2021) and small-scale aggregations using e.g. expert validation for visual realism and credibility (Chandler et al, 2022). The empirical data plan should also consider the changing seasons and how management measures, e.g. mowing the vegetation, would affect suitable data collection times.

The shortage of taxonomically accurate 3D representations of species, across different ages and LoDs, still complicates ensuring visual consistency in virtual environments. As the field of 3D content generation advances rapidly (e.g. Chen et al, 2024), including animal models (Li et al, 2024), creators may increasingly turn to data-driven methods for producing these assets.

TOWARDS DIGITAL TWINS OF URBAN BIODIVERSITY

By leveraging the confluence of tools, immersive technologies, methods, and domains of expertise, urban planners can foster public understanding of biodiversity interventions, promote environmental awareness, and inspire pro-conservation attitudes. Unlike static models, future urban biodiversity digital twins could act as a digital monitoring tool, automatically tracking and visualising changes and the effectiveness of interventions over time. Automated data integration e.g. via APIs ensures included models remain dynamic and relevant (Rantanen et al 2023), allowing for (real-time) updates and adaptive decision-making based on changing parameters derived from the real environment and new insights. Future development should focus on integrating Geographic Information Systems (GIS), 3D modelling, game engines, different presentation methods such as through VR and automated data updating into a unified framework. This fusion leverages e.g. GIS's semantic data capabilities and ecological modelling (Xie et al 2021), combined with game engines' realistic visual and audio rendering, to effectively communicate biodiversity aspects to diverse audiences. In the field of architecture, such integrative systems could support nature-inclusive design processes, inform site-specific interventions, and enable early-stage evaluation of ecological impacts within planning workflows.

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