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From Diagrams to Experience: Data Visceralisation of Ecosystem State-and-Transition Models in Virtual Reality

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Figure 1: We use virtual reality to illustrate the dynamics of ecosystems based on state-and-transition models (STM) developed by ecology experts. The interface lets users apply environmental factors (e.g., prolonged flooding) and see how the environment evolves. They can see where they are located in the STM box-and-arrow diagram ("Full diagram" button) and transition to any of the other ecosystem states (purple tabs, e.g. halophytic state). We simulate 22 ecosystem conditions and 64 transitions.

ABSTRACT

Communicating complex scientific concepts to non-experts is a persistent challenge. The communication of ecological state-and-transition models (STMs) through box-and-arrow diagrams is one example. This paper explores how virtual reality (VR) can make STMs more accessible. Using ecosystem STMs as a case study, we present a proof-of-concept system enabling users to viscerally experience the content of the model. We followed a three-phased participatory design process: first, 2 ecology experts guided the development of a VR prototype. Next, 17 government environmental management professionals evaluated its utility and features. Finally, after refining the system, 12 VR researchers informed design considerations and improvements. Our findings provide practical insights for visualising STMs in VR, and also contribute to the

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emerging field of "data visceralisation". We found this approach engages users and supports understanding of qualitative aspects of real-world phenomena. However, complex models like ecosystem STMs require the creation of accurate and extensive simulations. We conclude with a discussion for future directions.

CCS CONCEPTS

• **Human-centered computing → Information visualization**; **Virtual reality**.

KEYWORDS

Virtual Reality, Immersive Analytics, Ecosystems

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1 INTRODUCTION

In an era where complex scientific data needs to be communicated to diverse audiences, translating intricate models into accessible formats remains a significant challenge. State-and-transition models (STM) [47] are widely used in scientific disciplines to analyse and communicate dynamic systems, including ecosystems. These models are traditionally depicted through detailed box-and-arrow diagrams which, while precise, can attain levels of complexity that make them difficult for non-expert stakeholders to interpret [4].

This issue is particularly relevant to environmental management, where understanding and predicting complex interactions is crucial for informed decision-making. Ecosystem models developed by researchers have the potential to aid in making such predictions, but have frequently fallen short in this regard [1]. According to Schuwirth et al. [44], this is partly because of transdisciplinary language barriers preventing transfer from experts to stakeholders, leaving valuable scientific knowledge ignored. While efforts have been made to improve the comprehension of scientific data for non-experts, persistent difficulties limit the ability of institutions to leverage it for management [18].

Virtual Reality (VR) has the potential to translate dynamic models into intuitive and accessible knowledge. Rearranging large datasets in interactive spatial layouts has been shown to improve sense-making and data exploration by extensive immersive analytics research [15]. However, merely converting 2D data into 3D is not sufficient: a 3D graph, point cloud, or bar chart displayed in VR remains as visually disconnected from its real-world meaning as its 2D counterpart. To restore the link between data and meaning, one approach is to translate what the data symbolises into direct visuals, or "data visceralisations" [35]. For example, crowd movements can be visualised with 3D human characters walking among reconstructed buildings rather than abstracted as blue dots on a 2D map [8]. Increasing studies suggest that visceralisations improve non-experts' ability to grasp the data's meaning and show great promise to demystify complex processes [24, 25, 56, 57].

Previous work has primarily focused on visceralising relatively simple and static data, typically involving isolated dimensions that can be represented directly and intuitively [25, 35]. In contrast, STMs describe dynamic systems with multiple interacting components and temporal changes. Visualising STMs requires capturing not only static states but also the transitions between and interactions within these states over time. This complexity makes them fundamentally different to the other types of data previously addressed in immersive analytics research. Thus, there is a critical need to explore how VR and data visceralisation techniques can be adapted to represent dynamic systems like these.

This paper explores STM visualisation in VR by looking at the concrete example of ecosystem STMs. Specifically, we address the question *how would one visceralise ecosystem STM data in VR?* To do so, we adopted participatory design methods involving three phases: first, ecology experts experienced with ecosystem STMs helped us understand traditional diagrammatic representations (i.e. box-and-arrow diagrams) and develop a VR visualisation prototype. Second, this prototype was presented to environmental management professionals to gauge perceived usefulness, potential adoption, and required features. Finally, our prototype was improved using this feedback and presented to VR experts unfamiliar with ecosystem STMs. This final step aimed to assess the communicative aspects of our system with non-experts of ecosystem data, but also to investigate how to further leverage VR capabilities in our design.

The resulting proof-of-concept immerses users in the STM of an Australian ecosystem called *Inland floodplain eucalypt forests and woodlands*. Through VR, users are able to viscerally experience what the boxes and arrows represent by directly witnessing how the environment would look and sound like in each part of the STM diagram. A user interface (UI) lets them explore factors such as rainfall, insect outbreaks, or human activity and observe how they cause the ecosystem to transition to other states or expressions.

In this paper, we explore the design and development process of this ecosystem STM visualisation. We present insights and considerations for future work aiming to create data visceralisation of STMs in VR. We also discuss the challenges linked to this visualisation approach, their limitations, and the need for future research. Our contributions can be summarised as follows:

- A participatory design study involving key stakeholders to explore STM visualisation in VR for the first time;
- A proof-of-concept system successfully visceralising complex STM data, making it more accessible and engaging;
- Actionable design considerations and practical insights that can guide future data visceralisation projects.

Developed through interdisciplinary collaboration, our system offers a dynamic environment that allows the active exploration of the repercussions of resource exploitation and management, with the goal of informing policy changes in the future. Our contributions advance the field of immersive analytics and data visualisation, showcasing VR's potential to make complex information accessible to a broader audience. However, they also underscore the need for research to simplify the creation of detailed natural environments in VR, which requires significant effort and technical proficiency.

2 RELATED WORK

Immersive technologies have demonstrated potential in demystifying scientific data to a wider audience. Here, we introduce previous works that explored VR visualisation for non-expert users, and provide context for the visualisation of ecosystem STMs.

2.1 Immersive Analytics and Visceralisation

Using immersive technologies to understand complex data is at the centre of the immersive analytics research field [8]. The initial motivation for using these technologies stemmed from their capacity to portray large datasets in 3D space, enabling multiple points of view and embodied interactions [15]. Research demonstrated that immersive displays are capable of offloading cognition efforts when exploring data by providing embodied interactions and spatial layouts [30, 37, 39, 46, 55]. For example, Laha et al. [31, 32] showed that immersive visualisation of volumetric data provided improvements in time performance and accuracy compared to non-immersive displays when searching for features, making spatial judgements, identifying clusters, or quantitative estimations.

While spatial and quantitative data visualisation have been broadly explored in VR, much less attention has been paid to visualising conceptual models and processes. This type of data is traditionally visualised through 2D diagrams like oriented graphs (e.g. box-and-arrow diagrams, flowcharts) which can be found in most scientific domains [52]. For example, genomics researchers use oriented graphs to model how genes influence each other in cellular processes [26]. To visualise process models in VR, Zenner et al. [53, 54] proposed a system that automatically translates oriented graphs into an interactive VR environment. The result is a 3D graph where nodes are walkable platforms and arrows are tubes into which the user can input information bits to access other platforms. In our research, we chart a different direction and create virtual environments that dispense with abstraction and directly *visceralise* box-and-arrow diagram content.

Visualisations like graphs are powerful, but they sometimes rely on a degree of abstraction that causes the link between the visuals and underlying meaning of the data to be lost. To address this limitation, the concept of *data visceralisation* was proposed by Lee et al. [35]. Inspired by storytelling research, this approach seeks to elicit a "visceral" sensation of the data by directly showing its meaning to the user [3]. Increasing evidence suggests that this approach can improve sense-making in ways that traditional 2D displays or abstract formats cannot match [2, 29, 50].

Data visceralisation has mostly been applied to illustrate easily translatable quantitative data (e.g., speeds, US debt [35], water level [21]). Huang et al. [23] started exploring more complex cases, looking at forest species composition and forecasts from multidimensional datasets, leveraging procedural generation to create data-driven visceralisations of future scenarios. In this paper, we explore the visceralisation of STMs starting from their diagrammatic representation rather than datasets, and we take on a co-design approach rather than procedural generation.

2.2 State-and-Transition Models Visualisation

STMs were introduced in the 1980s as a practical tool for managing vegetation, to help structure and interpret vegetation dynamics in rangelands [5]. In 2010, a US National Ecological Site Manual was created to standardise ecological site descriptions and STMs across various agencies [49]. Since then, box-and-arrow diagrams have become the standard representations of ecosystem STMs.

Box-and-arrow diagrams originated in early theoretical research to help illustrate broad concepts and theories [47]. Their popularity grew due to their ability to summarise key points, define terms within multidisciplinary teams, and depict hypothesised effects [33]. Beyond academia, variations of these diagrams are often used to formalise processes like managing customer complaints in support centres or inspecting goods upon delivery [54].

When used for ecosystem STMs, box-and-arrow diagrams visualise ecosystem dynamics: the boxes represent ecosystem expressions, while the arrows indicate the pathways of disturbance and recovery between these expressions [42] (see example in Figure 2). Text annotations describe the timescale at which these changes occur (e.g., seasonal, decadal) and how they vary across landscapes (e.g., alluvial plains, uplands).

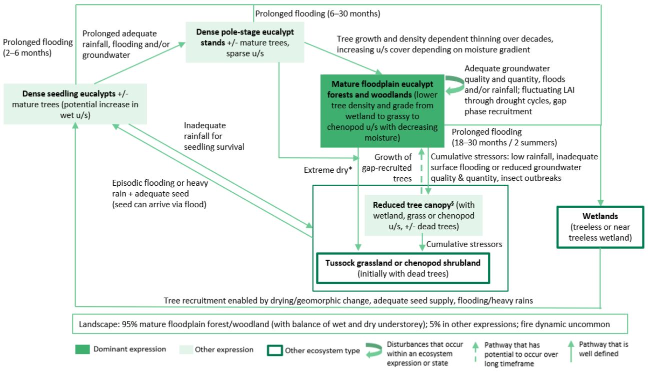

Figure 2: Box-and-arrow diagram representing the dynamics of the reference state for the *Inland floodplain eucalypt forests and woodlands* ecosystem. Extracted from [43] (see modified STMs in Appendix A).

Although they help simplify complexity, interpreting STMs can be challenging, even for seasoned ecologists [9]. The content within boxes may be abstract, and many arrows are double-ended, implying that everything is interconnected and influences everything else. Additionally, multiple STMs are often needed to depict ecosystem dynamics under different scenarios (e.g., with or without contemporary human activity), requiring readers to piece together how these diagrams relate. Consequently, such figures are both valuable and difficult to interpret, especially for non-experts [33].

To aid interpretation, scientific reports often provide written descriptions and photographs of the environments represented by the STMs [49]. However, descriptive photos are not always accessible, and placing legible text and images next to the diagram is often impractical without sacrificing clarity. Additionally, STM presentations can span multiple pages, making it challenging to interpret the information without frequent cross-referencing.

There is a need to reconsider how we visualise and engage with abstract models and processes. Since Grice and Macleod [19] pointed out the lack of development in STMs in 1994, little progress has been made in their design. VR allows complex data to be represented in 3D human-scaled space where embodied interactions are possible, leading to reduced cognitive load and improved comprehension [15]. Therefore, by enabling users to experience dynamic transitions directly, we propose that VR offers tools to address current limitations of STMs.

2.3 Communicating Ecosystem STMs to Stakeholders through VR

Since the introduction of ecosystem STMs, our understanding of ecosystems and the effects of management practices has expanded, resulting in increasingly complex models [34]. This deeper knowledge is expected to support decision-making aligned with sustainable management principles [38]. However, land management involves stakeholders with diverse backgrounds and goals besides sustainability [27]. Land managers must balance not only physical landscape changes but also societal and industrial demands, which can significantly affect the acceptance of sustainable strategies [20].

Recent reviews highlight the growing trend of immersive technologies being used not just for visualisation, but also for persuasion [12, 16]. By simulating concrete scenarios or decision outcomes, immersive technologies can evoke emotional responses and intuition about the implications of the data. For example, VR simulations have been employed to depict urban flooding [7, 14], melting glaciers [48], changes in tree biomass [23], invasive species [28, 41], bushfires [9, 17], and coral bleaching [22], offering users lifelike encounters with environmental issues. These visualisations have shown promise in enhancing comprehension, evoking emotions, and motivating action [12].

In this work, we decided to focus on ecosystem STMs because we believe that VR is a promising tool to engage a wider audience on issues associated with environmental management, but also because they are multidimensional, and therefore make an ideal case study for larger visualisations.

3 DESIGN METHODS

We employed the *research through design* methodology outlined by Zimmerman et al. [58], which uses design as a tool for inquiry and knowledge generation. This approach is well-suited for developing innovative technological solutions where user input is essential. Our goal was to explore how VR could make complex STMs more accessible to non-experts. Through a participatory design process involving ecology experts, environmental management professionals, and VR researchers, we aimed to incorporate varied perspectives into the design and functionality of our envisioned system. Our research process followed three key phases, each aimed at progressively refining our prototype and building our understanding of how these visualisations could be effectively applied in environmental management contexts:

(1) First, we engaged with two ecology experts to gain an understanding of the type of information that box-and-arrow diagrams of ecosystem STMs convey and identify the ways we could represent them in VR. This allowed us to design and build an initial VR prototype letting users immerse themselves inside the visceralisation of an STM diagram, based on data from a published report [43].
(2) We subsequently used this system as a technology probe for 14 environmental management professionals from the Department of Energy, Environment and Climate Action of Victoria, Australia. Using their feedback, we refined our prototype and created visualisations of three additional STMs, complementing the first one.
(3) Finally, the improved prototype was presented to VR experts to obtain insight that people unfamiliar with VR systems would not have been able to give us, but also from the perspective of people who were not acquainted with ecosystem STM data. This feedback served to establish design considerations for future work expanding our research to other complex STMs.

The next subsections outline the methods used in each phase. Approval was received from our university's ethics committee.

3.1 Phase 1: Co-design with Ecology Experts

We invited two ecology experts (paper authors Anna Richards and Katrina Szetey) to join our co-design phase. Both had extensive knowledge of ecosystem STMs and a strong interest in innovative data representation techniques. In consultation with them, we chose to use the technical report of Richard et al. [43] as a case study. This 118-page document details five ecosystem types at the Gunbower-Koondrook-Perricoota forest icon site, using text, photographs, and STM box-and-arrow diagrams. The report was initially created to demonstrate the use of ecosystem accounting in decision-making and local stakeholder engagement.

We initially focused on visualising a single ecosystem type from the document — the *Inland floodplain eucalypt forests and woodlands*. This ecosystem is represented by four STM diagrams: one showing the reference state dynamics (Figure 2) and three depicting modified state dynamics when a disrupting factor is introduced (Appendix A). We began with the diagram of the reference dynamics in Phase 1 and expanded to the other diagrams in Phase 2. This ecosystem was an ideal case study due to the abundance of information and active interest of local government stakeholders.

Procedure. Our co-design phase involved 11 online meetings and 18 follow-up emails. The initial meetings focused on understanding how ecosystem STMs function, what they represent, and their purpose. Subsequent discussions centred around visualisation and experience design, including the level of realism, environment size, and transition between states and expressions. Finally, as visualising ecosystem dynamics involved showing specific plants and biomes, our later conversations focused on selecting species, their distribution, and their prevalence.

In-between these meetings, we developed our prototype and shared progress asynchronously. Additional details and reference photos provided via email clarified the visual appearance of these ecosystem expressions for our visualisations. Since the ecologists were in different locations and lacked VR headsets, live screen sharing and video recordings were used to demonstrate features during online meetings. The outcomes of our discussions were compiled on a Miro board that was shared with all participants, containing notes, sketches, wireframes, and screenshots.

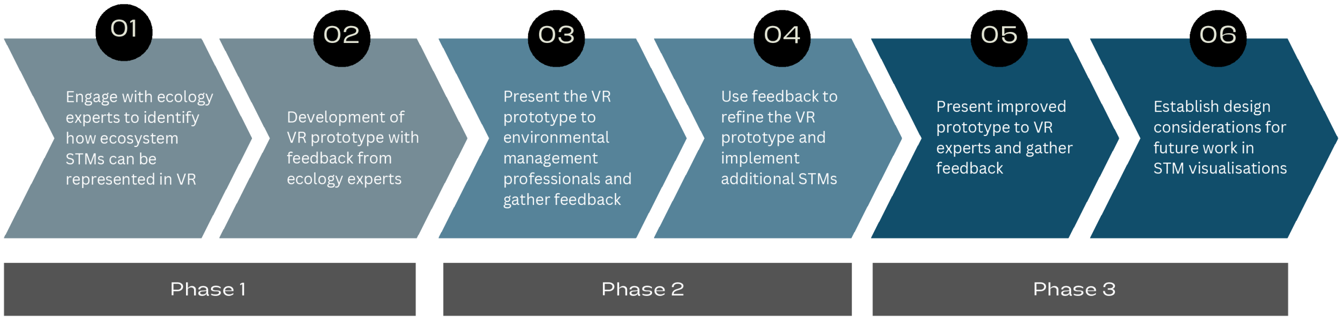

Figure 3: Three-phase process used to design our ecosystem STM visualisation.

3.2 Phase 2: Feedback Sessions with Environmental Management Professionals

In the second phase, we held feedback sessions with environmental management professionals from the Department of Energy, Environment and Climate Action (DEECA, Victoria, Australia[1]) to explore their practical needs as key stakeholders. These professionals act as intermediaries between the government, industry actors, communities, and environment specialists to coordinate the government's climate action agenda. They regularly engage with ecology experts and are a primary audience for the environmental reports these experts produce. Therefore, while they come from diverse fields, they are all familiar with ecosystem STMs through their work.

Procedure. Participants were chosen based on their professional roles and their involvement in delivering the government's environmental policies. We aimed to gather a varied group of employees to capture a range of experiences and expectations regarding the use of technology in environmental management. Participants were recruited through an internal agency-wide invitation. The sessions took place over an afternoon at their office. Before the individual sessions, we gave a 20-minute presentation to introduce participants to our research project and its goals. The presentation outlined our co-design process, introduced the case study STMs and box-and-arrow diagrams, and provided an overview of our 3D modelling, VR and visualisation approach. We framed the VR system as a technology probe instead of a final product, and highlighted the importance of their feedback for shaping its future development.

After the seminar, the feedback sessions were run in designated meeting rooms set up with our VR equipment, and with enough clear space to allow anyone wearing a headset to take a few steps within the virtual environment. Each participant was encouraged to verbally share their observations and reactions to the VR-simulated ecosystem in successive 15-minute sessions. The VR experience lasted around 8 minutes, offering a comprehensive yet manageable viewing of all STM boxes in the system. When the participant was ready, the experimenter manually triggered the transition to the next box of the diagram in a pre-defined order, ensuring consistency across participants and with the STM's cause-and-effect progression. A manipulation check was orally made to confirm that the participants could distinguish each box represented.

Figure 4: Showcase of other candidate ecosystems that could be visceralised in VR. Left: *Box gum grassy woodlands.* Top right: *Snow gum woodlands.* Bottom right: *Mallee woodlands.*

After removing the VR headset, participants were shown three other virtual environments that we had developed in a previous project on a large monitor, illustrated in Figure 4. These environments did not visualise STM transitions but served to encourage participants to consider how other ecosystems could be similarly visceralised through VR. Finally, participants completed an online survey to provide detailed feedback on the system's perceived utility, accessibility, and potential integration into their workflow (see details in Appendix B).

3.3 Phase 3: Interviews with VR Experts

In the final phase of our project, we engaged with VR experts to gather feedback on the improved VR system from Phase 2. The interviews had two main objectives: (i) to assess whether the prototype effectively communicated scientific information to non-experts, and (ii) to gather insights on best practices in VR design and usability.

Procedure. Participants were recruited through an internal call within Monash university, including academic staff, engineers, and PhD students. The expertise of these participants in immersive technologies was ideal to complement the previously collected feedback. Each 45-minute feedback session was individual and conducted in our University's experimental space with the same equipment used in previous phases.

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[1] https://www.deeca.vic.gov.au/

Upon arrival, participants completed a demographics questionnaire and were introduced to the research context. They were given an overview of the ecological data (report and STM diagrams) and the VR system's purpose, aligning their understanding with the needs of the target user group. The experimenter, while wearing the VR headset, demonstrated all system interactions on a screen, including how to navigate and interact with the ecosystem data. After resetting the system, participants were given the headset and controllers for a short, guided training session, allowing them to practice interactions such as teleporting and exploring different ecosystem states.

Participants were then asked to complete two tasks: (i) describe the changes between two specific ecosystem expressions, and (ii) list all expressions linked to a particular ecosystem state. These tasks assessed their understanding and interaction with the VR depiction of ecosystem dynamics. They were encouraged to share observations and ask questions throughout. After 15 minutes in VR, the participants removed the headsets and were given a short break. Then, they completed the System Usability Scale (SUS) [6] and took part in a 30-minute semi-structured interview to provide qualitative feedback on the system's interactivity, immersion, engagement, and communication value (see Appendix C).

4 RESULTS

The results are organised to reflect the iterative development of our system, from initial design collaborations with ecology experts to feedback sessions with environmental management professionals, and concluding with VR expert reviews.

4.1 Phase 1: VR Probe Design and Implementation

Given the recent development of data visceralisation, there are no guidelines on how to approach data like STMs. Discussions with the ecology experts helped us determine how to present the data so that it is scientifically accurate yet intuitive for non-experts. Below are accounts of key design decisions.

4.1.1 Co-design Decisions.

- **Q: What level of detail and realism should the visceralisation have?** Previous work on data visceralisation includes varying levels of realism, from high-fidelity [23] to simplified and cartoonish representations [35]. Ecology experts emphasised the importance of visuals that convey real environments rather than fictional ones, with a certain level of realism critical for identifying species and subtle ecological changes. This aligns with Huang et al. [23], who observed the necessity of providing sufficient detail to distinguish data, such as differentiating tree species. Consequently, we opted for high-fidelity visuals, custom-designing 3D models to ensure ecological accuracy and consistency.
- **Q: Should we represent an existing location?** Regarding whether to model an existing place, Lee et al. [35] illustrated two approaches: one-on-one visual replicas of specific data sources or a generic model applicable to all sources. In our case, a generic and representative environment was deemed sufficient to demonstrate the concept. The STMs in our case study describe ecosystem dynamics broadly across regions like northern Victoria and inland New South Wales, Australia, rather than a specific location.
- **Q: Can a single virtual landscape effectively visceralise the STM?** Conversations with the ecologists revealed that, in practice, ecosystems behave differently depending on geographical locations (e.g., near rivers, at higher elevations), and it would require modelling these different settings to take this into account. However, location-dependent changes are usually omitted in STM diagrams and were also omitted in the ones we used. We resolved that most situations could be represented within a single, versatile landscape incorporating key attributes. This approach could account for the majority of ecological variations without complicating the VR experience.
- **Q: What size should the STM visceralisation environment be?** We wanted to limit the costs of creating expansive environments. With feedback from the ecologists, we determined that all landscape transitions could be made visible in a small perimeter around the user without having to walk long distances, assuming that the user's position is initialised in a relevant location. A wooded floodplain was ideal because it allowed a comprehensive view of the changes.
- **Q: What elements do each STM box contain?** To make the visceralisation as representative as possible, we worked with the ecologists to determine the essential species and underlying terrain for each expression described by the STMs. Key native and invasive species, their distribution, and prevalence were identified for each box in the diagram.
- **Q: Could the ecosystem STM's boxes be visually distinguished by non-experts?** We considered whether some visual changes operated in the STM might not be directly visible or too subtle for unacquainted users to notice. The ecologists provided us with reference photographs illustrating each expression of the STM, showing the visual change between the boxes. Implicit phenomena could still be indirectly observed through the appearance of certain species (e.g. salt bushes appear after groundwater salinisation). As some changes looked more subtle, we decided to express the transitions to other boxes by applying progressive but rapid visual changes. In this way, users would be able to directly observe the elements that are impacted, and notice how they contrast against those in the previous box. We planned a manipulation check for this in the Phase 2.

4.1.2 Implementation. The groundwork above set the stage for our initial implementation. Below, we break down its technical aspects.

System Overview. Developed with Unity 2021.3.12f1[2], the system resulting from Phase 1 immersed users inside a visceralisation of the reference state of the *Inland floodplain eucalypt forests and woodlands* ecosystem, illustrated in Figure 1. In this first prototype, users cannot choose which boxes to visit; instead, the system cycles through a pre-defined, plausible pathway (arrows) between expressions (boxes). Users begin inside the dominant expression of

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[2] https://unity.com/

the STM (green box in Figure 2) and are presented with a virtual forest in the corresponding expression.

During each transition, a floating UI indicates the environmental factor driving the change and the destination expression by highlighting the relevant arrow and box in the original diagram. Once the UI disappears, users observe the changes over 4 seconds. A master script controls the simulation, tracking the current expression and activating additional scripts to modify individual scene elements:

- **Water**: a water level script dynamically moves the water with linear interpolation (lerp) between five preset height positions, from no water to heavy flooding.
- **Audio**: an audio mixer script fades between a selection of ambient audio snapshots for each expression. Additional spatial sounds are randomly played in specified locations. For example, the sounds of frogs emerge in the *Wetland* expression featuring flooded areas.
- **Shrubs and grass**: a vegetation script manages changes in plant species, adjusting their density and colour to reflect the current ecosystem expression. Gradual transitions, such as plants appearing or changing from green to yellow, visually represent shifts in the ecosystem.
- **Trees**: a specific script was created for the *Eucalyptus camaldulensis* (river red gums) as they are critical to visualising changes. Prefabs were made for saplings, pole-stage trees, mature trees, dead trees, and stumps. Based on the current expression, the script determines which prefab to display via a randomised percentage. For example, a sapling may grow into a pole-stage tree and eventually into a mature tree during certain transitions. Percentages are used to decide if a tree will die or be cut down and replaced by a stump.

In our VR scene, one tree model was more important than any other: a large ancient river red gum was placed near the user's starting position and stayed as a visual landmark across all ecosystem expressions. This tree, while showing superficial appearance variations, aimed to provide the sense of being in a fixed location, despite the flora around it changing with each expression.

3D Vegetation Modelling. We created 3D models of previously selected plants by using SpeedTree [3], a node-based editor for procedural plant generation. Throughout the modelling process, we shared our 3D models with the ecology experts to obtain feedback on their visual accuracy and adjust them. To expedite the modelling of river red gum trees with varying health conditions, we purchased a SpeedTree asset and optimised it for Unity, reducing its complexity. The tree's shape was adjusted based on reference images, and different versions were made to depict healthy, stressed, and dead states. SpeedTree's randomisation and material editor enabled quick variations and texture adjustments, while its integrated billboarding, level of detail (LOD), and wind system features improved efficiency and realism in Unity. LODs were generated for each tree version to enhance performance and minimise the visual "popping" of models swapping out at varying distances.

Blender[4] and SpeedTree were used to convert high-poly Archviz[5] models into optimised game-ready assets (e.g. in Figure 5). Our process involved separating the models into segments, rendering them as 2D textures, creating a texture atlas and UV projecting onto planes. These planes were duplicated, positioned to replicate the original model, and merged into a single mesh with LODs. Normal directions were adjusted for uniform lighting and shadows, and a material shader was applied in Unity to simulate wind through vertex displacement. Unity's Built-in Render Pipeline was used due to its stability and easy integration with assets. A physically based rendering (PBR) approach was used within this pipeline for more realistic lighting and materials.

Figure 5: Examples of 3D model variations. Top left: *Rytidosperma caespitosum.* Top right: *Themeda triandra.* Bottom: *Atriplex spinifera.*

Terrain and Vegetation Placement. The terrain was manually sculpted in Unity using built-in tools. The main terrain tile was 200 metres squared and was surrounded by eight tiles of the same size to create the illusion of an endless landscape. These outer tiles had less detail as they were never viewed up close. Textures were manually applied: mud near wet areas, dirt and twigs along the banks, and roots and grass on higher ground. Normal mapping was used to add additional surface details.

Plant models were placed on the terrain using a custom-built generation system, allowing control over plant type, spacing, and terrain texture placement, while avoiding objects like logs or rocks. For instance, trees only generate on root textures, and plants were excluded from flooded areas. The system also randomised plant models, together with their scale and rotation, adding natural variation. Water levels were simulated with a large plane featuring a material shader for animated ripples and environmental reflections. This plane was animated to rise and fall, simulating floods either filling or draining away from the terrain. Figure 6 shows examples of visuals for two expressions.

Sounds. We implemented dynamic audio track mixing, where individual tracks are combined into a cohesive soundscape at runtime. Field recordings were edited in a Digital Audio Workstation (DAW) to create a base "atmos" track. Additional sound objects, such as animals sounds, were positioned in space. Sound locations were either random or attached to 3D objects. Both pitch and volume were randomised to reduce repetition. This approach allowed for a small number of sounds to create a rich soundscape. Timers were

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[3] https://store.speedtree.com/

[4] https://www.blender.org/

[5] https://archvizartist.com/

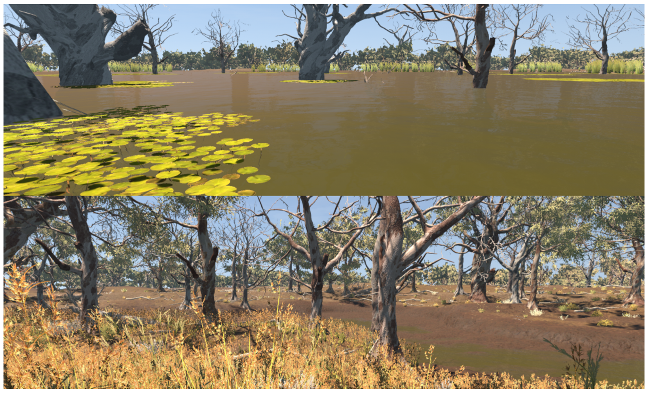

Figure 6: Two examples of STM boxes simulated in the same location. Top: *Wetland* expression. Bottom: *Reduced tree canopy* expression.

used to control how often randomised sounds played, simulating animal population changes through sonic cues.

VR Rendering. The Unity project was made VR-compatible for HP Reverb G2 displays using the OpenXR[6] package. Users could see 3D controller models in place of their hands and walk in the environment. A real-time directional light was used to simulate sunlight, rotating with the sun's position to reflect the time of day and year. This setup controls the angle of shadows, lighting colour, and how light interacts with atmospheric effects (e.g. clouds). The sun's position is the average location within the shown ecosystem.

4.2 Phase 2: Stakeholder Feedback and Refinements

Our VR probe was presented to 17 environmental management professionals, whose roles and expertise varied. Five participants specialised in technical areas such as GIS analysis, biodiversity data systems, and spatial analytics. Seven were involved in environmental policy, planning, regulation, and natural resource management. Four worked on field-based programs like weed management or bushland reserve monitoring. One participant specialised in environmental communication and engagement. All had normal or corrected-to-normal vision and reported no previous VR-related motion sickness, or relevant motor or sensory deficits. Volunteers did not receive compensation of any sort.

4.2.1 Environmental Management Professionals Feedback. Three participants were excluded from the analysis due to incomplete data. The survey responses of the remaining 14 participants were coded by theme to quantify and evaluate patterns and specific areas of concern or praise. We then chose to run a descriptive analysis to obtain a global overview of the feedback and identify the most commonly raised comments, enabling us to set priorities for the next iteration.

Added Value of VR. Overall, participants gave positive feedback on the advantages of using VR to interpret ecosystem STMs. Eight participants highlighted VR's effectiveness in improving the understanding of ecosystem states and transitions. Six of them pointed out the benefits of VR's dynamic visualisation, while five emphasised its engagement factor. Three participants identified cerain immersive aspects of VR, such as presence and realism, as critical for interpreting ecological changes.

Foreseen Audience. When discussing the potential audience for these visualisations, opinions varied, indicating the versatility of the tool. Four participants identified the general public and decision-makers (including senior executives, developers, and department advisers) as key audiences. Three suggested that land managers and owners would benefit significantly, while others saw the potential for broader appeal, suggesting educational sectors and community groups as possible beneficiaries.

UX Suggestions. To improve the understanding of ecological transitions, six participants recommended integrating explanations of transition causes through narration or on-screen text. Four suggested that modifying the diagrams could make the transitions easier to interpret. Additionally, individualised interactions such as user-triggered transitions and educational features like quiz pop-ups were also proposed to aid user comprehension.

Vegetation and Wildlife. Most feedback on the visual aspects of the VR system centred on the representation of natural elements. Seven participants suggested improving vegetation by adjusting tree and grass heights or adding more diversity with shrubs and ground litter. Five participants recommended adding animal models, and three proposed expanding the sound library to include more bird species. Additionally, participants confirmed they could visually distinguish the different boxes from each other.

These findings were used to develop the second iteration of our proof-of-concept, as detailed in the next section.

4.2.2 Implementation Update. This new development phase aimed to increase the interactivity of the VR experience while incorporating feedback from environmental management professionals. The result let users select which STM box to explore instead of following a predefined path in the diagram.

User interface. We introduced a UI that mirrored the traditional box-and-arrow diagram in our case study, depicted in Figure 7. This floating 2D interface allowed users to select transitions within the STM. A finite state machine in C# ensured users could only make transitions that were logically connected to their current expression. The UI displayed the current expression at the centre, with arrows leading to potential future expressions and descriptive text explaining the ecological factors driving the transition. Users interacted by pointing the VR controller and pressing the trigger to select a path, which then visualised the environmental changes to a new expression. To improve user orientation within the STM, we also added a "Full Diagram" button which shows the entire box-and-arrow diagram in a separate tab. To encourage exploration, the diagram only revealed the boxes and arrows the user had previously visited or interacted with.

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[6] https://www.khronos.org/openxr/

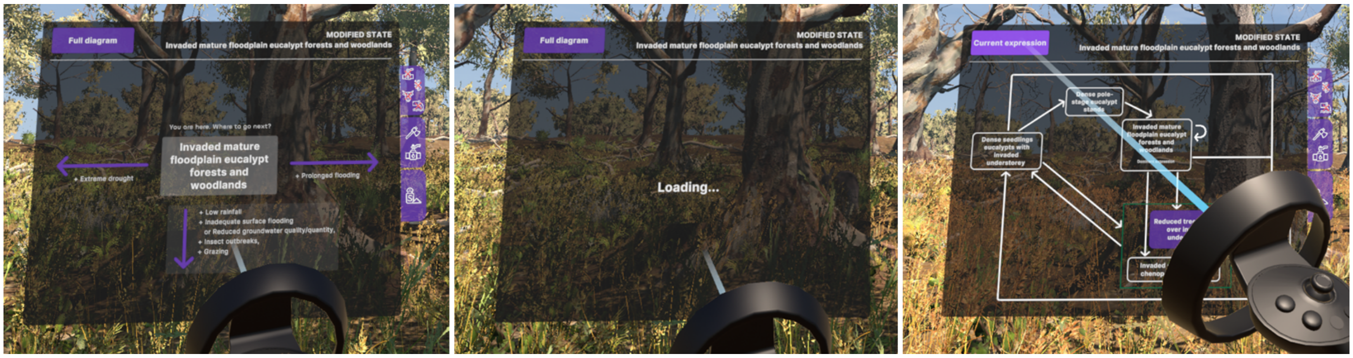

Figure 7: User interface. Left: Main navigation menu, showing the current state (header), expression (box), and connected expressions (arrows). The purple tabs on the right take the user to the other STMs. Middle: the transition is loading. Right: Full diagram view. The box being currently visualised is highlighted in purple. When another STM is accessed, this diagram is also updated to match the chosen STM.

Additional STMs and animals. To broaden the VR experience, we added three STMs representing modified ecosystem states in addition to the original reference state: invaded state, reduced canopy state, and halophytic (saline soil) state. Users swapped between these states via UI tabs (see Figure 7), with each transition taking them to the dominant expression (green box) of the selected STM while also updating the displayed diagram. In consultation with ecology experts, we also incorporated animated models of native and non-native fauna, such as kangaroos and cows, into relevant ecosystem expressions. Simple routines guide these animals along predetermined paths and behavioural animation loops (e.g., walking and grazing).

Navigation. Finally, to facilitate exploration, a teleportation feature allowed users to quickly move to predefined points of interest, such as river banks or forest edges, as indicated by visual markers. The number of teleportation points was limited to encourage users to physically walk in the virtual space.

4.3 Phase 3: VR Expert Evaluation

A total of 12 participants were recruited to test the Phase 2 prototype, all of whom had academic or professional experience with VR. All participants were recruited from the same university and had backgrounds in deploying, developing, researching, or teaching VR. They included a lab manager and VR programmer, a technical developer, a professor in immersive analytics, four PhD candidates researching VR and immersive analytics, and five tutors and assistant lecturers teaching VR application development. They all had normal or corrected-to-normal vision and reported no previous VR-related motion sickness, or relevant motor or sensory deficits. Volunteers did not receive compensation of any sort.

4.3.1 System Usability Scale (SUS) Results. When testing our VR probe, all participants were able to successfully complete the designated tasks. SUS responses were coded between 1 and 5. Item 1 of the SUS ("I'd like to use this system frequently.") was removed from the scale because the system was not designed for frequent use, and the participants in this study were not the intended end users. Previous work [36] showed that removing a single item from the SUS does not significantly affect the psychometric properties of the scale if the score multiplier is adjusted. Therefore, we used an adjusted multiplier of 100/36 as recommended.

The SUS analysis yielded an average usability score of 75.93, placing the system in the above-average usability range, meaning most users found it to be both usable and effective. The responses reflect participants' views on aspects including complexity, ease of use, confidence, and the need for technical support. Response trends can be summarised as follows:

- The majority of participants found the system easy to use, with many agreeing or strongly agreeing that the system was well-integrated and that they felt confident using it.
- There was general disagreement with statements about the system being unnecessarily complex or inconsistent, indicating that participants found the system intuitive and well-designed.
- A small number of participants were neutral about whether the system was cumbersome to use and suggested areas for improvement, though this was not a dominant theme.

While these results provide useful insights into the system's usability, it is important to note that the feedback is from VR experts, whose experience may differ from that of beginner users. Although no major usability issues were identified, further testing with VR beginner users would help confirm the system's accessibility to a wider audience. Nonetheless, the current results suggest that the system is intuitive and well-designed for its intended use.

4.3.2 Interview Results. The interviews were analysed using the thematic analysis method proposed by Braun and Clarke [11]. This allowed systematic exploration of the key insights provided by the VR experts, focusing on their feedback regarding system interactivity, immersion, usability, and potential areas for further refinement. The following paragraphs present the thematic findings.

Communication. The system provided an effective medium to communicate environmental changes. The presence of animals and the transitions aided in portraying a vibrant and evolving landscape. Three participants commented that the animals facilitated a clear depiction of the impact of external forces on natural processes. E.g., *"I was surprised [...] how invasive species, like cows, would change the environment."* The animals were popular enough for one user to recommend more direct interactions with them. Two participants further mentioned that the experience made them feel responsible for the environment and the impact of human presence. One user said, *"I feel there's a sense of loss when you can kill trees, or when you apply drought and suddenly they die."*

These factors highlighted the system's ability to effectively visceralise ecological data. One participant noted, *"I think this is a good showcase of the power of visualisation for people that aren't used to this and don't think of this stuff."* Another emphasised the program's strength in translating complex data into simple visuals, stating, *"It's very useful for translating complex data about the natural environment because it's hard to imagine the effects of small changes without considering the long-term impacts."*

Eight participants viewed this method of communicating research as a potentially effective way to convey ecological changes to policymakers. The ability to visually present dense and complex data in an immersive, and rapid experience was seen as a strong tool for engagement. One remarked that *"Being able to visually say it, I think, is easier than reading a report. It's one thing just to read the text on a paper... but actually being able to push a button and see the environment change is much more vividly detailed."* Some feedback recommended focusing on key information and providing more context, addressing concerns that the presentation might not be specific enough for policymakers and similar audiences.

Navigation. The navigation design was seen as an effective system for moving through the various states and expressions of the environment. One participant noted, *"You want to navigate everywhere."* The experience was intuitive enough for participants to easily track the different expressions. However, three users suggested that clearer guidance on where they could or should go would enhance the experience. Additionally, three more participants mentioned that teleportation had a limited range, and suggested expanding the range and number of points to further encourage exploration of the environment. The diagrams of individual states were helpful for mapping the areas users explored. Three participants noted that the diagrams assisted in forming mental maps that connected one box to another. One participant commented, *"Easy to change everything, to change the state... in the environment by just one click."* However, five participants found the full diagram view confusing and suggested merging the four STM diagrams into a single, overarching map to more clearly explain the links between states and expressions. Another recommendation was to allow users to see where they had previously been, along with the ability to freely navigate between different states and expressions.

User Interface. The UI was found easy to use. Two users commented on the ability to use it without needing any prior instruction or noted that the system was simpler than they had anticipated. One participant remarked, *"About the UI, I think it was simple, easy to use. I like the touching with the controller."* The colour design was praised for its clarity, and the text components effectively detailed what was happening in the scene. As one participant said, *"The UI was really intuitive as well. I really liked the little tabs popping out so I could actually read them."* This contributed to the overall usability and experience. Still, seven users found certain UI elements hard to interpret or redundant, especially without prior context. Two also noted a sense of overstimulation. To address this, one suggested reducing the number of tabs and overall UI presence. The addition of audio prompts or pop-ups was also recommended. One participant proposed *"a double selection"* mechanism to provide progressive amounts of details.

Immersion. The graphics, sound design, and overall scenery ensured an immersive experience for participants. The immersion was highly appreciated, with participants feeling fully absorbed in the digital environment. The quality of the surroundings was praised for building a strong sense of presence, with many users stating that their expectations for realism were not only met but exceeded. This was largely due to attention to detail, such as the colour palette, shadows, and falling leaves. One participant remarked, *"It's absolutely convincing, especially the shadows."* Comments about poor visuals were rare, but some did observe the graphics lagging. This was particularly noted with the trees. To further enhance the accuracy of the environment, some users suggested adding a weather system to visualise the changes and resulting impacts on the environment. *"You could change the weather and increase either manually or automatically the water level to kind of see what areas are affected"*.

The soundscape had a positive impact on the user experience, contributing to making the environment seem expansive and inhabited. One participant noted: *"The sounds helped me understand that I am progressing to a different state."* Users noted this sometimes generated emotional reactions from them. However, five participants also described the spatial sounds as confusing or too loud at times.

5 DISCUSSION

This work explored data visceralisation to visualise complex ecosystem STMs in VR and make them accessible to non-expert stakeholders. Our participatory design process involving ecologists, environmental management professionals, and VR researchers, led to the creation of a prototype. Unlike traditional visualisation, which often relies on abstract encoding, our approach renders the meaning of data directly. This approach extends prior work on data visceralisation [24, 35] by showing how complex, process-based models, rather than just quantitative metrics, can be experienced in VR.

Our focus was on creating an immersive first-person experience, using a high level of visual fidelity to maximise user engagement. Indeed, previous work employing realistic visuals and first-person perspectives often showed strong emotional responses and immersion [14, 17, 22, 23]. However, different visual styles such as abstract representations (e.g. low-poly [40]), as well as alternative perspectives (e.g. vantage points [17]) could also prove effective in conveying complex information while reducing computational load and development time. Exploring the combination of viewpoints and visual styles may determine the optimal balance between fidelity, user engagement, and resource efficiency, ensuring that the system remains accessible and scalable for broader applications.

Secondly, while our system primarily focused on visually apparent changes, implicit shifts in the ecosystem were not directly addressed. For example, salinisation was represented by the appearance of salt bushes, but the increase of salt in the soil and groundwater was not directly observable. Therefore, identifying the link between a phenomenon and certain species or ecosystem health without expert guidance may remain challenging. One potential solution suggested by the VR experts could be the addition of situated elements, such as interactive icons, overlays, or text, to provide contextual explanations. Vogt et al. [51] previously explored the benefits of such annotations in VR in supporting learners. By applying text annotations and audio explanations to 3D visualisations of molecular interactions, they found these cues could help guide attention, maintain engagement, and improve learning outcomes. Taking inspiration from this research, just-in-time but also just-in-place information on species or environmental changes could be developed to help users interpret the scene more effectively.

Interviewing VR experts in our last phase allowed identifying further improvements that end users with no VR experience would have been unlikely to think about. For example, although we provide a view of the original STM diagram in the UI, some participants shared it was hard to keep track of pathways to specific boxes. VR experts' suggestions included providing a "history" of visited boxes or portals allowing for their side-by-side comparison. Hybrid approaches letting users switch between 3D graph representations (e.g. in [53]) and immersive first-person visceralisations like ours may be promising. Users could "dive" into specific nodes of the 3D graph and explore their visceralised content, benefiting from both abstract and concrete visuals.

Another point of note is that, while ecosystem STMs typically depict ecological changes as deterministic, many transitions are inherently uncertain. The visual changes users observe in our system do not account for the probability that these transitions will occur in reality. To account for these uncertainties, it is possible to incorporate methods like those used by Huang et al. [23], allowing users to explore a range of potential outcomes in VR based on varying inputs and confidence intervals [23]. Similarly, Hadar et al. [20] visualised alternative landscape scenarios under different management strategies, providing a way to communicate uncertainty about future environmental changes. Communicating model uncertainty was beyond the scope of our work, as we focused on visceralising STM diagrams that inherently lack probabilistic data.

Finally, while our prototype focuses on Australian ecosystems, the underlying approach can be extended beyond this specific context. Many other process models, including those supply chain management, communication, or education [53], rely on process diagrams or state-transition logic to explain change over time. Our design method, which begins from these diagrammatic structures and builds immersive experiences around their logic, could be applied to any domain where dynamic relationships are key to understanding. However, generalising this approach will require adapting the visual design, interactions, and domain-specific semantics to ensure that the visceralisation aligns with audience expectations and the nature of the data being communicated. The following section provides design considerations to support such adaptation.

5.1 Design Considerations

Based on the insights gained from our participatory design process, we have identified several design considerations that can guide future research in STM visceralisation with VR. These considerations are generalisable to other kinds of data and aim to improve the effectiveness of visualisations.

Balancing simplicity, fidelity, and re-usability. While high-fidelity renderings may evoke stronger emotional responses and better communicate distinct species, they come at the cost of higher resource demands and complexity. Simpler, more abstract visuals may suffice to convey key information without overwhelming users or the system and can be more easily repurposed across different datasets and scenarios but may sacrifice some emotional impact and detail. However, maintaining a plausible visual appearance is crucial, even for less detailed models, to ensure correct interpretation. Design decisions about these aspects must be based on the experience targeted for the visualisation.

Tailoring cues to goals. In VR experiences intended to support communication and decision-making, providing adequate context is important to ensure that users can interpret the STM dynamics in line with the intended message. The focus on specific sensory cues, therefore, must be driven by the visualisation goals. For instance, if the aim is to illustrate non-reversible environmental changes, extra effort should be invested in crafting the visual elements that communicate these shifts. If the aim is to emphasise changes in fauna, then animals and the sounds they make should be prioritised. Not all visualisations will require the same approach. Ultimately, there is no one-size-fits-all solution, and the design must be adapted.

Leveraging audio. The potential of audio is often overlooked in VR visualisation. Incorporating ambient sounds, dynamic audio cues, or narrative elements can enrich a visualisation and provide users with a deeper, more intuitive understanding of complex information. Thoughtful integration of sound can also significantly improve the user's immersion and the perception of changes in the environment, especially when visual cues are subtle. However, a careful balance is needed; overusing audio can detract from the overall experience.

Interactivity for enhanced sensemaking. While embodied interactions with the environment may not always be necessary for understanding the data itself, they play a significant role in helping users make sense of complex systems. Encouraging users to physically move through space and interact with elements may support more intuitive comprehension, building spatial awareness and understanding of scales.

Scaffolding mental models. To support building a coherent mental map of how different states are related, one should consider including features that help users track changes and navigate seamlessly through the system. Facilitating easy navigation between states, allowing users to revert changes, replay steps, and switch between multiple viewpoints can provide clarity and reveal connections that are otherwise invisible. In cases where UIs are employed to navigate different states or datasets, it is essential to communicate how user actions affect the environment. This likely becomes increasingly important as the complexity of the STM being visualised grows.

5.2 Limitations and Future Work

Beyond the potential improvements mentioned earlier, our system presents several limitations and opportunities for future work. First, although we have proven the feasibility of creating realistic ecosystem STM visualisations, the system was labour-intensive to develop.

The custom creation of 3D assets required substantial time and resources, limiting the scalability of our approach. Future research should explore ways to streamline the asset creation process, perhaps leveraging AI-based generative models to automate 3D model production. Interestingly, not every species of flora is necessary to visually summarise a given ecosystem; for example, only 4% of flora is needed to reliably represent Mediterranean landscapes [20]. Investigating similar thresholds for other data would be worthwhile to reduce the burden of asset creation in future developments.

Further steps are also needed to bring VR visceralisations of ecological landscapes into the hands of non-expert stakeholders. Developing onboarding instructions will be necessary to guide users through both the VR interactions and the interpretation of ecological simulations, enabling laypeople to navigate the system autonomously. Recently published design guidelines [10] on VR onboarding practices can be used to create such materials. Additionally, annotation tools could be developed to let users tailor the system to specific needs without requiring technical expertise. For instance, a toolbox could enable users to create interactive text or audio annotations, highlight virtual elements, or magnify small-scale phenomena, as suggested by our participants. Although not mentioned in the feedback, it could also be interesting to investigate how to replace our 2D interface by physics-based interactions. Designing interactive "metaphors", such opening a jar full of insects to trigger a transition towards an insect-invaded expression, could provide a more intuitive understanding of causality. Investigating how to design such metaphors for multifactor transitions would be an interesting area of research.

Lastly, while our system shows promise as a decision-making support tool, we have not evaluated its usability with VR novice users or its influence on their decisions. Our contribution here lies in providing the first step—demonstrating how immersive systems can be designed to bridge the gap between complex scientific data and intuitive, accessible knowledge. Future work will need to investigate how these immersive visualisations influence real-world decisions, exploring their capacity to change attitudes in practical environmental management contexts. Approaches such as that of Sermarini et al. [45] could be adapted to evaluate user decisions based on scenarios, comparing conditions where immersive STM visceralisations are used against traditional material. Given prior research on the ability of VR to enhance sensemaking [2, 13, 46], we anticipate that such immersive visualisations will have a meaningful impact on decision-making outcomes.

6 CONCLUSION

This paper introduced the design process of a VR system for visualising complex STMs, making abstract data more accessible to non-experts. The results show that immersive, high-fidelity visuals have a strong potential to enhance user engagement, understanding, and emotional connection to the data. Our contributions include key design considerations for immersive visualisation, balancing fidelity, interactivity, and accessibility to improve data interpretation. While our case study focused on ecosystem STMs, the approach we propose is applicable to any domain that uses diagrammatic or process-based models–such as public health, economics, or education–where users must understand state changes and causal relationships. By transforming abstract representations into embodied, spatial experiences, this work opens new directions for communicating dynamic systems through immersive technologies. Further research will be needed to evaluate broader impacts and explore different design approaches.

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