

# Key factors to enhance efficacy of 3D digital environments for transformative landscape and urban planning

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## HIGHLIGHTS

- Integrating human-environment interactions in 3D digital environments is essential to accelerate sustainability transformations.
- Considering cross-scale spatial and temporal dynamics requires further development of point cloud technologies.
- Using 3D digital environments to foster imagination demands caution regarding knowledge and certainty overstatements.
- Immersive VR tools can help trigger radical changes through emotional responses to design proposals.
- Scaling “deep” with 3D digital environments can be achieved by integrating active sensing by and with people.

## ABSTRACT

The unprecedented expansion of digital technologies has led to a rapid increase in the development and application of 3D digital environments for landscape and urban planning in the past two decades. Considering the significant challenges in guiding human societies towards sustainability, these technologies must not only assist decision-makers in adapting to changes but promote fast, transformative shifts in the relationship between human societies and nature. Based on a set of global exemplars, this Perspective Essay outlines six key factors that can enhance efficacy of 3D digital environments to guide knowledge-informed landscape and urban planning. We call for (1) explicitly representing dynamic interplay between the social, ecological, and technical systems, (2) exploring the integration of design with simulation models to address cross-scale dynamics, (3) developing features to foster imagination, (4) employing multisensory stimuli to encourage profound changes in environmentally and socially sustainable behavior, (5) tailoring the incorporation of active sensing by and with non-experts into 3D digital environments to better acknowledge indigenous and local knowledge systems, and finally, (6) carrying out a usability evaluation to facilitate participation and collaboration in an efficient co-creation process. We conclude by recommending the establishment of a collaborative knowledge platform that unites researchers, developers, and stakeholders for stimulating social-ecological-technological system thinking in the development of 3D digital environments and harnessing the technological advancements to accelerate and drive the needed transformative change within urban and landscape planning.

## 1. Introduction

Digitalization is expected to catalyze land use transition towards sustainability (Mondejar, Avtar et al., 2021). Emerging technologies, such as smart energy grids or real-time remote sensing monitoring, are being promoted to extend our capacity for making informed decisions, enabling more efficient and sustainable utilization of Earth's resources (Grêt-Regamey, Switalski et al., 2021). 3D digital environments in particular have attracted attention in their capacity to support participation and collaboration of diverse stakeholders (Gill and Lange, 2015, Lovett, Appleton et al., 2015, Billger, Thuvander et al., 2017, Staffans, Kahila-Tani et al., 2020), a basic requirement for democratic knowledge-informed planning processes (Rydin, 2007, Davoudi, 2012).

They are computer-generated, immersive spaces, mimicking real-world environments, which can often be explored and interacted using digital devices such as computers, virtual reality (VR) headsets, or augmented reality (AR) devices. Integrated into deliberative processes, 3D digital environments are expected to help shape more legitimate, credible, and salient solutions (Gill and Lange, 2015, Lovett, Appleton et al., 2015, Hayek, Von Wirth et al., 2016, Billger, Thuvander et al., 2017). However, despite significant technological advancements, they have not significantly increased the levels of public participation (Nasr-Azadani, Wardrop et al., 2022), impeding the possibility of developing holistic, objective and fair solutions.

Social-ecological system science posits that in systems characterized by cross-scale interactions and dynamic interplay between humans and

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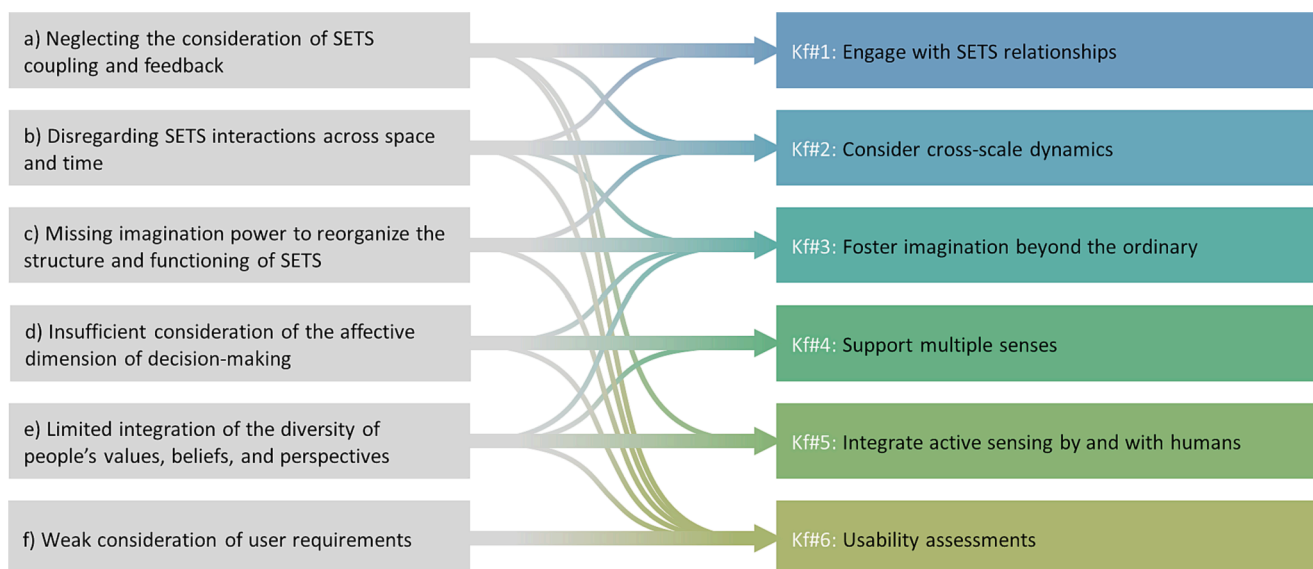
the environment, conventional methods that treat people, technology, and the environment as separate entities cannot work because it tries to separate the inseparable, and assumes what is truly dynamic as static (Reyers, Folke et al., 2018). In order to better align with the complex challenges of the rapid and fundamental human-driven alterations of the Earth system, we thus might need to reconsider the development of 3D digital environments in the context of highly complex, coupled social-ecological-technological systems (SETS) (McPhearson, Pickett et al. 2016, Depietri and McPhearson, 2017). This Perspective Essay proposes six factors to consider when developing and using 3D digital environments to make the technology part of complex adaptive systems, helping recast our relationships with the environment.

3D digital environments have been developing fast in the past two decades and range from photorealistic 3D geovisualizations (Biljecki, Stoter et al. 2015, Jaalama, Fagerholm et al. 2021) to real-time digital twins using acoustic and visual elements (Batty, 2018, Tao, Zhang et al. 2018, Ketzler, Naserentin et al. 2020). In recent years, there have also been strong technological developments in display and user interfaces to facilitate communication between humans and computers, as well as between users. VR 3D geovisualizations with spatial reference allow users to explore the real world, and AR solutions overlay real experiences with perceptual information (Çöltekin, Lokka et al. 2016). In addition, Earth Observation (EO) data and mobile geospatial data generate extensive real-time information that can be integrated into digital twins to facilitate citizens feedback (White, Wutich et al. 2010), and voluntary geographic information (VGI) platforms enable the collection and analysis of a wide range of data provided by individuals (Bordogna, Carrara et al. 2016). Very recent developments in extended reality allow to interpret gestures and expressions in real-time using multiple cameras and sensors, and are already used in medical applications (Masalkhi, Waisberg et al. 2023). Finally, AI-powered rendering, animation, and modeling are enabling even more sophisticated and immersive visual-acoustic experiences. However, in light of this increasing availability and accessibility of digital environments (Alsop, 2022) as well as their widespread adoption across various disciplines, the dream of achieving a technological breakthrough to support landscape and urban development towards sustainability has not yet materialized.

Current 3D digital environments are often designed and used to communicate static goals with planned outcomes, rather than supporting an adaptive process between people's values, beliefs, and

perceptions and planning proposals, to deliberate dynamic development pathways. This reductionist use is known to not suffice for achieving sustainable and equitable futures considering the dynamics, hyper-connectivity and complexity of coupled SETS (Leach, Reyers et al., 2018, McPhearson, Cook et al. 2022) (Fig. 1, a). Reyers, Moore et al. (2022) highlight that sustainable development has to be viewed as a dynamic process, shifting the focus from understanding what encompasses a desired outcome to how different development pathways are co-shaped. Present-day 3D digital environments, however, fail to incorporate spatial and temporal cross-scale and cross-sector perspectives, and are not effectively involving stakeholders (Nasr-Azadani, Wardrop et al. 2023) to navigate boundaries and integrate changes in perceptions along the planning process (Fig. 1, b). In addition, 3D digital environments are rarely designed to initiate creative thinking helping to move beyond ordinary ideas (Fig. 1, c) nor to support multiple sensory experiences to understand emotions driving human behaviour (Lerner, Li et al. 2015) and build a sense of agency (Brügger, Demski et al. 2021) (Fig. 1, d), thus unable to support a value-driven informed navigation towards sustainability. Without in-depth usability assessments, they are often unable to integrate various worldviews and the influence of values, norms, and beliefs anchored in cultural contexts on the decision processes, hindering their ability to make changes that deeply effects community, culture and society (Fig. 1, e). A full integration of knowledge about SETS contexts of actions with the 'inner worlds' of stakeholders in an iterative participatory or collaborative process is known to allow negotiating goals and co-producing knowledge (Grêt-Regamey, Switalski et al., 2021). Seminal work in landscape aesthetics have also highlighted the importance of integrating biological laws with cultural rules and personal strategies (Bourassa, 1991). Some 3D digital environments allow stakeholders to influence the outcomes by modifying the underlying modeling (White, Wutich et al. 2010, Schroth, Pond et al., 2011), in particular in the area of risk management (Spaulding, Grilli et al., 2016, Fenech, Chen et al., 2017, Stempel and Becker, 2019), but they do not adapt to changing stakeholders' values, beliefs, and perceptions, and thus do not allow co-evolution with the changing SETS domains (McPhearson, Cook et al., 2022) (Fig. 1, f).

Against these knowledge gaps and based on global exemplars, in this Perspective we discuss key factors that we identify as crucial when developing and using 3D digital environments (Fig. 1). We derive the six factors from the concept of coupled SETS allowing to define points of interventions in complex systems, where 3D digital environments can



**Fig. 1.** Current gaps (a-f) and suggested key factors (kf) to consider when developing and using 3D digital environments for enhancing efficacy in transformative landscape and urban planning.

help steer such systems even under uncertain futures. We go through the technological solution and the application context of our exemplars following Eilola et al. (2023) who, based on a systematic mapping of literature, suggest a framework for developing and reporting the application of 3D digital environments in the context of communicative urban and landscape planning. The four main categories in the framework include: (1) the digital 3D tool production tackling the question on how and based on what information the 3D digital environment is produced and which preconditions it sets to visualization content, (2) user interface addressing how the 3D digital environment is conveyed to the users, thus, conditioning the human–computer interaction, immersiveness of the 3D experience, and human-to-human communication, (3) communicative engagement, specifying for what kind of stakeholder engagement the 3D digital environment is intended for, and (4) planning context laying out for what kind of planning contexts and purposes the 3D digital environment is intended for (Table 1). We focus on development pathways, where SETS perspectives are mutually considered (McPhearson, Cook et al., 2022), recognizing feedback effects and nonlinear changes, and prioritizing learning and communication (Elmqvist, Andersson et al. 2019). We consider these key factors to be crucial to go beyond the current state of the art and practice and to advance the application of digital 3D technologies in a way that actually supports navigating the dynamics of human–environment relationships.

## 2. Key factor #1: Engage with the SETS relationships that shape the system

Unprecedented sustainability challenges require a better understanding of the complex and evolving links between the SETS domains (Rockström, Steffen et al., 2009, McPhearson, Cook et al., 2022). Failure to recognize these SETS coupling and feedback can lead to significant environmental problems and the failure of solutions (Carpenter, Mooney et al., 2009, Reyers, Folke et al., 2018). While social-ecological systems science has made good progress in highlighting the interactions connecting social and ecological systems (Fischer, Gardner et al., 2015), less progress has been made in developing and implementing practical approaches that accommodate, or even feature, the interdependencies and the complex and dynamic relationships between people and the planet (de Vos, Biggs et al., 2019) and their changes across life-span and geographical locations (Kendal and Raymond, 2019). Many researchers have recognized the need to take a co-production approach (Mastrángelo, Pérez-Harguindeguy et al., 2019, Norström, Cvitanovic et al., 2020, Bruley, Locatelli et al., 2021), but the plurality of knowledge and methods challenges the integration across the dimensions. Moreover, current digital tools put forward a unidirectional approach by showing a physical 2D or 3D design or a plan and asking people's opinions, views and reactions that it elicits. However, such an approach typically does not allow for evaluation of the proposals and feedback of changes, hindering the co-creation of solutions (Salliou, Arborino et al., 2023). Engaging with SETS relationships provides thus an essential entry point to facilitate the understanding of the complex interplay between humans and their environment, as well as the backbone to guide the efficacy of 3D digital environments for transformation towards sustainability (Fig. 2).

An iterative loop between design and science has been shown to foster a collective and creative process, where science can engage with actions (Nassauer and Opdam, 2008, Musacchio, 2009, Childers, Cadenasso et al., 2015), generating a means to deliberate and negotiate conflicting goals (Walliss and Rahmann 2016). Geographic Information Systems (GIS) and Computer-Aided Designs (CAD) have opened new options to evaluate designs (Steinitz, 2012) and scenarios (Vollmer, Costa et al., 2015). Design and plans can be manipulated in real-time and real agents can add and remove elements in the landscape and directly evaluate the change in the performance of the designs. This requires common syntaxes such as codes and patterns (Cantrell and Mekies, 2018) and a common digital language to allow communication

between disciplines (Urech, Dissegna et al. 2020). Each system has, however, its own interface and thus generates its own cognition and emotional responses with associated issues of uncertainty, credibility, and bias in interpreting the imagery (Kostelnick, McDermott et al. 2013, Stempel and Becker, 2019). Credibility is not enough to consider something scientific, but needs to encompass ideas related to legitimacy and authority (Stempel and Becker, 2021). This entails careful evaluation of the diversity and inclusivity in 3D environments, including representation of different cultures, genders, and backgrounds (Sheppard and Cizek, 2009, Saldias, Reinke et al., 2021), as well as conducting extensive monitoring of the reached outcomes (Stempel and Becker, 2019).

Furthermore, harnessing the feedback systems between the various dimensions to understand transformative potentials of the systems not only calls for understanding the interactions between systems' components but to assess how the system can reorganize itself to balance control with functionality (Elsawah, Filatova et al., 2019). This requires coupling the design technologies with simulation models to allow assessing changes in system structures and their effects on the development pathways. Co-evolutionary social-ecological models have seen important developments in the last decade (Gross, 2010, Herrera, Cosenza et al., 2011) but have not yet been coupled with immersive, communication tools, thus providing interesting developments to allow negotiating adaptation and transformation pathways of complex SETS in a co-production process (Norström, Cvitanovic et al., 2020). Such a process is also expected to support transformative learning rather than achieving a particular, pre-defined outcome (Boström, Andersson et al., 2018). However, informed digital environments per se do not guarantee an understanding of the transformation process, nor do they ensure that people comprehend how they will respond to these changes in real-time. Factors such as the '3Ds' (disclosure, drama, and defensibility) of (Sheppard, Shaw et al., 2008) are essential to consider when implementing such processes. As with any interactive 3D visualizations, this necessitates not only an awareness of the fine balance between persuasiveness, knowledge and certainty in people's perceptions of visualizations (Stempel and Becker, 2021), but also a thoughtful attention to issues related to tracking and recording of individual actions. In 3D digital environments, individuals may have their actions and interactions tracked and recorded, especially when these environments are used in social or work settings. Privacy and surveillance aspects are becoming more prominent, particularly also in the context of AI utilization (Jobin, Ienca et al., 2019).

### 2.1. Singapore – Designing and planning for nature-based urban cooling

Point cloud technologies provide a unique medium for 3D representation and shaping of landscapes (Girot, 2020). They are not just a data structure, but both a representation of a space and the physical environment, allowing for complex computational design thinking approaches (M'Closkey and VanDerSys, 2017). Beyond their function of representing the current situation in a realistic manner, they can be manipulated to represent future landscape scenarios (Urech, Dissegna et al., 2020). The point clouds collected using Terrestrial Laser Scanner (TLS), Airborne Laser Scanner (ALS) or Unmanned Aerial Vehicles (UAV), can be manipulated, their features extracted and reconstructed to create new designs. This same information can be used to evaluate the performance of the design. Such an iterative feedback loop between design and science has been developed for assessing thermal comfort in Singapore, a tropical city experiencing strong urban heat island effect.<sup>1</sup> (Salliou, Arborino et al., 2023). New neighborhoods with open spaces coming along with various types of greenery can be composed and evaluated using the absorbed energy of solar radiation by urban surfaces

<sup>1</sup> Singapore 3D digital environment (kf#1 (see Appendix A)): [https://www.youtube.com/watch?v=ugn3M9Ur\\_IU](https://www.youtube.com/watch?v=ugn3M9Ur_IU).

Table 1

Descriptions of 3D digital environments used in the global exemplars reflected through the four-category framework developed by Eilola et al. (2023).

Descriptions of 3D digital environments used in the global exemplars.	Digital tool production How and based on what information the 3D digital environment is produced and which preconditions it sets to visualisation content?	User interface How is the 3D digital environment conveyed to the users thus conditioning the human-computer interaction, immersiveness of the 3D experience and human-to-human communication?	Communicative engagement For what kind of stakeholder engagement the 3D digital environment is intended for?	Planning context For what kind of planning contexts and purposes the 3D digital environment is intended for?
	<b>Processing platform</b> Source data Visual realism Open sourcing	<b>Platform for viewing</b> Display type Real-time 3D technology User functions	<b>Participants engagement<sup>1</sup></b> Medium of communication Form of collected data	<b>Administrative or geographic scale</b> Visualised situation End user groups <sup>2</sup> Knowledge needs <sup>3</sup> Purposes of using the tool
kf#1 Singapore Designing urban cooling	3D game engine point clouds photo-realistic code	3D game engine 2D screen real-time 3D rendering design building scenarios using point cloud tool, change view perspectives	collaboration digital external platform scenario creation	neighbourhood hypothetical planners/citizens/ public sector converging facilitate understanding, discussion
kf#2 Zürich, Switzerland Linking the above- and belowground	3D game engine point clouds photo-realistic code	3D game engine VR goggles pre-rendered change view perspectives	participation computer application with virtual reality goggles questionnaire	city current planners/ citizens / public sector diverging/converging facilitate understanding
kf#3 Madagascar Visioning the forest-frontier	R studio and python Google street view or photographs mixed, photo-realistic code	web platform paper, 2D or VR goggles pre-rendered modify source data (images) using various sketching tools, change view perspectives	collaboration digital external platform or paper collage vision creation	landscape hypothetical villagers converging discussion, co-creation
kf#4 Switzerland Accelerating the energy transition	3D game engine point clouds photo-realistic code	3D game engine VR goggles pre-rendered change view perspectives, single 3D view perspective, rate stimuli	participation computer application with virtual reality goggles electro-dermal sensor	landscape hypothetical citizens diverging collection of preferences and emotions related to scenarios
kf#5 Turku, Finland Co-designing broadly accepted city blocks	3D city model with survey tool point clouds, oblique aerial photos photo-realistic data	web browser 2D screen real-time 3D rendering change view perspectives, pre-determined fly-through, select buildings or open boxes, place ideas with map markers	participation digital external platform questionnaire	landscape current and future experts diverging feedback collection, facilitate understanding, discussion tool
kf#6 Canada Customizing for climate change adaptation	GIS, 3D city model simulations, photos non-realistic, photo-realistic data	analog, web browser poster, slides, 2D screen pre-rendered change view perspectives in the virtual globe	participation non-digital medium, online questionnaire questionnaire	one city block current and future citizens diverging Collection of preferences for future development

<sup>1</sup>Mode of communicative engagement: Participation (par) refers to working and communicating with a broad public and collaboration (col) means working in small, selected groups (Staffans et al., 2020). <sup>2</sup>End user: Defined as people who are envisioned as those who will use the 3D digital environment to involve others or who will themselves use it to participate independently or take part in collaborative activities (Eilola et al., 2023). <sup>3</sup>Knowledge needs: Diverging (div) knowledge refers to opening up planning to multiple voices and converging (conv) knowledge refers to closing down and assessing the value of generated knowledge and ideas (Staffans et al., 2020).

and vegetation (Dissegna, Yin et al., 2019) to understand the performance of new urban development options best adapted to the climatic situation. This workflow was embedded in a Unity-based game engine environment (Virtanen, Daniel et al., 2020) to support a collaborative process in a user-friendly real-time interaction facilitated by a 2D screen. It allows citizens and planners in Singapore not only to get information about the performance of the suggested future developments and a deeper understanding of the quality and aesthetics of that space but to discuss advantages and disadvantages of the scenarios. Developing long-term performing solutions would, however, require linking design-based user-interface to coupled SETS models to allow understanding future climate and socio-economic changes and their impacts on the design. A first step would be to link such design-based coupled models to an interactive visual user-interface. Fed by increasingly available LiDAR data, such platforms could allow stakeholders to engage with the relationships that shape the system, and ultimately create, innovative, adaptive, value-driven sustainable solutions.

### 3. Key factor #2: Consider cross-scale dynamics

SETS are increasingly intertwined across spatial and temporal scales (Cash, Adger et al., 2006). Ignoring these linkages can lead to unexpected outcomes (Gunderson and Holling, 2002, Al-Sehrawy and Kumar, 2020), jeopardizing adaptation and transformation towards

sustainability. What appears to be stable at one scale can become an abrupt change or a random variability at another scale. For example, local urban systems strongly driven by global trade, international institutions, finance, communication and information flows need to be considered in the frame of dynamic global processes to enable development towards sustainability (Seto, Reenberg et al., 2012). Tools used in landscape and urban planning, however, mostly provide an understanding of local, place-based processes rather than communicating the interconnectivity and interdependence of the SETS across spatial and temporal scales. While current digital tools have made rapid advancements in representing current situations in real-time through digital twins (Batty, 2018, Al-Sehrawy and Kumar, 2020), failure to communicate short and long-term dynamics across space and time will not allow developing novel governance arrangements that allow to steer the complex SETS. Embedding contextualized, localized systems into global and local interconnectivities has potential to allow identifying threshold effects with significant large-scale consequences including high costs or irreversible changes (Liu, Mooney et al., 2015, Leach, Reyers et al., 2018).

There is a need to move beyond a focus on specific places as such and consider how patterns and processes of places are affected by interactions across scales. While tools exist to estimate the impacts of interventions across scales, such as footprint calculators (Čuček, Klemeš et al., 2012, Batty, 2018, Al-Sehrawy and Kumar, 2021), they do not

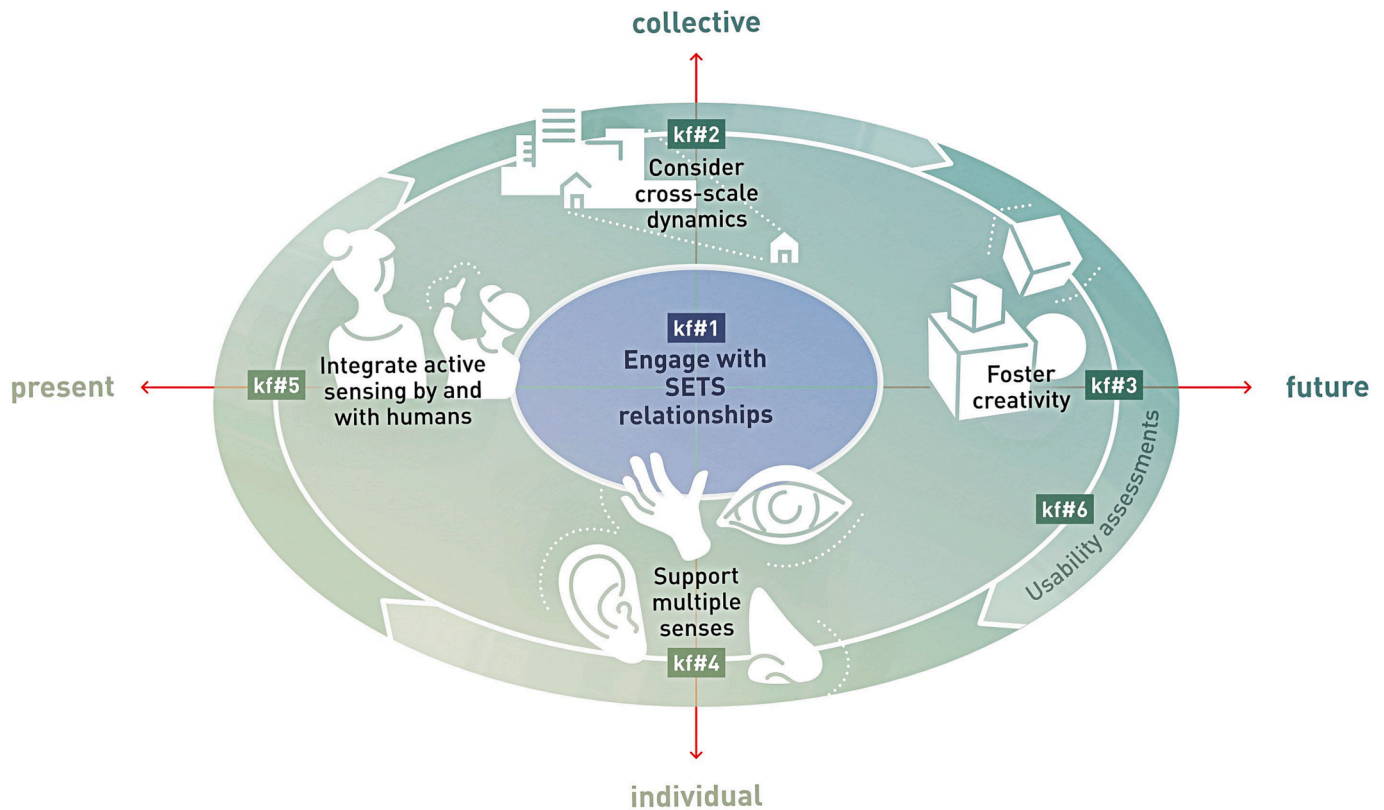


Fig. 2. Six key factors and their interconnections for applying 3D digital environments to help steer transformation towards sustainability.

integrate the multiple scales and their respective interactions. Nested frameworks, such as the one described by Ostrom (2007), would allow for disentanglement of interactions and resulting outcomes across time and place, but lack their operationalization in digital planning tools. 3D digital environments used in landscape and urban planning have addressed multiple connected scales by using zoom and pan functions in web map interfaces, but this does not enable an understanding of the dynamic interactions between scales. Dynamic integration across temporal and spatial scales would require linking global and local SETS simulation models and embedding such models in a design user-interface. Initial endeavors have been undertaken by the Global Climate Geodesign Challenge (IGC, 2023), and planning has taken initial steps to link immersive datasets across space to create a new understanding of the 3D connections of space above and below ground. Such linkages of systems demonstrate the importance of connecting disparate systems, especially in urban development where below ground development is often not coordinated with above ground plans and activities. However, developing such cross-scale dynamic digital environments for informed decision-making has still a long way to go. Besides the lack of data at similar temporal and spatial scale, cross-sectoral simulation models, such as Land-Use Transport-Interaction (LUTI) models (Lopane, Kalantzi et al., 2023), are often only informative for experts, and the processes not transparent and prepared in such a way that they are accessible to everyone (Nasr-Azadani, Wardrop et al., 2022) (see Fig. 2), leading to discrimination and exclusion of stakeholders in the decision-making process.

### 3.1. Zürich, Switzerland – Integrating above- and below ground planning

LiDAR datasets at various scales are increasingly available worldwide (Kakoulaki, Martinez et al., 2021). However, these include mostly above ground data. The subsurface datasets, which are distributed in various consulting or management offices, are often heterogeneous, inaccessible, and usually not yet linked to the above ground information.

In particular in dense cities, where lots of services are moved to the underground in order to meet the many and growing needs for space, an uncoordinated development above and below ground can hinder the development of green and blue infrastructures, which need an intact underground structure (Law, Ng et al., 2021). A first digital twin has been developed for the city of Zurich, linking above and below ground LiDAR data in a Unity-based game engine environment (Virtanen, Daniel et al., 2020), making it possible to navigate through the space and assess the impact of development in the space (Vollmer and Girot, 2023). Especially the new city department specialized in planning urban trees requires a detailed understanding of the soil structure in the city to implement their goals of significantly increasing the numbers of trees until 2029 (Schubert, 2021). The 3D point cloud not only allows for the visualization of detailed urban forms, vegetation, and underground structures but also for a spatial experience in motion when navigating through space with virtual reality goggles. The pre-rendered multi-dimensional integrated “x-ray” of the landscape allows the subsurface to be visible and legible.<sup>2</sup> This is not only useful for planners and the public sector to implement climate adaptation measures, but also for citizens to support an informed dialogue about the importance of unsealed green surfaces in urbanized environments. However, such an integration across space only offers a limited perspective on cross-scale dynamics and fails to adequately represent the temporal, institutional, jurisdictional, management, and knowledge aspects that are crucial for understanding and guiding SETS interactions. An important next step would be to understand the dynamical relationships between the points cloud themselves and eventually link these dynamics across spatial and temporal scales, as recently shown using computational design thinking, to create new adaptive landscapes (Fricker and Kotnik, 2023).

<sup>2</sup> Zürich 3D digital environment (kf#2 (see Appendix A)): <https://www.youtube.com/watch?v=oSDSuTmg1Y4>.

#### 4. Key factor #3: Foster imagination beyond the ordinary

Complex sustainability challenges are interconnected and require more than incremental steps in relation to the current entrenched nature of unsustainable SETS (Díaz, Settele et al. 2019). It is not enough to continue applying good solutions that have already been invented but still work; the challenge is that a fundamental reconfiguration and rewiring of the focal system is required to find new transformative and resilient solutions (Elmqvist, Andersson et al. 2019). Radical change is often characterized by a fundamental reorganization of the structure and functioning of SETS (Fedele, Donatti et al. 2019, Palomo, Locatelli et al. 2021). This requires not only a reorganization of the structures and functions of a system, but is also accompanied by changes in values, norms, beliefs, and governance. However, innovation and action often accompany changes in social or ecological systems, leaving out radical changes in human-environment interactions. Triggering disruptive, radical change requires creative ideas supported by individuals or communities, especially when the idea aligns across scales and among diverse actors (Folke, Polasky et al. 2021). Highly interactive, creative co-development processes have been shown to lead to shared values among stakeholders and enable transformative thinking about the future (Bennett, Solan et al. 2016, Merrie, Keys et al. 2018, Pereira, Davies et al. 2020) (see Fig. 2).

In the context of urban and landscape planning, immersive digital tools have high potential to support creative thinking for sustainability transformation in SETS (Sheppard, Shaw et al., 2011, Merrie, Keys et al., 2018). Such tools have been shown to allow making the information more understandable and salient. Furthermore, they can trigger affective responses that are relevant and motivating, and ultimately, bolster creativity and a sense of agency with the challenges represented (Nicholson-Cole, 2005). Current game engines allow to fully engage people with the surrounding environment. With their high level of realism and their interactive environments, they increase the identification of the user with the situation (Al-Kodmany, 1999, Hayek, 2011, Tobias, Buser et al., 2016), and can help reach a higher level of participation on Arnstein's ladder (Nasr-Azadani, Wardrop et al., 2023). They can act as boundary objects between different stakeholders and within communities allowing to improve the shared understanding of a situation (Hadar, Orenstein et al., 2021), and deliberate about long-term uncertain futures (Schroth, Pond et al., 2011). In particular, when critical local situations are to be negotiated, maintaining ambiguity can help people develop ideas by providing projection surface for interpretation (Schumann, Strothotte et al., 1996, Prats and Garner, 2006). However, it is crucial to maintain transparency regarding the creative nature of these endeavors and the role of scientific information and technological feasibility in their development. Attention should be given in particular to overstatements related to knowledge and certainty of the performance of these new solutions (Kostelnick, McDermott et al., 2013).

##### 4.1. Madagascar – Visioning the forest-frontier

To illustrate how digital tools can help design new, creative futures that can also be disruptive compared to the status quo, we present a case from rural Madagascar (Celio, Andriatsitohaina et al., 2023). The biodiversity-rich forest has been protected, restricting land access for farmers and exacerbating conflicts between cash crop cultivation (vanilla and cloves), subsistence farming (paddy and upland rice growing in shifting cultivation systems), and biodiversity conservation (Schneider et al., 2022). Swiss and Malagasy scientists supported by villagers organized a visioning process to identify tangible transformative factors strengthening inhabitants' capacity to act using the visioning tool 'sketchtool' (<https://sketchtool.ch/>). The digital tool enables 360° Google Street View images or photographs to be manipulated to create visions. The images can be preprocessed using Generative Adversarial Networks, a type of generative deep learning model, to generate generic views of a landscape type. Users can manipulate the scenes by adding

landscape elements such as trees, hedgerows, buildings, roads, and infrastructure, or take a more disruptive approach by removing buildings or other landscape elements. The visioning tool allowed communities to co-create one shared vision per village representing their desired futures.<sup>3</sup> As electricity was missing in the village, the visioning elements were pre-generated and transformed into collage material allowing to generate scenes in a paper format, similar to the scenes one would have generated with the tool. A follow-up reconstruction of the visions allowed to see the future land use developed in VR goggles. In conjunction with a land use model, the visions enabled discussion of different development pathways and the socioeconomic and environmental conditions necessary to achieve the visions. New shared ideas were generated and deep values could be discussed that influenced stakeholders' decision-making.

#### 5. Key factor #4: Support multiple senses

Emotions are known to modulate human decision-making (Lerner, Li et al., 2015). Understanding the role of and harness the emotions, thoughts, identities and beliefs of individuals to drive human behavior is, however, highly challenging (Heberlein, 2012). The feeling of being attached to a place has, for example, been shown essential for modifying environmental behavior (Lewicka, 2010). In contrast, a loss of emotional feelings is highly correlated with low place attachment, and ultimately low social cohesion, and engagement with places (Grêt-Regamey and Galleguillos-Torres, 2022) (Hayek, 2011). While emotional feelings can be triggered by visualizations (Daniel and Meitner, 2001, Nicholson-Cole, 2005), they alone do not define perception. Research is showing that there exists a broad range of sensory and non-sensory pathways influencing nature experiences (Hunter, Eickhoff et al., 2010, Stuster, 2011). The sum of visual (sight), auditory (sound), olfactory (smells), and tactile (touch) inputs are often greater than their individual effects (Reyers, Moore et al., 2022). Supporting multiple senses is thus essential to trigger 'deep leverage points' (Abson, Fischer et al., 2017, Fischer and Riechers, 2019, Ives, Freeth et al., 2020) or, in other words, the 'inner world' of sustainability (O'Brien, 2018).

While the film, video, and gaming industries have begun to harness the various senses to elicit emotions (Obriest, 2015), landscape and urban planning has focused on visually conveying the benefits of nature, including reducing stress or anxiety (Ulrich, 1979, Moore, 1981). However, recent studies have shown the importance of incorporating visual, auditory, and even olfactory features when examining the perception of urban and landscape scenes (McClean, 2016, Hedblom, Gunnarsson et al., 2019, Grêt-Regamey and Galleguillos-Torres, 2022). Immersive multi-sensory VR tools not only facilitate dynamic experience-based evaluation of space, but have been shown to increase emotional responses to design proposals (Meenar and Kitson, 2020) and are effective in activating place-making (Globo, Beza et al., 2022). Incorporating multiple senses when conveying information also enhances memorization, and learning (Aggleton and Waskett, 1999), which is essential for supporting radical changes. While, technically visualizations have been successfully linked to auditory information (Manyoky, Wissen Hayek et al., 2014), olfactory and tactical representations have not yet found their way into daily planning. Computer-generated odors are still cumbersome and expensive, and information on the olfactory characteristics of different landscapes is lacking. However, rapid developments in the media industry provide exciting avenues to deepen our understanding of the role of senses in triggering changes in individual beliefs, values, worldviews, and eventually paradigms of thoughts associated with radical change (O'Brien, 2018) (see Fig. 2).

<sup>3</sup> Madagascar 3D digital environment (kf#3(see Appendix A)): <https://poly-box.ethz.ch/index.php/s/ESuNYWBPdvgWnJw>.

### 5.1. Switzerland – Accelerating energy transition through emotions

To increase the share of renewable energy resources, new infrastructures need to be built in the landscapes. In most democratic countries, this requires acceptance of the new infrastructures. In Switzerland, the current energy crisis has led to a modification of the energy act, allowing rapid implementation of new infrastructures in mountain areas. Such radical changes can, however, only be implemented with the support of local communities. Linking acoustic and visual information to investigate individual's preferences for the new landscapes provided the basis for developing a national spatial strategy for renewable energy infrastructures (Spielhofer, Fabrikant et al., 2017, Spielhofer, Hunziker et al., 2021). Visual 3D point cloud scenes were linked to acoustic information of the landscape and the new infrastructures in a Unity-based game engine environment (Virtanen, Daniel et al., 2020) to determine citizen's preferences for renewable energy systems in different landscape types.<sup>4</sup> In addition to assessing landscape qualities, participants' physiological (electrodermal) responses using skin conductance sensors to the pre-rendered hypothetical landscapes with varying levels of renewable energy were examined. After each stimulus, participants were also asked to rate their emotions using a controller that appeared in the VR as a laser, pointing at different standardized pictures, allowing to measure valence (from happy to unhappy) and arousal (from excited to calm). The collected information showed that the coherence of the visual and acoustic signals of the infrastructure with the surrounding landscapes was crucial for the choices. Understanding the influences of new infrastructures on multiple senses is therefore key to implementing radical changes in landscapes. However, visualizing the future and measuring people's current emotions does not consider changes in social-ecological interactions in the future. Participants' views on climate change, for example, can increase their feelings of urgency to deal with the matter (Sheppard, 2005), but does not represent the attitudes of future generations towards future changes.

## 6. Key factor #5: Integrate active sensing by and with people

Transformative changes take place across three interacting spheres, the practical sphere including realized planning interventions, the political sphere encompassing regulatory instruments, institutions and community engagement processes for governing transformation, and the personal sphere with individual beliefs, values and worldviews (O'Brien, 2018). When it comes to accelerating sustainability transformations, however, the latter of the three spheres, the personal, has the largest potential for supporting *current* transformation as it encompasses the two others (see Fig. 2). This calls for the integration of intentional and unintentional active sensing by and with non-experts into 3D digital environments. The consideration of different perspectives is essential to support the radical and multi-dimensional transformation processes and the development of broadly accepted solutions (Grêt-Regamey, Switalski et al., 2021).

The integration of active sensing into 3D digital environments needs to be customized depending on the purpose of communication (participation vs. collaboration), the engagement (Billger, Thuvander et al., 2017), the phase of planning process (goal setting, visioning, plan making, evaluation, finalization, monitoring) (Staffans, Kahila-Tani et al., 2020), and the competency of participants. Until now, 3D visualizations in landscape and urban planning have mostly been used for communication in participatory processes rather than for negotiating various perspectives in collaborative settings (Eilola, Jaalama et al., 2023). For example, non-realistic 3D digital environments can help people focus on various attribute or spatial data aspects when analysing

the planning area, while realistic 3D environments are useful in understanding the causes and effects of developments (Hayek, 2011). Actual ways of gathering data that reflect the beliefs, values and perceptions of people are multiple and commonly include creating models or scenarios in the digital environment, responding to questionnaires or voting on planning options realized inside the digital interface or outside of it, recording discussions of the participants or interviewing them. Their integration into 3D digital environments is, however, rare, but shows high potential for enhancing the recognition of and work with indigenous and local knowledge systems (Eilola, Käyhkö et al., 2021), and supporting negotiation processes. Interestingly however, several authors (Schroth, 2010, Nasr-Azadani, Wardrop et al., 2022) have demonstrated that highly sophisticated technologies have been applied less frequently in higher levels of participation, arguing that the need for complex visualization techniques decreases with competencies. Therefore, it is essential to address the tendency to overestimate the role of digital environments in acceptance procedures. The emotional feedback collected in the virtual realms will very likely not match real-life processes, as "what you see is not always what you get" (Downes and Lange, 2015, Groulx and Lewis, 2019), and should thus only be used to open options for collaborating and negotiate goals, beliefs, and values.

### 6.1. Turku, Finland – Co-designing broadly accepted city block plans

The city of Turku, Finland, has successfully integrated active sensing into a 3D digital environment to facilitate a detailed participatory spatial planning process of the city with planners, technology companies, and researchers (Eilola, Käyhkö et al., 2021). A photorealistic 3D city model with integrated survey tool was promoted to the citizens to gather their views and preferences regarding the future development of a specific city block.<sup>5</sup> The 3D digital environment was produced integrating the technologies of the two companies, namely by using open access point cloud and oblique aerial photo data in a browser-based 3D city model to which a map-based survey component was integrated to allow place-based commenting of different types of future preferences. Using their mobile phone or computer, any Turku citizen could respond to the novel type of web browser-based survey integrating immersive 3D visualization. The participatory process was linked to the draft preparation phase of the detailed planning in the area and the gathered citizen data used as material in the subsequent architectural and real estate development competition. The communicative action was targeted to get to know the area and to provoke the individual preferences and values. To foster these aims, the platform allowed to freely change view perspective, take a predetermined fly-through around the area, to switch on planned buildings or open information boxes, and most importantly, place future subjective preferences using map markers (i.e. supporting a 3D Public Participation GIS approach). The researchers involved also developed analysis methods for treating the new type of 3D PPGIS data gathered (Hasanzadeh, 2023, submitted). The 3D city model of Turku will be an integral part of urban planning process in the future and the planners stated the innovative participatory process, realized in public-private-academia collaboration, gave valuable insights on how 3D digital environments can be used with citizens. One ultimate aim for the planners was also that the visually effective participatory process would enhance understanding of change that the plan area was going to face and potentially enhancing acceptability of it. Such exemplars, however, also highlight the need to overcome the digital divide and increase accessibility to disadvantaged groups (Bouzuenda, Fava et al., 2022), which is discussed in more details in key factor #6.

<sup>4</sup> Switzerland 3D digital environment (kf#4 (see Appendix A)): <https://polybox.ethz.ch/index.php/s/ESuNYWBPdvgWnJw>.

<sup>5</sup> Turku 3D digital environment (kf#5(see Appendix A)): <https://new.map-tionnaire.com/q/4bzs27mcb38c>.

## 7. Key factor #6: Provide usability assessment

Transformation towards sustainability requires the engagement of the users in a co-production process (Turnhout, Metze et al., 2020). Some actors have, however, often more time and resources, knowledge and skills, enabling them to shape the process to serve their interests. Designing various types of 3D digital environments that allow the engagement of the broad population, including marginal actors, calls for a careful co-design of the tools and a testing phase in which tools can be experimented in various institutional spaces (Lovett, Appleton et al., 2015; Zhang, Geertman et al. 2019). As the 3D digital environment will contain high information density, in particular if supported by real-time information or interactivity (factor #1), dynamic interactions between scales (factor #2), or by functions to trigger creative thinking (factor #3) and support multiple senses (factor #4), it will need to fulfill key user requirements including user friendliness, accessibility and tools for active user involvement. In addition, evidence shows that in 3D digital environments some people have perceptual challenges including experience of discomfort such as simulator sickness or eye strain (Lambooj, Jsselsteijn et al., 2009; McIntire, Havig et al., 2014), challenges in the depth perception (Biland and Çöltekin, 2017), or simply experience the challenge of not seeing in stereo in 3D (Ware, 2004). Although people may consider 3D virtual landscape visualizations more explanatory compared to 2D maps in landscape planning (e.g. (Virtanen, Daniel et al., 2020)), some participants can experience cognitive challenges including varying ability to cope with the information offered in the 3D environment (Huk, 2006). Previous exposure with 3D gaming technologies might increase the performance in 3D digital environments giving an indication that training has potential to tackle some of the challenges (Green and Bavelier, 2007; Sungur and Boduroglu, 2012). However, contrasting evidence also shows that interest in games and gaming has not affected the way a person perceives a 3D geovisualization (Jaalama, Fagerholm et al., 2021).

Unfortunately, applied 3D digital environments do not necessarily include usability evaluations. A recent review by Eilola et al. (2023) highlighted that only half of the reviewed cases in communicative landscape and urban planning applying 3D visualizations with various stakeholders offered any, and often limited, indication of the usability of the applied tools and technologies. Billger et al. (2017) also highlight that most usability studies are experimental and prototype studies. Real planning process and implementation studies are exceptional (e.g. Salter et al., 2009), although good examples exist, such as the one by Lindqvist & Campbell-Arvai (2021) that highlights an iterative co-creation process of a 3D design tool for landscape planning involving of experts and citizens. However, the knowledge gap highlighted by Çöltekin et al. (2016) almost a decade ago still remains a key issue: there is no established understanding regarding what kind of data we should opt to show in the 3D digital environment, what type of representation we should use, for what task types, and for whom.

Usability assessments can advance understanding of which 3D digital environments are suitable for what type of communicative actions and planning contexts. Usability evaluations should address aspects such as effectiveness, efficiency and satisfaction in achieving specific goals or the appropriateness of the solutions offered (Bleisch, 2012). In designing user experience in human-computer interaction (HCI), usability evaluation methods can be categorized into: expert-based methods, participant-based methods (i.e., “user testing”), and data analytics (Benyon, 2019). In expert-based methods an expert evaluates a design or user interface (e.g. heuristic evaluation) while in participant-based methods empirical user testing is organized to examine how the interface is used for task completion and to gather direct user feedback. Data analytics methods are based on collecting computational user data (Benyon, 2019). A thorough usability assessment would secure that the tools support participation and collaboration of stakeholders in an effective co-production process.

### 7.1. City of Kimberley, Canada – Customizing 3D digital environments for climate change awareness

Schroth et al (2015) present a longitudinal study revising the long-term effectiveness of the use of different presentation formats including virtual globes in planning for climate change mitigation and adaptation in the city of Kimberley in Canada, including rising snowlines and changing hydrological regimes, forest pest infestations, and increasing fire season lengths. Photos and simulation results were integrated into GIS and a virtual globe model to communicate the vulnerability of the population to climate change. The process was evaluated using pre/post comparison of questionnaires, subjective ranking of the visualization media, structured in-depth user interviews, and, after 22 months, with phone interviews. The evaluation revealed among the majority of participants the added value and the effectiveness of the visualization in increasing awareness, understanding, adding depth to on-going deliberations, and surprisingly change in behavior towards and shared goal. However, the virtual globes were inaccessible for some participants, especially older people. A similar pattern was found in an urban 3D participatory e-planning process using virtual geographic environment, where spatial abilities strongly affected users' performance (Chassin, Ingensand et al., 2022). In analogy to monitoring the learning in transformative research to identify key features of transitions (Van Mierlo and Beers, 2020), more exemplars as well as a blueprint for the application of 3D digital environments to support transformation would allow to develop a body of knowledge to improve the capabilities of 3D digital environments to deal with changes.

## 8. Discussion and conclusions

3D digital environments have the potential to support democratic and knowledge-informed landscape and urban planning, but key factors must be met to ensure that the tools are useful and effective in guiding sustainable and equitable development pathways. In particular, we will need to (1) go beyond static representation and develop digital environments representing the dynamic interactions between SETS using a common language across the social, ecological, and technical perspectives, (2) investigate how design technologies can be coupled with simulation models to deal with spatial and temporal dynamics across scales, (3) increase creative features in the digital environments to enable shared understanding among stakeholders for radical changes towards sustainability, (4) activate visual, auditory, olfactory, and tactile cues to foster deep changes in sustainable environmental and social behavior, (5) customize the integration of active sensing by and with non-experts into 3D digital environments to enhance the recognition of indigenous and local knowledge systems, and last but not least (6) conduct a usability assessment to support participation and collaboration of stakeholders in an effective co-production process. Placing the overall approach of engaging with the SETS relationships that shape the system (kc#1) in the center stage (Fig. 1), the further development of 3D digital environments will need to bridge tensions between two axes: (1) from individual to collective actions by supporting multiple sense (kc#4) and considering cross-scales SETS dynamics (kc#2), and (2) from addressing present perceptions of the issues at stake by integrating active sensing by and with people (kc#5) to fostering creativity for a better future (kc#3). The validity of the developments will need to be conducted in a co-production process supported by a comprehensive usability assessment (kc#6).

How these key factors are put into practice will differ depending on the context, scale and challenge the actors are exposed to. The elaboration of common languages, for example, will need to consider different worldviews, knowledge, and skills (Nasr-Azadani, Wardrop et al., 2023). As such, the process is similar to working with boundary objects, which can frame the usability assessments and provide a solid nexus for communication and collaboration among disparate stakeholders to drive transformation through bridging conflicting logics without

ignoring diversity (Franco-Torres, Rogers et al., 2020). The efficacy of 3D digital environments will, however, strongly depend on who has power when decisions are made. Most of the 3D digital environments presented here could be used to empower citizens and operationalize the higher levels of Arnstein's ladder of citizen participation (Arnstein, 1969), but none of the exemplars generated processes that made them widely accessible. Furthermore, open access and worldwide data coverage will need to be fostered to support evidence-based decision-making and the monitoring of development progresses. In particular, when integrating active sensing into 3D digital environments, participants will need to be informed about the collection of their data and supported by informed consent forms and protected or anonymized to ensure privacy (Grêt-Regamey, Switalski et al., 2021). This connects also to the fast-developing AI technologies that embrace multiple risks, including transparency, privacy, bias, access, value lock-in and associated power-seeking behaviour, that have not been clearly articulated with respect to communicative urban and landscape planning (Chen et al., 2023). The development of technologies to deal with cross-scale dynamics will require new out-of-core rendering techniques, allowing to hold data outside the active computing memory, which are still in their infancy but are rapidly evolving in gaming technologies (Virtanen, Daniel et al., 2020), as well as increased data storage capacity. When creating features for visioning shared futures, we will need to explicitly recognize and address power and equity asymmetries and increase transparency and accountability in the process (Pascual, 2022), and finally there is a necessity to integrate our various senses in the 3D digital environments and even more importantly to develop new approaches to integrate the digital tools into analog processes, not excluding art performances and other communication means.

While younger generations are early-on exposed to 3D digital environments, the new technologies are only slowly percolating into conventional landscape and urban planning tasks. The creation of a physical and virtual knowledge platform bringing practitioners, researchers, developers and stakeholders together could be the basis to foster the adoption of the technological advancements and help development towards sustainability. Our intent is a call to (a) stimulate SETS thinking in the development of 3D digital environments, (b) motivate practitioners and researchers to work with the AI community to develop and implement guidelines and strategies tackling ethical challenges related to the use of 3D digital environments, and finally (c) exchange on technical standards and best practices of planning processes integrating 3D digital environments across disciplines to support public's full involvement across sectors and ultimately democratic legislation.

#### Declaration of competing interest

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

#### Data availability

Data will be made available on request.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.landurbplan.2023.104978>.

#### References

- Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., Von Wehrden, H., Abernethy, P., Ives, C. D., & Jager, N. W. (2017). Leverage points for sustainability transformation. *Ambio*, 46(1), 30–39.
- Aggleton, J. P., & Waskett, L. (1999). The ability of odours to serve as state-dependent cues for real-world memories: Can Viking smells aid the recall of Viking experiences? *British Journal of Psychology*, 90(1), 1–7.
- Al-Kodmany, K. (1999). Using visualization techniques for enhancing public participation in planning and design: Process, implementation, and evaluation. *Landscape and urban planning*, 45(1), 37–45.
- Al-Sehrawy, R., & Kumar, B. (2020). Digital twins in architecture, engineering, construction and operations. A brief review and analysis. *International Conference on Computing in Civil and Building Engineering*.
- Al-Sehrawy, R., & Kumar, B. (2021). Digital twins in architecture, engineering, construction and operations. A brief review and analysis. *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering: ICCCBCE 2020*.
- Alsop, T. (2022). "VR headset unit sales worldwide 2019-2024." *Statista*.
- Arnstein, S. R. (1969). A ladder of citizen participation. *Journal of the American Institute of Planners*, 35(4), 216–224.
- Batty, M. (2018). *Digital twins*, SAGE Publications Sage UK: London, England., 45, 817–820.
- Bennett, E. M., Solan, M., Biggs, R., McPhearson, T., Norström, A. V., Olsson, P., Pereira, L., Peterson, G. D., Raudsepp-Hearne, C., & Biermann, F. (2016). Bright spots: Seeds of a good Anthropocene. *Frontiers in Ecology and the Environment*, 14(8), 441–448.
- Benyon, D. (2019). *Designing user experience*. Pearson UK.
- Biland, J., & Çöltekin, A. (2017). An empirical assessment of the impact of the light direction on the relief inversion effect in shaded relief maps: NNW is better than NW. *Cartography and Geographic Information Science*, 44(4), 358–372.
- Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Çöltekin, A. (2015). Applications of 3D city models: State of the art review. *ISPRS International Journal of Geo-Information*, 4(4), 2842–2889.
- Billger, M., Thuvander, L., & Wästberg, B. S. (2016). In search of visualization challenges: The development and implementation of visualization tools for supporting dialogue in urban planning processes. *Environment and Planning B: Urban Analytics and City Science*, 44(6), 1012–1035.
- Bleisch, S. (2012). 3D geovisualization—definition and structures for the assessment of usefulness. *ISPRS annals of the photogrammetry, remote sensing and spatial information sciences*, 1, 129–134.
- Bordogna, G., Carrara, P., Criscuolo, L., Pepe, M., & Rampini, A. (2016). On predicting and improving the quality of Volunteer Geographic Information projects. *International Journal of Digital Earth*, 9(2), 134–155.
- Boström, M., Andersson, E., Berg, M., Gustafsson, K., Gustavsson, E., Hysing, E., Lidskog, R., Löfmarck, E., Ojala, M., & Olsson, J. (2018). Conditions for transformative learning for sustainable development: A theoretical review and approach. *Sustainability*, 10(12), 4479.
- Bourassa, S. C. (1991). *The Aesthetics of Landscape*. NY: Belhaven Press.
- Bouzuenda, I., Fava, N., & Alalouch, C. (2022). Would 3D digital participatory planning improve social sustainability in smart cities? An empirical evaluation study in less-advantaged areas. *Journal of Urban Technology*, 29(3), 41–71.
- Brügger, A., Demski, C., & Capstick, S. (2021). How personal experience affects perception of and decisions related to climate change: A psychological view. *Weather, climate, and society*, 13(3), 397–408.
- Bruley, E., Locatelli, B., & Lavorel, S. (2021). Nature's contributions to people: Coproducing quality of life from multifunctional landscapes. *Ecology and Society* 26.
- Cash, D. W., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., & Young, O. (2006). Scale and cross-scale dynamics: Governance and information in a multilevel world. *Ecology and society*, 11(2).
- Cantrell, B., & Mekies, A. (2018). *Codify: Parametric and computational design in landscape architecture*. Routledge.
- Carpenter, S. R., Mooney, H. A., Agard, J., Capistrano, D., DeFries, R. S., Díaz, S., Dietz, T., Duraiappah, A. K., Oteng-Yeboah, A., & Pereira, H. M. (2009). Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences*, 106(5), 1305–1312.
- Celio, E., Andriatsitohaina, R. N. N., Llopis, J. C., & Grêt-Regamey, A. (2023). Assessing farmers' income vulnerability to vanilla and clove export economies in northeastern Madagascar using land-use change modelling. *Journal of Land Use Science*, 18(1), 55–83.
- Chassin, T., Ingensand, J., Christophe, S., & Touya, G. (2022). Experiencing virtual geographic environment in urban 3D participatory e-planning: A user perspective. *Landscape and Urban Planning*, 224, Article 104432.
- Chen, M., Claramunt, C., Çöltekin, A., Liu, X., Peng, P., Robinson, A. C., ... Lü, G. (2023). Artificial intelligence and visual analytics in geographical space and cyberspace: Research opportunities and challenges. *Earth-Science Reviews*, 104438.
- Childers, D. L., Cadenasso, M. L., Grove, J. M., Marshall, V., McGrath, B., & Pickett, S. T. (2015). An ecology for cities: A transformational nexus of design and ecology to advance climate change resilience and urban sustainability. *Sustainability*, 7(4), 3774–3791.

- Çöltekin, A., I. Lokka, M. Zahner and L. Halounova (2016). On the usability and usefulness of 3D (geo) visualizations—A focus on virtual reality environments, ISPRS. Čuček, L., Klemes, J. J., & Kravanja, Z. (2012). A review of footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production*, 34, 9–20.
- Daniel, T. C., & Meitner, M. M. (2001). Representational validity of landscape visualizations: The effects of graphical realism on perceived scenic beauty of forest vistas. *Journal of Environmental Psychology*, 21(1), 61–72.
- Davoudi, S. (2012). The legacy of positivism and the emergence of interpretive tradition in spatial planning. *Regional Studies*, 46(4), 429–441.
- de Vos, A., Biggs, R., & Preiser, R. (2019). Methods for understanding social-ecological systems: A review of place-based studies. *Ecology and Society*, 24(4).
- Depietri, Y. and T. McPhearson (2017). “Integrating the grey, green, and blue in cities: Nature-based solutions for climate change adaptation and risk reduction.” Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice: 91-109.
- Diaz, S., Settele, J., Brondizio, E. S., Ngo, H. T., Agard, J., Arneeth, A., Balvanera, P., Brauman, K. A., Butchart, S. H., & Chan, K. M. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, 366(6471), eaax3100.
- Dissegna, M. A., Yin, T., Wei, S., Richards, D., & Grêt-Regamey, A. (2019). 3-D reconstruction of an urban landscape to assess the influence of vegetation in the radiative budget. *Forests*, 10(8), 700.
- Downes, M., & Lange, E. (2015). What you see is not always what you get: A qualitative, comparative analysis of ex ante visualizations with ex post photography of landscape and architectural projects. *Landscape and Urban Planning*, 142, 136–146.
- Eilola, S., Jaalama, K., Kangassalo, P., Nummi, P., Staffans, A., & Fagerholm, N. (2023). 3D visualisations for communicative urban and landscape planning: What systematic mapping of academic literature can tell us of their potential? *Landscape and Urban Planning*, 234, Article 104716.
- Eilola, S., Käyhkö, N., & Fagerholm, N. (2021). Lessons learned from participatory land use planning with high-resolution remote sensing images in Tanzania: Practitioners’ and participants’ perspectives. *Land Use Policy*, 109, Article 105649.
- Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K., & Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature sustainability*, 2(4), 267–273.
- Elsawah, S., T. Filatova, A. J. Jakeman, A. J. Kettner, M. L. Zellner, I. N. Athanasiadis, S. H. Hamilton, R. L. Axtell, D. G. Brown and J. M. Gilligan (2019). “Eight grand challenges in socio-environmental systems modeling.” *Socio-Environmental Systems Modelling 2*.
- Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L., & Hole, D. G. (2019). Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, 101, 116–125.
- Fenech, A., Chen, A., Clark, A., & Hedley, N. (2017). Building an adaptation tool for visualizing the coastal impacts of climate change on Prince Edward Island, Canada. In *Climate change adaptation in North America: Fostering resilience and the regional capacity to adapt* (pp. 225–238).
- Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., & Hughes, T. P. (2015). Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environmental Sustainability*, 14, 144–149.
- Fischer, J., & Riechers, M. (2019). A leverage points perspective on sustainability. *People and Nature*, 1(1), 115–120.
- Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., & Chapin, F. S. (2021). Our future in the Anthropocene biosphere. *Ambio*, 50, 834–869.
- Franco-Torres, M., Rogers, B. C., & Ugarelli, R. M. (2020). A framework to explain the role of boundary objects in sustainability transitions. *Environmental Innovation and Societal Transitions*, 36, 34–48.
- Fricker, P., & Kotnik, T. (2023). *Patterns of Interaction: Computational Design Across Scales*. Springer Nature.
- Gill, L., & Lange, E. (2015). Getting virtual 3D landscapes out of the lab. *Computers, Environment and Urban Systems*, 54, 356–362.
- Giroto, C. (2020). *Cloudism. Architecture and Nature*. Birkhäuser: 96-101.
- Globa, A., Beza, B. B., & Wang, R. (2022). Towards multi-sensory design: Placemaking through immersive environments—Evaluation of the approach. *Expert Systems with Applications*, 204, Article 117614.
- Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological science*, 18(1), 88–94.
- Grêt-Regamey, A., & Galleguillos-Torres, M. (2022). Global urban homogenization and the loss of emotions. *Scientific Reports*, 12(1), 22515.
- Grêt-Regamey, A., Switalski, M., Fagerholm, N., Korpilo, S., Juhola, S., Kyttä, M., Käyhkö, N., McPhearson, T., Nollert, M., & Rinne, T. (2021). Harnessing sensing systems towards urban sustainability transformation. *npj Urban Sustainability*, 1(1), 40.
- Gross, J. J. (2010). The future’s so bright, I gotta wear shades. *Emotion review*, 2(3), 212–216.
- Groulx, M., & Lewis, J. L. (2019). Merely “Design Marketing”? Professional Perspectives on the Use and Misuse of Environmental Visualizations in Community Engagement. *Journal of Planning Education and Research*, 39(3), 273–284.
- Gunderson, L. H., & Holling, C. S. (2002). *Panarchy: Understanding transformations in human and natural systems*. Island Press.
- Hadar, L., Orenstein, D., Carmel, Y., Mulder, J., Kirchoff, A., Perevolotsky, A., & Osem, Y. (2021). Envisioning future landscapes: A data-based visualization model for ecosystems under alternative management scenarios. *Landscape and Urban Planning*, 215, Article 104214.
- Hasanzadeh, K., Fagerholm, N., Skov-Petersen, H., & Olafsson, A. S. (2023). A methodological framework for analyzing PPGIS data collected in 3D. *International Journal of Digital Earth*, 16(1), 3435–3455.
- Hayek, U. W. (2011). Which is the appropriate 3D visualization type for participatory landscape planning workshops? A portfolio of their effectiveness. *Environment and Planning B: Planning and Design*, 38(5), 921–939.
- Hayek, U. W., Von Wirth, T., Neuenschwander, N., & Grêt-Regamey, A. (2016). Organizing and facilitating Geodesign processes: Integrating tools into collaborative design processes for urban transformation. *Landscape and Urban Planning*, 156, 59–70.
- Heberlein, T. A. (2012). *Navigating environmental attitudes*. USA: Oxford University Press.
- Hedblom, M., Gunnarsson, B., Irvani, B., Knez, I., Schaefer, M., Thorsson, P., & Lundström, J. N. (2019). Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Scientific Reports*, 9(1), 10113.
- Herrera, J. L., Cosenza, M. G., Tucci, K., & González-Avella, J. C. (2011). General coevolution of topology and dynamics in networks. *Europhysics Letters*, 95(5), 58006.
- Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of Computer Assisted Learning*, 22(6), 392–404.
- Hunter, M. D., Eickhoff, S. B., Pheasant, R. J., Douglas, M. J., Watts, G. R., Farrow, T. F., Hyland, D., Kang, J., Wilkinson, I. D., & Horoshenkov, K. V. (2010). The state of tranquility: Subjective perception is shaped by contextual modulation of auditory connectivity. *Neuroimage*, 53(2), 611–618.
- IGC, I. G. C. (2023). “The Global Climate Geodesign Challenge.” from <https://www-igcollab.hub.arcgis.com/pages/gcgc>.
- Ives, C. D., Freeth, R., & Fischer, J. (2020). Inside-out sustainability: The neglect of inner worlds. *Ambio*, 49, 208–217.
- Jaalama, K., Fagerholm, N., Julin, A., Virtanen, J.-P., Maksimainen, M., & Hyyppä, H. (2021). Sense of presence and sense of place in perceiving a 3D geovisualization for communication in urban planning—Differences introduced by prior familiarity with the place. *Landscape and Urban Planning*, 207, Article 103996.
- Jobin, A., Ienca, M., & Vayena, E. (2019). The global landscape of AI ethics guidelines. *Nature Machine Intelligence*, 1(9), 389–399.
- Kakoulaki, G., Martinez, A., & Florio, P. (2021). *Non-Commercial Light Detection and Ranging (LiDAR) Data in Europe*. Luxembourg: Publications Office of the European Union.
- Kendal, D., & Raymond, C. M. (2019). Understanding pathways to shifting people’s values over time in the context of social-ecological systems. *Sustainability Science*, 14, 1333–1342.
- Ketzler, B., Naserintin, V., Latino, F., Zangelidis, C., Thuvander, L., & Logg, A. (2020). Digital twins for cities: A state of the art review. *Built Environment*, 46(4), 547–573.
- Kostelnick, J. C., McDermott, D., Rowley, R. J., & Bunnyfield, N. (2013). A cartographic framework for visualizing risk. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 48(3), 200–224.
- Lambooi, M., W. IJsselstein, M. Fortuin and I. Heynderickx (2009). “Visual discomfort and visual fatigue of stereoscopic displays: A review.” *Journal of imaging science and technology* 53(3): 30201-30201.
- Law, K., Ng, F., Kwan, J., & Wong, J. (2021). An Exploration of the Planning Approach for New Development Area with Underground Space in Hong Kong. *IOP Conference Series: Earth and Environmental Science*. IOP Publishing.
- Leach, M., Reyers, B., Bai, X., Brondizio, E. S., Cook, C., Díaz, S., Espindola, G., Scobie, M., Stafford-Smith, M., & Subramanian, S. M. (2018). Equity and sustainability in the Anthropocene: A social-ecological systems perspective on their intertwined futures. *Global Sustainability*, 1, e13.
- Lerner, J. S., Li, Y., Valdesolo, P., & Kassam, K. S. (2015). Emotion and decision making. *Annual review of psychology*, 66(1).
- Lewicka, M. (2010). What makes neighborhood different from home and city? Effects of place scale on place attachment. *Journal of environmental psychology*, 30(1), 35–51.
- Lindquist, M., & Campbell-Arvai, V. (2021). Co-designing vacant lots using interactive 3D visualizations - Development and application of the Land. Info DSS. *Landscape and Urban Planning*, 210, Article 104082.
- Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., & Kremen, C. (2015). Systems integration for global sustainability. *Science*, 347(6225), 1258832.
- Lopane, F. D., Kalantzi, E., Milton, R., & Batty, M. (2023). A land-use transport-interaction framework for large scale strategic urban modeling. *Computers, Environment and Urban Systems*, 104, Article 102007.
- Lovett, A., Appleton, K., Warren-Kretzschmar, B., & Von Haaren, C. (2015). Using 3D visualization methods in landscape planning: An evaluation of options and practical issues. *Landscape and Urban Planning*, 142, 85–94.
- M’Closkey, K., & VanDerSys, K. (2017). *Dynamic patterns: Visualizing landscapes in a digital age*. Taylor & Francis.
- Manyoky, M., Wissen Hayek, U., Heutschi, K., Pieren, R., & Grêt-Regamey, A. (2014). Developing a GIS-based visual-acoustic 3D simulation for wind farm assessment. *ISPRS International Journal of Geo-Information*, 3(1), 29–48.
- Masalkhi, M., E. Waisberg, J. Ong, N. Zaman, P. Sarker, A. G. Lee and A. Tavakkoli (2023). “Apple Vision Pro for Ophthalmology and Medicine.” *Annals of Biomedical Engineering*: 1-4.
- Mastrangelo, M. E., Pérez-Harguindeguy, N., Enrico, L., Bennett, E., Lavorel, S., Cumming, G. S., Abeygunawardane, D., Amarilla, L. D., Burkhard, B., & Egoh, B. N. (2019). Key knowledge gaps to achieve global sustainability goals. *Nature Sustainability*, 2(12), 1115–1121.
- McIntire, J. P., Havig, P. R., & Geiselman, E. E. (2014). Stereoscopic 3D displays and human performance: A comprehensive review. *Displays*, 35(1), 18–26.
- Mclean, K. (2016). Towards a visual voice for smells. *Landsc Archit Front*, 4, 131–141.
- McPhearson, T., Cook, E. M., Berbés-Blázquez, M., Cheng, C., Grimm, N. B., Andersson, E., Barbosa, O., Chandler, D. G., Chang, H., Chester, M. V.,

- Childers, D. L., Elser, S. R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R. L., Iwaniec, D. M., Kabisch, N., Kennedy, C., Markolf, S. A., Matsler, A. M., McPhillips, L. E., Miller, T. R., Muñoz-Erickson, T. A., Rosi, E., & Troxler, T. G. (2022). A social-ecological-technological systems framework for urban ecosystem services. *One Earth*, 5(5), 505–518.
- McPhearson, T., Pickett, S. T., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., & Qureshi, S. (2016). Advancing urban ecology toward a science of cities. *BioScience*, 66(3), 198–212.
- Meenar, M., & Kitson, J. (2020). Using multi-sensory and multi-dimensional immersive virtual reality in participatory planning. *Urban Science*, 4(3), 34.
- Merrie, A., Keys, P., Metian, M., & Österblom, H. (2018). Radical ocean futures-scenario development using science fiction prototyping. *Futures*, 95, 22–32.
- Mondejar, M. E., Avtar, R., Diaz, H. L. B., Dubey, R. K., Esteban, J., Gómez-Morales, A., Hallam, B., Mbugu, N. T., Okolo, C. C., & Prasad, K. A. (2021). Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet. *Science of The Total Environment*, 794, Article 148539.
- Moore, E. O. (1981). A prison environment's effect on health care service demands. *Journal of Environmental Systems*, 11(1), 17–34.
- Musacchio, L. R. (2009). The scientific basis for the design of landscape sustainability: A conceptual framework for translational landscape research and practice of designed landscapes and the six Es of landscape sustainability. *Landscape Ecology*, 24, 993–1013.
- Nasr-Azadani, E., Wardrop, D., & Brooks, R. (2022). Is the rapid development of visualization techniques enhancing the quality of public participation in natural resource policy and management? A systematic review. *Landscape and Urban Planning*, 228, Article 104586.
- Nasr-Azadani, E., Wardrop, D. H., & Brooks, R. P. (2023). Pathways for the utilization of visualization techniques in designing participatory natural resource policy and management. *Journal of Environmental Management*, 333, Article 117407.
- Nassauer, J. I., & Opdam, P. (2008). Design in science: Extending the landscape ecology paradigm. *Landscape Ecology*, 23(6), 633–644.
- Nicholson-Cole, S. A. (2005). Representing climate change futures: A critique on the use of images for visual communication. *Computers, environment and urban systems*, 29(3), 255–273.
- Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., Bednarek, A. T., Bennett, E. M., Biggs, R., & de Bremond, A. (2020). Principles for knowledge co-production in sustainability research. *Nature sustainability*, 3(3), 182–190.
- O'Brien, K. (2018). Is the 1.5 C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, 31, 153–160.
- Obrist, M. (2015). Multi-sensory media experiences. Proceedings of the ACM International Conference on Interactive Experiences for TV and Online Video.
- Ostrom, E. (2007). "A diagnostic approach for going beyond panaceas." Proceedings of the National Academy of sciences 104(39): 15181-15187.
- Palomo, I., Locatelli, B., Otero, L., Colloff, M., Cruzat, E., Cuni-Sanchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., & Jiménez-Aceituno, A. (2021). Assessing nature-based solutions for transformative change. *One Earth*, 4(5), 730–741.
- Pascual, U. (2022). "Methodological Assessment of the Diverse Values and Valuation of Nature: Summary for Policy Makers."
- Pereira, L. M., Davies, K. K., den Belder, E., Ferrier, S., Karlsson-Vinkhuyzen, S., Kim, H., Kuiper, J. J., Okayasu, S., Palomo, M. G., & Pereira, H. M. (2020). Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. *People and Nature*, 2(4), 1172–1195.
- Prats, M. and S. Garner (2006). "Observations on ambiguity in design sketches." *Tracey the online journal of contemporary drawing research*: 1-7.
- Reyers, B., Folke, C., Moore, M.-L., Biggs, R., & Galaz, V. (2018). Social-ecological systems insights for navigating the dynamics of the Anthropocene. *Annual Review of Environment and Resources*, 43, 267–289.
- Reyers, B., Moore, M.-L., Haider, L. J., & Schlüter, M. (2022). The contributions of resilience to reshaping sustainable development. *Nature Sustainability*, 5(8), 657–664.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., & Schellnhuber, H. J. (2009). A safe operating space for humanity. *Nature*, 461(7263), 472–475.
- Rydin, Y. (2007). Re-examining the role of knowledge within planning theory. *Planning theory*, 6(1), 52–68.
- Saldias, D. S. M., Reinke, K., McLennan, B., & Wallace, L. (2021). The influence of satellite imagery on landscape perception. *Landscape Research*, 46(6), 749–765.
- Salter, J. D., Campbell, C., Journeay, M., & Sheppard, S. R. J. (2009). The digital workshop: Exploring the use of interactive and immersive visualisation tools in participatory planning. *Journal of Environmental Management*, 90(6), 2090–2101.
- Salliou, N., Arborino, T., Nassauer, J. I., Salmeron, D., Urech, P., Vollmer, D., & Grêt-Regamey, A. (2023). Science-design loop for the design of resilient urban landscapes. *Socio-Environmental Systems Modelling*, 5, 18543.
- Schneider, F., Llanque-Zonta, A., Andriamihaja, O. R., Andriatsitohaina, R. N. N., Tun, A. M., Boniface, K., Jacobi, J., Celio, E., Diebold, C. L., & Patrick, L. (2022). How context affects transdisciplinary research: Insights from Asia, Africa and Latin America. *Sustainability science*, 17(6), 2331–2345.
- Schroth, O. (2010). From information to participation: interactive landscape visualization as a tool for collaborative planning, vdf Hochschulverlag AG.
- Schroth, O., Pond, E., Campbell, C., Cizek, P., Bohus, S., & Sheppard, S. R. (2011). Tool or toy? Virtual globes in landscape planning. *Future Internet*, 3(4), 204–227.
- Schroth, O., E. Pond and S. R. Sheppard (2011). "Integration of spatial outputs from mathematical models in climate change visioning tools for community-decision making on the landscape scale." DLA-Digital Landscape Architecture: 246-255.
- Schroth, O., Pond, E., & Sheppard, S. R. (2015). Evaluating presentation formats of local climate change in community planning with regard to process and outcomes. *Landscape and Urban Planning*, 142, 147–158.
- Schubert, L. (2021). "Stadt bäume für die Zukunft: Beurteilung der Eignung von einheimischen und fremdländischen Baumarten im urbanen Raum und Ermittlung ihrer Kühlleistung sowie ihrer Trockenstressverträglichkeit mithilfe baumphysiologischer Messungen."
- Schumann, J., T. Strothotte, S. Laser and A. Raab (1996). "Assessing the effect of non-photorealistic rendered images in CAD". Proceedings of the SIGCHI conference on human factors in computing systems.
- Seto, K. C., A. Reenberg, C. G. Boone, M. Fragkias, D. Haase, T. Langanke, P. Marcotullio, D. K. Munroe, B. Olah and D. Simon (2012). "Urban land teleconnections and sustainability." Proceedings of the National Academy of Sciences 109(20): 7687-7692.
- Sheppard, S. R. (2005). Landscape visualisation and climate change: The potential for influencing perceptions and behaviour. *Environmental science & policy*, 8(6), 637–654.
- Sheppard, S. R., A. Shaw, D. Flanders and S. Burch (2008). "Can visualization save the world? Lessons for landscape architects from visualizing local climate change." *Digital Design in Landscape Architecture*: 29-31.
- Sheppard, S. R., & Cizek, P. (2009). The ethics of Google Earth: Crossing thresholds from spatial data to landscape visualisation. *Journal of environmental management*, 90(6), 2102–2117.
- Sheppard, S. R., Shaw, A., Flanders, D., Burch, S., Wiek, A., Carmichael, J., Robinson, J., & Cohen, S. (2011). Future visioning of local climate change: A framework for community engagement and planning with scenarios and visualisation. *Futures*, 43(4), 400–412.
- Spaulding, M. L., Grilli, A., Damon, C., Crean, T., Fugate, G., Oakley, B. A., & Stempel, P. (2016). STORMTOOLS: Coastal environmental risk index (CERI). *Journal of Marine Science and Engineering*, 4(3), 54.
- Spielhofer, R., Fabrikant, S. I., Vollmer, M., Rebsamen, J., Grêt-Regamey, A., & Wissen Hayek, U. (2017). 3D point clouds for representing landscape change. *Journal of Digital Landscape Architecture*, 2017(2), 206–213.
- Spielhofer, R., Hunziker, M., Kienast, F., Hayek, U. W., & Grêt-Regamey, A. (2021). Does rated visual landscape quality match visual features? An analysis for renewable energy landscapes. *Landscape and Urban Planning*, 209, Article 104000.
- Staffans, A., Kahila-Tani, M., & Kytä, M. (2020). 20. Participatory urban planning in the digital era. *Handbook of Planning Support Science*, 307.
- Stempel, P., & Becker, A. (2019). Visualizations out of context: Addressing pitfalls of real-time realistic hazard visualizations. *ISPRS International Journal of Geo-Information*, 8(8), 318.
- Stempel, P. J., & Becker, A. (2021). Is it scientific? Viewer perceptions of storm surge visualizations. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 56(2), 120–136.
- Stuster, J. W. (2011). *Bold endeavors: Lessons from polar and space exploration*. Naval Institute Press.
- Sungur, H., & Boduroglu, A. (2012). Action video game players form more detailed representation of objects. *Acta psychologica*, 139(2), 327–334.
- Tao, F., Zhang, H., Liu, A., & Nee, A. Y. (2018). Digital twin in industry: State-of-the-art. *IEEE Transactions on industrial informatics*, 15(4), 2405–2415.
- Tobias, S., Buser, T., & Buchecker, M. (2016). Does real-time visualization support local stakeholders in developing landscape visions? *Environment and Planning B: Planning and Design*, 43(1), 184–197.
- Turnhout, E., Metz, T., Wyborn, C., Klenk, N., & Louder, E. (2020). The politics of co-production: Participation, power, and transformation. *Current Opinion in Environmental Sustainability*, 42, 15–21.
- Ulrich, R. S. (1979). Visual landscapes and psychological well-being. *Landscape research*, 4(1), 17–23.
- Urech, P. R., Dissegna, M. A., Girot, C., & Grêt-Regamey, A. (2020). Point cloud modeling as a bridge between landscape design and planning. *Landscape and Urban Planning*, 203, Article 103903.
- Van Mierlo, B., & Beers, P. J. (2020). Understanding and governing learning in sustainability transitions: A review. *Environmental Innovation and Societal Transitions*, 34, 255–269.
- Virtanen, J.-P., Daniel, S., Turppa, T., Zhu, L., Julin, A., Hyyppä, H., & Hyyppä, J. (2020). Interactive dense point clouds in a game engine. *ISPRS Journal of Photogrammetry and Remote Sensing*, 163, 375–389.
- Vollmer, D., Costa, D., Lin, E. S., Ninsalam, Y., Shaad, K., Prescott, M. F., Gurusamy, S., Remondi, F., Padawangi, R., & Burlando, P. (2015). Changing the course of rivers in an Asian city: Linking landscapes to human benefits through iterative modeling and design. *JAWRA Journal of the American Water Resources Association*, 51(3), 672–688.