Applied Geography 112 (2019) 102095

Contents lists available at ScienceDirect

Applied Geography

journal homepage: http://www.elsevier.com/locate/apgeog

Augmenting physical 3D models with projected information to support environmental knowledge exchange

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ARTICLE INFO

Keywords:
Participatory GIS
3D-printed landscapes
Participatory modelling

ABSTRACT.

Participatory GIS has emerged as a useful tool for participatory planning and collaborative decision making. Many participatory GIS approaches are low-tech methods, including using physical objects such as 3D topographical models to assist with landscape recognition. More recently, physical 3D models have been augmented with light projection of digital landscape information and simulation models. Here we describe approaches currently being employed using 3D Projection-Augmented Landscape Models (3DPALM). We also explore the potential of emerging approaches that bridge traditional 3D participatory GIS and geosimulation models. Case studies are presented from Australia, Mexico and Canada that use physical 3D landscapes augmented with geosimulation models to support participatory planning, education and cross-cultural knowledge exchange. The work described in this paper suggests there are significant opportunities for the wider use of 3DPALM application to support a broad range participatory planning applications.

1. Introduction: 3D projection-augmented landscape modelling

Participatory GIS has emerged as a useful tool for participatory planning and collaborative decision making (Dunn, 2007; Elwood, 2006; Mccall & Dunn, 2012). So as to actively engage with and empower local communities participatory GIS employs a wide range of approaches to counter the potentially disempowering need for specialised mainstream GIS skills (Elwood, 2006; Fox et al., 2016). These include using physical models to assist landscape recognition and the transfer of spatially explicit knowledge (Mccall & Dunn, 2012; Rambaldi et al., 2006). More recently physical 3D models have been augmented with projected landscape information and, in some cases, landscape process simulation models have been developed (Petrasova, Harmon, Petras, & Mitasova, 2015, p. 135).

This paper explores the use of 3D projection-Augmented Landscape Models (3DPALM) to support community engagement, participatory planning and cross-cultural knowledge exchange. First we review the use of physical 3D landscapes to support participatory planning. We then describe novel methods for extending interaction with the physical surface through light projection of digital information. We present three applications of 3D Projection-Augmented Landscape Models (3DPALMs) with case studies from Australia, Canada and Mexico.

Little has been published to date about the application of Projection-Augmented Landscapes for community engagement. Furthermore, to the author's knowledge, there has been little published research on the intersection of landscape process simulation models, participatory planning and 3D tactile landscapes. Through addressing these gaps in the current literature this work aims to contribute to this evolving approach. This work also aims to provide grounding for the development of 3DPALM applications through reviewing the range of approaches in the context of current 3D participatory GIS practice. Finally, the work aims to provide a better understanding of the potential of this approach to support community engagement and planning outcomes in a variety of remote, low-resource and more developed contexts.

1.1. 3D landscape models for participatory planning

The use of 3D physical landscape models to facilitate terrain orientation and familiarization date back millennia, with the earliest documented applications being for military planning (Stempien, 2002; "Terrain Models", n. d.). Three-dimensional physical landscape models are now being applied to a broad range of education, communication

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https://doi.org/10.1016/j.apgeog.2019.102095
Received 12 December 2018; Received in revised form 1 August 2019; Accepted 2 October 2019
Available online 7 October 2019

and mapping activities where the abstraction of traditional 2D maps can act as a barrier to engagement and comprehension. Three-dimensional topography models have been shown to increase substantially the ability of viewers to orient themselves and translate landscape knowledge to a map space and have thus become a common tool in support of participatory mapping activities (Becu, Bommel, Botta, Le Page, & Perez, 2014; Castella, Bourgoin, Lestrelin, & Bouahom, 2014; Brown & Kyttä, 2018; Roggema, 2014).

Landscape models have traditionally been crafted in a solid form, using paper mache or wood, or as temporary constructs using soil or sand (IAPAD, no date). Although these methods are ancient, many of the same construction and interaction techniques are still being used today. A contemporary example is the use of sandbox-based landscapes created by emergency service professionals to role-play responses to wildfire scenarios (Miller & Kassem, 2012). Scenario gaming in military and emergency response contexts encourages lateral and strategic thinking in complex spatial situations. It facilitates landscape recognition and understanding of landscape processes that are tied to topographic context.

Underpinning the usefulness of physical landscape models are the complex multi-sensory processes involved in developing our internal 'mental maps'. In their seminal research, Siegel and White (1975) described three types of knowledge involved in cognitive maps: 1) landmark knowledge, 2) route knowledge, and 3) survey knowledge. Landmark knowledge is built on identifying and placing ourselves in relation to unique objects in a landscape and their proximity to one another. Route knowledge is developed through connecting paths as we move between landmarks. Survey knowledge is a comprehensive understanding of the relative location of features in a landscape such as in topographic maps. Mental maps are primarily a combination of landmark and route knowledge; the former being primarily visual, the latter being predominantly sensorimotor. Sensorimotor experiences, like those gained with tactile, physical 3D maps, integrate physical movement with visual perception. This multi-sensory understanding of landscapes is represented well by physical 3D models as they provide a more direct connection to our mental maps of landscapes where terrain features act as easily recognisable landmarks (Rambaldi, 2006a; Rambaldi & Callosa-Tarr, 2010). Furthermore, the embodied engagement with physical landscapes is seen as key for building a sense of space and relationship between landmarks in even small-scale or modelled landscapes (Herman & Siegel, 1978; Siegel & White, 1975). This is replicated in the models through our ability to touch, trace and feel texture, which connects us to non-visual experiences of movement and terrain (Hu, Ginns, & Bobis, 2015).

In addition to the development of spatial cognition, the benefits of multisensory engagement have more broadly been shown to have significant learning outcomes (Chao, Huang, Fang, & Chen, 2013; Hu et al., 2015). A body of research on neuroanatomical learning suggests that the human brain evolved to develop and learn via multi-sensory stimuli (Kim, Seitz, & Shams, 2008; Lehmann & Murray, 2005; Shams & Seitz, 2008). Similarly, education research has shown that multimodal teaching substantially increases learning outcomes (Sankey, Birch, & Gardiner, 2010) and incorporation of 3D models in education programs leads to marked improvements in map-reading skills (Carbonell Carrera et al., 2017). There has been an increasing interest in the tactile/haptic dimension within geography and geographic methods (Dixon & Straughan, 2010; Rossetto, 2019) that explore the embodied nature of engagement with geographic information through both traditional physical maps and touch screen digital interactions.

In summary, 3D physical landscape models support cognitive integration of personal and abstract spaces by helping individuals to locate themselves in landscapes. This, in turn, aids communication of spatial knowledge and improves learning and understanding through multisensory engagement. New technologies build on this to provide further opportunities to enhance these benefits by supporting more dynamic displays of information and interactivity.

1.2. Applications connecting digital and physical landscapes

New digital approaches to landscape visualisation and model production have emerged over the last decade. Digital visualizations, virtual reality (Ball, Capanni, & Watt, 2008; Griffon, Nespoulous, Cheylan, Marty, & Auclair, 2011; Lin, Chen, & Lu, 2013; Lin et al., 2015; Wang, Miller, Jiang, & Donaldson-Selby, 2015; Zhang, Chen, Li, Fang, & Lin, 2016), and immersive environments (Costanza et al., 2014; Heckbert & Bishop, 2011; Jeong & Gluck, 2003; Liang, Shen, Gong, Liu, & Zhang, 2017; Torrens, 2015) have been developed as techniques to support spatial data visualisation. These methods are now intersecting with physical landscape models by using projection augmentation to display digital data with dynamic and interactive simulations (Stevens et al., 2002; Priestnall, Gardiner, Way, Durrant, & Goulding, 2012; Petrasova et al., 2015, p. 135). Importantly projection augmented models, unlike virtual reality, do not blinker or exclude the user's surroundings and consequently facilitate engagement in a shared environment. This sharing and the attendant dialogues between people and the spatial data constitutes the critical component of participatory mapping and is a feature well supported by projection augmented 3D spaces (Bennett & Stevens, 2005).

In addition to the development of new visualisation techniques, the emergence of affordable 3D printing technologies and free global digital elevation datasets have opened up new opportunities for the creation of detailed, low-cost 3D landscapes (Horowitz & Schultz, 2014; von Wyss, 2014; Burian and Brus, 2016; Hasiuk, Harding, Renner, & Winer, 2017). This has coincided with the availability of free software and web portals for automated production of ready-to-print landscape models (Fisher et al., 2018).

New techniques to create physical landscape models and the use of projection augmentation have resulted in the development of applications supporting planning, training and knowledge exchange (Stevens et al., 2002; Priestnall et al., 2012; Amburn, Vey, Boyce, & Mize, 2015; Petrasova et al., 2015, p. 135; Torrens, 2018). These can be broken up into three common approaches of increasing complexity (1) projection-augmented landscapes, (2) projection-augmented landscapes connected to interactive simulation models, and (3) projection-augmented landscapes with laser-scanning that respond to model manipulation.

An early example of 3DPALM was from Massachusetts Institute of Technology's Tangible Media Group who created a 3D landscape with projected data for use in architectural design (Fielding-Piper, 2002). More recently Priestnall et al, (2012) used projection augmented relief models to display geographic and historical data including dynamic simulations exploring landscape processes. The use of computer simulation is also key to the SimTable application where users sculpt sand, and infrared interactivity generates light-projected layers of relief shading on the sand surface. SimTable allows interactive exploration of fire, floods, and emergency response scenarios (Simtable, 2014).

Surface interactivity can be achieved using a 3D laser scanner that captures the surface shape of the model as it is modified by users. This form of interactivity allows projected simulations to react directly to the changes in a malleable surface, usually sand, and has been incorporated into a wide range of applications from simple children's arcade games to sophisticated augmented reality sandboxes focused on teaching landscapes processes (Fielding-Piper, 2002; Petrasova et al., 2015, p. 135). Petrasova's work uses a Microsoft Kinect laser scanner to digitally map a 3D landscape in real time and respond to physical changes produced by the addition of moulded clay or other physical markers. Changes in the 3D landscape are fed into GIS software for spatial analysis and new landscape properties are displayed.

In addition to a range of projection augmentation approaches, a variety of materials have also been used in the building landscape surfaces ranging from sand to 3D-printed plastics (Amburn et al., 2015; Petrasova et al., 2015, p. 135). Sand-based applications such as the SimTable and augmented sandbox applications provide an interactive space. In these setups, geographic exactness of the 3D medium is not required as relief shading in the projected layers provides topographic detail. Some laser scanning surface applications use more sculptable mediums such as clay or 'kinetic sand', sand coated in a silicone compound that makes it easier to mould. Applications using solid models generally rely on recent advances in computer-based manufacturing tools to 'print' landscapes using either subtractive or additive methods. Subtractive printing uses a computer-controlled (CNC) router to carve landscapes out of base material, usually layered wood. This technique allows the creation of large models relatively quickly. However, the entry costs to this form of construction are high and so it usually only available to dedicated industrial workshops. The most common form of additive 3D printing uses heated thermal plastic, laying down extruded filament to build up a printed surface (von Wyss, 2014).

There are varying benefits provided by different landscape mediums related to cost, set-up flexibility, portability and form of tactile engagement (Table 1). Sand projection is the easiest to employ and has the greatest level of tactile engagement. Sculpting sand to fit an elevation projection requires physical engagement, often including multiple participants, similar to traditional participatory GIS approaches. Although not providing physical detail through projection augmentation, the sand-scape becomes an information-rich topographically-detailed space. A key advantage of the 3D printed model is the accurate topographic detail shown, allowing meaning to be transferred to the landscape with or without projection. While the ephemeral nature of sand models emphasizes a performative approach to model engagement, solid models are more suited to permanent display allowing ongoing engagement with a detailed landscape representation after a projection augmented event.

As described there are multiple degrees of complexity and cost in both the creation of 3D surfaces and the form of interactivity used, ranging from the simple sand-based projection of map information to complex laser scanning surface interactivity on digitally manufactured landscapes. However, underlying all these PALM configurations are the three key elements; tactility, three-dimensionality and interactivity.

1.3. Geosimulation, participatory GIS and 3D landscapes

Many projection-augmented applications use simulation models of landscape processes to provide interactivity. The intersection of spatially explicitly data-sets and simulation modelling to create dynamic models is often referred to as geosimulation (Benenson & Torrens, 2003; Torrens & Benenson, 2005; Heckbert & Bishop, 2011). The power of geosimulation models is their ability to add a temporal dimension to static GIS analyses and thus allow the exploration of evolving human-ecological processes (Heckbert & Bishop, 2011; Costanza et al., 2014). Simulation modelling is also widely implemented as a participatory process. Participatory modelling is used to improve the accuracy and relevance of what is being modelled and, through scenario simulations, engage stakeholders in planning processes. Participatory modelling also builds cooperation and capacity amongst participants (Heckbert, Baynes, & Reeson, 2010; Millington, Demeritt, & Romero-Calcerrada, 2011; d'Aquino & Bah, 2013; Le Page et al., 2017), as well as mutual learning and discussion (Ruankaew et al., 2010). Similarly, participatory GIS is commonly used to increase stakeholder engagement and the incorporation of local knowledge into planning processes (Elwood, 2006; Mccall & Dunn, 2012), and 3D participatory GIS uses the third dimension to support mapping local knowledge (Elwood, 2006; Mccall & Dunn, 2012).

3DPALM geosimulations combine many of the key aspects of participatory modelling and 3D participatory GIS. However, combining these methods results in a wholly new participatory engagement approach which seeks to provide all participants with equity of comprehension of the landscape and landscape interactions.

2. Case studies

Case studies are presented from Australia, Mexico and Canada (Fig. 2). The Australian case studies used sand and 3D-printed models augmented with projected geosimulations of fire behaviour, for use in fire management planning activities with Indigenous and rural stakeholders. The example from Canada used 3D-printed models augmented with a hydrology geosimulation to support the education of catchment hydrology and flooding. The Mexico case study used 3D-printed landscapes and the projection of multiple terrain layers to assists engagement with local farmers to explore sustainable agricultural practices.

2.1. Northern Australia savanna fire management

Savanna landscapes are the most fire-prone biome on earth and their management has significant biodiversity, greenhouse gas (GHG) and livelihood impacts (Russell-Smith et al., 2009). In northern Australia, there has been an increasing effort to improve fire management by using fire mapping data to help guide prescribed burning programs.

Simple geosimulations of fire spread were created for use in a 3DPALM format to help fire managers visualise and understand key environmental data in a way that enabled a more sophisticated understanding of fire behaviour. Four applications are described below. These include simulations developed for two contexts: remote Indigenous communities and for the general public; identified as red and blue dots respectively in Fig. 1.

2.1.1. Indigenous fire management support

The Arnhem Land region covers an area of 97,000 km^2 of northern Australia (Fig. 1) and is owned by Indigenous Traditional Owners. Fire management is a traditional practice in Arnhem Land and after some

Table 1
Landscape mediums and usability attributes.

	Tactile engagement	Costs	Portability	3D Accuracy	3D Flexibility	Display Scalability
Sand	High: participants mould sand to fit a projected landscape.	Low: Projector and stand set-up ~1k	High: easy to relocate/ setup, sand can often be sourced locally	Low: relies on projection for detail	High: Easily remodelled to new landscapes	High: Scale only restricted by the projection area and the quantity of sand available.
Kinetic Sand/ Clay	High: participants mould sand to fit a projected landscape.	Low: Projector and stand set-up + sand ~1.5k	Medium: clay usually used in combination with CNC landscape.	Medium More detailed than sand alone - can be sculpted	High: Easily remodelled to new landscapes	Medium: Usually small, expensive to upscale.
3D Subtractive (CNC)	Low: No interaction required.	High: Initial setup costs + routing material costs 10-20k	Medium: large carved wood landscapes can be difficult to transport.	High: does not require projection for topographic detail	Low: once printed can not be remodelled	High: Large landscapes can be produced.
3D Printed Additive	Medium: Can be built as a 3D jigsaw.	Medium: Initial setup costs + material printing costs 3-4k	High: landscape tiles easily moved.	High: does not require projection for topographic detail	Low: once printed can not be remodelled	Medium: Printing time and costs increase considerably with up-scaling

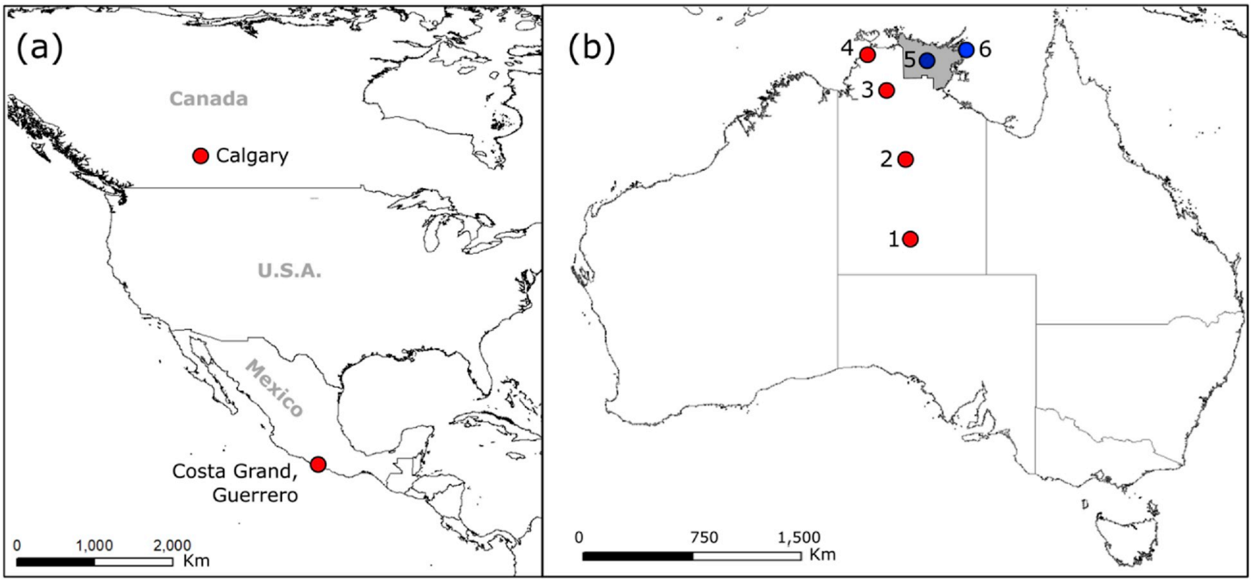

Fig. 1. (a) Canadian and Mexican case studies, related to hydrology and flooding and farmer community engagement respectively. (b) Australian case studies in rural communities (red dots), (1) Alice Springs, (2) Tennant Creek (3) Katherine (4) Darwin and Indigenous communities (blue dots), (1) Nulhumbuy and (2) central Arnhem Land. Arnhem Land is shaded grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

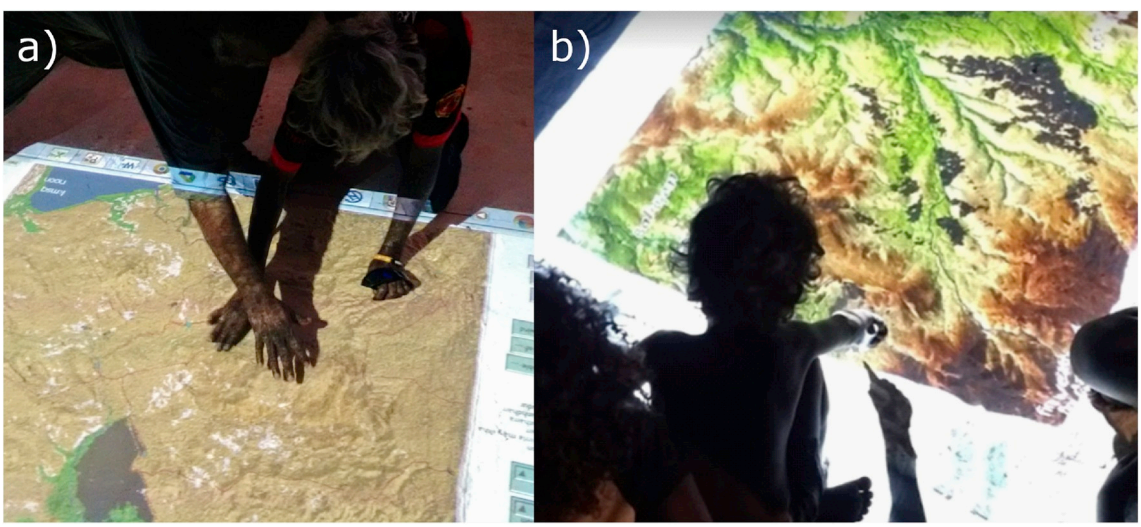

Fig. 2. Interaction with the sand-based 3D Projection-Augmented Landscape Models for workshops in a) Nhulunby and b) Central Arnhem Land.

interruption has once again become an important part of the local economy. In Arnhem Land, 3DPALM fire simulations are being used to support training and fire management planning in a diverse cross-cultural and cross-linguistic space. The 3DPALM simulation was used in fire planning meetings in Nhulunbuy in 2017, and in Central Arnhem Land in 2017 and 2018.

2.1.2. Format of the PAL set-up

This application used sand as the projection surface with an infrared light detector attached to the projector to allow surface interactivity. The infrared interactive system allowed participants to initiate simulation of fires directly on the sand surface using either an infrared light pen or a cigarette lighter as the source of light. Participants were able to sit around the model, comment and interact (Fig. 2). A short throw projector was used allowing projection of the fire simulation onto an area of around 1.5×1.2 m from a simple table-based projector mount.

2.1.2.1. Application and outcomes. In Nhulunbuy a local mine representative, emergency services, Indigenous rangers, Indigenous Traditional Owners and non-Indigenous ranger coordinators were present at the workshop. The use of the model started with sand-sculpting to form the terrain surface. This involved the mine representative working together with Indigenous and non-Indigenous rangers on their hands-and-knees, creating a fun and collaborative situation before simulation modelling of fire management discussion had begun. The practical utility of black and white hands working together to create the model established a metaphorical basis for the subsequent dialogue around the model. The 3DPALM simulation facilitator then explained the model function and set some digital fires as examples, illustrating the role of a range of fire weather and land cover variables on fire behaviour. This stimulated discussions led by traditional land-owning elders who explained their lived experience of recent fires in the area, which were simulated by the 3DPALM. From the specific instances and the examples modelled key regional fire management issues and concepts arose in discussion. Feedback from the exercise suggested that the 3DPALM enhanced the workshop through supporting cross-cultural communication which relied in large part on a shared understanding of the landscape and landscape fire interactions which all participants could 'see'. Participants, most of whom had participated in other forms of land management planning forums, felt the 3DPALM approach led to more inclusive learning and better land management planning. As one Indigenous ranger said:

> *"everyone shared knowledge, both Yolngu [Local Indigenous] and Balanda [White Person/Outsider] …. not shy".*

In central Arnhem Land the 3DPALM fire simulations were used to support fire management training workshops run over several days in small, remote 'outstation' communities. Traditional fire management and fire behaviour knowledge was shared between Indigenous and non-Indigenous facilitators during discussions and whilst conducting active burning in the surrounding country. These daytime activities were supplemented in the evening by the 3DPALM fire simulation models. The sand-based fire simulation was set-up outside under the stars and provided another forum to discuss management priorities and fire behaviour issues. The use of a cigarette lighter to initiate digital fires had a strong resonance with the participants as it mirrored the active burning practice from earlier in the day. The 'theatre' of the 'digital fire' brought people in, especially very young people (<10yo) in the first instance (Fig. 3). This allowed older people to narrate stories about the impacts of good and poor fire management in their own traditional, local language. One of the non-Indigenous facilitators described the impact of the application in this way:

> *"The 3D model was set up just beyond the campfire light and the brightness of the projected image on the white sand quickly attracted all those who were at the campfire. It provided an excellent extension of the reflective work being done by the campfire. People were able to run simulations and talk about the outcomes in the context of the fresh information they received that day, but also in terms of their longstanding knowledge of their country.*
>
> *Without doubt, one of the strong features of the 3D model was the fostering of intergenerational transfer. Mature community members immediately recognised the 3D simulation model as 'fun'. And in any event children quickly squeezed between the legs of their elders and sat right on the edge of the model with their elders looking over them. To be clear, the excitement generated by the 3D model was not limited to the children."*

The use of this technology supported the integration of western scientific data with traditional Indigenous knowledge, a significant goal of many PGIS applications. Significantly the 3DPALM was also found to be an important tool for intergenerational and cross-cultural knowledge exchange with senior Indigenous people sharing lived experiences of fire on their country with younger generations and non-Indigenous colleagues. Senior participants had an intimate knowledge of the country captured in the model and were quickly able to orient locations and landscape properties to a fine scale. Some had previously had the opportunity to participate in incendiary drops from helicopters which allowed them to quickly relate to the model image which appeared on the ground. Importantly however, all of those engaged were able to relate to the projected landscape without relying on abstract map symbology necessary in 2D modelling.

Participants were animated and voluble in the sharing of knowledge about fire in their landscape which has significance in the context of the growing Savanna Burning Carbon Farming projects (Russell-Smith and Whitehead, 2015) that require broad consultation and detailed strategic planning to ensure the best environmental, cultural and economic outcomes.

However, it is worth noting that the applications described were in the form of 'fly-in, fly-out' workshops and did not build capacity amongst the Indigenous participants in the ongoing use of the technology. A more 'empowering' approach would be for local land managers to be the ones owning and leading the use of the 3DPALM technology. To this end, further work is currently being conducted to integrate the use of the 3DPALM fire simulations as a standard operating tool within remote Indigenous ranger groups. This requires additional mentoring and technical assistance to ensure that there is sufficient capacity for ongoing use of the models.

2.1.3. Public education on a rural agricultural show circuit

A government wildfire agency (Bushfires NT) used the 3D fire simulations to build a better understanding by the public of fire behaviour and the need for strategic mitigation activities to reduce the risk of wildfires. The 3D fire simulations were used as part of a government rural extension activity at annual agricultural shows across the Northern Territory. The agricultural shows bring together farmers, supporting industries and government over three days in regional centres to support and celebrate agriculture and agriculture's contribution to the jurisdiction's economy and culture.

2.1.3.1. 1 Format of the 3DPALM set-up. This application used a printed

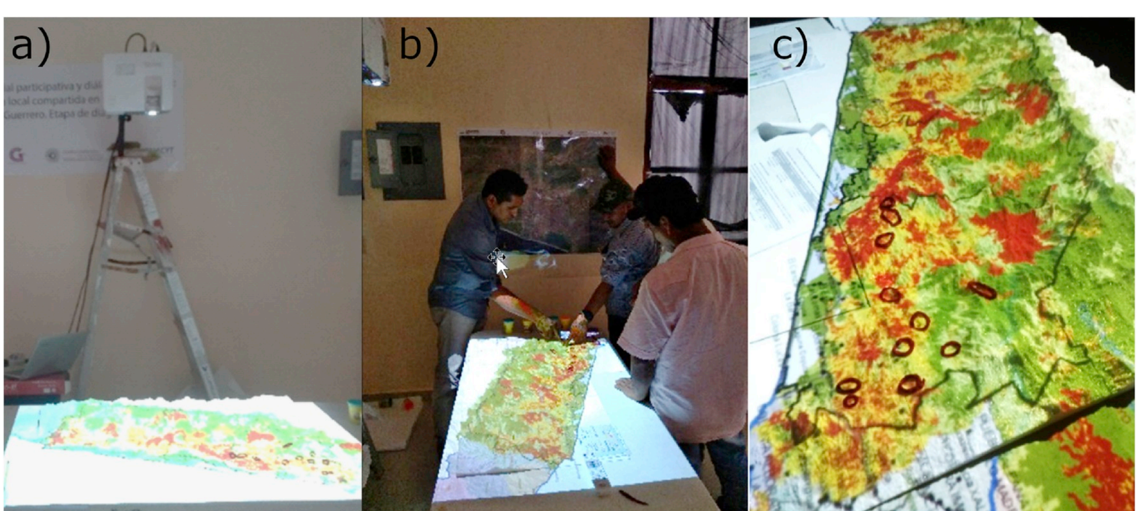

Fig. 3. Different stages and usages of 3DPALM with farmers of Costa Grande. a) setting up 3DPALM projector configuration, b) farmers analyze soil erosion layer, c) integrated local knowledge through marking the physical model with modelling putty.

landscape with minimal interactivity. A large 3D (110 cm × 80 cm) landscape was produced as 30 printed plastic tiles of an area of the Northern Territory's savanna (55,000 km^2) mostly managed for pastoralism. A monitor arm with an extension mount was made to enable a short throw projector to be attached to a table on which the landscape was placed. This application was housed within a temporary darkroom created for the purpose.

2.1.3.2. 2 Application and outcomes. The model was used for a three-month period (May–July 2018) at four rural agricultural shows across the Northern Territory (Fig. 2). Around six-hundred people viewed the projection model across all of the shows. The application was set-up and operated by a government community engagement officer. For speed and efficiency, videos were produced of simulation runs which illustrated key strategic fire management applications clearly and consistently. With narration and additional responsive explanation, the simulation videos allowed a complex land management story to be delivered in less than a minute. The dynamic 3D landscape projection was key to capturing public interest. This was particularly the case with younger people who had first been drawn to the technology. One man described how "My son found me and dragged me into the tent, he really wanted me to see this." Building on this initial audience captivation, the community engagement officer was able to guide the audience back to understanding the key points around good fire management. The community engagement officer also described how the PALM resulted in focused engagement including with senior politicians (Government Ministers) who attended the show.

Although the facilitator described the use of the model as being effective, he also commented on some technical issues around the projection print configuration. At different locations, he was faced with differing set-up infrastructure and each time required recalibration of the mechanism. An interesting finding from this application was the way the model attracted people from different demographics from the very young to the politically powerful. Staff from the bushfire agency commented how persistent efforts had been made over many years to engage with the public at the annual agricultural shows, with generally poor results. In contrast, the enthusiastic interest witnessed as a result of the 3DPALM display led to broad-ranging discussions around land management issues, policy and legislation and was felt by the procuring agency to be of great value.

2.2. Participatory spatial planning, Costa Grande, Mexico

The livelihoods of people of the Costa Grande in Guerrero State are primarily derived from agriculture. These communities use a farming method, known as 'milpa', involving multiple maize varieties and coffee in the uplands, and coconuts and mango at lower elevations. Although integrated agro-ecological practices are not unknown to the farmers of this region, recent agricultural technology developments and an increased government focus on crop productivity are resulting in erosion and a decline in soil fertility. In order to build a greater understanding of the impacts of changing agricultural practices on soil health, Guerrero es Primero, a local NGO working on sustainable development, and Centro Geo, a geographic research institute from Mexico City, have developed a participatory spatial planning strategy to examine soil erosion. 3DPALM technology has been used to support community engagement workshops to facilitate participatory spatial planning with reference to soil health.

During the workshops, erosion models were projected over a 3D-printed model so that participants could observe the effects of a range of cropping and soil management practices. The erosion models were produced using GIS modelling techniques based on varying land-use and forest cover combinations and local knowledge collected through field interviews with farmers.

2.2.1. Format of the 3DPALM set up

A large 3D model of Costa Grande basin was produced with 17 3D-printed tiles representing an area of approximately 10,140 km^2 where low deciduous forest and seasonal agriculture are the predominant land cover types. A short-throw projector was attached to a portable metal ladder, under which the 3D model could setup up (Fig. 3).

2.2.2. Application and outcomes

A total of 20 farmers participated in the workshop. The 3D model was introduced to participants who were initially engaged in the tactile task of assembling the 'jigsaw' of the 3D printed tiles into the completed landscape model. This process required cooperation and discussion and, importantly, articulation of the existing cognitive map of the district. Subsequently, modelled landscape data including soil erosion potential, agricultural suitability and climate variability were projected over the 3DPALM to promote discussion around the potential outcomes from various agricultural management practices (Fig. 3). Participants found it useful to physically annotate the model with local knowledge about current land use and potential risks and opportunities. The annotation was done using modelling putty, creating non-permanent lines and polygons. The use of modelling putty also added another dimension to the tactile engagement with the modelling processes. It was noted that the farmers created very precise and detailed markings using close observation of the 3D terrain as a guide.

Participants found the 3DPALM with soil erosion scenarios useful in generating new insights into sustainable cropping and soil practices according to the topography as well as the social/cultural characteristics of their territory. Importantly the 3DPALM approach increased discussion of the causes of soil erosion and, subsequently, to potential solutions. Further to this, participants were excited by the ability of the 3DPALM to show their entire district and the way it allowed them to identify key locations with reference to a holistic comprehension of the topography.

> *"I have never seen something like this [...] initially, I thought that was only about a 3D model but with the projection I'm able to clearly identify hills, routes and localities, with the 3DPALM I easily locate myself in territory" (Alejandro, farmer of Coyuca de Benitez, México)."*

> *"3DPALM show maps more realistic [...] hills are clearly portrayed, and paths and roads are clearly shown [...] I have a top-down vision perspective [...] I can identify hills and mountains which from the ground are hidden by each other ... It makes me feel as if I were a giant because I can grab the hill of the neighboring community" (Andrés, farmer of Coyuca de Benitez, Mexico).*

Participants also volunteered additional uses of the model including climate risk assessments, monitoring their agricultural projects and as a tool to better communicate their needs and aspirations to representatives of the federal government.

Projection of imagery over the 3D model made local farming knowledge and the impacts of changing farming practices spatially explicit within the context of local topography. The 3D display not only made it easier for participants to 'place' themselves in the landscape but was also important for understanding how topography affected soil loss. Being able to see the slope, a key factor in erosion modelling, in 3D made understanding of the soil loss scenarios more intuitive.

The mapping process exposed clear differences between local and scientific knowledge. Local knowledge in Costa Grande was spatially specific and detailed while the modelled spatial data was general and large scale. The 3DPALM helped integrate these local and broad scale perspectives. The projection of layers provided information about the extent and spatial variation of biophysical factors and impacts, while local knowledge helped to validate and qualify those factors in terms of type and degree of spatial manifestations. The 3DPALM facilitated increased involvement of the farmers through debate and collective reflection. This, in turn, lead to the co-creation of knowledge and supported informed decision-making by enabling participants to explore new solutions and alternative development options.

2.3. Hydrology and flooding: Calgary, Canada

In June 2013, the most costly natural disaster to date in Canada occurred in a flooding event which impacted the city of Calgary and surrounding communities. The flooding was a cumulation of many factors which affected the volume of water in the Bow and Elbow rivers which converge in downtown Calgary, an area of high land value and therefore high consequence. To date, several mitigation activities have been proposed, including constructing large-scale reservoirs, local-scale riverbed restructuring, upstream revegetation, diversion engineering and wetland restoration, among others. In order to facilitate an understanding of the complex hydrological system and the likely tradeoffs between possible mitigation options, a catchment-scale hydrological and hydraulic simulation model was developed. In order to increase stakeholder understanding of the many factors which interplay before and during a flooding event, a 3DPALM was created and used as an education medium. The Bow River Basin 3DPALM was developed as part of a package of geosimulation tools to increase the understanding of environmental change in Alberta, Canada. The 3D-printed surface and projection augmentation was an add-on to existing project work applying simulation models to support land-use planning.

2.3.1. Format of the 3DPALM set-up

This application used a large 3D-printed landscapes (110 cm × 80 cm) with multiple tiles. The primary landscape unit printed for simulation was of the whole Bow-River catchment. This was augmented by a finer resolution print of the area of the confluence of the Bow and Elbow Rivers in Calgary (Fig. 4.). The two scales helped develop an understanding of whole-of-catchment processes driving flood events and then to focus in on the area of greatest economic impact. The fine-resolution Calgary 3D print used high resolution LIDAR data and provides a much clearer picture of flood and topography interactions in the region of greatest impact.

2.3.2. Application and outcomes

The Bow River 3DPALM was used in a variety of settings over a three year period (2015–2017). The main location was within an applied laboratory setting where it was a showpiece to demonstrate the agency's R&D activities. The next most common setting was in boardroom-style meeting rooms of government agencies. With approximately 30 min of setup time, the boardroom was arranged to run a participatory modelling session with 5–10 people actively participating. Lastly, the 3DPALM was used in conference/workshop settings to demonstrate the approach.

The Bow River 3DPALM was part of a program of using geosimulation models to support collaborative planning exercises. The standard way to present results from the models was as a Powerpoint presentation using videos of geosimulation runs. During multiple presentations in this format, it was noted that, on average, about half of the audience gained a clear understanding of the hydrological processes being presented. In contrast, it was found that the delivery of the same concepts using the 3DPALM allowed effective communication in about half the time with a far greater degree of comprehension amongst participants. It became clear that the addition of the third dimension was important to building an understanding of a complex hydrological system where topography played a key role.

The Bow River Basin 3DPALM was also demonstrated at a large forum convened by the City of Calgary as a response to the 2013 floods. This major event was attended by the public, government and industry representatives and researchers. The 3DPALM was used to visualise pre-prepared model runs to an audience of about 60 people. Interestingly in this setting, most of the audience responded by video recording the presentation. This reaction resulted in the presenter feeling as if he was part of a performance in which the audience was deeply engaged in the explanatory narrative being delivered in a way not previously experienced. This engagement led to the development of a 3DPALM for the local emergency management authority's emergency response centre to assist the communication of flood risk to visitors.

A key finding from this application was the way that the key purpose of the flood modelling exercises, i.e. building an understanding of complex hydrological processes and facilitating informed discussion around flood response, was only really effective when viewed in the 3DPALM format. Not only were participants in model demonstrations better able to understand the processes being described, they were more deeply engaged in the material being presented.

3. Discussion: 3DPALM as a participatory method

3.1. 3DPALM and participatory GIS practice

Traditional PGIS applications are commonly focused on capturing local/traditional knowledge as an end goal. In contrast, the PALM applications described here focused on knowledge sharing and co-creation of knowledge rather than knowledge capture *per se*. Whilst capturing traditional spatial knowledge in a map space can be empowering by facilitating improvements in authority in many contexts, there is an inherent reliance on comprehension of 2D mapping conventions that are not always shared equally. Further, there may actually be advantages to growing individual cognitive mapping models that leave spatial knowledge fluid and ambiguous. This is particularly the case in many Indigenous knowledge systems where landscape meanings are often not fixed in space and time, boundaries are not discrete and interpretation, processes and stories evolve over time. The need to mark and define a permanent truth can be problematic, empowering select interpretations of a mapped 'truth'. An alternative, provided by 3DPALMs, is to leave the 3D model blank, only displaying spatial information as projected

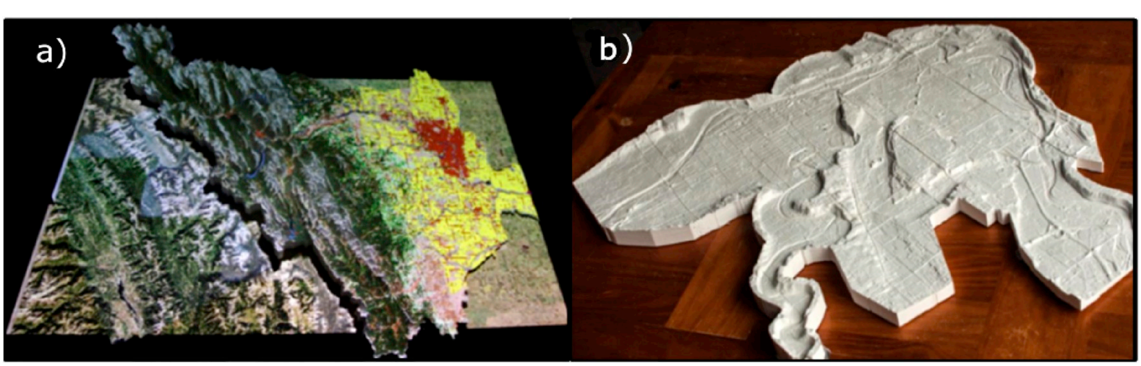

Fig. 4. Set-up for the Bow River basin 3DPALM, showing a) the larger-scale catchment 3DPALM projecting land cover on the 3D-printed surface, and (b) a 3D print of the smaller-scale region of Calgary, Alberta, without light projection.

light markings. In this regard, a key benefit of 3DPALM is the ability to display multiple landscape interpretations, for example scientific 'data' such as satellite imagery, habitat maps, terrain metrics or traditional knowledge. In the Costa Grande, traditional knowledge was marked in a temporary and malleable form using modelling clay as part of a process of facilitating community discussion, not as a means for capturing knowledge. In the Indigenous northern Australian applications, landscape knowledge was transferred to participants through stories, with reference to the 3D terrain models through touch and gesture. The co-created knowledge was discussed and appended to existing narratives of fire and its management.

The importance of the 3D physicality of the models in Northern Australia was described by one of the workshop facilitators in the following way:

> *"I was very impressed at the change that the 3D model brings about in the way people interact with each other and the spatial data in the presence of the model. They tend to be more communicative and use a greater degree of body language and so on. This change is enhanced with the 3D model. People do not merely stand by the map, they squat down, touch it, talk and point at features. They look up to discuss features with colleagues standing nearby."*

Another significant difference between traditional 3DPGIS and 3DPALM techniques is the processes of model production. For traditional 3DPGIS applications, the involvement of a participant group in an intensive landscape construction process using cardboard and papier-mâché is critically important. This can take many days and provides a forum that allows participants to share knowledge and discuss shared histories. Whilst most 3DPALM set-ups use pre-constructed landscapes, some methods, such as sand modelling, encourage active engagement with the 3D model creation process. The use of sand models was particularly powerful in the context of Australian Indigenous community land management workshops. At Dhimurru, for example, people from vastly different cultural backgrounds came together to create the sand-scape. As with traditional 3DPGIS, this physical engagement in the model construction was an important component of 'embodied' engagement, bringing new ways of thinking and transforming relationships between participants and mediators.

Whilst construction participation is also possible with 3D printed models created as multiple tiles requiring assembly, with participants examining and rotating the 3D tiles in their hands while trying to find where they fit into the emerging landscape model, there were some powerful advantages in the use of sand. This includes the familiarity, cheapness and accessibility of the medium and the metaphor of using 'earth' to sculpt earth. In addition, the scalability of sand was also important. Whereas, with the 3D printed surfaces, the technical process of aligning the print to fit the projection can be time-consuming and frustrating, with sand the landscape is moulded to fit the projection, the process is usually rapid, fun and integrated as a collaborative part of the modelling process. In contrast, a key advantage to the 3D printed models is the detailed landscape information they provide. This was described as an important attribute in traditional Costa Grande where local knowledge was overlaid on the 3D print with reference to close observation of the printed detail. In addition, 3D printed landscapes have a greater degree of permanency and can be left on-site and used subsequently by a community with or without projection augmentation.

While 3DPALM applications do not support the 'slow' model building process of traditional 3DPGIS, the phase of knowledge sharing extends through the construction phase and continues once set-up has been completed in the form of interaction with projected information and simulations. Furthermore, the speed and simplicity of PAL model implementation through the use of sand or 'pre-printed' landscapes on-site can be a real benefit where there is limited time available for community engagement. Tangible pre-constructed or sand-based 3D landscapes can be employed by almost anyone in a wide variety of workshop formats to assist in sharing local spatial knowledge. In contrast, traditional 3DPGIS risk prioritising and 'solidifying' the interpretation of landscape meaning into the hands of those with time to participate in a resource-intensive 3DPGIS workshop.

3.2. Participatory simulation and 3D landscapes

The power of spatially explicit simulation models for natural resource management planning is that they allow stakeholders to improve their understanding of a system's complexity and of the feedbacks between natural resource dynamics and social behaviours while simultaneously facilitating informed interactions between stakeholders (Barreteau, Le Page, & Perez, 2007). The North Australian examples used a simulation 'game' of fire spread, focusing on facilitating discussion and learning through the description of key fire spread principles. The Canadian flood modelling example adapted more sophisticated flow modelling tools which resulted in an interactive simulation application with capacity to describe a broad range of management outcomes. In both of these contexts, the way that the 3D representation assisted with building engagement with complex processes proved very important. In the case of the flood modelling application, the visually rich 3DPALM enabled outcomes to be presented in a manner that conveyed meaning to a wide range of end-users. The realistic landscape visualisation rapidly built awareness and affected behaviour and policy by bringing consequences 'home' to people in a compelling manner not witnessed by the facilitators during many years of workshops using 2D mapping.

In all of the case studies described here, a key objective was to generate improved decisions and outcomes in various environmental parameters through a broader understanding of the range of issues extant in the different community sectors, e.g. among Indigenous communities, politicians, scientists and so on. It is well recognised that decisions that are driven by stakeholders tend to generate better outcomes and approaches to community engagement have sought to identify the most effective way to engage. Arnstein (1969) proposed an 8-step ladder of citizen participation which has been widely adopted as the basis for consideration of the degree of commitment to real community engagement (Davis & Andrew, 2017). In this model, engagement moves from consultation which is characterised as 'tokenism' to partnership, delegated power and citizen control which Arnstein identifies as "citizen power". Solutions and decisions that incorporate empowerment of citizens tend to be the ones which succeed, with less conflict and greater agency exhibited by all parties who feel they have a stake in the design and implementation of the process (Voinov & Bousquet, 2010). Achieving this is predicated not only on the nature of the information and the way it is provided but also on the social relations between the participants in the engagement space. The ability of participants to communicate effectively, exchanging information and knowledge with a relatively high degree of trust, catalyses the formation of new understandings (as the participants' quotes reveal). The 3DPALM applications remove a key disparity between different participant groups; the requirement of a good degree of technical understanding of 2D mapping conventions and symbology. The 3DPALM provides a 'level playing field' of comprehension about the basic landscape features and processes being discussed. This provides a basis for information sharing that is characterised by (rapid) development of dialogue and communication among participants, including those from different community sectors and cultures.

In addition to aiding comprehension of landscapes, the ability of the 3DPALM approach to build rapport, as well as its more general success, appears to lie in the ability of participants to 'play' with the models. This is not a trivial point - it is well accepted that play is not only a key learning strategy but also liberates a range of social and cognitive interactions within and between participants (Morrison, 2013; Smith & DeFrates-Densch, 2008). In the case studies provided here, the 'fun' generated in establishing the sandscape moved the discussion from 'scientific' simulations to a focus of on sharing ideas and lived experiences. Not only were mutual understandings of the environment shared around the sandscape but also different perspectives and world views. While a qualitative assessment based in part of extensive experience of use of 2D models in the past, the observed emotional engagement, excitement, volume and degree of dialogue witnessed in the observed interactions in these case studies, lead us to assert that the 3DPALM approach is an effective additional tool to support community engagement with complex human-ecological systems and issues.

4. Conclusions

This paper describes a range of 3DPALM applications with three key attributes that reconfigured the way that people interacted with spatial data; multi-sensory engagement, multi-dimensional representation and thinking through play. Tactile and kinetic engagement were important components of many of the applications described, as was being able to interact with landscape information in a shared space. The third dimension was also seen as critical for both being able to identify landscape features and for understanding landscape processes without recourse to extensive knowledge of 2D mapping. The addition of dynamic simulations effectively turned the models into four-dimensional spaces, further engaging participants with complex processes. In summary the case studies suggest that multi-sensory, multi-dimensional models can alter the way we think, interact and learn with geospatial information.

While physical 3D models are being more commonly used to support spatially explicit participatory processes, they have been largely limited to static representations requiring significant investments of community time. This paper has demonstrated the potential for using projection-augmented landscapes to enhance engagement with and understanding of spatial data. The methods and applications described demonstrate the potential simplicity and utility of this approach, even in low resource and remote contexts.

3D printing technology and projection equipment are no longer expensive. Software and input data, including digital elevation data for 3D model construction, are also now freely available. The use of sand models was found to be powerful in the context of community mapping events and provides a simple alternative to printed models. The availability of the required tools and techniques means that barriers to broader adoption of 3DPALM techniques are low. As long as a projector can be set up to point down and appropriate mapped spatial data is available to display, it is relatively easy and quick to start exploring the 3D map projections. To date, there has been limited research on the opportunities provided by intersecting geosimulation, participatory planning and 3D tactile landscapes. Participants sense of having a 'helicopter' view of their country or being 'giants' suggests an empowerment not expected at the outset of the workshops but which generated significant shifts in comprehension of the issues and systems being discussed. The work described in this paper suggests there are significant opportunities for the wider use of 3DPALM application to support participatory GIS, planning and education.

Acknowledgements

The authors would like to thank the following contributors for assistance; Dhimurru Aboriginal Corporation, Lisa Roger, Lucas Fiddaman, Chris Mallon, Quinn Barber, Micheal O'Flatharta and Stephen Garnett. They also thank the communities of Buluhkaduru and Malanyangakk in Northern Australia and the communities of Atoyac, Tecpan, Coyuca and Benito Juarez in Costa Grande, Guerrero in Mexico.

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