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Research Paper

Visualising the urban green volume: Exploring LiDAR voxels with tangible technologies and virtual models

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ABSTRACT

The distribution of vegetation within urban zones is well understood to be important for delivery of a range of ecosystem services. While urban planners and human geographers are conversant with methodologies for describing and exploring the volumetric nature of built spaces there is less research that has developed imaginative ways of visualising the complex spatial and volumetric structure of urban vegetation from the treetops to the ground. Using waveform LiDAR data to measure the three-dimensional nature of the urban greenspace, we explore different ways of virtually, and tangibly engaging with volumetric models describing the 3D distribution of urban vegetation. Using waveform LiDAR data processed into voxels (volumetric pixels) and experimenting with a variety of creative approaches to visualise the volumetric nature of the data, we describe the development of new methods for mapping the urban green volume, using a combination of Geographic Information Systems (GIS), Minecraft, 3D printing and Computer Numerical Control (CNC) milling processes. We demonstrate how such methodologies can be used to reveal and explore the complex nature of the urban green volume. We also describe the outcome of using these models to engage diverse audiences with the volumetric data. We explain how the products could be used readily by a range of urban researchers and stakeholders: from town and city councils, to architects and ecologists.

1. Introduction

1.1. The urban green volume

Cities and towns are volumetric entities and their social, political, natural and economic functions are played out in three dimensions. When considering the volumetric structure of urban landscapes, one must consider heterogeneous mixtures of built structures extending into the sky (Graham & Hewitt, 2012), coupled with subterranean excavations (Garrett, 2016), interspersed with landscape and vegetation structures also exhibiting vertical and subterranean characteristics (Davison, Huck, Delahay, & Roper, 2008; Gaston, Warren, Thompson, & Smith, 2005), all at varying heights, depths and spatial scales. In human geography this three-dimensional (3D), vertical urban axis has received considerable academic attention. For example, Hewitt and Graham (2015) argue that the vertical nature of urban spaces is "fundamental to the nature of modern cities", while Graham (2012) suggest the need for a fully volumetric urbanism to address "the ways in which horizontal and vertical extensions, imaginaries, materialities and lived practices intersect and mutually construct each other".

1.2. Urban volumetric modelling and visualisation

A major research challenge with this volumetric urbanism lies in the production of urban plans that are able to capture and communicate the diverse and complex forms that comprise the volumetric character of the city. This challenge exists, write Ahmed and Sekar (2015), because "urban planners are reluctant to use 3D tools" – suggesting that this is caused by the cost and complexity of data processing, modelling and integration coupled with "the lack of appropriate skills available for incorporating 3D models into everyday planning processes". Corroborating this, Ireson (2000) adds that "it is a challenge to rethink our perspective on the significance of the vertical zones […] as contexts for specific patterns of architectural design, or types of interaction between people, or people and the city itself". Of course, tools such as Geographic Information Systems (GIS) are widely employed by urban

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planners and architects to facilitate decision-making and allow "more meaningful public involvement in planning processes" (Foster & Brostoff, 2016); while architectural research and practice has long used computing technology to visualise urban landscapes in various ways (Shiode, 2000). However, many examples of urban planning models distil the 3D complexity of urban spaces to a planar 'raster' surface. Where volumetric entities can be embraced within GIS (e.g. within ESRI's 'City Engine' software, to provide one example), the focus is placed on improved 3D description of built environment elements, and does not include an accurate way of modelling volumetric urban ecology. In parallel, many of the critical discussions concerning urban volumes amongst geographers have focused on built structures in cities, i.e. the anthropocentric nature of that volume. The lack of integration of volumetric vegetation-scapes into such models may well be driven by the anthropocentric city, but we propose that it is likely also a product of the lack of academic work that evaluates the three-dimensional characteristics of urban nature. This oversight, until recently has been driven by the lack of data describing at sufficiently fine-scale, the 3D qualities of urban vegetation. Landscape research is not solely to blame for this oversight: urban greenspace research is itself heavily reliant on non-volumetric representations with planning maps and GIS analyses replete with 2D models describing the spatial arrangements of urban vegetation primitives (e.g. simplified maps showing classified areas of grass, shrubs or trees; (Grafius et al., 2016; Gupta, Roy, Luthra, Maithani, & Mahavir, 2016)). 3D greenspace modelling is also inconspicuous within architectural praxes, we suggest largely because the planning system doesn't require it. And yet, the latest research suggests that failing to include volumetric representations of the urban greenspace into models describing ecological connectivity results in biases and over-estimations of the connectedness of patches within urban areas (Casalegno, Anderson, Cox, Hancock, & Gaston, 2017). There is a need to address this problem experimentally by making the first attempts to visualise new volumetric information describing the urban green volume to progress research into urban ecology and landscape planning.

1.3. Volumetric urban vegetation

Humans instinctively understand that all greenspace (urban and non-urban) is volumetric rather than two-dimensional. The structure of the urban green volume is alive, and determines how humans and animals interact with it and each other: the urban space influences songbird movement between garden feeders (Cox, Inger, Hancock, Anderson, & Gaston, 2016); human behaviour is modified by the presence of trees (Rasmussen, 2004); and the dynamic movements of other taxa are affected by it, e.g. bumblebees vault hedges to forage amongst allotment plants (Ahrné, Bengtsson, & Elmqvist, 2009). Alongside, a growing body of work points to the importance of urban vegetation for delivering multiple ecosystem services (Gaston, Ávila-Jiménez, & Edmondson, 2013), for example, vegetation cover is positively associated with a lower prevalence of depression, anxiety and stress (Cox, Shanahan, Hudson, Plummer et al., 2017). Using LiDAR to visualise urban topographic models aimed at informing the work of planners and architects is not new (Batty et al., 2001; Shiode, 2000). However, the inclusion of accurate three-dimensional depictions of greenspace in architectural modelling and UK planning processes is not yet widespread. Certainly, greenspace data repositories, such as Greenspace Information for Greater London CIC (GiGL) [http://www.gigl.org.uk/about-gigl] inform these processes, but the requirement for three-dimensional analysis and submission is limited. However, there remain uncertainties in understanding the quantifiable functional relationships between greenspace quality (where the 3D structure of urban vegetation is a useful proxy (Lehmann, Mathey, Rößler, Bräuer, & Goldberg, 2014) and delivery of many critical ecosystem services (Jim & Chen, 2009).

1.4. Waveform laser scanning

While there are plentiful examples of discrete return LiDAR data being used within landscape planning models to understand urban vegetation distribution and its implications (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011; Shanahan, Lin, Gaston, Bush, & Fuller, 2014; Vukomanovic, Singh, Petrasova, & Vogler, 2018) such work only provides either a 2.5 dimensional view of urban vegetation or else a coarse resolution (tens of metres) volumetric map unsuitable for urban studies (Hancock, Anderson, Disney, & Gaston, 2017). This is because discrete return LiDAR provides only limited information on the understory characteristics (Anderson, Hancock, Disney, & Gaston, 2015). In this work, we exploited the additional 3D canopy information present in waveform laser scanning data. Waveform LiDAR provides information from the vegetation canopy top all the way down to the ground, allowing understory information to be retrieved (Anderson, Hancock, Disney, & Gaston, 2016; Hancock et al., 2017). Using such information we set out to explore new ways visualising the urban green volume in its full 3D volumetric complexity. We wanted to explore whether virtual and tangible technologies could bring to life the three dimensional complexity of urban vegetation for the benefit of scientists, planners and architects alike. In this paper we address a critical research challenge in translating volumetric waveform LiDAR data into interactive information for general exploration. In this work, waveform LiDAR data (Anderson et al., 2016) were used to generate 'voxel' (volumetric pixel – see Hancock et al. (2017) for details) models showing the three-dimensional arrangement of urban vegetation density in three UK towns. To achieve this and explore different approaches to the research problem, we worked as an interdisciplinary art-science collaboration comprising remote sensing scientists, digital craft makers, artists, ecologists and programmers, and experimented with various methods for visualising the complex voxel data from Hancock et al. (2017) including 3D printing, Computer Numerical Control (CNC) milling, and interactive visualisation in the game Minecraft. We displayed the results in various venues engaging a variety of stakeholders and passively observed participants' reactions. The paper reports on the process of delivering these visualisations and tangible models and we explore the extent to which such representations could be used for enhancing citizens' and scientists' understanding of the urban green volume in an accessible way.

2. Methods

2.1. Study areas: The "cranfield Triangle" – An urban zone north of London, UK

This study was conducted in the 'Cranfield triangle'. This defines a region in southern England, UK, comprising the three adjacent towns of Milton Keynes (52°02′N, 0°45′W), Luton (51°53′N, 0°25′W), and Bedford (N52°58′N, 0°28′W). This area has a human population of c. 609,501 (2011 Census, UK), and covers 166 km^2. Several other research papers describe the study system and provide a full rationale for situating the work in this area (Anderson et al., 2016; Cox & Gaston, 2016; Cox et al., 2016; Cox, Shanahan, Hudson, Fuller et al., 2017; Hancock et al., 2017). In summary, the Cranfield triangle provided a continuum of urban spatial structural forms, including a Victorian industrialised town (Luton), a 'new town' development with designed urban greenspace (Milton Keynes), and a historic medieval market town containing mixed urban forms including Victorian features and modern industrial zones (Bedford).

2.2. Remote sensing data

The Natural Environment Research Council Airborne Research and Survey Facility collected remote sensing data from a piloted Dornier 228 aircraft between June and September 2012 during four flights. The aircraft was carrying different sensors: a standard digital camera (Leica RCD105 CH39), an imaging spectrometer (AISA Eagle) and a waveform-capable LiDAR instrument (Leica ALS50-II) that was also able to deliver standard discrete return LiDAR data. The spectrometer covered the wavelength region from 407.08 nm (blue) to 1007.10 nm (near infrared) in 253 bands.

2.3. Waveform LiDAR data processing

The first stage in processing the remote sensing data was to produce a binary layer describing the distribution of green and non-green spaces across the towns, so as to focus the waveform LiDAR analysis only on the greenspace elements. For this purpose data from the Eagle Imaging Spectrometer were used to generate a Normalized Difference Vegetation Index (NDVI; (Tucker, 1979)): a widely used index for discriminating vegetated (NDVI ≥ 0.2) from non-vegetated (NDVI < 0.2) areas. In this project, the thresholded NDVI data provided a binary map of greenspace distribution across the Cranfield triangle, with the 0.2 NDVI threshold chosen following Liang (2004). The NDVI map is a classical way of modelling the 2D distribution of urban greenspace – it shows the location of green-covered areas, but it does not allow for a volumetric characterisation of the green volume since it is a function of the top-of-canopy reflectance, and so only tells the user about the overlying vegetation presence or absence. To generate volumetric data about the canopy structure beneath the canopy tops, it was necessary to utilise the waveform LiDAR data, which have been shown as being capable of producing full volumetric models of the canopy structure, from the tree-tops to the ground (Anderson et al., 2006, 2016; Hancock et al., 2017; Lindberg, Olofsson, Holmgren, & Olsson, 2012; Wagner, Hollaus, Briese, & Ducic, 2008).

The waveform LiDAR data (captured at a footprint density of between 0.25 and 4 footprints/m^2 (Hancock et al. (2017)) were processed to generate gap fraction estimates along each laser beam where the NDVI data indicated that vegetation was present at the canopy top. The signal was denoised (Hancock, Disney, Muller, Lewis, & FOSTER, 2011), deconvolved (Hancock, Lewis, Disney, Foster, & Mueller, 2008) and corrected for attenuation (Harding, Lefsky, Parker, & Blair, 2001). Gap fractions for each beam were averaged into “voxels” (volumetric pixels) of 1.5 m by 1.5 m (horizontal) by 50 cm (vertical) resolution – this voxel resolution was chosen because the beam density of the airborne LiDAR data meant that the x,y voxel resolution could not be finer than 1.5 m without causing gaps. Due to the focus of the study on urban vegetation, particularly in the understory, we wanted to be able to detect small shrubs, hence why the z resolution was set at 50 cm. The full methodology for the voxel processing is described in Hancock et al. (2017), which also provides open-source code for the workflow. The voxel signal – i.e. the values contained within each processed voxel, were the vertically projected canopy cover. It is finally important to highlight that the NDVI product was not volumetric – we assumed that where vegetation was indicated by a positive value of this index at the surface (canopy top), hidden features revealed beneath were also vegetation objects. It is possible that some volumetric elements in the understory detected by the waveform LiDAR were not vegetation objects but given the setting of the study, we assumed these false positives to be small in number. They would also show up as geometric objects and in scanning the data we found no such errors.

The best way to understand the voxel products generated through this process is to imagine them as building blocks of the city volume. The blocks carry information about the content of the volume (in this case, the focus was only on the vegetated volume) and the proportion of that volume that is filled. For some of the tangible products generated in the project it was necessary to convert the voxel signals into a binary dataset where the presence of a signal in the voxel was used to indicate the presence of vegetation. We applied this processing to all voxels where the signal exceeded 0.01 to define the presence of vegetation – this was found to be effective at filtering noise error (Hancock et al., 2015). Finally, we projected the 3D voxel presence of each stratum into its corresponding 2D surface projection on the ground. The result was a volumetric model that allowed vegetation structure to be explored in 3D. Data were exported from this process as GeoTIFFs, measuring 260 × 260 pixels of 1.5 m × 1.5 m resolution in x and y. For each x and y 2D pixel dimension of the tile there were 70 ‘heights’ (i.e. in the z dimension), starting at 0 m and incrementing by 0.5 m vertically through the urban volume, meaning that volumetrically each GeoTIFF block comprised ~67,000 horizontal voxels (1.5 m × 1.5 m) and which equates to 4,732,000 voxels in the full cube (i.e. 1.5 m × 1.5 m × 0.5 m voxel resolution per 390 m by 390 m by 35 m tile). When each GeoTIFF ‘tile’ was stacked, it became a 3D representation of the space. It is important to highlight that until this study, there were no true volumetric data describing urban vegetation structure from the tree-tops to the ground at such a fine spatial resolution within urban environments, so the novelty of the resulting visualisation experiments flows from the fine resolution fully volumetric, and validated voxel models (Hancock et al., 2017) used as inputs to the visualisation methods. The following section details the processes that were tested to visualise the urban volumetric patterns and structures.

2.4. Visualisation approaches

2.4.1. Geographic Information Systems (GIS) and graphical 3D plot approaches

A first step towards visualising the data was to use existing visualisation tools within GIS spatial analysis software. Increasingly commonly, GIS software can enable 3D visualisation of georeferenced surfaces and the possibility to overlay such surfaces with other spatially based data including raster layer maps (i.e. grids of pixels in a matrix data structure) and vector layer maps (spatial elements coded as points, lines, polylines, polygons or more complex intersecting polygons).

The great advances of so-called “3D GIS” visualisation are the capability to overlay different geospatial datasets, even using maps from different geographic projection systems. In reality many of these tools enable only quasi-3D (2.5D) modelling or visualisation since every given location is typically only represented by a single height value unless full volumetric height data are available, as is possible with voxels. The software we utilised for the GIS visualisation of the voxel data (these are truly 3D) was the free-to-use ‘QGIS’ (QGIS development team, 2016) and its ‘QGIS2threejs’ plugin (AKAGI, 2016). QGIS2threejs is a 3D visualisation tool powered by WebGL technology, whilst the “three.js” JavaScript library is able to export 3D data (i.e. Digital Surface Models – DSM or Digital Terrain Models – DTM) overlaid with raster and vector maps to a web browser, enabling zoom and rotation of the 3D surface for visualisation. We also used the QGIS plugin OpenLayers (version 1.4.1 https://github.com/sourcepole/qgis-openlayers-plugin) to enable aerial map (Bing, 2016) overlay with digital surface models of topography, so as to visualise the aerial map as 3D surfaces re-shaped using the DSM. Additionally, we imported a building volume layer into the GIS system and used Qgis2threejs to extrude vector polygon surfaces to cubes using a constant height to define the height of the polygons throughout the model. As input for the building vectors we used the Edina Ordnance Survey data that showed the location of building outlines (Edina, 2013). Further, we also tested another useful capability of the QGIS2threejs-GIS system which is to draw a surface plane at a variable height and transparency to visualise objects above a specific height threshold. In addition, we processed an ulterior 3D surface model representation including the DSM (derived from voxel data) and overlaid it with a raster categorical map derived by the DSM and NDVI layers. This output map consisted of four classes including:

1) Grass (NDVI ≥ 0.2 and DSM < 0.5 m);
2) Trees and shrubs (NDVI ≥ 0.2 and DSM ≥ 0.5 m);
3) Roads and paved surfaces: (NDVI < 0.2 and DSM ≤ 0.5 m);
4) Buildings and other constructed surfaces: (NDVI < 0.2 and

DSM > 0.5 m);

A major limit to most GIS approaches is their reliance on providing a surface visualisation perspective that excludes the ability to see canopy elements that exist below the canopy top (e.g. the understory). Anything below the surface of the DSM (i.e. the single height measure so commonly used in 2.5D visualisations) is masked so that large parts of the voxel layer data are lost and not represented. This is partly because full voxel models describing environmental variables are still rather rare, and until such data become commonplace there will be no technical imperative for GIS to become fully 3D. A technical solution to this limitation involves the use of 3D graphical plot approaches available through specialised graphical software packages that can plot point data in a 3D space (e.g. R Core Team (2016), Williams and Kelley (2016)). To experiment with this we used 'gnuplot' software (Williams, 2016). The voxel GeoTIFFs were converted into x,y,z coordinates and we plotted the corresponding voxel signal value of presence/absence of vegetation for each point (the scripting routine for generating 3D plots is available on github as described in the 'data accessibility' section of this paper). Using the 3D plotting approach is helpful to keep the full information of the voxel elements (including the below DSM elements). Gnuplot is also able to provide zoom/rotate visualisation capabilities, but 3D plot approaches lose the map layer overlay potentials of the GIS approach.

2.4.2. Vertical slice animated gifs

A straightforward way to view 3D voxel data is to change the perspective from the map 'top-down' view to a 'side-on' viewpoint, viewing the volume from the ground-up and visualising the data from the pavements to the tree-tops. Voxels were stacked to create vertical cross sections through each of the cities, allowing the perspective to be changed from an aerial to a frontal view. In order to do this we utilised Python's imaging library (PIL) to extract a single row from every voxel image to create a new 'slice' image, rendering the voxel intensity values as an 8 bit greyscale value (0–255) per pixel. It was then possible to move the slice through the voxel image over time, creating multiple images as frames in order to provide animated walkthroughs of small areas of a town. We used this approach to prototype the classification system used in Minecraft as detailed in Section 2.4.3. Later work coded the vertical slice elements using the earlier described NDVI to label objects as 'built structures' or 'vegetation'.

2.4.3. Minecraft visualisations

There are a range of computer graphics packages designed to render 3D information which can be used to aid understanding of, and explore the 3D nature of the urban spaces, for example povray (http://www.povray.org/), Unity (https://forum.unity.com/) and blender (https://www.blender.org/). For this study, the Minecraft engine, which represents its worlds with voxel 'blocks', and thus offers an ideal toolkit from which to explore the volumetric nature of the urban voxel data, was chosen. Using regular grids of voxels reduces the need for intersection tests over mesh based computer graphics techniques (Amanatide & Woo, 1987). We implemented the visualisations using Minecraft on the Raspberry Pi, a variant of *Minecraft Pocket Edition* (https://Minecraft.gamepedia.com/Pocket_Edition) because it provides a Python application programming interface (API) for educational purposes which could be used to read the voxel geotiff format data with relative ease.

The Minecraft worlds were constructed by combining the two remote sensing datasets, the 3D voxel data (represented as a set of 2D floating point TIFF images for each height volume sample) and the 2D NDVI data (a single floating point image for the entire area at a different scale). We used the Geospatial Data Abstraction Library (GDAL) to extract the region of the NDVI image for a specific voxel image and rescale it so 1 NDVI pixel matched 1 voxel. Our script for reading the data into Minecraft iteratively loaded each block position, first reading the corresponding voxel to obtain the density value, then reading the NDVI value. The voxel data were then thresholded: any voxel that was deemed to be more dense than 0.01 (i.e. filled with > 1% vegetation) was set as a Minecraft block, otherwise the block was removed. If a voxel had a density above the threshold, then the NDVI and height value were used to give an indication of its contents. Minecraft comes with hundreds of different options visually to code material type (which determine the colour and texture of the block), five of which were used to visualise the classification of the LiDAR voxels. Table 1 gives details of the classification scheme applied to the Minecraft worlds.

Table 1
Classification scheme used in Minecraft for codifying voxels according to their likely land cover.

Category	Minecraft Material	Height threshold	Vegetation threshold
Trees	Leaves	height > 8 m	NDVI ≥ 0.2
Shrub	Green Wool	3 m ≤ height ≤ 8 m	NDVI ≥ 0.2
Grass	Grass	height < 3 m	NDVI ≥ 0.2
Building	Brick Block	height ≥ 3 m	NDVI < 0.2
Road	Bedrock	height < 3 m	NDVI < 0.2

We experimented with various display options for the Minecraft worlds. It was possible to create 'green space only' models by using the classification method to filter out voxels flagged as containing buildings and roads and replacing them with empty space. In this case we needed to add an extra base layer of solid ground under the lowest voxel layer, an assumed "ground level" - this was built using only the NDVI data to classify the voxels, and setting them all to solid. Without this there would be holes in the ground in some areas.

A specific challenge with implementing the Minecraft modelling was that the voxels represented non-cuboid areas of space (1.5 × 1.5 × 0.5 m), while Minecraft blocks are perfect equal cubes within the model. Therefore while a simple 1:1 mapping of Minecraft blocks to LiDAR voxels was useful for initial tests and for gaining understanding of the data, we found that it resulted in a vertical stretching of the resulting forms. This scaling problem was solved by building each voxel out of nine Minecraft blocks in a 3 × 3 grid, to provide the required 3 × 3 × 1 aspect ratio.

2.4.4. 3D printed and CNC milled tangible representations

Voxel data from the Minecraft Pocket Edition were next loaded into MCEdit (http://www.mcedit.net/) a tool for editing Minecraft worlds. The city voxels could then be selected and imported into the PC version of Minecraft. This permitted export to Mineways (http://www.realtimerendering.com/erich/Minecraft/public/mineways/), a software tool for selecting areas of Minecraft models, setting block dimensions, omitting floating blocks and exporting files for physical rendering in 3D printing or Computer Numerical Control (CNC) milling devices. Models were visualised using MeshLab (http://meshlab.sourceforge.net/) software to check for errors before milling or printing. Three types of tangible models were created: CNC milled models, single colour plastic 3D printed models and full colour sandstone 3D printed models. The methods followed to generate each are explained below.

CNC milling (a subtractive model making process where a solid block of material is carved out) was trialled for several areas of Luton and Milton Keynes. Data were exported from Mineways as .obj files, and imported into Autodesk® Inventor® software for conversion to .stl files. Mayka Expert 8.0 software was then used to programme the CNC milling tool, in which a two-phase radial tool path was set for the use of 6 mm and 3 mm drill bits; speed and feed rates were determined by the software. This radial toolpath was chosen to prevent the fragile step/vertical areas of the models from breaking or snapping due to vibration. The programmed-pathways were then sent to a Roland MDX-540, a bed milling machine equipped with a XYZ drive system.

Initial tests were undertaken to determine the quality of the experimental fabrication and form-generation for exploration of the urban greenspace structure before final models were milled in two phases: rough cut and refined finish. Initial tests were undertaken to determine the quality of the experimental fabrication and form-generation for exploration of the urban greenspace structure before final models were built. This digital craft making process was experimental and focused on producing tangible outcomes suitable for use in public engagement. Several models were milled over five-days, averaging two every five hours, dependant on the complexity of the step/vertical areas, and the refinement of the finish. To meet the requirements of the exhibition display the final models were cut down to match the printed maps. These different tests and final models are evaluated below.

Single colour plastic (Acrylonitrile butadiene styrene, ABS) 3D printing was trialled for several areas of Luton. 3D printing is a cheap and widely available method of producing 3D models, and is additive rather than reductive like CNC milling. ABS is a strong non-brittle thermostable plastic, suitable for heavy handling. Voxel data from Luton where the land cover patterning was diverse and mixed (containing buildings and greenspace) was chosen and exported using Mineways as a .wrl file (a standard file format for representing 3D data for printing), selecting the option for strong and flexible white plastic with each Minecraft block represented by a 0.7 mm print size. The same region was printed using a file containing no buildings, to make a comparable model showing only the greenspace. The models were printed using Shapeways (http://www.shapeways.com/), an online 3D printing service.

Finally, we experimented with full colour sandstone 3D printing to show the classification of the voxel data and its' 3D distribution. Mineways includes an option for sandstone printing, and exports a .wrl file containing shape, colour and texture information for upload to Shapeways. A small region of the Luton voxel data containing buildings, roads and greenspace was chosen for sandstone printing. We used colours and textures representative of the classifications in the voxel data – brown buildings, grey roads, pale green grass, mid-green shrubs, dark green trees. Sandstone is the only material capable of full-colour 3D printing. The material is hard but brittle, and so is not suited to daily handling – the colours fade on exposure to water. Epoxy-resin coatings can be brushed on by hand to deepen colours, smooth the surface, and add some additional strength, however this was not deemed necessary for this project. The full-colour sandstone printing method uses the Minecraft materials to colour the print, but comes with its own limitations due to the material used. In order to produce a print cheaply enough that covered a big enough area within one of the cities (Luton) we needed to print at 1 mm per block (3 × 3 × 1 mm LiDAR voxel). The first problem with sandstone material is that supported walls must be 2 mm or greater thick, and free-standing walls need to be 3 mm or greater thick. With individual voxels being 1 mm high the print was unstable in areas where a single voxel extended from the side of a structure. In order to remove this problem without distorting the shape we recreated the world using 3 × 3 × 3 voxels overlapping them by 2 voxels in height downwards, which meant edges could never be < 3 mm, but steps between voxels could still have a single voxel (1 mm) height difference. The second problem was that even with this method there were still places where voxels meet corner to corner, resulting in a weakened structure. The solution to this was to thicken the voxels further by two Minecraft blocks in the other directions to give every voxel an overlap with its neighbours – greatly strengthening the weak areas but still resulting in the correct shape:aspect ratio.

3. Results and discussion

3.1. GIS and graphical 3D plot visualisations

Fig. 1 shows various GIS-based visualisations of the data. An overlay between the DSM from voxel layers with raster (aerial map) and vector (buildings) layers is visible in Fig. 1a. In Fig. 1b we set height thresholds to highlight only the top of the vegetation canopy. A different visualisation of the voxel derived DSM is represented in Fig. 1c. Here we show different surface classes for vegetation (tall and short) and built surfaces (roads/paved or buildings). The limitation of standard GIS visualisations is that they can, at best provide a 2.5D view of the data – i.e. a 2 dimensional representation of spatial data, colour coded with additional information describing height. The three dimensional nature of the voxel data explored herein (describing vegetation density in voxel blocks through the vertical volume) could not be explored fully by exploiting basic GIS functionality since most current software does not offer full 3D topology as standard (although there are processing routes emerging within specialised software, for example using a 3D plug-in for Grasshopper GIS). Instead, we used a 3D plug-in for QGIS (Qgis2threejs) which overlays maps (e.g. terrain data, map canvas image and vector data) with different projections on the fly without the need to reproject the data sources to a common spatial reference system. Secondly, the plugin exports the output maps to a web browser allowing a full exploration of a 3D model from a bird's eye view (Fig. 1a) with a possibility to add a transect height section (Fig. 1b) and also provides the option to zoom in/out and use a fly-through mode. In addition, we also explored an alternative 3D visualisation of voxel data using the graphics package GNUPlot (Fig. 2). GNUPlot offers powerful command line software for point data plotting with the advantage of embedding linux bash-awk programming languages for data slicing, data query, and for directly converting GeoTIFF file formats into point clouds within the same scripting routine. Another advantage of gnuplot versus other graphical software for 3D point plots (e.g. R software) is that it is capable of reading points within a file line by line and not charging the full set of data into the RAM memory which causes delay in the visualisation process. We found this to be of particularly critical importance when working with large datasets such as the LiDAR voxel layers explored here. Fig. 2 shows a point-based visualisation achieved using GNUPlot (GNUPlot cannot plot voxels but represents these as points instead), evidencing the improved ability to explore the urban green volume over standard GIS-based approaches.

3.2. Vertical slice animated GIFs

Fig. 3 shows various 'slices' through areas of Luton. Fig. 3(a) and (b) show greyscale visualisations where the brightness of the pixels is scaled to indicate the intensity of the voxel signal, and thus in the case of greenspace, the density of the vegetation at that point in the volume. Fig. 3(c) shows the same area with two versions of the visualisation. Top, is the greyscale version, and below is the classified version where the vertical slice elements were classified using the earlier described NDVI to label objects as 'built structures' (orange, NDVI < 0.2) or 'vegetation' (green, NDVI ≥ 0.2). Figs. 3(e) and 2(f) show different views of the colour coded classified areas of the city. In Fig. 3 it is clear that the voxel data are penetrating through the tree canopies to the ground, and the intricate sub-canopy structures are brought to life through this 'vertical slice' viewpoint of the urban space. In Fig. 3(a), for example, the patch of trees on the left of the slice has a very clear understory, while the dense patch of trees shown in both the greyscale and colour versions in Fig. 3(c) shows a clear pattern as evidenced by the speckle structure of the voxel data when viewed sideways-on.

3.3. Minecraft worlds

Fig. 4 shows Minecraft visualisations of three areas of the city of Luton – both with (left hand side of Fig. 4) and without (right hand side of Fig. 4) built structures. The worlds created in Minecraft allow participants to explore virtually and experience a city using a familiar first person viewpoint. Minecraft itself provides an existing, well understood interface that is good for presenting the data in public exhibitions. The use of a Raspberry Pi also allowed us to present technology used in visualisation in an accessible manner as it is low cost and a familiar gaming tool.

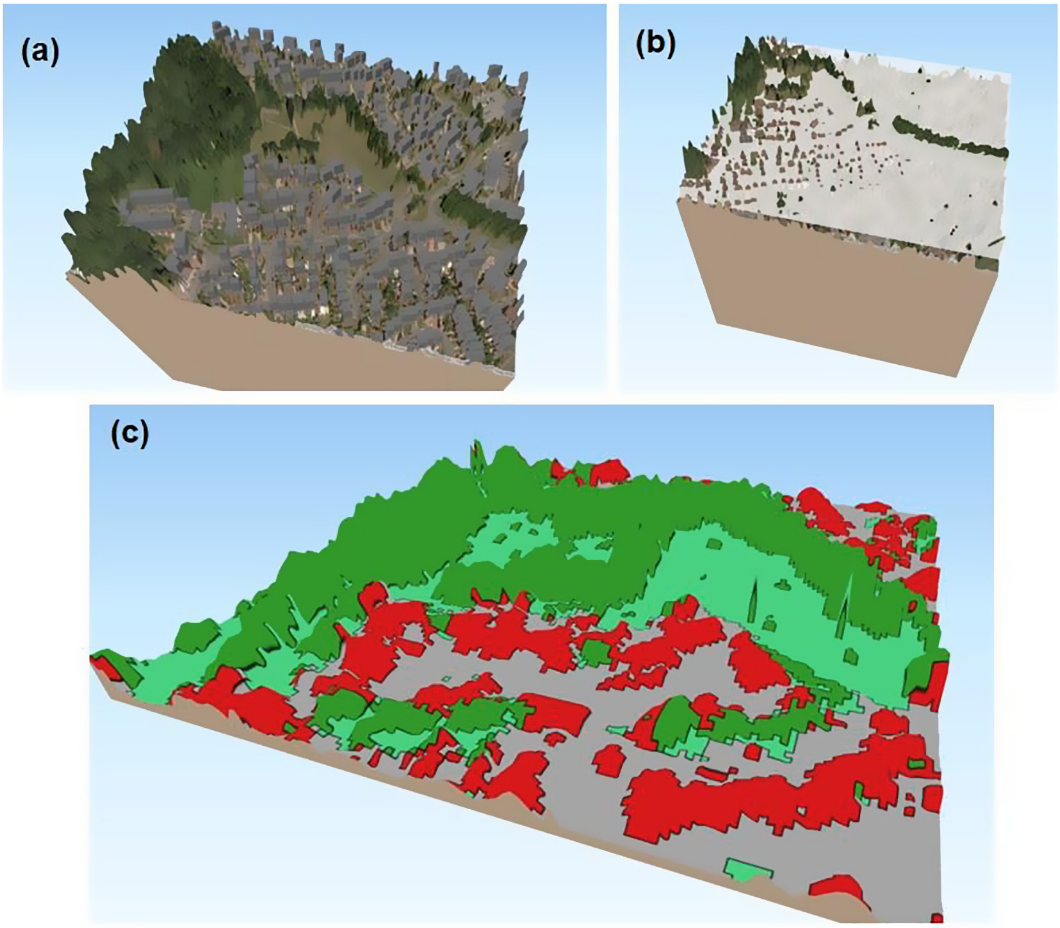


Fig. 1. Examples of methods for visualising volumetric voxel data using 2.5D approaches in Geographic Information Systems. (1a) Vegetation surface height (DSM) overlaid with aerial image (Bing, 2016) and buildings (Contains Ordnance Survey data © Crown copyright and database right 2013) drawn from polygon vector layers extruded as cubes to a height of 4 m. (1b) as in (1a) but visualisation limited to the vegetation surface height (DSM) above 4 m height. (1c) DSM overlaid with a 4 class map including: grass (light green), trees and shrubs (dark green), roads and paved surfaces (grey), and buildings and other constructed surfaces (red). All were generated using Qgis software (QGIS, 2016) and the Qgis2threejs plugin was used to generate Fig. 1a and 1b. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We suggest that using simple gaming tools such as Minecraft, as demonstrated here, provides a highly stylised and easy to understand view of an otherwise complex dataset, where the stylised Minecraft blocks aid the ‘suspension of disbelief’ required in order to understand the complexity of the urban landscape. The blocks are simple, and yet still permit users to visualise objects in a city, while their schematic form allows the understanding of more abstract data. In this way, Minecraft allows experimentation with speculative understandings of non-human urban dwellers and how they may utilise or see the city. For example, it is possible to filtering human structures, for example roads or rail infrastructure may be barriers from a non-human perspective, rather than the communication links they represent in human understanding. The use of serious games and 3D games technology and simulation in policy and organisational planning is well documented (Mayer, 2009; Rebolledo-Mendez, Avramides, Freitas, & Memarzia, 2009) including the use of these kinds of perspective shifts (Valkering, van der Brugge, Offermans, Haasnoot, & Vreugdenhil, 2012).

3.4. CNC mill experiments

CNC milling is an advanced technology, originally developed by the Massachusetts Institute of Technology (MIT) in the 1950s and we chose to use it because it is easily accessible to architects and planners through ‘FabLabs’, makerspaces, universities and private workshops. The materials used are relatively inexpensive and we found it offered an efficient method of production with a range of materials. In this case the digital craft maker had access to a university workshop, and therefore did not pay for mill time. However, milling is relatively inexpensive to outsource at approx. £30 p/h (London, UK as at May 2018). Alternatively, many architects and designers have their own mill in-house, or choose to belong to collective workshops, where an annual fee covers access to a range of resources and equipment. The technology was well-suited to the voxel dataset but in generating various outputs, we encountered several challenges.

Firstly, some of the data, filtered through Mineways into Minecraft .objs, contained ‘flyaway’ voxels, i.e. blocks of vegetation not fixed to the main sample. Many of these pieces represented foliage attached to branches: overhanging areas not connected to the ground or any adjacent greenspace, which appeared to float in mid-air. These flyaway blocks did not translate well during the software transfer process, during which they were automatically connected to the closest vertical body of greenspace. Therefore, when using a CNC mill with a XYZ drive system these floating voxels were integrated into a single surface geometry, creating a unified 3D model of the greenspace. Essentially, the blocks and the ‘air’ between them were read as one solid form.

To precision cut the cubed structure of these models we used 6 mm and 3 mm drill bits, programmed in a radial drill path, across three different materials (Styrofoam, SikaBlock M450 and SikaBlock M700). We initially experimented with CNC milling extruded polystyrene foam (Styrofoam) due to its low cost (Fig. 5 shows the process of milling the

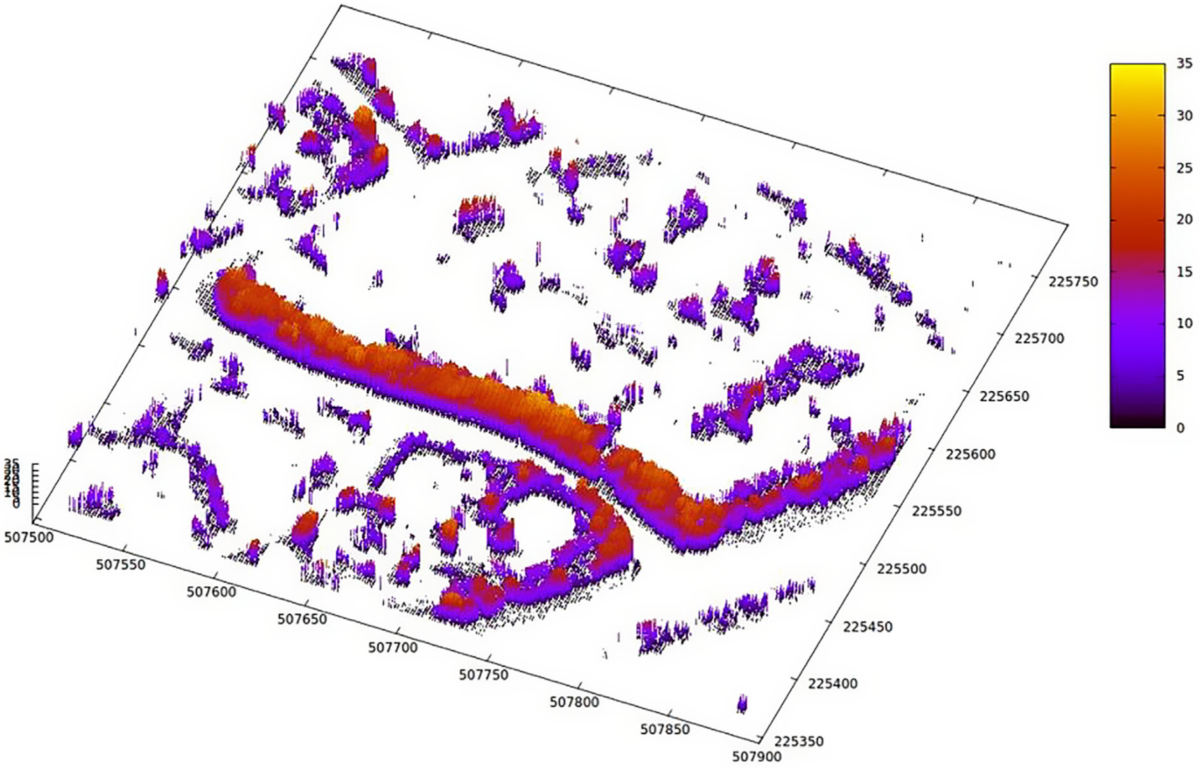


Fig. 2. GNUPlot point-based visualisation of voxel data showing the 3D structure of the urban green volume. To a greater extent than GIS, this approach allows for the volumetric nature of the greenspace to be visualised, with voxels colour coded according to height, with purple/blue hues representing lower vegetation canopies than red/orange hues. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Styrofoam for an area of Luton). Styrofoam is often used to prototype models in the early stages of design. It is easy to mill and widely used to produce site models in architecture. It is light at 52 kg/m^3 and relatively cheap at approximately £2.00 per 100 mm^3 block. Styrofoam's aerated texture does not always allow a high-precision finish to be achieved due to low-edge stability. However, this material can be used to create cost efficient working models for use in both the schematic design and design development phases in architecture.

Fig. 5d shows the final CNC milled model of Luton's green and built architecture. This was milled from a 400 × 400 × 100 mm block, scaled such that 10 mm represented approximately 10 m (1:10,000; Fig. 5a and b) and cost £35.55 to produce. Each voxel is doubled in size horizontally, and the visualisation is mirrored. To render this, we experimented with thresholding the greenspace data at varying levels, to reduce flyaway blocks and show only the densest vegetation – this representation used a voxel intensity threshold of 0.2 (i.e. where voxels were only included in the build of this tangible model if there was > 20% of the voxel volume filled with vegetation). We found that setting the voxel threshold this high resulted in an under-representation of greenspace in the final build. We also encountered challenges in translating the geographic co-ordinates from the original voxel layers through the various processing stages, to the final product. The impact of these workflow translations sometimes resulted in slight offsets in geographic positioning in the final model, relative to the original data.

Fig. 6 shows the results of the Styrofoam CNC milled product (Fig. 6a) next to two further products: orange extruded polyurethane board (SikaBlock® M450, Fig. 6b) and taupe rigid polyurethane board (SikaBlock® M700, Fig. 6c). The M450 product (Fig. 6b) has a finer texture than blue Styrofoam (Fig. 6a), having a density of 450 kg/m^3, which allows for higher edge-stability when milling. Understandably, it is more expensive at approximately £4.00 per 100 mm^3. The area shown in Fig. 6b was a mixed residential area of Luton, milled from a 180 × 180 × 100 mm block, scaled such that 10 mm represented approximately 10 m (total cost £12.44). The robustness of the material allowed slightly more detail to be shown in the model. The M700 material was the hardest of all three materials tested with a density of 700 kg/m^3, also making it the costliest (approximately £5.00 per 100 mm^3) – producing the small model shown in Fig. 6c (cut from a block roughly 100 mm^3), scaled such that 1 cm represented approximately 13 m, costing £5.16. In experimenting with this material, we found it to be rather brittle and therefore sensitive to the reverberations of the mill in action. As such, the production speed had to be significantly slowed to avoid breakages. In all cases the models shown in Fig. 6 were produced using the same 0.2 voxel intensity threshold as described previously, resulting in some of the greenspace being omitted from the models. Additionally the vertical axis of each voxel (i.e. the height representation in these models) is three times the scaling of x,y due to the original voxels being 1.5 × 1.5 × 0.5 m – resulting in vertical distortion in these tangible models.

These first experiments with converting real canopy density data into tangible models for exploration provided low cost and quick turnaround models before looking at the more expensive options. These models were used to identify problems such as floating blocks and used to refine our data export process. Even though it cannot replicate accurately areas of overhanging vegetation (since the manufacturing process does not allow for disconnected voxels), this technique allows much larger scale models to be generated than 3D printing which may be more important in some situations.

3.5. 3D printing experiments

Our initial experiments with 3D printing proved time-consuming, materially inefficient and somewhat disappointing in terms of overall results. The workflow of filtering the voxel data into vegetated/built structures and then converting the Minecraft models into 3D printable .obj files proved particularly challenging and we produced several

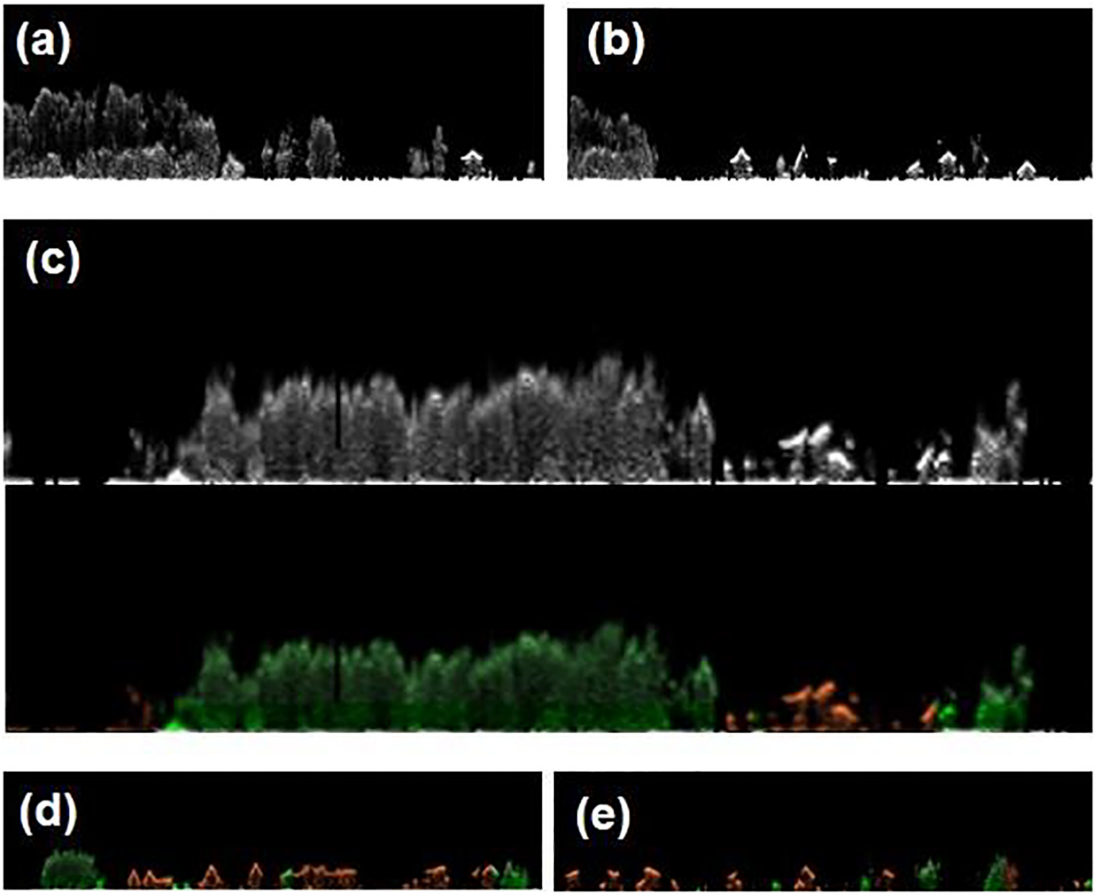


Fig. 3. Still screen-captures of the vertical slice animations generated using Python coding to explore the structure of the urban spaces and greenspaces from the tree- and roof-tops to the ground.

outputs that failed to deliver accurate representations of the 3D nature of the urban system particularly in terms of visualising the greenspace structure in 3D. Once we had experimented further with CNC milling, and determined the appropriate thresholds and pre-processing steps to take, we embarked on a more detailed investigation of 3D printing technologies for a small residential area of Luton near Allsworth Road. This area was chosen because it contained a good mixture of built structures (housing) and residential gardens and roadside trees. The results – printed using white PLA plastic on boards of 180 × 180 mm are shown in Fig. 7. The models measured 180 × 180 mm, scaled such that 10 mm represented approximately 7 m, and cost £67.05 for the greenspace and buildings model, and £52.98 for the greenspace only model. These corrected for the vertical bias representation encountered in the earlier shown CNC milled products, by building each voxel out of nine Minecraft blocks in a 3 × 3 grid, to represent the 3x3x1 aspect ratio of the original voxel data (1.5 × 1.5 × 0.5 m). We further developed this using the Minecraft colour scheme, to produce the sandstone print shown in Fig. 8 – the final model was 170 × 180 mm, scaled such that 10 mm represented approximately 5 m, and printing this model cost £124. Note that in Fig. 8, there is some misclassification of the voxels evident. The shrub hedge along the roadside was misclassified as buildings (brown in the 3D printed model), and shadows from the hedge were sometimes misclassified as shrubs (mid-green linear features extending out from the hedge). The Minecraft modelling and the tangible sandstone-printed output brought these misclassification errors to light.

3.6. Responses from exhibitions

The tangible models and Minecraft visualisations were presented at several research-focused and public events during 2016 and 2017 (Fig. 9 shows two example exhibits at the University of Exeter in November 2016, and at an art festival hosted by the Newlyn Art Gallery, Cornwall UK in April 2017). Each exhibition was preceded by a short seminar in which the science behind the project, the data analysis and the creative process was explained by different members of the research team to diverse audiences. The purpose of these exhibitions was twofold: first, to share the science of the urban greenspace research undertaken, and second, to gain informal feedback about the various visualisation methods used in the experiment.

We gathered informal feedback from around twenty individuals who interacted with us, and we report the results of discussions below. Importantly, these observations were not derived from organized focus groups or structured interviews, but were instead anecdotal observations gathered during conversations between co-authors of the paper and participants within these sessions. Making the tangible models available for people to hold, rotate and interact with, alongside Raspberry Pi screens allowing participants to play with the Minecraft visualisations resulted in a variety of interesting conversations. During these sessions we engaged with artists, architects, ecologists, landscape researchers, farmers and children. Key discussion points summarizing the interactions and conversations we held with these groups are summarized in the following paragraphs, to provide evidence of the diverse conversations that the work has generated.

The models generated interest amongst architects who sprang into animated conversation about the general lack of greenspace and green-volume data in building design programs. The architects we talked to said that the tangible models (particularly the CNC and 3D printed versions) could be used to powerful effect in communicating the importance of green architecture when designing new urban forms,

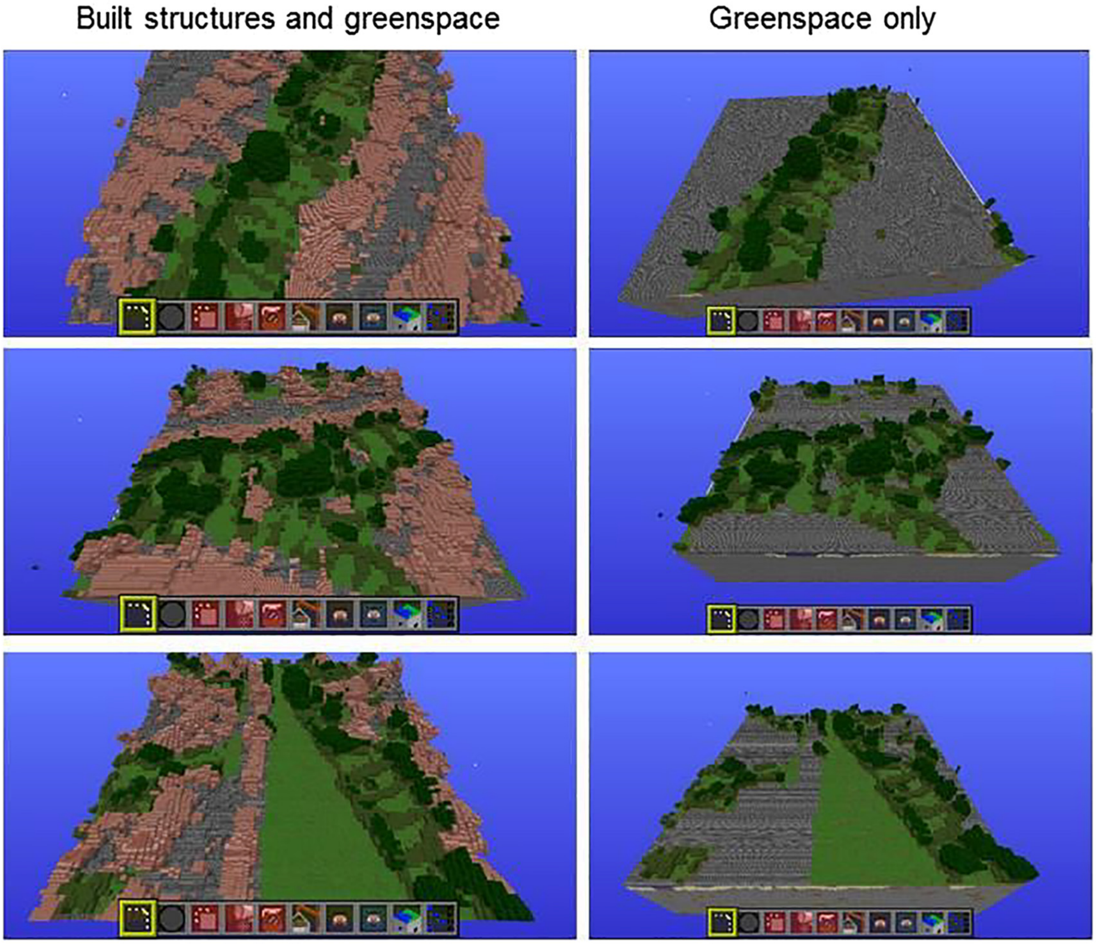


Fig. 4. Still screen captures of the Minecraft visualisations for three areas of Luton with different greenspace distributions. On the left hand side of the figure, the Minecraft worlds are shown with all buildings and built structures included. On the right hand side, the built structures have been removed to show the city from a greenspace-only perspective.

both for incorporating nature connectedness into new designs, and for visual realism in communicating the likely impact of new developments on local environments. The architects who viewed our work were keen to integrate LiDAR data into their own future visualisations and in planning applications.

Amongst ecologists there was excitement about the ways in which the Minecraft models could bring about new understanding of non-human experiences in the green volume. For example, one ecological scientist expressed how the ability to 'be in' the model would allow one to experience the urban environment as another species – e.g. a bird, doormouse or squirrel might do. Another participant began to imagine how the waveform LiDAR data could be used to estimate energy expenditure of key organisms in particular habitats, as a result of seeing the vegetation visualised volumetrically via the Minecraft game. Certainly, the ability to view the 3D vegetation data in new ways brought such conversations to the fore and brought new ideas to life amongst scientific audiences.

Children were most interested in interacting with the Minecraft visualisations, presumably because this was a technology that they were familiar with already. While they didn't pass too much comment on the data, it was clear that their level of engagement with the urban models and the ease with which they could explore the landscapes through Minecraft, suggested that this would be a powerful tool for science communication. Other researchers are already generating new Minecraft worlds from freely available open-access LiDAR data, for example see the Southampton open map created from open access LiDAR data provided by the UK Environment Agency (https://www.Minecraftworldmap.com/worlds/x0San#/6035/64/-3067/-6/0/0) and Denmark has produced an open source map of the entire country based on LiDAR data (https://www.youtube.com/watch?v = 6rMebJWiNUQ&feature = youtu.be). So there exists an opportunity to utilise such data and harness visualisation technology to communicate contemporary issues in environmental science (e.g. deforestation, land use change, habitat fragmentation) to children and wider audiences through virtual gaming interfaces.

Farmers and landscape researchers expressed an interest in using these techniques alongside freely available LiDAR data to visualise farm-scape environments for communicating agri-environmental issues to a broad range of stakeholders. As a result of demonstrating the data and models to a group of agricultural researchers, the authors are now exploring new research on this theme.

Artists were very engaged with the tangible models initially, asking questions about the technologies used and the creative process of producing the models. These conversations then led to others about the nature of changing urban spaces, fueled by the artists' own experiences in their urban or suburban neighbourhoods. We had an interesting discussion with a group of artists who had not realized that there were a fleet of national survey aircraft capable of gathering data using laser scanners and cameras, and so ensued a conversation about remote sensing, privacy and surveillance.

Importantly, the process of engaging actively with a diverse audience using these tangible and virtual models, allowed the research team to hold conversations with a wide variety of people on the scientific work around urban greenspace and its impacts on human wellbeing. In

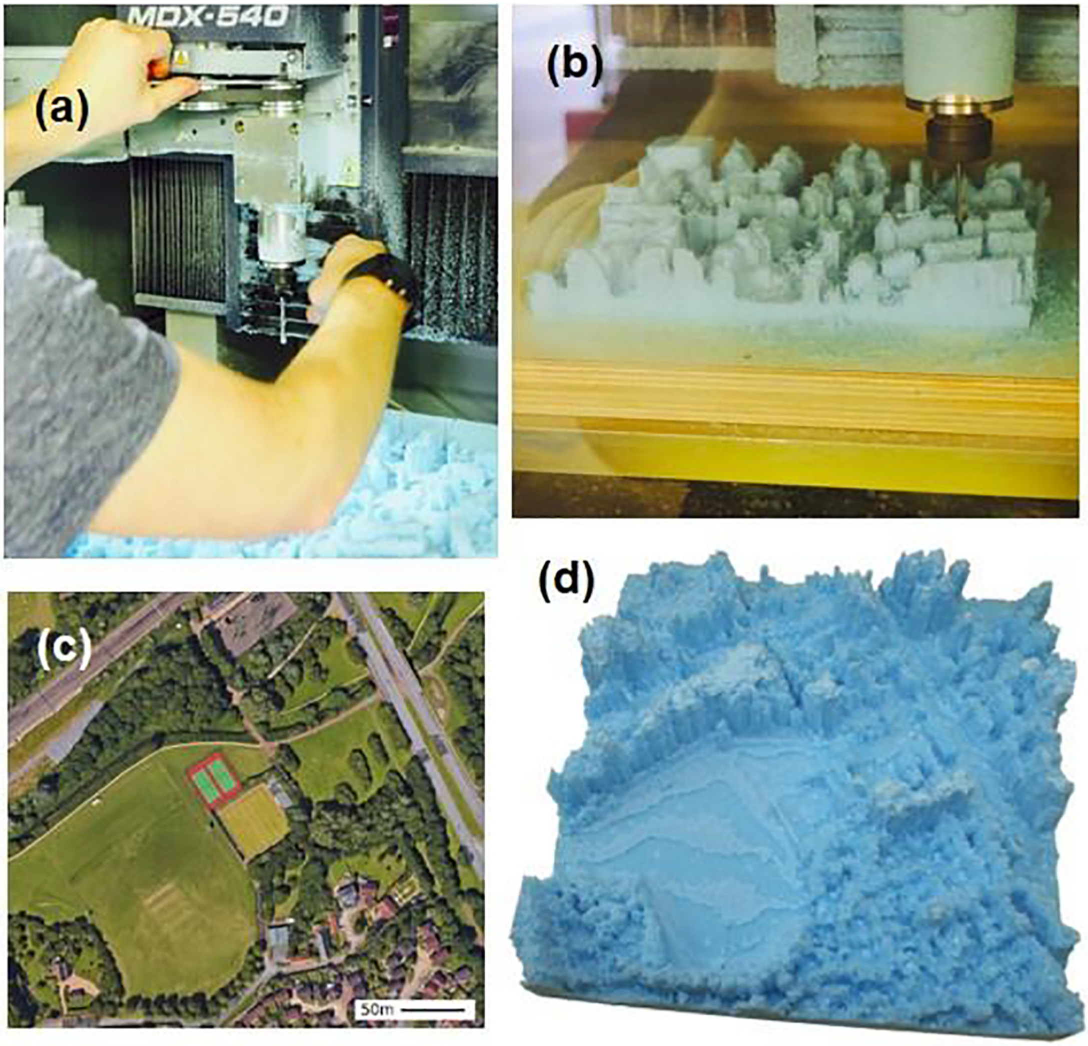


Fig. 5. The production of CNC milled tangible visualisations of the voxel data. (a) the milling machine being set-up, (b) the milling as it took place; and (c) and (d) a diverse park area of Luton and its associated CNC milled model, which includes both built structures and greenspace.

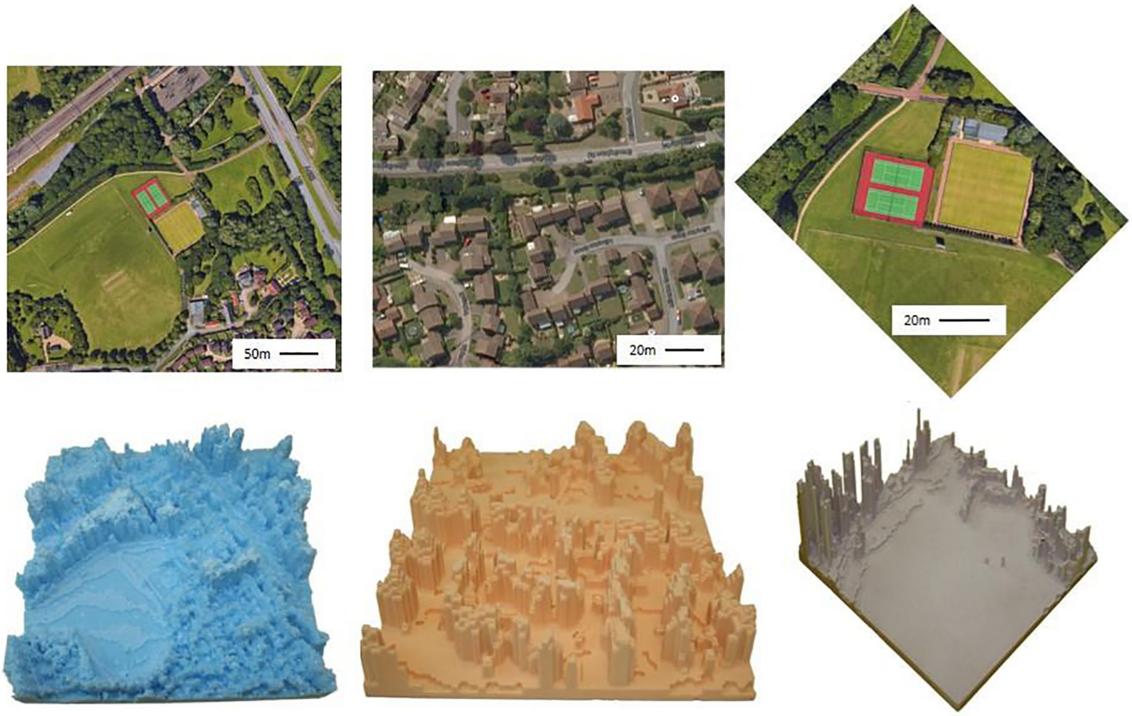
particular, being able to hold the models and explore them in Minecraft gave rise to a variety of questions about urban trees, wellbeing and nature connectedness amongst the audiences. Through these conversations we were able to bring a range of new scientific findings (largely stemming from the broader aims of the project that funded the work, (e.g. Cox and Gaston (2016), Cox et al. (2016), Anderson et al. (2016)) to the attention of the public, so these models proved to be an effective vehicle for engaging the public in conversations about broader environmental science research. Similarly, few people knew of the new open-access availability of LiDAR data in the UK, and many were surprised that it would be possible to obtain discrete return LiDAR data (freely from repositories such as data.gov.uk), so the project exhibitions were successful in spreading the message about open data. Our approach of using tangible models and tactile interfaces to bring the city to life for different audiences parallels approaches currently being developed to aid city navigation by blind and partially sighted people (https://touch-mapper.org/en/). So, we argue that transforming geospatial data into tangible models can make cities, and spatial data more accessible to broader audiences, which is important in a range of science communication and environmental planning contexts.

4. Conclusions

This paper has demonstrated new methodologies for exploring and representing the diverse, and typically highly heterogeneous, 3D green space structures that exist within all towns and cities. The importance of urban green space for public health, nature connectedness, and delivery of ecosystem services is now well-known (Gaston et al., 2013; Wolch, Byrne, & Newell, 2014) and yet, urban plans and models generally omit information about the urban green volume which, we argue, is a key component to consider when reviewing, planning and managing the distribution of urban green infrastructure.

New volumetric data from systems such as waveform LiDAR (and to a lesser extent, freely available, yet, more basic discrete return LiDAR) hold great promise for helping improve the representation of urban green space (and volume) modelling within the urban planning process. Technical methods allowing raw laser signals to be transformed into 3D voxelised models describing the spatial and volumetric distribution of urban vegetation now exist (Hancock et al., 2017), but the products generated are often too intangible and complex for policy makers, city planners or other citizens to use, and understand. Such data also require considerable transformation to enable them to be used effectively for communicating key issues. Furthermore within architecture, greenspace in all its volumetric, networked detail is often omitted, and is rarely represented accurately in the design and planning process.

To explore the different ways in which this volumetric information can be engaged with, we have, for the first time experimented with and demonstrated how open-source visualisation tools such as Minecraft



(a) Blue extruded Styrofoam
400 x 400 mm

(b) Orange extruded polyurethane
board, SikaBlock® M450
180 x180 mm

(c) Taupe rigid polyurethane
board, SikaBlock® M700
100 x 100 mm

Fig. 6. Comparisons of three CNC milled products showing different areas of Luton.

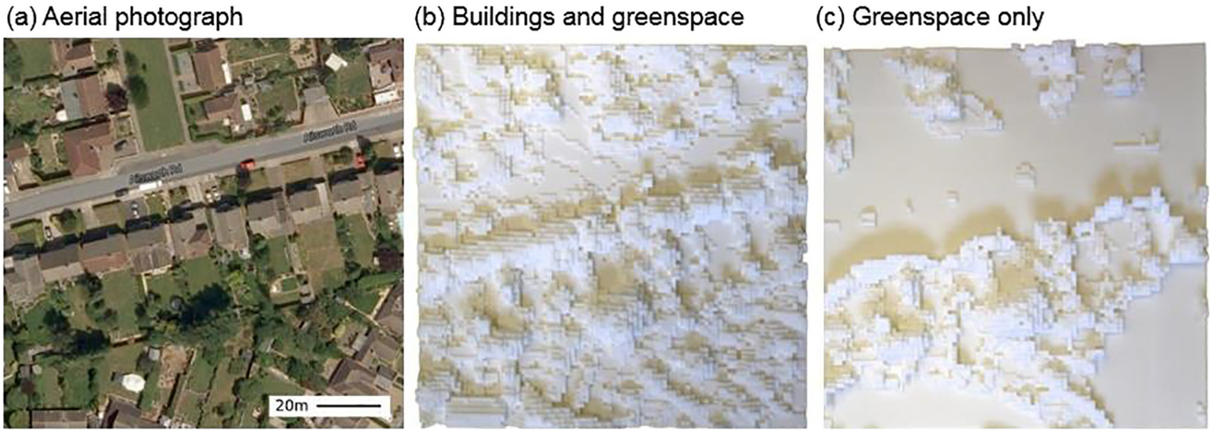


Fig. 7. 3D printed white PLA plastic prints, 180 × 180 mm generated from Minecraft .obj file, Luton. The aerial photograph (a) shows the approximate extent of the 3D printed site, (b) shows the model representing all the buildings and greenspace; (c) shows the model representing only greenspace within the same area. In this model, the vertical scaling problem was solved by building each voxel out of nine Minecraft blocks in a 3 × 3 grid, to provide the required 3 × 3 × 1 aspect ratio.

and tangible technologies (e.g. CNC milling and 3D printing) can improve understanding of greenspace importance and complexity. We are not alone in proposing this – the use of Minecraft has been highlighted through architectural visualisations of urban space, and specifically, one architect highlights that, "architecture should be more like Minecraft", where the "fictional worlds empower people with the tools to transform their own environment" […] "where our knowledge and technology doesn't limit us, but rather enables us to turn surreal dreams into inhabitable space, to turn function into fact" (Ingels, 2015).

We suggest that geographers and ecologists have a responsibility to communicate their research and to share complex spatial and volumetric data to a range of stakeholders, and this project evidences how some of this communication can be achieved through digital craft, incorporating LiDAR data, Minecraft and tangible model-making into a broader communicative process. In experimenting with such approaches we have demonstrated that it is possible to represent the complexity of urban vegetation in easy-to-understand ways that could be readily used by a range of researchers and stakeholders, from town and city councils, to remote sensing scientists, architects and ecologists. Reflecting on this process, the strength of such diverse approaches lie in their tangible interface that brings greenspace visualisation to life for both professional and lay audiences (addressing the need for best practice in public engagement). Batty et al. (2001) describe this as backward and forward visualisation, where "*backward visualisation* involves developing visual tools and imagery which support experts and professionals, while *forward visualisation* supports a less informed constituency, the public at large, but more specifically, particular interest groups" (406, 2001).

Fig. 8. Full colour sandstone 3D print, 170 × 180 mm, from Minecraft .obj file, Luton shown alongside an aerial photograph of the site. Colours are representative of the classifications in the voxel data – brown buildings, grey roads, pale green grass, mid-green shrubs and dark green trees. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Examples of tangible voxel exhibitions shown at the Newlyn Art Gallery, Cornwall, UK (top row: 2017) and the University of Exeter (bottom row: 2016). Photographs are author's own.

Looking to the future, where virtual and augmented reality (VR/AR) methods will come to the fore as planning tools within geography and architecture, the described project shows how integration of volumetric information from waveform LiDAR data into the process can bring the reality of the city's green volume to life in a virtual sense. Engagement with volumetric green space through VR or AR technologies and using real data describing city green structures, may pave the way for more empathetic planning (e.g. experiencing the city as a bird or bat), and thus for improved management to enhance ecological connectivity. Reflecting on our own practices, we acknowledge that the major limitation with methods such as 3D printing and fabrication lie in the display of dynamic information which can provide feedback to user input. We suggest that VR technology would also be rather limited in scope in this respect since it provides a disembodied individual perspective, however AR could be utilised more effectively to provide a secondary information overlay - for example the use of projection mapping to provide predictions of urban greenspace change following a new development, via manipulation of model parameters over a static 3D printed map. Towards the future, tangible interfaces will be extended via the use of robotics technology and haptic feedback (https://www.media.mit.edu/projects/bigbarchart/overview/) to provide a more fully embodied exploration of data. These interfaces indicate new potential for the shared collaborative understanding required for increasingly complex data and policy decision making. While global cities become increasingly managed and experienced volumetrically, there will be a need to combine accurate 3D data with immersive or tactile visualisation tools to effectively communicate, navigate and manage space and place.

Acknowledgements

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Data accessibility

This project was undertaken in the spirit of open-source science and full details of the project as it was underway can be found on the following blog https://fo.am/greenspace/. Waveform lidar and optical data from the NERC-ARSF flight (reference: 'RG 12/10') are archived at the Centre for Environmental data Analysis portal (CEDA) (http://www.neodc.rl.ac.uk/). Potential adopters of our methodology will be faced with computational challenges in translating the waveform signal into voxel data due to the complex issues of multiple scattering and signal attenuation, to give just two examples. In this respect, we provide an open source code to process the voxel data, full details of which can be found in (Hancock et al., 2017) and at https://bitbucket.org/StevenHancock/voxelate. The scripting routine for generating 3D plots is available at https://github.com/stefano-cornwall/urbanConnect.

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