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Online interactive thematic mapping: Applications and techniques for socio-economic research

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ABSTRACT

Recent advances in public sector open data and online mapping software are opening up new possibilities for interactive mapping in research applications. Increasingly there are opportunities to develop advanced interactive platforms with exploratory and analytical functionality. This paper reviews tools and workflows for the production of online research mapping platforms, alongside a classification of the interactive functionality that can be achieved. A series of mapping case studies from government, academia and research institutes are reviewed. The conclusions are that online cartography's technical hurdles are falling due to open data releases, open source software and cloud services innovations. The data exploration functionality of these new tools is powerful and complements the emerging fields of big data and open GIS. International data perspectives are also increasingly feasible. Analytical functionality for web mapping is currently less developed, but promising examples can be seen in areas such as urban analytics. For more presentational research communication applications, there has been progress in story-driven mapping drawing on data journalism approaches that are capable of connecting with very large audiences.

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1. Overview

The use of online mapping and spatial search has become ubiquitous, with hundreds of millions of desktop and smartphone users regularly accessing mapping services.[1] Furthermore spatial data and mapping is also widespread in social media, with users sharing and tagging geolocated media through various crowdsourcing applications. These 'geoweb' tools amount to a revolution in how the public view, create and interact with geospatial data (Goodchild, 2007; Haklay, Singleton, & Parker, 2008). Yet while platforms such as Google Maps and OpenStreetMap present huge topographic databases of the globe, there are no such comparable global mapping platforms for socio-economic data, such as demographic, economic and environmental indicators. Socio-economic mapping platforms are typically limited to a single nation-state at a particular data scale, with a lack of indicator breadth and analytical functionality.

The potential advantages of using web mapping tools to integrate socio-economic data into global and national platforms could be substantial in terms of facilitating research and allowing the public to compare and contrast locations across the world using a range of indicators. There are many interest groups concerned with socio-economic representation and analysis, from international and national governance agencies to universities, environmental science institutes, national statistics bodies, Non-Governmental Organisations (NGOs), think-tanks and similar organisations. The global mapping of socio-economic data was an important part of Al Gore's original 'Digital Earth' vision (Gore, 1998) that anticipated online mapping innovation, but thus far global data integration has focussed overwhelmingly on topographic and remotely sensed data.

Several barriers have been restricting developments in online socio-economic cartography. Innovation in web mapping has been driven mainly by large tech companies (Plewe, 2007) seeking market share in lucrative spatial search and mobile markets, with socio-economic mapping given comparatively little attention. Furthermore there are challenges with socio-economic data itself, in terms of access restrictions, online sharing restrictions and integrating data between nation states (Kitchin, 2014; Masser, 2005). Due to the high costs of national censuses, socio-economic data can be limited, particularly in the global south (Linard & Tatem, 2012). Finally there has been a lack of easy-to-use software tools capable of creating high quality thematic mapping sites.

In recent years a number of trends have emerged that are overcoming many of these barriers. The open data movement has been central to the release of a wide range of public sector datasets for free in standardised and shareable form (Kitchin, 2014). In addition to data releases, there has been significant technological and software innovation allowing sophisticated thematic maps to be delivered within standard web browsers (O'Brien, 2015). Much of the innovation is being driven by open-source software, with free and powerful tools that are expanding the user-base of online cartographers (Steiniger & Hunter, 2013). Finally the aesthetics and techniques of thematic mapping and related visualisations have become increasingly mainstream through media and business trends such as data journalism (Weber & Rall, 2012) and visual analytics (Thomas & Cook, 2006). Together these innovations are expanding the scope of online geovisualisation capabilities to embrace both socio-economic datasets and the visualisation and spatial analysis techniques to explore them.

This paper provides an overview of the recent innovations in online socio-economic data and interactive thematic mapping tools. Workflows for producing thematic mapping sites are defined, alongside a classification of the interactive functionality for research applications. Case studies of recent thematic mapping sites from academia, government and research institutes are reviewed, illustrating what can be achieved and opportunities for future developments.

2. Review contexts

Firstly the research applications of online interactive mapping are discussed, and related to established scientific roles for cartography. This is followed by an overview of the main data and software innovations that are underpinning recent developments in online interactive mapping.

2.1. Online interactive mapping for research

Cartography is used in several areas of scientific research, and these roles can be categorised according to the stages of scientific enquiry in which they are applied (Roth, 2013). Applications during early exploratory stages of research aid 'visual thinking' (DiBiase, 1990), allowing data to be better understood and assisting hypotheses formulation. MacEachren (1994) defines such exploratory cartographic tasks as 'revealing unknowns', entailing high levels of human–map interaction by specialist users for their own analysis. Cartography is also frequently applied during later presentational stages of research for 'visual communication', where a single optimal solution is presented to a wider audience (DiBiase, 1990). Presentational applications involve 'presenting knowns', involving low human–map interaction for a public audience (MacEachren, 1994).

As online mapping allows results to be shared with potentially large public audiences online, it has advantages for the latter presentational research roles. Online research maps are most commonly static images of results, which are relatively straightforward to produce and for viewers to understand. This relative simplicity contrasts with the greater user engagement required for interactive maps. Interactive mapping is defined here as cartography where users can change aspects of the map representation, thus requiring a two-way relationship between the map and the map user (Roth, 2013). Interactive cartography is more closely aligned with the exploratory stages of scientific analysis where human–map interactions are high level and iterative, complementing hypothesis formulation and related tasks (MacEachren & Monmonier, 1992). These exploratory tasks are typically undertaken using desktop GIS and geovisualisation software which offer comprehensive tool suites of cartographic and spatial analysis functions.

[1] Market leader Google Maps claims to have over a billion monthly users across all platforms (Google, 2012). Apple, Microsoft, Yahoo and OpenStreetMap also provide large global mapping services.

The above framework accounts for the vast majority of the research uses of cartography. Yet technological innovations can challenge current practice and open up new possibilities. Current online interactive mapping tools essentially provide a hybrid of presentational and exploratory mapping functionality. They are capable of delivering widespread access to geovisualisation *and* a high level of user interaction. This functionality comes at the cost of requiring more cartographic engagement from users, and a longer development time from map-makers. These hybrid characteristics tend to be advantageous for quite specific research contexts. The exploration of large datasets in one such context, where the number of variables and their complexity override the traditional presentational mapping approach of 'presenting knowns'. Another important research context occurs in spatial data analysis applications where there are advantages in extending analytical capabilities beyond specialists to wider multi-disciplinary audiences.

It is increasingly common for research projects to use multiple (spatial) data inputs, and for data to itself be a major research output that can subsequently be incorporated in further research projects (Borgman, 2007). These research data exchange processes are linked to open data trends (discussed in Section 2.2), and the emerging fields of big data (Kitchin, 2013) and open GIS (Sui, 2014). From the data user perspective, there is demand for tools that provide an accessible overview of large complicated datasets, and that allow data to be downloaded and synthesised. Interactive online mapping solutions are a promising approach for open data infrastructure roles as these can provide an intuitive means of overviewing datasets from a spatial perspective.

It is also increasingly common for online applications to include basic analytical functionality. Visual analytics is concerned with providing data-driven insights to aid decision making (Keim, Kohlhammer, Ellis, & Mansmann, 2010; Thomas & Cook, 2006), and this approach can be seen in popular web analytics and business analytics tools (Chaudhuri, Dayal, & Narasayya, 2011). These tools allow non-technical multi-disciplinary and policy audiences to ask questions of data and understand trends. Research fields that are currently developing interactive map visualisations in analytical contexts include geodemographics, health geography and urban analytics, as discussed in the case studies (Section 4).

Note that there are also advances in cartographic interaction occurring in research fields such as participatory GIS (Rouse, Bergeron, & Harris, 2007), decision support systems (Geertman, Toppen, & Stillwell, 2013) and geodesign (Goodchild, 2010). These applications are beyond the scope of this paper, but there is potential for these fields converging with online interactive mapping in the medium term.

These evolving research roles for online interactive mapping are both innovative and challenging. A fundamental design tension results from the aim of developing mapping tools for both specialist researchers and more general audiences. Another challenge is the development costs required to create online interactive mapping sites with a combination of IT, cartographic and design skills required. Yet a period of significant innovation in cartography is occurring. It is entirely appropriate for academic research to experiment with new tools and take advantage of new opportunities for collaboration and public engagement as these emerge.

2.2. Open data

Mapping and visualisation platforms are inherently dependent on the underlying data. Recent open data initiatives are transforming the availability and ease of access to high quality public sector data, most prominently in North America and Western Europe (Kitchin, 2014; Open Knowledge Foundation, 2014). Governments and related public agencies hold a huge range of datasets covering demographics, housing, health, education, crime, economics, environment, energy, transport, real estate and culture. From a research perspective this is a vast resource. All the mapping case studies described in this paper utilise open data.

Open data is generally defined as data that is free to access, use, and share with attribution (Pollock, 2006). Increasingly public datasets are online and free to download in standard formats, and can legally be shared and republished, including in the form of interactive maps. A common rationale for open data initiatives is to stimulate new digital economy services, and this has encouraged the standardisation of datasets for automatic importing, including standardising IDs and data formats (Kitchin, 2014), again with benefits for interactive map production.

Major open data catalogues include the US government open data portal site, data.gov, which launched in May 2009, and the UK data.gov.uk launched in January 2010 (Hogge, 2010). The main aim of data catalogues is to overview what data is available, standardise data formats and metadata, and provide a focal point for open data initiatives and newly released datasets (O'Carroll, Collins, Gallagher, Tang, & Webb, 2013). City governments have also been early innovators. Portland began releasing open public transit data as early as 2006 (Rojas, 2012). The San Francisco site datasf.org launched in 2009 (Nath, 2011), including web mapping features. From this starting point, city open data sites have become widespread across North America, Europe and Australasia, with sparser adoption in Asia, Latin America and Africa.

The mapping of socio-economic open data requires datasets to be matched with geospatial geometry data, principally administrative zone boundaries. Nation states vary considerably in regard to the availability and legal status of administrative spatial data. The US has traditionally followed an open data approach, with census boundaries and core topographic data freely available. In countries such as the UK, national spatial data is state copyright. The UK sought to resolve this conflict through creating an Open Government License (OGL) in 2010, enabling the release of census, administrative boundary and some topographic mapping products as open data (Kitchin, 2014). These datasets are used by the UK case studies discussed in this paper.

2.3. Online mapping software

The first basic web map appeared in 1993 (Putz, 1994), and many public mapping sites such as MapQuest and Streetmap followed in the late 1990s (Plewe, 2007). These sites were constrained by low bandwidth dial-up connections and client–server interaction technologies that required a full page refresh for every map update. This resulted in a relatively poor user experience with small map images and slow user response times (Haklay et al., 2008). A second generation of sites using Web Mapping Server (WMS) software from commercial vendors like ESRI and Autodesk also emerged from the late 1990s onwards (Plewe, 2007). This approach allowed customised mapping and much greater spatial analysis functionality, but remained deficient in terms of complicated user interfaces (Haklay et al., 2008). The high software and hardware costs also restricted online map creators to large government agencies and corporations.

The key breakthrough in mass-market web mapping came with the launch of Google Maps in 2005. The site featured full screen maps with panning and zooming in near real-time, achieved using broadband-enabled AJAX technologies (Zucker, 2007). This 'web mapping 2.0' or 'slippy maps' interface paradigm has been subsequently adopted by all the major mapping platforms. Google Maps was also an innovator in custom web maps, making it very easy to overlay point data on top of the Google basemap. This 'mash-up' functionality was formalised in Google Maps API in 2005 and has been extremely popular for embedding custom maps on user websites (Haklay et al., 2008). Web mapping 2.0 innovations did not however mean that thematic mapping sites for research applications could easily be developed, in fact quite the opposite. Early Google Maps functionality restricted the volume of data and types of thematic representation that were possible. Successful early efforts to overlay choropleth map layers on Google Maps required developing custom software solutions (Gibin, Singleton, Milton, Mateos, & Longley, 2008), and were subsequently rare. Further progress in web mapping software functionality and accessibility was needed to allow interactive thematic maps to become mainstream. This is essentially what has happened in the last decade.

Recent progress in online mapping software has been led by open source developments. There is a large geospatial open source development community, supported by the Open Source Geospatial Foundation (OSGeo) (O'Brien, 2015). The success of crowdsourced global mapping project OpenStreetMap (OSM) has been an important stimulus for open source software, as OSM maps are served using popular open source tools (Haklay & Weber, 2008). Unlike early custom web mapping tools, these open source solutions are extremely flexible and can produce a wide range of interactive map types for research projects, as well as being free to download. There are however technical barriers to using these tools, which have restricted their use to specialists. The commercial potential of widening the market of web cartographers has stimulated further innovation, with the development of cloud services web mapping software. In this model user map data is uploaded to a cloud server, reducing the technical skill demands and need for server access (Zastrow, 2015). Overall there is now an array of powerful and flexible software options available for delivering online interactive mapping projects for research applications. The capabilities of the main tools are reviewed in detail in Section 3.

2.4. Web visualisation and infographics

As the web has matured into a ubiquitous platform of information dissemination so the popularity of interactive online media has greatly increased, including data visualisation. Recent advances in web mapping can be seen as part of wider online data visualisation trends. From the rather rudimentary beginnings of the web in the 1990s, web technologies such as HTML, JavaScript and SVG have greatly advanced their graphical and data manipulation capabilities and are now being used to deliver engaging and powerful interactive sites (Anthes, 2012). These advances are evident in the popular trend of information graphics or infographics, which are eye-catching visualisations and multimedia features designed to tell an engaging story through data (Weber & Rall, 2012). Infographics are a cornerstone of the evolving data journalism approach developed by publications such as the New York Times and Guardian. Representational variety is a feature of infographics, with many forms of maps, charts and plots used, often employing high quality design and interactivity (Cairo, 2012).

The implications for researchers of the popularity of online data visualisation are generally positive. There appears to be an expanding online audience engaged with data visualisations such as interactive maps. Another useful benefit is that new powerful web visualisation libraries have been developed, such as D3 (Data Driven Documents) (Bostock, Ogievetsky, & Heer, 2011) which is used by case study examples in this paper. Good quality data journalism can also provide useful design inspiration for researchers in terms of how to construct accessible narratives around data analysis. There are also some challenges with the increasing popularity of data visualisation, mainly in relation to the neogeography critique of non-specialist visualisation authors breaking basic rules of cartography and statistics (Haklay et al., 2008). Nevertheless these are interesting trends presenting many opportunities for data visualisation researchers, particularly in relation to public engagement.

3. Online thematic mapping tools and functionality

To understand what is possible using online thematic mapping for research, we review the software tools that are available, and the cartographic and interactive functionality that these tools provide. Usability has been central to the development of online mapping (Haklay et al., 2008; Tsou, 2011) and remains central in designing new thematic mapping sites, including more specialist research sites. Related to usability, this review is restricted to mapping solutions for standard web browsers without additional software. This is the most accessible approach based on robust and open standards. This criteria exclude web maps that use digital globe software such as Google Earth, and maps that use browser plug-in technologies such as Adobe Flash.

Another important issue on the production side is the technical skills and overheads required to create mapping sites. Producing a very simple static map typically takes a few hours, and similarly producing a basic interactive map is generally relatively quick (particularly using cloud services tools). But interactive mapping sites with new interactive features can take many weeks to develop. Appropriate design decisions are required to ensure feasible production times.

3.1. Online thematic mapping development software tools and workflows

The process of developing online mapping sites can be broken down into three stages as shown in Fig. 1. Stage 1 involves gathering the original map data (often from the open data sites discussed in Section 2.2), and performing any preparatory geoprocessing tasks. This is typically a desktop software process. Stage 2 is a desktop-to-server process whereby the spatial data is uploaded and used to create a mapping service which serves the map data to the user's web browser. There are several routes to achieving this as discussed below. Finally Stage 3 is essentially a web design process where the mapping interface is developed, using a web mapping client library to handle integration between the client browser page and the mapping service/services. This latter stage is central to the implementation of any interactive functionality and the usability of the mapping site in general.

3.1.1. Self-hosted web mapping

An overview of the main approaches for creating an online mapping site is shown in Table 1. The first 'self-hosted' route involves hosting the map data on your own or institutional server. This is a powerful and flexible approach due to the array of high quality open-source software available, though is demanding in terms of technical skills. The second 'cloud-services' route involves uploading your map data to a cloud service, which avoids the need for your own server but typically introduces monthly fees. And finally the 'infographics' route limits map data and navigational flexibility in favour of simplicity and story-led design.

Within the self-hosted approach, there is an important distinction between pre-rendered and on-the-fly map data. Map data is most commonly delivered using pre-rendered raster map 'tiles' (a regular grid of georeferenced images) using compressed image formats for quick delivery to the client browser. For mapping platforms with many data layers this translates into large server storage demands. On-the-fly rendering avoids this problem by setting up the map server to render map data in real time. Technically this is a more complicated approach, but it increases flexibility and can incorporate dynamic data. Another related innovation is the switch from raster to vector map data. Raster map tiles remove vector geometry information during rendering, thus limiting potential interactive functionality. The alternative of vector map data (which can also be served as scalable tiles) is technically more challenging, but improves interaction and visualisation possibilities, particularly on the client side (Gaffuri, 2012).

For self-hosted web mapping applications, many of the leading software tools are open source, including PostGIS/PostgreSQL for spatial data storage, Mapnik for map rendering and the two most popular web mapping client libraries, OpenLayers and Leaflet (O'Brien, 2015). The development of these tools has been closely linked to OpenStreetMap (OSM): a street-level spatial database of the globe that is constantly being updated. The challenge of serving the massive OSM database to thousands of users has meant that scalability and speed were essential features for these open source tools. Consequently their performance is competitive with commercial software (though their ease-of-use typically is not).

Fig. 1. Core stages of online interactive mapping development.

Open source software has also influenced the practice of online cartography, particularly through the style-based approach developed by tools like Mapnik. Mapnik is a sever-based software library for rendering online maps, capable of producing high quality cartography due to the implementation of advanced anti-aliasing and a sophisticated style-based map symbology system. As online mapping involves rendering large areas of the globe at multiple scales, online map design is inevitably rule-based. There is little scope for the manual design adjustment that is common in traditional cartography. Decisions such as symbol rendering orders and label placement are determined through programming symbology rules, which in the case of Mapnik are specified using a system of XML styles. This is a very flexible approach, as the same data can be comprehensively restyled in many different ways. For example there are multiple versions of OSM—a public transport version, a hiking version, a humanitarian version—all created using different Mapnik styles. This flexible approach is very relevant for socio-economic mapping applications, as there is often the need to tailor the map symbology to the research theme being explored. Unlike the previous era of map 'mash-ups', online cartographers can now have total control over the entire map design. The style-based approach has also become embedded in cloud services tools, as described below.

3.1.2. Cloud services web mapping

While the self-hosted approach has many advantages in functionality and price terms, there are two significant development barriers: the need for server access, and the need for server programming expertise. The vast majority of potential online cartographers do not have the skills and hardware to meet these requirements. Addressing this untapped market is the basis of a growing geospatial tech sector: web mapping cloud services. In the cloud services model the user runs a cloud service desktop/web client application to upload their map data to a cloud account. The cloud service then handles all the server-side processes (Stage 2 in Fig. 1) in the background. This allows the user to skip to stage 3 and view their data as an interactive web map on their cloud service account webpage, or copy and paste some basic lines of HTML to have the map embedded on their own webpage. As a result the number of potential users of web mapping cloud services is much larger than the self-hosting market. There is a financial cost to the user, as cloud services typically use a sliding scale of monthly fees from cheap basic accounts to several hundred dollars per month for popular sites with large data requirements. Several services currently offer free educational accounts.

Google Maps API was the original inspiration for web mapping cloud services but offered very limited functionality in thematic mapping terms. Google has more recently improved its custom mapping options, with services including My Maps, Fusion Tables and the Google Maps JavaScript API (Table 1). These tools remain however designed for overlaying data on Google basemaps, rather than for the thematic mapping of large research datasets. Instead recent progress in cloud services mapping has been led by new web mapping companies, principally Mapbox and CartoDB (Zastrow, 2015). Mapbox uses OSM data and software built around Mapnik and Leaflet to offer fully customisable online maps. Cartography is controlled using a language called CartoCSS, which provides an easy-to-use means of controlling the underlying Mapnik styles. CartoCSS is based on Cascading Style Sheets, a long-established standard in web design (Lie & Bos, 2005), and consequently the structure is familiar to many designers and general users. The flexibility of Mapbox tools means they can be used effectively for high quality research thematic mapping, as shown in the case study examples, although there are limitations in relation to map interactivity (this is changing as Mapbox switches to vector data).

Another recent cloud mapping start-up is CartoDB. In this service user vector data is rendered on-the-fly, using a system built on PostGIS and Mapnik. CartoDB is designed for thematic mapping, and is very powerful in terms of interactivity, dynamic styling and filtering. It is also easy-to-use with a user interface similar to Google Fusion Tables, as well as allowing cartography to be customised using CartoCSS and SQL. Although some basic mapping functions are currently lacking in CartoDB, it is an impressive platform that is likely to become increasingly popular.

As well as new start-ups, established GIS companies have also moved into cloud services. ESRI, the leading provider of desktop GIS, has developed the ArcGIS Online service, which is integrated with ArcGIS desktop software for easy data uploading. Additionally the ArcGIS Online JavaScript API includes many spatial analysis functions that are notably absent from other cloud services. There are however some problems with using ArcGIS Online for building research mapping platforms at present. It is less flexible than the open source Mapbox and CartoDB, without the precise cartographic control that these tools provide. The pricing scheme is also intended for large enterprises and is less accessible for individual researchers. ArcGIS Online is currently a less popular option for researchers, though this may change in the future as the platform evolves.

Overall cloud mapping services are opening up thematic web mapping tools to a much larger audience. Developers of thematic mapping platforms can choose whether to go down the self-hosting web mapping development route, which provides the greatest flexibility and control while being technically demanding. Or alternatively there is the cloud services route, with much lower technical hurdles, but the prospect of some high fees if the project requires large volumes of server space or attracts a high numbers of users.

3.1.3. Infographics web mapping

The third infographics web mapping route contrasts in its approach and functionality. Generally infographic maps have a fixed spatial extent without navigation, with the data can be stored as flat files that do not require a map server. This approach tends to make infographic maps straightforward to use, but with much less scope for data exploration functionality. While infographic maps are generally simpler in terms of navigation and spatial data, they can feature sophisticated interactivity and animation, particularly given the capabilities of JavaScript and SVG.

Note that it is possible to mix the self-hosting, cloud services and infographics approaches to create web mapping hybrids and try to combine the advantages of the different approaches. This is discussed further in the case-studies section.

3.2. Online thematic mapping functionality

Based on the software tools described in the previous section, we can assess the online thematic mapping functionality that is currently possible with the different mapping approaches, and where this functionality is relevant for research applications. The degree of interactive

Table 1
Online thematic mapping approaches: Workflows and tools.

Mapping Approach	Workflow Stages and Tools			Strengths & Weaknesses	
	Spatial Data Preparation	Data Hosting & Map Serving	Web Browser Interface Design	Strengths	Weaknesses
Self-Hosted Web Mapping	**GIS Software** QGIS, ArcGIS, MapInfo… **Geovis. Tools** Python (e.g. matplotlib, Cairo), R(e.g. ggplot, Shiny), Java (e.g. GeoTools)…	*On-the-Fly Map Serving* **Database Storage-** PostGIS, MySQL, SQLite… Flat files-GeoJSON, TopoJSON, Shapefile, KML… **Map Rendering-** Mapnik, MapServer, GeoServer, custom server *Pre-Rendered Map Serving* **Tile Rendering-** Mapnik, MapServer, GeoServer, custom renderer **Tile Serving-** MapServer, GeoServer, TileStache, custom server	**Web Mapping JavaScript Client Libraries-** OpenLayers, Leaflet **General Web Design Tech.-** HTML 5, CSS, JavaScript, JQuery, PHP, SVG…	Very Powerful Very Flexible Free open source tools	Advanced tech. skills required Server access required Map serving performance linked to server quality
Cloud Services Web Mapping	**Cloud Services Web/Desktop Interface-** Google My Maps/Cloud Platform/Fusion Tables, Mapbox TileMill/Studio, CartoDB, ArcGIS Online, Tableau…	*Map hosting and serving handled by cloud service*	**Cloud Services Templates** **Cloud Services Web Mapping Libraries/APIs** Mapbox.js, CartoDB.js, Google Maps JavaScript API, ArcGIS JavaScript API, Tableau API **General Web Design Tech.**	Simpler-Server skills not required Some powerful solutions Cheap/free for simple maps Good map serving performance	Monthly charges for popular sites Limits on hosting More limited flexibility
Infographics Web Mapping	**Visualisation Packages** Python, R, Java... **GIS Software** **Design Software-** Illustrator, Inkscape..	**Flat File Storage-** SVG, (Geo)JSON, CSV, XML **Database Storage-** MySQL, SQLite…	**Infographics JavaScript Libraries-** D3, WebGL, chart libraries… **General Web Design Tech.**	High quality design possible, including interactivity & animation Simpler Flexible	Fixed map extent-no standard navigation and zooming Limited geometry and map detail No direct importing of spatial data

functionality has consequences for site usability, with specialist users generally more familiar with advanced mapping functionality and interactive exploratory platforms.

3.2.1. Data layers selection

Data selection decisions determine what data is available to the user and influences the degree of user control. A high number of data layers is very useful for exploratory research mapping platforms, enabling the flexibility of online mapping to come to the fore. The technical ability to overlay and switch between multiple raster and vector data layers is standard in web mapping client libraries, and is straightforward to achieve in the self-hosting and cloud-services mapping approaches. The inclusion of many data layers does however introduce data volume challenges on the map server. The self-hosting approach is best suited for large data volumes, particularly where on-the-fly rendering is implemented.

3.2.2. Thematic map representation

The wide range of possible mapping types is an important strength of thematic mapping, as cartographers can select between varying techniques according to the data and map context (Dent, Torguson, & Hodler, 2008). All the self-hosting, cloud services and infographics web mapping solutions enable the most common choropleth, line, point and proportional symbol thematic maps to be produced. Additionally there are capabilities for more advanced mapping types such as dasymetric maps, cartograms and 2.5D maps, some of which are illustrated in the case study examples. Generally mapping platforms with multiple data layers use a consistent representational approach for all data layers, but it is also possible to offer map users the option of interactively changing the thematic map type by preparing multiple layers for the same data.

3.2.3. Navigational interactivity

The ability to seamlessly pan and zoom around the map is standard functionality in the self-hosting and cloud services mapping tools. Navigational or viewpoint (Roth, 2012) interactivity can be powerful, allowing the user to browse between areas of interest, and explore maps from international to local contexts. There are however some challenges when implementing navigational interactivity for socio-economic data. Multi-scale socio-economic datasets are generally restricted to large national surveys such as censuses, and to big data sources that can be aggregated, such as mobile data. Map designs need to be tweaked for each map scale or 'zoom level' to provide appropriate levels of detail. Finally increasing the number of zoom levels also increases the hosting demands for pre-rendered tiles (approximately $\times 4$ for each zoom level increase).

The easiest way to minimise these issues is to restrict navigational interactivity using the maximum zoom level setting. Mapping platforms that require detailed zoom levels, for example built environment level visualisations, are likely to require the self-hosting approach. Another alternative is to remove navigational interactivity altogether, and have a fixed scale and extent map as is common in infographic maps. The simplicity of fixed scale mapping can boost usability and save development time.

3.2.4. Display and classification interactivity

Display interactivity describes presentational changes to cartographic representation, such as layer visibility, colour schemes and symbology class breaks. All of the mapping approaches give precise control over these elements to web cartographers. It is an interesting design decision whether map users should be given the ability to change these settings (Roth, 2013). This functionality is likely to appeal to specialist users who are familiar with customising their mapping experience, but risks overcomplicating interfaces. Exploratory sites often benefit from display options, with the ability to changing numerical classification schemes particularly useful (Brewer & Pickle, 2002). Vector data complements display interactivity, as it has the potential for colour schemes and classifications to be controlled on the client-side. Display interactivity functions can be achieved using any of the main mapping approaches, but more advanced functions are not standard features in web mapping libraries. This introduces a time cost to develop these user interface functions.

3.2.5. Analytical interactivity

Analytical or data interactivity (Crampton, 2002) is the ability to ask questions of data, query statistics, highlight outliers and similar tasks. It is not feasible to match the analytical comprehensiveness of desktop geovisualisation software; rather the focus for online mapping has to be on choosing particular functions that are insightful for the specific research application. This can be as simple as displaying map indicator values when the user's cursor moves over a polygon, or integrating maps with charts to enhance data insights.

Analytical functionality can be achieved using all the main mapping development approaches but, similar to display interactivity, development time is required due to the lack of analytical functions in web mapping libraries. One option is to integrate analytics/infographics libraries with web mapping libraries, as shown in the case studies examples. Analytical map functionality also benefits from vector map data, as raster data lacks the spatial geometry and feature ID information to enable analytical queries. There are currently some useful work-a-rounds for raster data like UTF grids[2] and vector overlays, but ultimately these solutions are inferior to full vector data.

3.2.6. Narrative interactivity

This final aspect of online mapping relates to the framing of the user experience, in terms of features such as map tours and guides, and the combination of maps with interpretative text. Such functionality is often used in educational and data journalism mapping applications to guide the user through the data visualisation and explain results (Segel & Heer, 2010). These features can help make mapping platforms more accessible. Research mapping platforms are often integrated with reports and blogs that discuss results, and there is scope for using map guides to introduce new users to site interfaces and user options. Narrative functions can be developed using standard web design technologies, and some basic features like map tours are often included in web mapping libraries.

4. Interactive mapping case studies

4.1. Case studies selection and site details

The online mapping case studies illustrate what can be achieved using the tools and workflows described in Section 3. These exemplars have been selected based on the following criteria: their relevance for socio-economic research; their cartographic quality; their success in reaching large online audiences; and their innovation in interactivity (as defined using the categories set out in Section 3.2). Technical details on all the case study sites are provided in Table 2. The datasets used are all open data, except for the global city economic database used by the Global Metro Monitor site. The case studies selection has been restricted to examples from the UK, EU and USA, reflecting the current geography of spatial data infrastructure and the author's position as a GIS researcher in the UK.

The first two examples come under the heading of exploratory mapping platforms (Section 4.2.1). Datashine Census shows what can be achieved using the self-hosted approach, with over a thousand different data layers available for users to investigate, as well as advanced display and classification interactivity. The EU Cohesion Data Map provides a much simpler exploratory example using a cloud services approach.

[2] UTF grids encode feature IDs as an invisible text grid in JSON format. This allows basic mouse-over interactivity, but cannot retrieve the original geometry or dynamically style features.

Table 2
Mapping platform case studies details.

Case study site	launch date	Developers	Development route	Software tools	Interactive features	Main datasets used	Approx. development time[a]	Monthly users, first 3 months[b]
DataShine Census datashine.org.uk	June 2014	Oliver O'Brien & James Cheshire, UCL	Self-hosted on-the-fly mapping	Mapnik OpenLayers PostGIS PHP Python	1600 map indicator layers to explore, advanced custom interface. Data classification, map style & colour scheme adjustable by user. Mouse-over zone values.	UK Census 2011 Ordnance Survey Vector Map OpenStreetMap	6 months	33,000
EU Cohesion Data Map cohesiondata.ec.europa.eu	July 2014	Socrata Works consultancy for EU	Cloud services	Mapbox Leaflet	10 EU-wide map indicator layers. Basic mouse-over zone values.	European Commission Regional Policy Data	NA	NA
Global Metro Monitor 2014 brookings.edu	Jan 2015 (first version 2010)	Alec Friedhoff, Brookings	Infographics	R D3 JavaScript	3 global map indicators with different temporal ranges. Detailed mouse-over time-series statistics. Animated city statistics grouping tools.	Oxford Economics Moody's Analytics U.S. Census Bureau	2 months	12,000
LuminoCity3D luminocity3d.org	September 2014	Duncan Smith, UCL	Hybrid-cloud services/self-hosted/infographics	Mapbox Leaflet D3 & Dimple ArcGIS	40 map indicators. Chart and map linked selection brushing, mouse-over descriptive stats summary.	UK Census 2011 Land Registry Department for Energy & Climate Change	3 months	8000
Carbon Map carbonmap.org	March 2012 Update Nov. 2014	Duncan Clark & Robin Houston, KILN	Infographics	Python SVG animation Newman cartogram alg.	Cartogram animated transitions between 11 map indicators. Audio narrative introduction linked to map animations. Mouse-over country statistics.	Global Carbon Project World Bank BP World Energy Stats.	2 months	20,000 (initial launch) 70,000 (relaunch)

[a] Development time, single developer equivalent.
[b] The average number of monthly unique users in the first three months following the website launch, to the nearest thousand.

The exploratory examples are limited in terms of analytical interactivity, and this is the focus of Section 4.2.2 where the Global Metro Monitor and LuminoCity examples illustrate how statistical data can be integrated with online mapping using infographics tools. Finally the Carbon Map example shows how a narrative data journalism approach can make research outputs more accessible and reach a very large audience (Section 4.2.3).

All of the sites received a relatively high number of users in their first three months since their launch, with between 8000 and 33,000 unique monthly users (Table 2). Detailed survey evidence on the types of site users is not available, but some speculation can be made based on the social media interactions of users who recommended the case study sites. Social media users who shared the DataShine Census and LuminoCity sites include a broad spectrum of users, with social scientists, built-environment professionals, government users, community groups and IT businesses well represented (Smith, 2015). These enthusiastic sharers account for approximately 4% of the total site visitors, while a larger 16% of all users made repeat visits to the sites in the first three months. Social media data has not been available for the EU Cohesion Data and Global Metro Monitor sites, which are aimed at an international policy and economics audience. The last Carbon Map example is geared towards international environmental campaigning and educational users, and has generated tens of thousands of social media interactions. Overall the wider research impact of these sites appears promising, but more comprehensive survey evidence is needed to assess user engagement.

4.2. Case studies

4.2.1. Exploratory mapping platforms

As outlined in Section 2.1, online mapping platforms can function as an exploratory interface to large public datasets such as national censuses, economic surveys and research data catalogues. This role requires platforms to be comprehensive—covering the breadth and depth of these large datasets—and intuitive—enabling quick visualisation and navigation between the many variables. Sites from major public bodies like the US Census Bureau and UK Office for National Statistics do not currently meet these criteria, and better examples of exploratory platforms can be found in research lab outputs. One such example from the UK is the DataShine platform (O'Brien & Cheshire, 2015). This site launched in June 2014 mapping over 1600 summary statistics from the UK 2011 Census, from national to detailed neighbourhood scales (Fig. 2). The inclusion of such large data volumes is made possible by implementing the self-hosted on-the-fly rendering approach, using the open source tools Mapnik and OpenLayers. A custom interface was necessary to allow users to navigate the high number of data layers.

The DataShine platform also achieves innovation in display interactivity with custom data classification options, and in thematic representation with the census data clipped to urban form outlines. The combination of building outlines and carefully styled OSM topographic data clearly communicates the local built environment context of the demographic data. Overall the complexity of the site required substantial development time, drawing on experience from similar projects (e.g. Mateos & O'Brien, 2011). The site illustrates the capabilities of interactive mapping for intuitively exploring large open datasets, and has been a very popular tool as a result (Table 2).

Open source tools can produce powerful mapping sites, but the technical skill requirements and development times remain prohibitively high outside of specialist research centres. Simpler versions of exploratory mapping platforms are also possible using the cloud services approach. One interesting example comes from the European Union (EU) Cohesion Data mapping website, launched in July 2014. The site showcases the EU's detailed sub-national socio-economic open data, building on the long term European Observation Network for Territorial Development and Cohesion programme (EPSON, 2014). The site includes ten indicators, covering core topics such as employment, wealth and migration, with clear spatial disparities across national boundaries highlighted (Fig. 3). The main development tools used were Mapbox and Leaflet, delivering a relatively high quality user experience.

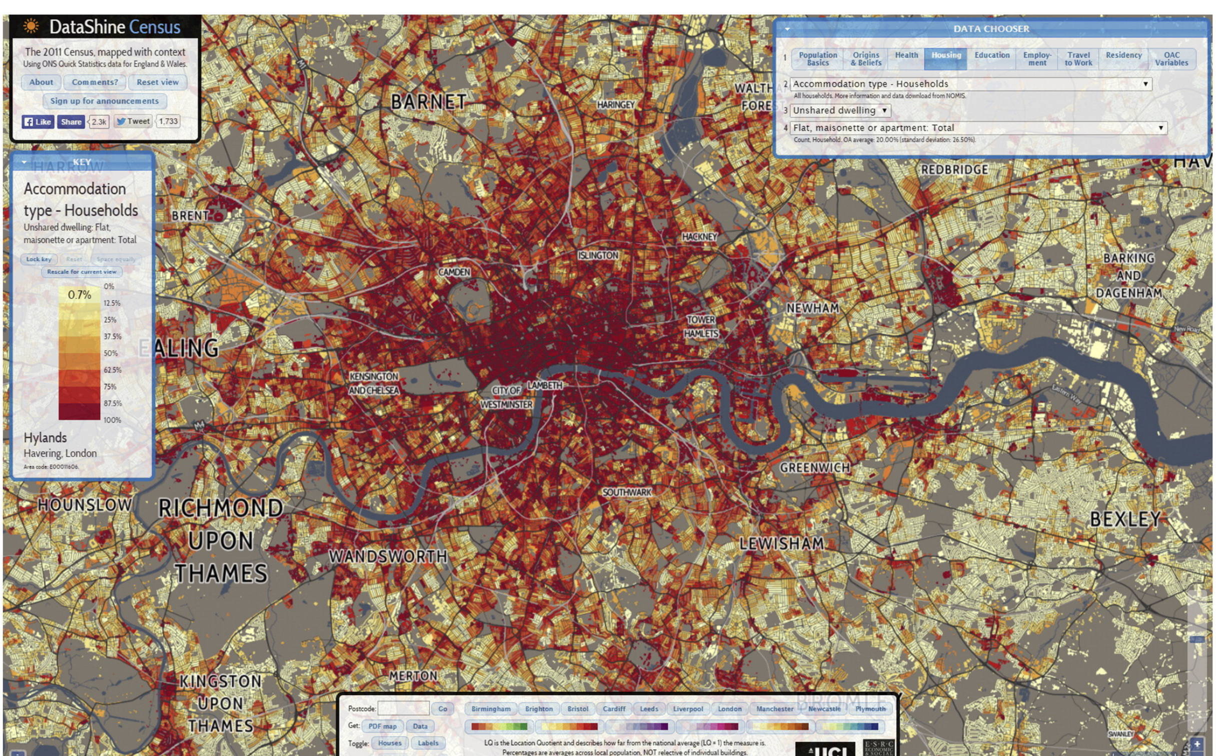

Fig. 2. DataShine Great Britain census map: Share of flats/apartments in 2011, Inner London.

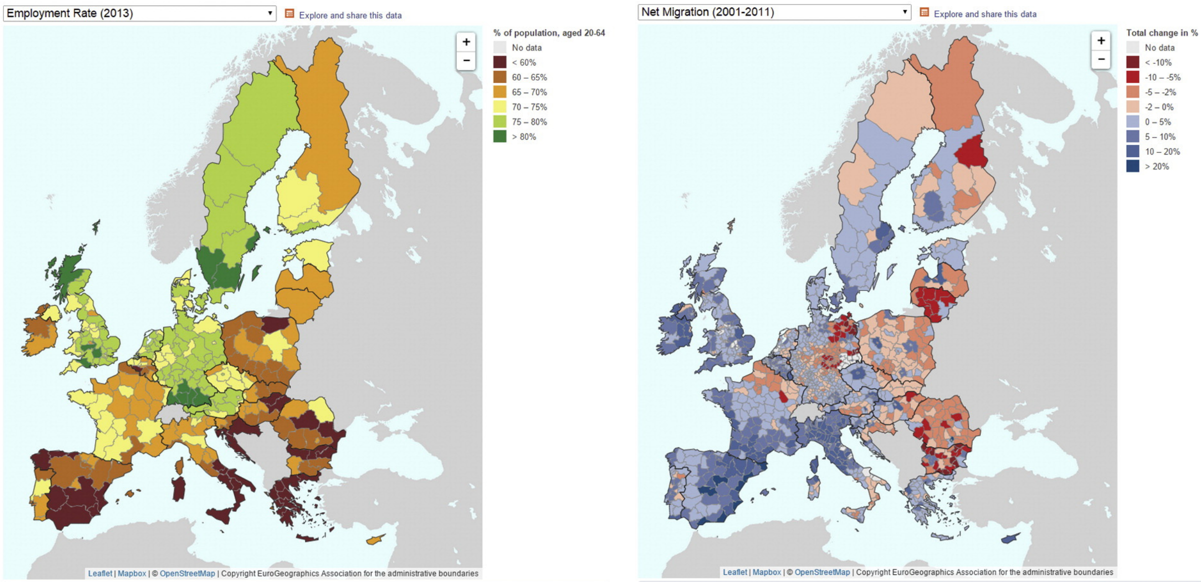

Fig. 3. EU cohesion data mapping website: Employment rate 2013 (left) and net migration 2001–2011 (right).

Although somewhat simple in terms of the number of data layers and interactivity, the site provides an intuitive visual overview to the EU's key datasets, and illustrates how basic exploratory platforms can present engaging and novel perspectives for policy research.

4.2.2. Analytical mapping platforms

While exploratory platforms provide an overview large datasets, they have little in the way of analytical functionality for users who want to directly ask questions of spatial data. Several fields are moving towards more analytical mapping online, such as health geography—see for example the Environment and Health Atlas (Hansell et al., 2014)—and geodemographics—see for example the UK Output Area Classification (Longley & Singleton, 2014). Another interesting area of analytical mapping innovation is the emerging field of urban analytics, which uses socio-economic indicators to measure 'urban performance'; i.e. identifying patterns and relationships that explain city outcomes. Amongst the leading innovators in urban analytics tools is the Brookings Institution. Their Global Metro Monitor tool maps the economic performance of 300 global city-regions, as shown in Fig. 4. The global scope is powerful, with clear patterns in global economic change identifiable. The site provides change over time and sectoral breakdowns for individual cities, as well as clustering functionality to visually group cities according to shared economic performance.

The site is an advanced example of the infographics mapping approach, with an SVG proportional circle map of a select number of economic indicators, and the use of the D3 library to create the map interface and animation transitions. The site has been developed in a modular fashion, and is updated with new global data on an annual basis. The engaging data and site design quality have resulted in a high number of site users (Table 2).

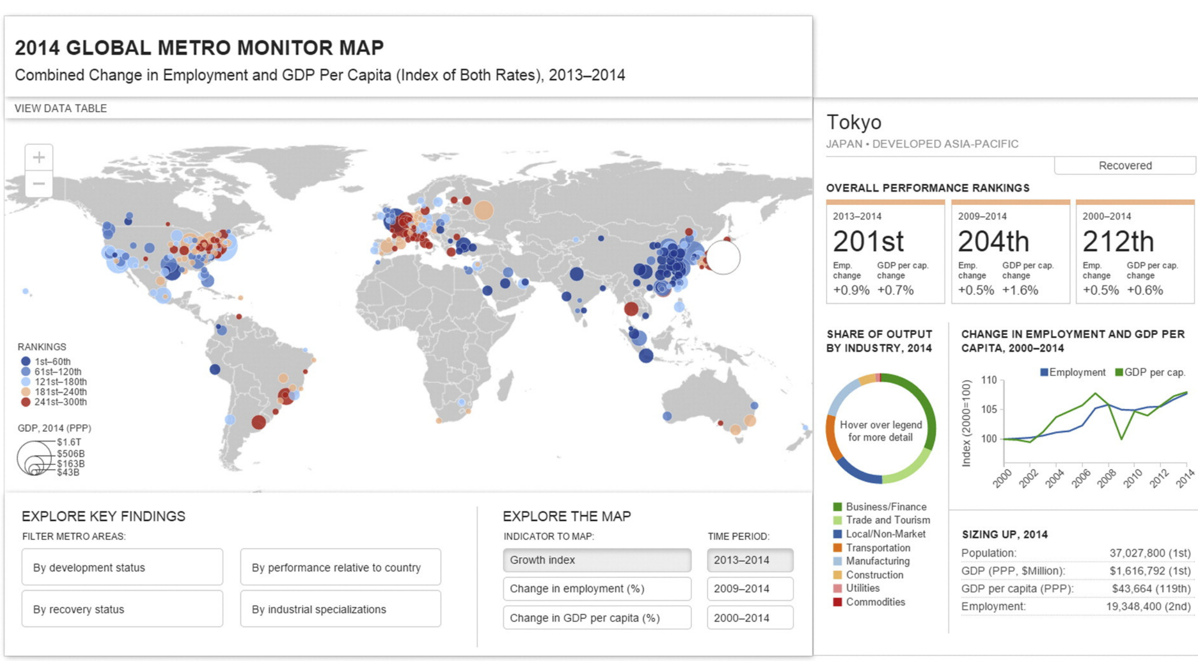

Fig. 4. Global metro monitor 2014: Combined employment and GDP change map with Tokyo selected.

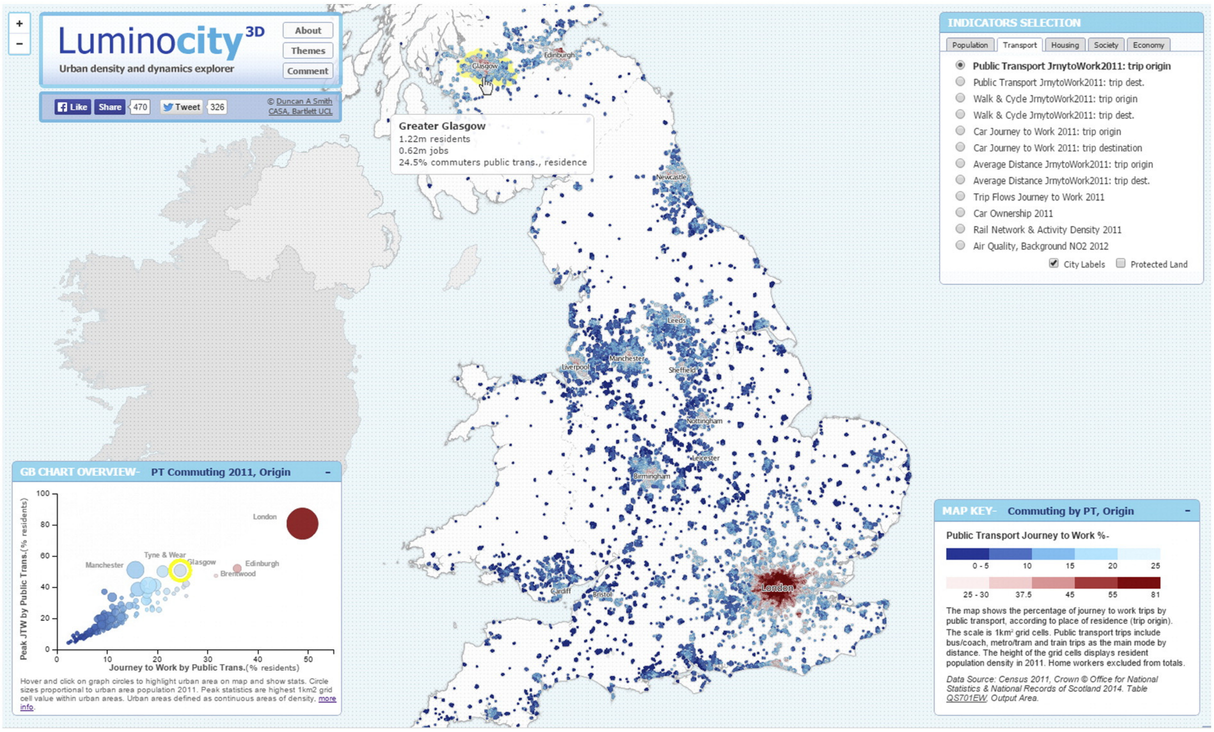

Fig. 5. Luminocity Great Britain mapping platform: Public transport journey-to-work 2011.

It is also possible to mix the analytical and exploratory mapping approaches by increasing the number of data layers and spatial resolution. This is the route taken by the LuminoCity mapping platform, which includes social, economic and environmental open data for cities in Great Britain, standardised on a 1 km^2 grid (Smith, 2014). The main innovative feature is the linking of mouse-over selections between the map and a summary chart, allowing quick identification of over-performing and under-performing cities for each indicator, as shown in Fig. 5. This 'brushing' functionality is achieved using a vector overlay on the raster map tiles, and linking the web mapping library Leaflet with infographics library D3. The site also includes thematic experimentation, with urban density visualised using a 2.5D extrusion approach. Overall the site highlights wide variation in city performance across a range of socio-economic dimensions.

The two urban analytics examples illustrate the rich potential of fusing web mapping and infographics approaches. Nevertheless the analytical functionality achieved remains basic. Standard desktop geovisualisation features like interactive histograms and basic descriptive and inferential statistics are currently absent from web mapping sites. These functions are time consuming to develop as they do not

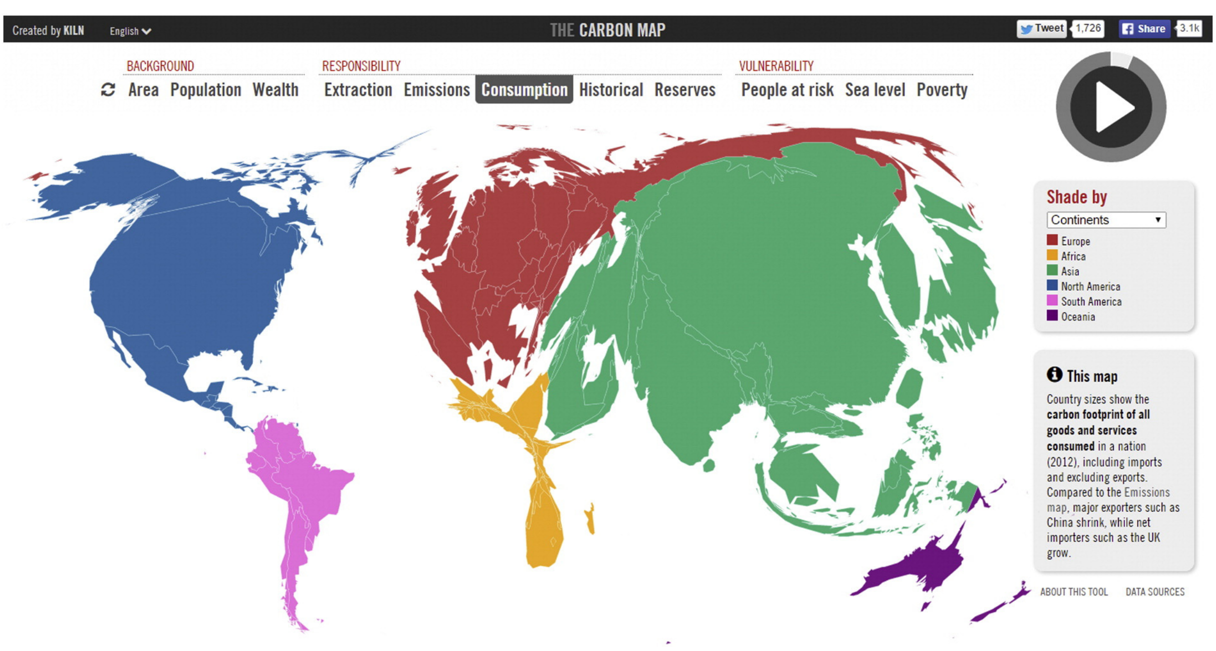

Fig. 6. The Carbon Map: cartogram of CO_2 emissions by consumption of goods and services 2012.

yet feature in web mapping libraries. The development of more analytically focussed web libraries is needed for this functionality to become established.

4.2.3. Data journalism and mapping

This last topic defines how mapping platforms are framed and experienced by users. Research mapping sites can benefit from integration with blogs and reports that discuss results and provide commentary. From the previous examples, the Global Metro Monitor site is particularly successful in integrating maps with research reports.

Data journalism provides useful examples of how to guide users through complicated data topics. The mapping site discussed here covers one of the most pressing research challenges: anthropogenic carbon emissions and climate change. The Carbon Map website (Fig. 6) summarises diverse perspectives on the measurement of national greenhouse gas emissions, visualising extraction, production and consumption metrics, as well as historical emissions and vulnerability to climate change. A global cartogram technique is employed, building on earlier geographical research (Dorling, Barford, & Newman, 2006; Gastner & Newman, 2004), with the addition of animated transitions between indicator maps (achieved using SVG animation functions). These transitions are linked through a voice-over tour that explains each of the map layers in turn. The narrative approach emphasises the stark contrasts between each of the different data perspectives in a powerful and accessible manner. The site has generated a huge online audience with over 250,000 visitors in total (Table 2), illustrating the ability of the data journalism approach to connect with the general public.

The Carbon Map example is mainly an educational and campaigning tool. Similar techniques could also be used in research applications. For example explaining different model scenarios using narrative techniques could be effective, or simply introducing users to platform interfaces through using map tours. Another approach would be for users to create their own tours and data interpretations and be able to share these online. At present these possibilities are not yet developed in research mapping sites.

5. Conclusions

5.1. Overview

This paper has investigated the use of interactive thematic mapping tools for visualising, exploring and analysing socio-economic data online. A series of case-studies have been discussed, highlighting considerable expansion and innovation occurring in online thematic mapping, including:

i) *The increasing availability of public sector data*
All of the mapping case studies reviewed used shareable public sector open data from city, national and international sources. The current momentum of the open data movement continues to widen access and present new analysis opportunities.

ii) *The development of powerful and accessible online interactive mapping tools*
Software developments are enabling a wide range of thematic mapping types to be produced with significant interactive functionality. Cartographic design is controlled using a flexible and powerful style-sheets approach. Self-hosted tools require server development skills, while web mapping cloud services have lower technical demands and a strong focus on user accessibility.

iii) *The expanding range of interest groups creating and using online thematic maps*
New opportunities to create online thematic maps are being taken up by academic research centres, government agencies, policy think-tanks and campaign organisations. This expanding market of online cartographers is occurring in tandem with the popularisation of online thematic mapping through trends such as infographics and data journalism.

5.2. Research capabilities and opportunities

The case studies reviewed highlight how new online interactive mapping tools are currently being applied in research, including their capabilities, limitations and emerging opportunities for future development.

5.2.1. Exploratory geovisualisation capabilities

Exploratory functionality for overviewing very large datasets has been shown by the case-studies. On-the-fly rendering techniques allow navigation between thousands of possible map layer variables. Such functionality is highly applicable to current research developments in big data, and for combining indicators across a range of demographic, economic and environmental dimensions. It can also allow multiple data scales and zonal boundaries to be included in the same platform, which could be useful for addressing modifiable areal unit related problems (Openshaw & Taylor, 1979). At present relatively advanced programming skills are required to implement exploratory mapping features, though this is likely to change.

5.2.2. International data visualisation insights

Another important trend is the development of new international socio-economic mapping sites, as demonstrated by the EU, Metro Monitor and Carbon Map examples. These examples show the opportunities that high quality international data can bring, with useful results for understanding growth and inequality. Although the amount of data gathering and synthesis work required to produce global sub-national datasets remains very high, overheads are falling as open data principles spread internationally and opportunities for further international analyses are likely to expand.

5.2.3. Analytical geovisualisation capabilities

The case studies have shown some promising signs for analytical functionality. Interactive map and chart integration is used in the urban analytics examples to allow intuitive data comparisons and providing temporal context. Overall however, analytical functionality in online mapping sites remains basic and it is rare to find platforms that feature core desktop geovisualisation functions. There are technical reasons for the lack of analytical functionality in online maps, including the reliance on raster map tiles and the lack of standard analytical functions in web mapping libraries. These technical challenges are being addressed with the current adoption of vector map tiles (Mapnik, OpenLayers and ESRI have all recently adopted the Mapbox Vector Tiles format) and the development of more analytically based web mapping tools such as the ArcGIS JavaScript API.

Another challenge relates to the cartographic design balance between meeting the needs of specialist research users and those of general users. As development overheads for creating online thematic mapping platforms fall, design flexibility will increase. It should become feasible to create platforms with adaptable interfaces for different user experience levels (Kang, Plaisant, & Shneiderman, 2003).

5.2.4. Research communication and public engagement

The case studies have shown that interactive mapping platforms can reach large audiences both from academia and the general public. The story-driven design approach from data journalism appears to be particularly successful at engaging audiences, and this approach could be used in research applications to guide users through more complicated datasets and models. This paper has not provided detailed survey evidence on usability and engagement, and more research is needed into this topic.

Overall the prospects for online research mapping are improving, and it remains to be seen to what degree these opportunities are taken up by research communities. Academic research centres feature in the case study examples discussed, as well as research bodies from government and the private sector. There are further research disciplines where interactive mapping can be applied, such as spatial economics, network analysis and built-environment studies. This indicates that there is much potential for expanding the research applications of interactive mapping in the future.

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