Volunteered Geographic Information for Sustainable Urban Development

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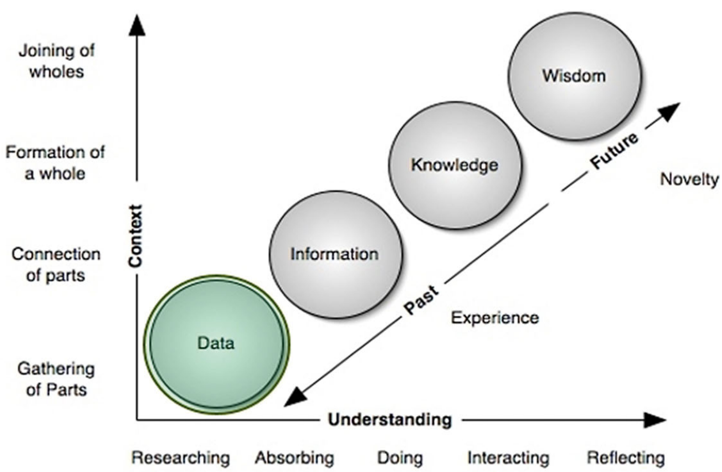
1. Introduction

By 2050, two thirds of the global population will live in cities (UN, DESA 2018). With this continuously increasing urban population and their footprint, the need to assess, map, and quantify the urban environments and their sustainable urban development with high spatial detail grows significantly. Metropolitan regions are complex coupled human-environment systems comprising urban agglomerations and their peri-urban hinterlands. Thus, understanding transformations of metropolitan regions and navigating those transformations toward more sustainable pathways, is of utmost societal relevance. An increasing urbanization makes urban areas highly dynamic (El Mendili et al. 2020), causing research on the detection of land consumption and building activities in cities to become even more important. In 2015, the United Nations highlighted the importance of "[m]ak[ing] cities inclusive, safe, resilient and sustainable" in Goal 11 of the SDGs (Sustainable Development Goals; UN 2021b). Target 11.3 focuses on the enhancement "of inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management". Target 11.7 again aims at the provision "of universal access to safe, inclusive and accessible, green and public spaces" (UN 2021b; Ravanelli et al. 2018). The effects of urban growth affect the coupled human-environment system with several social, economic, ecological, and cultural implications on different spatial and temporal scales (EEA 2006). One difficult problem for countries to meet the UN SDGs is a lack of access to relevant geospatial data supporting the measurement of the 231 unique indicators. In strengthening the capacity of national statistical offices, the UN propagates to ensure access to high-quality, timely, reliable, and disaggregated data based on geospatial information (UN 2021a). In that regard, the application of geographical information systems (GIS), remote sensing (RS), and global positioning systems (GPS) is promoted (UN 2021a). Another important geospatial data source for deducing human-environmental information can be seen in volunteered geographic information (Ibrahim et al. 2015).

In 1507, Martin Waldseemüller (as professor of cosmology) drew the first world map with “land masses in the west” based on the “Soderini Letter”, the infamous 1497 letter from Amerigo Vespucci to Pier Soderini: America was mapped for the first time (Goodchild 2007). Waldseemüller’s mapping activities could be understood as an early form of a current phenomenon: engaged, but not specially trained citizens create geodata on a voluntary basis. Goodchild (2007, 212) first termed the phenomenon of “a special case of the more general Web phenomenon of user-generated content” “volunteered geographic information” (VGI). VGI is also referred to as crowd data, user-generated content, geo web 2.0, citizen cyberscience, or participatory sensing. Contrary to citizen science, it exhibits a looser formalization, the know-how of the people involved, the relation to the topic, and a certain tension between activity and passivity (Arias de Reyna/Simoes 2016). Moving along the axes of “content” and “understanding”, VGI generates data and information as the foundation for knowledge and informed decision-making (fig. 1).

Fig. 1: Information as resource (Cleveland 1982; modified)



Users, transactions, or sensors are involved in the formation of VGI. Accordingly, the main sources of VGI are application programming interfaces of social media platforms (e.g., Twitter, Flickr, Instagram, GooglePlaces, Facebook, Uber, Strava, etc.), data brokers (e.g., DataSift, Gnip, AirDNA), communities (e.g., OpenStreetMap, Geograph, Wikimapia), or web scraping techniques (e.g., Wget, Selenium). But how does the “G” get in VGI? The geographic part originates in manual or automated georeferencing activities with geotags or in meta information on locations and hashtags. A typical example for an XHTML web page tag would look like this:

```
<meta name="geo.region" content="DE-NW"/>
<meta name="geo.placename" content="Bochum"/>
<meta name="geo.position" content="51.4441; 7.2609"/>
<meta name="ICBM" content="51.4428; 7.2624"/>
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VGI has changed the traditional way in which geospatial information is collected, produced, and distributed. Users have become producers. Hence, the potential for applying VGI for monitoring the SDGs, which are the "blueprint to achieve a better and more sustainable future for all" (UN 2020) is *eo ipso* given. Recent studies apply VGI for flood impact analysis (Barz et al. 2019), understanding patterns of social segregation (Taubenböck et al. 2018), and the creation of land use classifications (Olteanu-Raimond et al. 2020). The DFG SPP 1894 "Volunteered Geographic Information: Interpretation, Visualisierung und Social Computing", e.g., is focusing on a sustainable use of VGI software elements and their analytical possibilities.

The goal of this contribution is to present a short review of studies on VGI for sustainable urban development in the economic, social, and natural spheres. Subsequently, a study carried out at the Institute of Geography at the Ruhr University Bochum dealing with VGI in the context of land consumption and individual temperature stress in Western German cities is added. It bears the potential for an easy-to-use mapping activity in order to sensitize citizens for climate adaptation issues and participatory urban planning possibilities at once. A conclusion provides future perspectives of VGI in sustainable urban development.

2. Volunteered Geographic Information in Urban Studies

Spatially explicit information on land use and land cover is essential to understand the implications of driving forces, actors and factors, impacts and feedback loops as well as the configuration and composition of the pattern and dynamics of urban systems. Fonte et al. (2017) created an automated procedure to convert OpenStreetMap (OSM) data into land use and land cover maps using the nomenclatures of the Urban Atlas and Corine Land Cover. Both products are satellite-derived and among the most popular land use and land cover information sources on the European level. The VGI-based approach outperformed the satellite-based one in terms of minimal mapping units and spatial accuracy. The OSM initiative Humanitarian OpenStreetMap Team (H.O.T. OSM) is using open data for mapping infrastructures and their vulnerabilities in order to support disaster risk management in a fast, efficient, and exact manner. One example is the voluntary mapping of the hydrological system of Dar es Salaam (Dar Ramani Huria 2016) providing information on potential inundation areas. In that regard, Šterk/Praprotnik (2017) developed a smartphone app to speed up the acquisition and the reliability of emergency response calls. Automated data collection and calculation of road access times for emergency response units are used in day-to-day operations. Among disaster risk management applications, one can also find an approach by Vannoni et al. (2020) dealing with the mobility assessment based on VGI in the early phases of the COVID-19 pandemic.

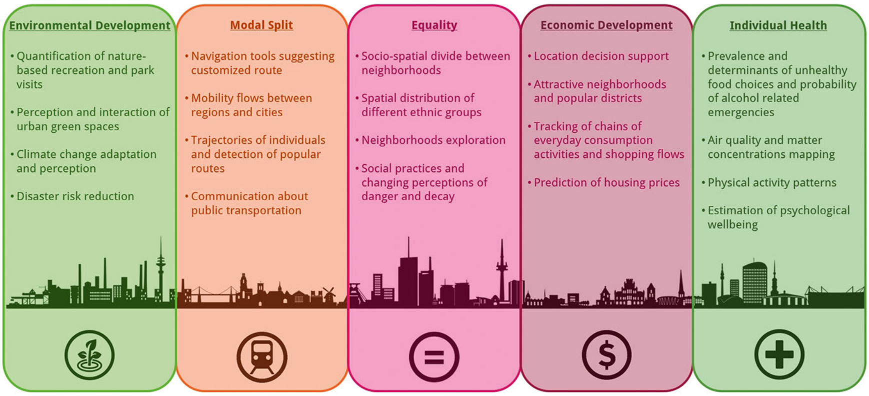
VGI exhibit the four big "v" of big data characteristics: volume, variety, velocity, and veracity (Bitkom 2014). There are several studies applying the big data potential of VGI to urban studies. Sun/Paule (2017) analyzed Yelp ratings in Phoenix, USA, indicating that high ratings are spatially structured, so that bars within or near the city center are more likely to get higher ratings than others further away. Ying et al. (2017) compared the interpersonal network and virtual network exchange in Chinese cities based on Sina Weibo microblog user relations to conclude that the degrees of cohesion and outreach in a city node were significantly positively correlated with the economic development level of the city. Sayegh et al. (2016) combined subjective and objective characteristics of built environments leveraging emotive perceptions of the urban actors. The findings can inform design decisions of urban planners. McArthur/Hong (2019) applied Strava source data in order to compare the most commonly used routes of daily bike commuters with their expected routes. The outcome helps to understand how street networks can be organized better in order to provide access to safe and unimpeded biking routes. In doing so, the path of a transformation toward a sustainable individual mobility behavior can be initiated. Ilieva/McPhearson (2018) reviewed over 100 studies dealing with the application of social media geographic information (SMGI) as a specific form of big data VGI (Campagna 2016). Investigation of social media (such as Twitter, Flickr, Instagram) enables sustainability researchers in conducting

- spatial analysis of user interests,
- temporal analysis of user interests,
- spatial statistics of user preferences,
- multimedia content analysis on texts, images, video, or audio,
- user behavioral analysis or
- spatial-temporal textual analysis.

I argue that as soon as it comes to the analysis of social media as a data source of VGI, one has to discuss the degree of voluntariness with which the users of social media contribute to a data base utilizable for scientific purposes. People participate within social media to communicate and exchange experiences or ideas. The purpose of geodata provision for scientists is rather involuntary, so that we actually deal with a special case of unvolunteered geographic information when it comes to SMGI. Nevertheless, the connection of semantic information and geoformation with the help of tags, geotags, images, or written text can be exploited as an important data source for analyzing, e.g., the experience of clean air as an important topic in-between social and natural spheres of urban systems. Most recently, Du et al. (2016) developed a sophisticated approach in order to mine alternative pollutant data to assess air quality in urban areas with a two-phase approach for opinion mining, targeting domain-specific knowledge and analyzing sentiments of crawled tweets. Yan et al. (2019) used geotagged check-in records on Sina Weibo, a Twitter-like platform, to systematically investigate the effect of air pollution on urban activity. Based on panel models, they found clear evidence that such an effect exists and varies between pollutants, visitors and residents, and different activity types.

Fig. 2 depicts how SMGI is currently utilized to analyze the various compartments of the urban system. Accordingly, studies dealing with the environmental development of inner urban areas and their perception (Guerrero et al. 2016; Keeler et al. 2015; Roberts 2017; Sessions et al. 2016; Sonter et al. 2016; Schwartz/Hochman 2014), urban mobility (Assem et al. 2017; Hawelka et al. 2014; Hasan/Ukkusuri 2014; Li et al. 2015; Lucchese et al. 2012; Luo et al. 2016; Schweitzer 2014; Paldino et al. 2015; Zhou et al. 2017), socio-cul-

Fig. 2: SMGI for analyzing the urban system and its compartments



tural equality (Adnan et al. 2013; Hoogendoorn/Gregory 2016; Shelton et al. 2015; Quercia/Saez 2014), economic development (Brandt et al. 2017; Lovelace et al. 2016; Martí et al. 2017; Zhai et al. 2015), as well as health and well-being (Ben-Harush et al. 2012; Chen/Yang 2014; Gore et al. 2015; Mitchell et al. 2013; Nguyen et al. 2016; Ranney et al. 2016; Widener/Li 2014; Yang/Mu 2015) have recently been carried out (Ilieva/McPhearson 2018).

In general, the question of accuracy and scientific rigor is not only important when one deals with data gathered by social media. Hence, quality assurance is an important aspect when it comes to VGI (Goodchild 2007). The credibility of data relies on its completeness, positional accuracy, attribute accuracy, logical consistency, and comparability. OSM, e.g., makes use of a variety of tools to ensure a certain level of reliability (OpenStreetMap 2021):

- reporting,
- error detection,
- visualization,
- monitoring,
- assistant tools as well as
- tag statistics.

Hollenstein/Purves (2010) detected typical error sources when it comes to the relation of name tagging and geotagging based on Flickr data. Besides objective errors like location or semantic errors, one also has to deal with the subjective representation of space. Keil et al. (2020) investigated the structural salience of landmark pictograms in VGI-based maps. The aim was to identify distance parameters that predict the structural salience of landmark pictograms in an object location memory. They conclude that landmark pictograms close to a memorized location or the cardinal axes of a memorized location are structurally salient. Results like these might improve the applicability of voluntary mapping activities such as OSM or WUDAPT.

The World Urban Database and Access Portal Tools (WUDAPT) project is a community-based project for gathering a census of cities around the world. One main aim is the classification of cities in local climate zones (LCZ) (Bechtel et al. 2019, Ching et al. 2018). The LCZ typology combines vertical and horizontal elements to ten building types and seven non-urban land cover types. Demuzere et al. (2020) anticipate that LCZ-based data sets deliver information on configuration, size, and shape of cities impacting important human and environmental relations such as human health and well-being, environmental hazards, energy demand, and climate mitigation. The application of the LCZ scheme by voluntary users generates urban data needed by climate models for simulating the impact of land use and land cover change on the overlying atmosphere.

3. "Too stuffy and too hot" – VGI for Climate-Adapted Urban Areas

Cities consisting of more than 50 percent of impervious land cover have a specific impact on ecological effects. Besides runoff and infiltration, the physical conditions of urban surface materials like concrete, bitumen, asphalt, tar, etc. are contributing to the infamous urban heat island (UHI) effect. Simply phrased, the UHI effect indicates the temperature differences between cities and their rural surroundings (Oke et al. 2017). Regularly, we observe higher temperature in urban areas than in rural surroundings. In that regard, Chen et al. (2020) concluded that in order to mitigate UHI effects, a reasonable urbanization mode needs to be promoted. This is directly addressed by SDG 11.b, demanding to "substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards […] mitigation and adaptation to climate change" (UN 2021b).

The citizen science project "Town and Country in the Flow – Network for the Creation of a Sustainable Climate Landscape (KlimNet)" pursued the goal to mobilize and bundle knowledge and commitment regarding climate change adaptation, especially among young adults, and thus stimulate concrete action. It aimed at the exchange between municipal administrations, civil society, and universities in North Rhine-Westphalia (NRW). KlimNet was funded by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety following a decision of the German Bundestag (funding code 67DAS098 ABC, 2017–2020) and implemented by the WILA Bonn Science Shop and the Universities of Bonn and Bochum. A three-step approach was pursued, consisting of providing information about climate change in the region, developing opportunities for action with the goal of a climate-resilient city, and institutionalizing the transfer of knowledge (fig. 3):

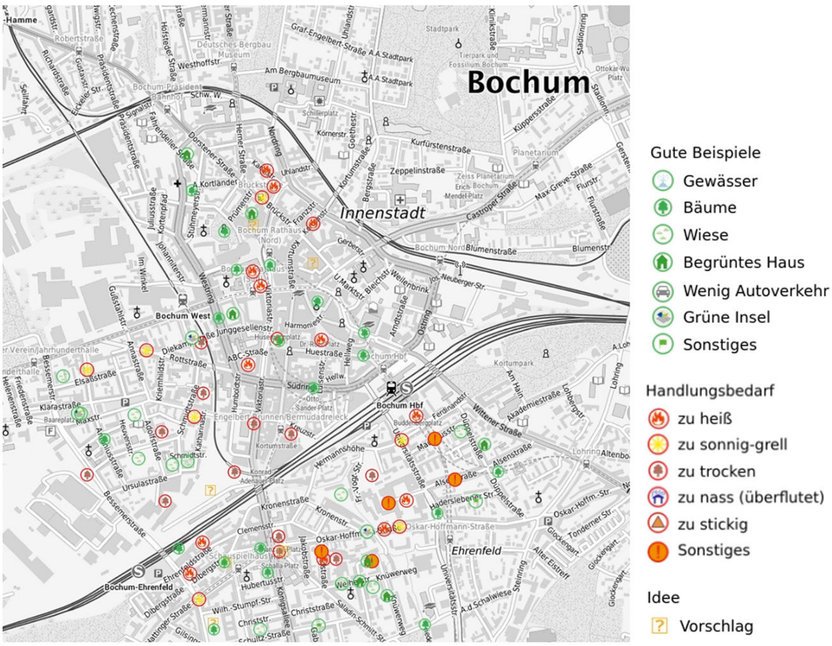
- provision of information on the possibilities for adapting to climate change in the region for local stakeholders and groups that are affected and active in the region,
- development of local options for action with the stakeholders themselves instead of implementing adaptation measures and

- anchor methods of knowledge transfer by the partnering communities in the long term.

Fig. 3: Guideline on participatory climate adaptation crowdmapping (WILA Bonn e.V. 2020)

One way to achieve these goals was the implementation of regular crowdmappings with interested citizens and young adults who have finished school but have not started their tertiary education path yet. The Geomatics Research Group of the Ruhr University Bochum was responsible for preparing a Web GIS required for the dissemination of past and future land consumption information on the one hand and for hosting the crowdmapping platform on the other hand. The structure of the developed Web GIS (klimnet.geographie.rub.de) is divided into four selectable main maps: the map of NRW serves as the start page and contains the land cover classifications. Each of the NRW pilot cities, i.e. Bonn, Gelsenkirchen, and Bochum, are represented in their own maps, in which crowdmapping is possible. For the crowdmapping, interested users need to choose their pilot study area, then a point in the map must be clicked and a category selected (fig. 4).

Fig. 4: Crowdmapping section in KlimNet (klimnet.geographie.rub.de)



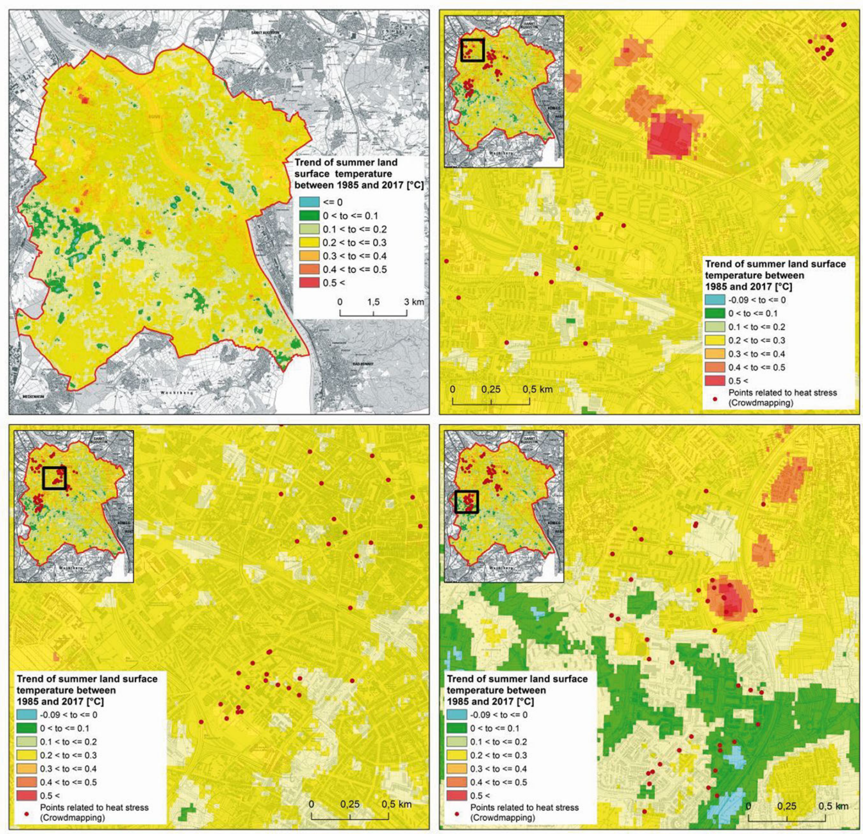
So far, one can choose between several categories. The 'good practice examples' category contains the classes 'water bodies', 'trees', 'meadow', 'vertical green', 'reduced traffic', 'green island' and 'other'; the category with needs for action contains the classes 'too hot', 'too sunny', 'too dry', 'too wet (flash flooded)', 'too stuffy' and 'other'. Finally, individual ideas can be added in the open category 'suggestion', like potentials for solar panels, green roofs, green islands, trees, or wildflower meadows. This should serve to identify special places in the cities where there is still a need for climate-adaptive measures versus where such measures have already been implemented. The monitoring is done by the users themselves. The administrator is able to change the class of registered locations or to remove them completely if some 'internet trolls' appear. The operation of the Web GIS is done using .json files and a QGIS project which contains the data for the Web GIS. An SQL database is used for the statistical data. Users are able to share their image detail from the map via Twitter and Facebook as well as a QR code.

Tab. 1: Overview of crowdmapping locations on climate adaptation in Bonn, Bochum, and Gelsenkirchen (NRW, Germany)

Type	*Count*
Good Practice Examples	
Water bodies	6
Trees	72
Meadows	40
Vertical green	32
Reduced traffic	3
Green island	19
Other	27
Need for Action	
Too hot	61
Too sunny	26
Too dry	33
Too wet (flash floods)	4
Too stuffy	6
Other	19
Ideas	
Suggestions	42

In addition to the crowdmapping section, maps depicting 32 years of urban expansion and resulting land consumption patterns are accessible via the portal (Ghazaryan/Rienow et al. 2021). The analysis of the maps shows that impervious surfaces comprised about 552,464 ha in 1985. Three decades later, impervious surfaces had increased by more than 167,000 ha in 2017. The dispersion and densification of urban areas come along with surface sealing processes affecting the thermal conditions of their direct surroundings. Accordingly, 390 locations have been mapped by citizens depicting good examples, action needed, and ideas related to climate adaptation (tab. 1). These locations have been mapped based on very subjective categories, experiences, and impressions. However, in total, 93 points were collected, reflecting locations inducing subjective thermal stress ('too hot': 61, 'too sunny': 26, 'too stuffy': 6). Fig. 5 shows points of that category mapped in the city of Bonn in the Southern part of the Rhine-Ruhr metropolitan region in comparison to Summer Land Surface Temperature (LST) trends from 1985–2017. The transformation of metropolitan configurations induced by land consumption dynamics can affect the thermal characteristics of a region. These changes are often studied using remote sensing-based LST. Particularly data from Landsat, the Moderate Resolution Imaging Spectroradiometer (MODIS) (Fu/Weng 2018), and NOAA's Advanced Very-High-Resolution Radiometer (AVHRR) (Khorchani et al. 2018) have been used for LST change assessment. Landsat 5, 7, and 8 data was accessed and analyzed using Google Earth Engine. The areas with significant trends can show the heating or cooling processes. Furthermore, LST was extracted for several locations of interest, such as areas where, according to crowdsourced information, changes of temperature and heat were observed (fig. 5).

Fig. 5: Summer LST trends 1985–2017 maps compared to locations related to heat stress gathered by citizens in Bonn, Germany

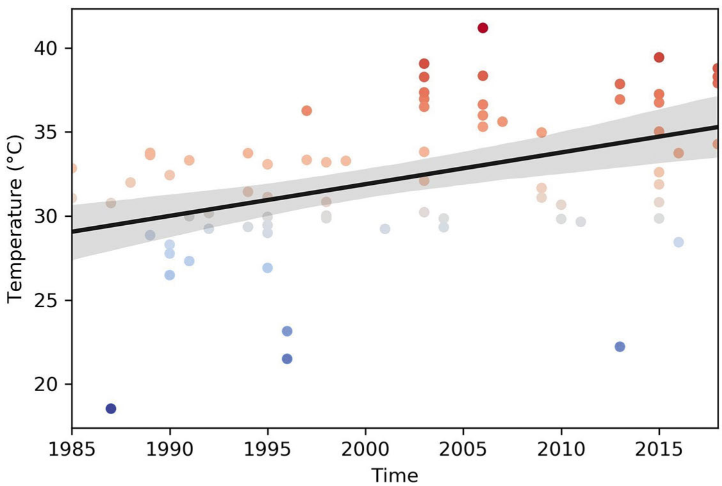


Most of the points are located in regions with an increase in the Summer LST. It indicates an UHI effect on a higher temperature level in 2017 than in 1985. Of course, one has to differentiate between canopy layer UHI (UHI_{UCL}) and surface UHI (UHI_{surf}). While UHI_{surf} is defined by "temperature differences at the interface of the outdoor atmosphere with the solid materials of the city and equivalent rural air to ground interface" (Oke et al. 2017, 198), UHI_{UCL} addresses

> the difference between the temperature of the air contained in the urban canopy layer, [i.e.] the layer between the urban surface and roof level (the exterior UCL), and the corresponding height in the near-surface layer of the countryside. (Oke et al. 2017, 199)

While the UHI_{surf} type can be measured remotely via satellites, UHI_{UCL} needs to be measured with temperature sensors at fixed points or acustical wind direction instruments like mini-sodars (sonic detection and ranging) (Oke et al. 2017). However, the small study demonstrates that even in places where no significant increase in Summer LST has been measured, citizens feel exposed to thermal stress and action is needed.

Fig. 6: Average mean of the Summer LST trends of all crowd-mapped locations related to climate adaptation in Bonn 1985–2017. Each dot represents a day of a year in the Landsat archive



Furthermore, fig. 6 plots all points mapped by the citizens against the LST development from 1985–2017. In reference to table 1, most of the crowd-mapped points are dealing with good practice examples reflecting where climate-adaptive measures have already been implemented. Hence, despite already existing good practices in configuring and compositing the urban neighborhood and thus mitigating climate change impacts, a steady increase of the LST over the last decades can be observed. Taking action is still necessary.

4. Future Perspectives

It has been shown that VGI is a promising source for information and data on urban sustainability topics. In that regard, table 2 presents the opportunities and challenges remaining when it comes to the application of VGI in urban studies. Besides a high volume, variety, velocity, and veracity of data and topicalities, VGI comes with low-cost investment and is publicly available. Still, quality assurance and subjectivity are important challenges for the future. The issue of data privacy becomes more and more urgent in regard to the rise of SMGI and probable unvolunteered geographic information. Additionally, having citizens involved in participatory projects raises awareness for scientific topics but also expectations which need to be satisfied quickly.

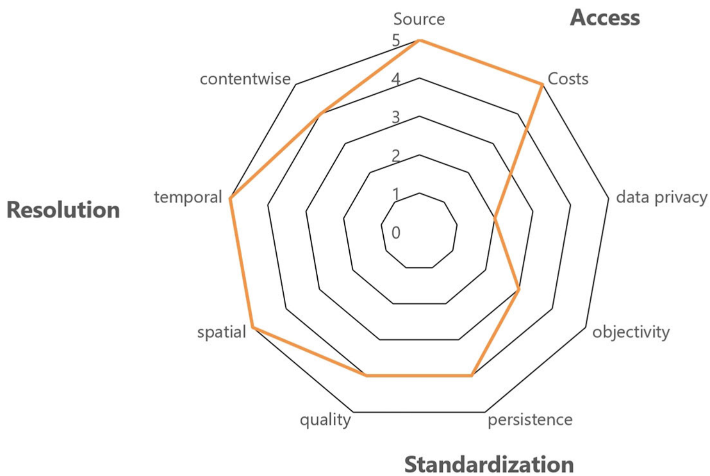
Tab. 2: Opportunities and challenges of VGI in urban sustainability studies

Opportunities	***Challenges***
High data topicality	*Quality assurance*
Big data characteristics (volume, variety, velocity, and veracity)	Community maintenance
Open data	Subjectivity
Low cost	Trolling
Participation of the public	High expectations
Issue-specific	Data privacy

Urban areas are open and dynamic systems in which macro-level patterns are a result of behavioral-driven processes of micro-level actors (Batty 2005; Geist et al. 2006). Accordingly, urban sprawl is a direct effect of the interaction and decision-making processes of individuals as well as public and private stakeholders. Those interactions are performed continuously and simultaneously by decision-makers showing an irrational and adaptive behavior. They change the state of the whole system and additionally react to these changes. Thus, urban systems reach a level of self-organization in which actors determine factors and conversely (Haase et al. 2012; Inostroza/Zepp 2021). It is a horizontal and vertical interplay within and between organizational levels, making the urban system elastic (Geist et al. 2006). The social subsystems undergo a path-dependent transition, implicating their own structural transformation and that of their environment (Geist et al. 2006). Perceiving and detecting these alterations, actors are able to modify their behavioral attitudes. This results in attenuating mechanisms ("negative feedback loop") reducing the speed and intensity of change. In contrast, amplifying mechanisms can also be initialized, leading to an acceleration of degrading effects ("positive feedback loop"). In doing so, a clear distinction of what is significant cause and what is random correlation is very difficult (Kroll/Haase 2010). The resilience of urban systems is not constant. At certain thresholds, critical nodes are reached where internal or external influences previously thought of as unproblematic can have unpredictably higher impacts and determine the future trajectory of urban systems (Batty et al. 2006). These bifurcations illustrate that the cause-effect relationship within urban systems is neither linear nor unilateral. Urban systems cannot simply be explained by the equilibrium result of a certain set of driving forces. They exhibit characteristics of hysteresis so that future developments and changes of urban systems are not only influenced by the current environment, but also by the past one (Alcamo et al. 2006).

Most recently, concepts from biology have found their way into urban studies in order to address the complexity of urban systems and treat them like socio-ecological systems. Accordingly, Andersson et al. (2021) introduced the concepts of traits to frame the support of urban sustainability. A functional trait is a feature of an organism determining the organism's response to pressures and its effects on ecosystem processes or services. Socio-ecological traits mediate reactions to selective socio-ecological filtering or determine effects on ecosystem processes or services. The three dimensions of a socio-ecological traits framework consist of (1) observable traits of the urban envi-

Fig. 7: Characteristics of VGI for analyzing observable traits in socio-ecological systems



ronment, (2) feedback loops with individual and collective perceptions and decision-making, as well as (3) urban ecosystem planning and management. For the first dimension, easily accessible (low-cost, open-source, privacy-secure) data and information with high resolution (spatial, temporal, content-wise) is needed (fig. 7). Assuring the quality, persistence, and objectivity of VGI, this exciting and vivid source of geodata may find entrance into urban planners' work in order to shape policy decision-making.

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