Landscape and Urban Planning 204 (2020) 103921

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Remote sensing in urban planning: Contributions towards ecologically sound policies?

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GRAPHICAL ABSTRACT

ARTICLE INFO

Keywords:
Earth observation
Urban ecology
Systematic literature review
Open science
Ecosystem services

ABSTRACT

Remote sensing has evolved to become a key tool for various fields of environmental analysis, thus actively informing policy across areas and domains. To evaluate the degree to which remote sensing is contributing to the science of ecologically-oriented urban planning, we carried out a systematic literature review using the SCOPUS database, searching for articles integrating knowledge in urban planning, remote sensing and ecology. We reviewed 186 articles, analysing various issues in urban environments worldwide. Key findings include that the

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https://doi.org/10.1016/j.landurbplan.2020.103921
Received 9 June 2020; Received in revised form 6 August 2020; Accepted 6 August 2020
Available online 27 August 2020

Science policy interface

level of integration between the three disciplines is limited, with only 12% of the papers fully integrating ecology, remote sensing and planning while 24% of the studies use specific methods from one domain only. The vast majority of studies is oriented towards contributing to the knowledge base or monitoring the impacts of existing policies. Few studies are directly policy relevant by either contributing to direct issues in planning and making specific design suggestions or evaluations. The accessibility of the scientific findings remains limited, as the majority of journal articles are not open access and proprietary software and data are frequently used. To overcome these issues, we suggest three future avenues for science as well as three potential entry points for remote sensing into applied urban planning. By doing so, remote sensing data could become a vital tool actively contributing to policies, civil engagement and concrete planning measures by providing independent and cost effective environmental analyses.

1. Introduction

A growing body of literature has been documenting the value of ecologically functioning urban systems (Elmqvist et al., 2018; Pickett et al., 2011). Scholars, policy makers and practitioners increasingly understand the ecological, economic and social-political benefits of implementing urban green and blue infrastructure (GBI) in cities, and their interactions (Andersson et al., 2019; Beatley, 2017). While scientific evidence is supporting an increasing acknowledgement of the interlinkages between ecological systems and human wellbeing (Mace, 2014), practical uses of ecological knowledge in decision-making remains limited (Cortinovis & Geneletti, 2018; Kirchhoff et al., 2013). In times of climate change and urban growth, social and environmental pressures are mounting on urban planning (2019b). The availability of actionable knowledge that can support planning decisions is often a barrier (Clark et al., 2016), and several studies highlighted the need for environmental analyses that provide spatially-explicit data in a timely, cost-efficient and repeatable way (Beichler et al., 2017; Palomo et al., 2018; Spyra et al., 2019).

One approach that could help to overcome the above-mentioned obstacles is deriving valuable information through remote sensing. Remote sensing provides data globally by satellites, and locally by airplanes or, more recently, smaller unmanned aerial vehicles (UAVs, commonly known as drones) and handheld devices (van der Linden et al., 2018). From these datasets, detailed information about various ecological processes shaping the urban environment can be derived such as the urban climate (Rosentreter et al., 2020), cooling and shading potential (Kong et al., 2014; Kremer et al., 2018), the distribution of urban green (EEA, 2018) or the state of vegetation concerning drought and ecological quality (Wellmann et al., 2018), among others.

Over the last few decades remote sensing data has become more available and accessible and can be considered a cornerstone in different fields of environmental analysis and monitoring (Dong et al., 2019), especially in agriculture (Lesiv et al., 2018), forestry (Hansen et al., 2013), and urban growth monitoring (Melchiorri et al., 2018; Zhu et al., 2019). Remote sensing underlies authoritative geospatial datasets, like the Urban Atlas in Europe (EEA, 2018), which are important for urban studies and planning authorities. Even though urban remote sensing is a well-developed subdomain in remote sensing science (Weng, 2019) the degree to which remote sensing is used in the science of urban ecological planning or is contributing to urban policy remains unclear. While wide-reaching initiatives are bringing general ecological guidance into urban planning from both the scientific (Urbio, Müller & Kamada, 2011; Animal Aided Design, Hauck & Weisser, 2015) as well as the planning community on various levels (see e.g. Kommbio dealing with the expansion of ecologically valuable areas in Germany, or the recent EU guidance 'on integrating ecosystems and their services into decision-making', EC, 2019), there are no such specific endeavours for bringing remote sensing data and methods into the planning practice.

The objective of this research is to investigate the state and shortcomings of remote-sensing contributions towards ecologically-oriented urban planning, and to derive strategic directions on how to improve the interaction between the involved disciplines. To this aim, we carried out a systematic literature review using the SCOPUS database, searching for peer reviewed articles applying remote sensing methods for ecologically sound urban planning to understand how remote sensing can be better utilized in urban Social-Ecological-Technological Systems (SETS, McPhearson et al., 2016). By ecologically sound urban policies, we understand a way of planning that integrates knowledge of ecological systems and their functionality with the aim of conserving and enhancing urban ecosystems, as well as ensuring a sustainable management and equitable distribution of the ecosystem services (ES) they provide (Niemela, 1999; Pickett & Cadenasso, 2008).

To do so, we put a spotlight on four structural and conceptual aspects of the reviewed literature. First, we assessed the ways remote sensing is used for the generation of applicable urban ecological knowledge by analysing the data, methods, and concepts adopted. Second, we assessed the level of integration between the three major scientific disciplines of remote sensing, ecology, and urban planning, by examining which combinations of disciplines generate what kind of knowledge. Third, we evaluated the different uses of remote-sensing knowledge along the policy cycle that describes the various steps between the formulation of policy goals to policy implementation and evaluation (Jann & Wegrich, 2007). Fourth, we evaluated the frequency of open source codes, data sharing and open-access publications in the analysed literature, since a high degree of openness is advantageous for the diffusion of scientific data and methods into applied fields. Hence, by quantitatively and qualitatively assessing these aspects, we answer the following questions:

- Which methods and frameworks are most commonly used for deriving applicable knowledge from the remote sensing data?
- What is the level of integration between the disciplines of remote sensing, planning and ecology?
- What phases of the policy cycle are tackled in the reviewed studies?
- How accessible are the methods and results in the literature corpus?

2. Methods

We conducted a structured literature review following the PRISMA guidelines (Moher et al., 2009) using the SCOPUS database, which features the largest peer reviewed journal coverage (Mongeon & Paul-Hus, 2016) excluding planning documents and other grey literature. We limited our search to scholarly articles in English and searched in the title, abstract and keywords using a combination of keywords to describe the three major disciplines investigated in an urban context:

TITLE-ABS-KEY

	((**urban** OR **city**)
AND	("**remote sensing**" OR "**Earth observation**")
AND	(**planning** OR **management** OR **policy**)
AND	(**ecolog*** OR "**green infrastructure**" OR "**ecosystem services**"))
AND	(LIMIT-TO (SRCTYPE, "j"))
AND	(LIMIT-TO (DOCTYPE, "ar"))
AND	(LIMIT-TO (LANGUAGE, "English"))

The first discipline was defined by the keywords 'remote sensing' and 'Earth observation' (EO), to also include ground based or hand held measuring devices. 'Planning', 'management' and 'policy' were used as search terms to capture the urban planning aspects at different strategic levels (more strategic/long-term to more operational/short-term). The ecological domain was described by 'ecolog*' including many linguistic facets of ecology, and by two major concepts combining planning and ecology. These were 'green infrastructure' combining the perspective of ecology and built or designed infrastructure and 'ecosystem services' combining ecology with human well-being.

The initial search was performed on 09 October 2019 and yielded 534 articles matching the keywords. We performed abstract screening, availability check and full text screening as described in Fig. 1, which resulted in 186 papers that were included in the final analysis (for a full list of bibliographical details please see Appendix 3). Abstracts were manually screened to decide whether or not the article matched our research scope. For instance, many articles did not specifically cover urban systems but rather addressed policy at a regional to national focus and thus had only minor relevance to urban analysis.

All selected papers were analysed using a structured review protocol (see details of the review framework in Appendix 2). This step generated a database describing both quantitative and qualitative aspects of the selected articles. Descriptive aspects included, among others, bibliographical information (e.g. accessibility of the paper), study design (e.g. spatial and temporal scale) and information regarding data (both remote sensing and non remote sensing data), methods and concepts used. For the classification of ecosystem services we used the TEEB classification (TEEB, 2010), in line with a previous regional assessment (Tavares et al., 2019). For the classification of green infrastructure components we referred to Pauleit et al. (2019). For the analysis of the spatial conceptualisation, we differentiated between 'ecosystem', representing an ecological approach, and urban matrix, urban form and urban functional zones, representing a planning or human oriented focus.

More interpretative aspects included an assignment of the study to one or more phases of the policy cycle and an evaluation of the methodological focus of the study. The policy cycle describes the various steps a policy item takes in between drafting, implementation and assessment (Jann & Wegrich, 2007). Along the cycle, we identified six distinct potential uses of knowledge generated by remote sensing. First, the 'formation of the knowledge base', which is knowledge that is of potential interest to planners and stakeholders but not immediately actionable and can be thus seen as closer to research. 'Planning policies' defines the use of knowledge to develop long term strategic plans, while a more detailed guidance for specific developments is considered a 'planning action'. Lastly, we included 'management' and 'monitoring', as infrastructure needs to be maintained, and the success of implementation and its effects on the environmental status should be

Fig. 1. Frequency of papers regarding remote sensing and planning (top right), remote sensing and ecology (top left) and both (top middle), which is the subject of this study and the subsequent screening process.

followed-up.

The methodological focus was evaluated with a set of exclusion criteria, e.g. a paper that only states ‘xy is important for policy’ does not cover the dimension of planning, a study that uses only pre-classified remote sensing data, does not have a methodological focus on remote sensing or a study that analyses the location of green structures in the city without mentioning ecological concepts or results does not have a focus on ecology. Based on this information, we clustered the papers into seven groups discerning different levels of interdisciplinarity. Three groups of papers with a methodological focus on one dimension (Remote sensing (R), Ecology (E), Planning (P)), three groups of dual integration (RE, RP, EP) and lastly the group integrating the three investigated disciplines (REP).

For each of the four groups combining at least two disciplines we performed text mining using the *tidytext* (Silge & Robinson, 2016) package in *R* to reveal systematic differences between studies with different levels of interdisciplinary integration. To do so, we calculated the term frequency–inverse document frequency (tf–idf), a widely used statistical measure to portray the importance of a word in a document corpus (Beel et al., 2016). Tf–idf is the product of two statistics, term frequency (tf – the actual frequency of a term in the corpus) and inverse document frequency (idf – a measure of how rare the word is putting more weight to rarer words). By putting more weight to rarer words, differences in texts can be analysed by omitting an arbitrary list of words for exclusion. In our case the corpus represented the abstracts of all articles selected for analysis. We thereby calculated this measure not for single words but rather for bigrams (i.e., a combination of two neighbouring words, for example ‘ecosystem service’) to better derive the context and the meaning of the term.

We further evaluated the social and physical context of cities included in the papers we reviewed. To do so we extracted all named cities of the manuscripts and used the Mapquest Geocoding API (available at https://developer.mapquest.com) to map each city. Thereof we analysed the location of the studied cities against two key social and physical parameters, namely the economic situation and climate change projections. For the first we used the UN's World economic situation and prospects report (UN, 2019a), to see if economic power is part of a potential unequal distribution of the studied cities across the globe. For the latter we used a Köppen-Geiger classification scenario by Beck et al. (2018), which is based on the IPCCs RCP8.5 scenario (representing the current worst-case scenario for the year 2100) to compare the frequency of the elicited literature corpus addressing climate change with the current prognosis. We compared the city trends with how far the scientific community is already contributing ideas in this direction, as climate change and its impact will have a severe impact on urban policies, societal thinking and also the science of environmental analysis (Elmqvist et al., 2019).

Finally, we evaluated the overall accessibility of the manuscript text, data and software used in each paper to approximate the access to methods or knowledge produced in the studies for (environmental) planning authorities or planning bureaus. For doing so, we classified the papers, data and software into two classes, namely whether or not they are freely accessible. Open-access publications, non-commercial open source software products, open remote sensing data and additional data that either available in public repositories or provided by governmental agencies in the first place were marked as accessible.

3. Results

We found that remote sensing data and methods are used for urban studies analysing different forms of Social-Ecological-Technological Systems in various geographical settings. The diversity is reflected by the fact that a total of 89 journals covering a wide range of research topics were included in the review. The most common journals were *Landscape and Urban Planning, Sustainability,* and *Ecological Indicators* (Fig. A3 in Appendix 1).

In total, the 186 reviewed articles studied 649 different cities spread across nations, continents, and climatic zones. A majority of cities are located in China and the USA with 299 and 130, respectively (Fig. 2 & Fig. A1 in Appendix 1). Of the ten most studied countries (by cities) six are located in East- and South East Asia. The African and the South- and Central American continents are the most underrepresented, along with the far north. Cities in different economic contexts are investigated with emerging countries representing the most intensively studied block (419 cities studied). This is followed by the developed states featuring 196 cities and lastly developing states (25) and least developed states (9).

The majority of studies analyse a single city or a single city plus its surroundings, in turn there are only two global and two continental studies. The majority of papers are framed in an urban growth context, with morphological growth (i.e. spatial expansion) being addressed in 45% of the studies and population growth in 33% (Fig. A1 in Appendix 1).

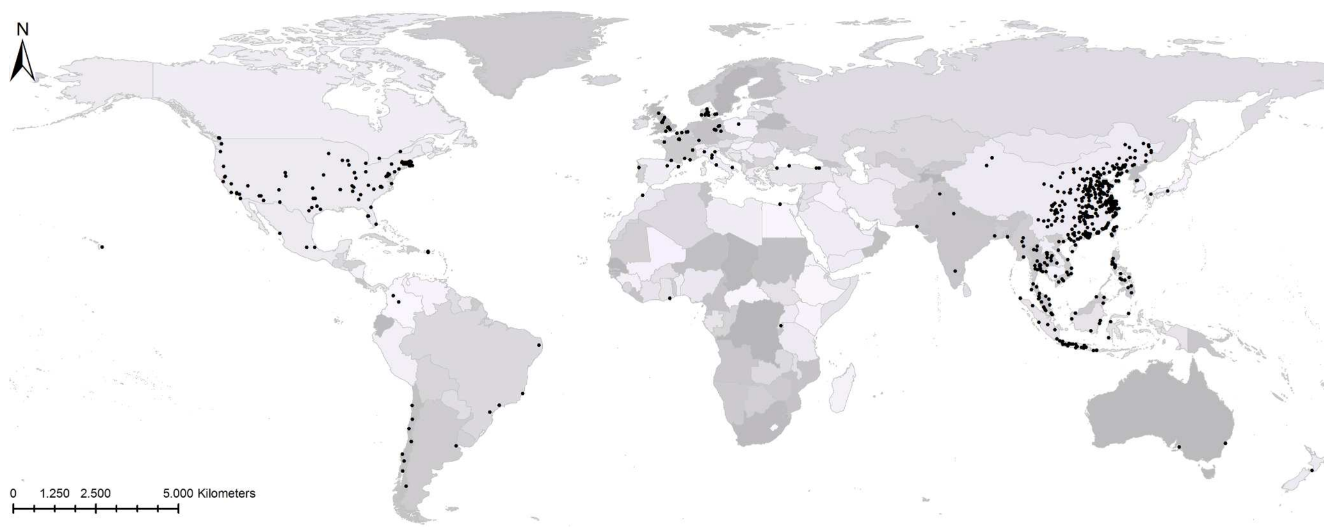

Fig. 2. Map showing the location of the 821 studied locations in 649 different cities. For a responsive, higher resolution web map please go to http://remotesensingforcities.org/wp/review-web-app/.

3.1. From data to knowledge

3.1.1. Data integration

There is a large variety of remote sensing and non remote sensing datasets used in the reviewed corpus. The most frequent source for remote sensing imagery were satellites and airborne imagery (especially RGB orthophotos) used in 68% and 24% of the studies, respectively. Pre-processed remote sensing derived products of varying origin were used in 30% and platforms aggregating different products (e.g. Google Earth or Bing) were used in 9% of the studies. Data from handheld devices and drones are rarely used (3% and 1% of the studies as of 2019, respectively). In terms of specific sensors, Landsat-related sensors (e.g. OLI, TM) were the most widely used, representing 30% of all remote sensing data used (24% optical, 6% thermal), followed by SPOT, MODIS, and ASTER with around 7% each. The relatively recently released data from European Sentinel satellites are sparsely used as of

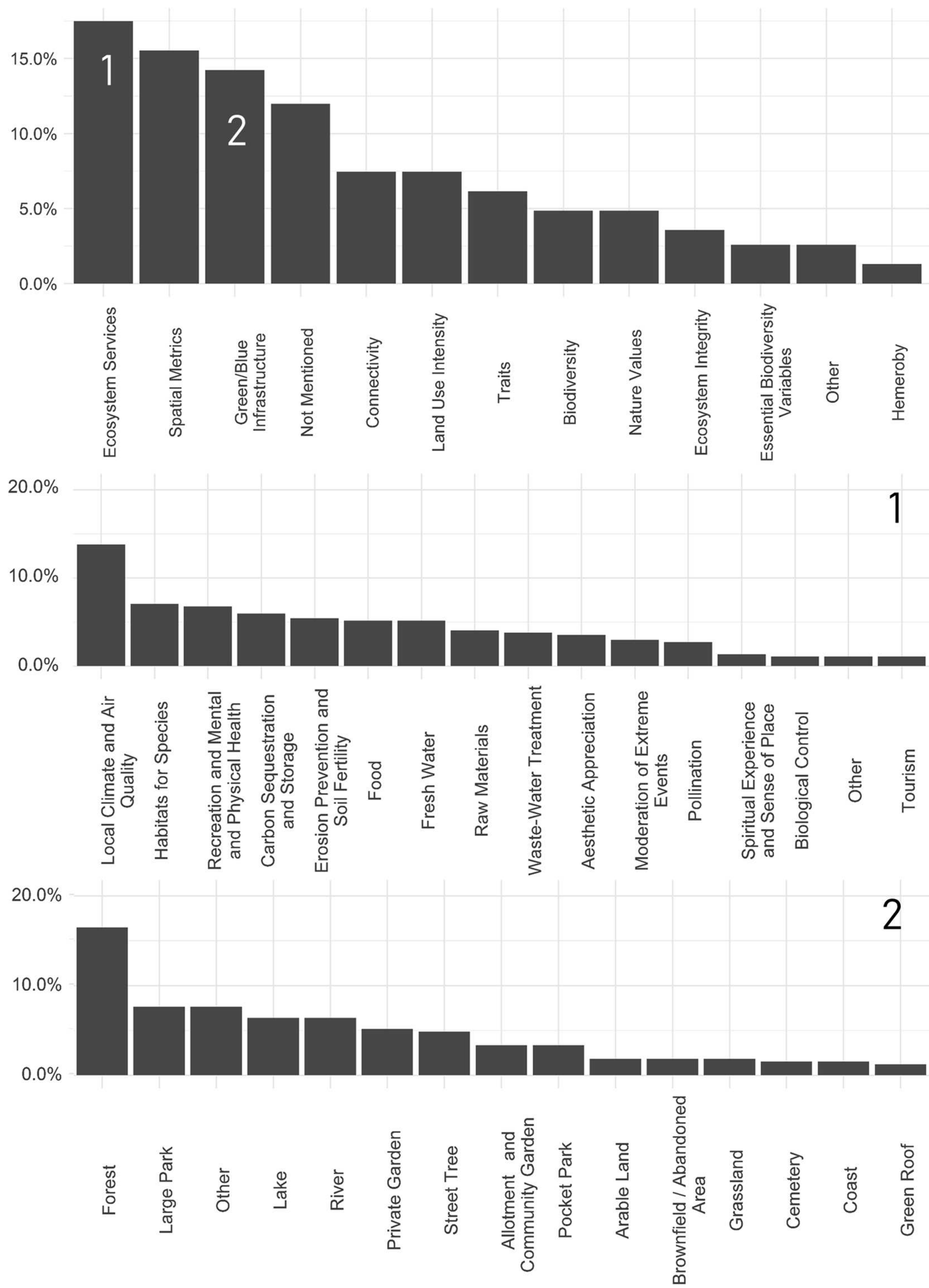

Fig. 3. Bar charts showing the frequency of concepts potentially serving as conceptual frameworks. Top: all concepts specifically mentioned in the papers. Centre: potential focal entry points into the concept of ecosystem services (column 1 in the top graph) as a link to the field of ecology. Bottom: potential focal entry points into the concept of green blue infrastructure (column 2 in the top graph) as a link to the field of planning. For instance, the concept of ecosystem services was mentioned only in ~15% of the papers, but it could have been used in up to 70% of the publications. Occurrences below 2% labelled as 'other'.

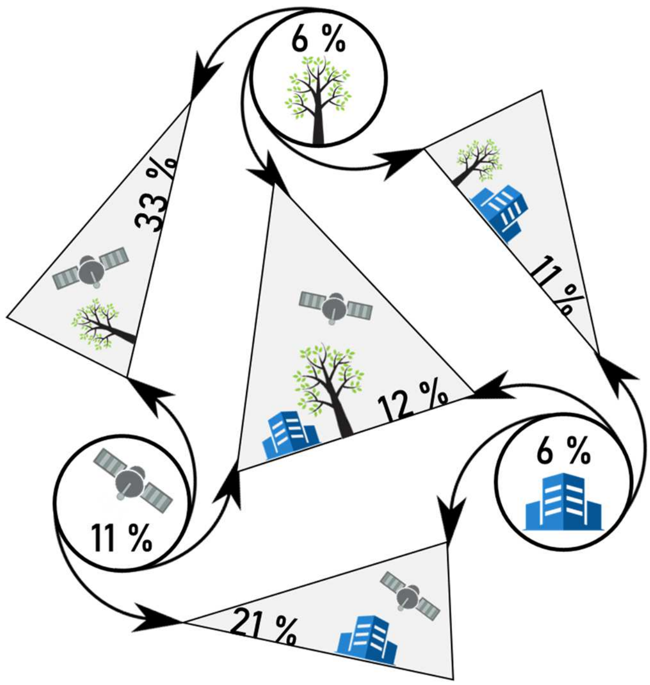

Fig. 4. Level of integration in the reviewed papers. The tree symbolises ecology, the satellite remote sensing and the building the planning domain, darker shades of grey symbolise a more frequent classification. Clockwise from the bottom left circle: 11% of the papers were classified as only regarding remote sensing, in turn 33% were found to include remote sensing and ecology, as arrows from the circles ecology and remote sensing end here. The triangle in the middle shows that 12% of the publications managed to integrate across the three disciplines.

2019 (Fig. A2 in Appendix 1). Airborne LIDAR (Light detection and ranging) was used in about 5% of the studies.

A variety of non remotely sensed data was used in the analysed studies including social, physical, and ecological datasets. Most common, are ready-to-use land-use & land cover (20%) and built infrastructure layers (10%), closely followed by social-demographic surveys (9%) and economic data (7%). Other types of data included biological data such as species community mappings (5%) and plant traits (3%), and environmental data like meteorological measurements (3%). 15% of studies do not report any other data being used besides remote sensing data.

3.1.2. Methods of remote sensing data analysis

There is a large variety of methods used (n = 52), most of them cited in less than two papers and therefore labelled as ‘other’ (Fig. A2 in Appendix 1). The most widely used methods are discrete classifications (16%). The most common classification approaches are geographic object-based (Geobia), pixel-based maximum likelihood classifications, and various other machine-learning approaches (e.g. SVM, RF) each slightly below 5%. The Normalised Difference Vegetation Index (NDVI) stands out among the indices (12%). Visual interpretation is frequently used (8%) and many studies list various steps of pre-processing like atmospheric correction (8%). The use of time-series is widespread, overall there are almost twice as many studies featuring temporal data than single point in time analyses (Fig. A1 in Appendix 1). Gaining in importance are thereby new data fusion approaches bringing together different sensors for increased spatio-temporal coverage or including new data sources such as LIDAR in the analysis workflow.

A considerable amount of studies provided sparse methodological details, either because a clear structure was missing or because the methods sections were lacking some important characteristics. About 20% of the studies do not report the method adopted, e.g. stating generically that ‘a classification was performed’, with no details about type of algorithm and settings. Furthermore, in another 20% of the papers we found no indication about which software was used.

3.1.3. Concepts

The major frameworks used to turn data into meaningful information for urban planning were ecosystem services (ES), spatial metrics, and green and blue infrastructure (GBI) (Fig. 3 on the top), each being specifically named in around 15% of the studies. Fig. 3 (labelled 1 to 2) shows the occurrence of subgroups within the above-mentioned frameworks (i.e. specific GBI components and specific ES). Some papers analyse aspects mentioned in the framework without explicitly referring to it. For instance, about 15% of the studies mention urban forests, and around 5% parks, lakes and rivers partly without labelling them as GBI.

All ES of the TEEB classification (TEEB, 2010) were analysed with help of remote sensing data (Fig. 3). The largest category is ‘habitat or supporting services’ with 35%, followed by ‘provisioning’, ‘regulating’ and ‘cultural services’ with 15% each. The most frequently studied individual service is ‘local air and climate regulation’ (14%). Slightly below follow ‘habitats for species’, ‘recreational aspects’ and ‘carbon storage’ with 10% each. Only a few papers value ecosystem services monetarily and even fewer take ecosystem disservices into account. Forests and large parks are the most frequently analysed type of green infrastructure and lakes and rivers the most frequently assessed blue infrastructure. Concepts especially suited and open for the derivation of ecologically meaningful information from remote sensing methods like the essential biodiversity variables (EBV, Pereira et al., 2013) in turn are only used a few times (3% of the studies).

The spatial conceptualisation is diversely framed across the papers. In 70% of the studies we could detect some form of spatial conceptualisation. ‘Ecosystem’ is the most frequently used concept inheriting a spatial component (14%). This is closely followed by various more planning and design oriented concepts used in around 10% of the papers each (urban form, urban matrix, urban functional zones).

Climate change is mentioned in 35% of the studies. Overlaying the city locations with current and future extent of bioclimatic zones data (Köppen-Geiger classification scenario by Beck et al. (2018) based on the RCP8.5 scenario), reveals that in 38% of the total studied cities a change in climatic conditions can be expected.

3.2. Levels of integration

3.2.1. Manual assessment

Classifying interdisciplinarity in the literature corpus reveals that only 12% of the papers cover all three disciplines, namely ecology, planning and remote sensing (Fig. 4). We found the largest connection to exist between ecology and remote sensing with a third of all papers integrating between these disciplines.

3.2.2. Text mining of the different integration clusters

We calculated the tf–idf measure for the four clusters integrating at least two disciplines shown in Fig. 4. The bigrams with the highest tf-idf values found in the respective abstracts are shown in Fig. 5. The centre cluster integrating all three disciplines is characterised by a diverse set of terms ranging from planning-related topics (e.g. tourism planning, Fung & Wong, 2007), to ecological parameters (e.g. green volume, Huang et al., 2013), to modelling (e.g. SLEUTH land use change model, Jantz et al., 2004), demonstrating that each of the three disciplines has potential for interdisciplinary connections. The ecology and planning cluster addresses topics such as light pollution (Kuechly et al., 2012), connectivity and neighbourhood characteristics (Lee et al., 2008). The planning and remote sensing cluster is dealing with the impacts of different urban structures (on e.g. ventilation potential, Fang et al., 2015; or property regimes D. Haase et al., 2019) and the integration of other technological data sources like mobile phones (Tu et al., 2018).

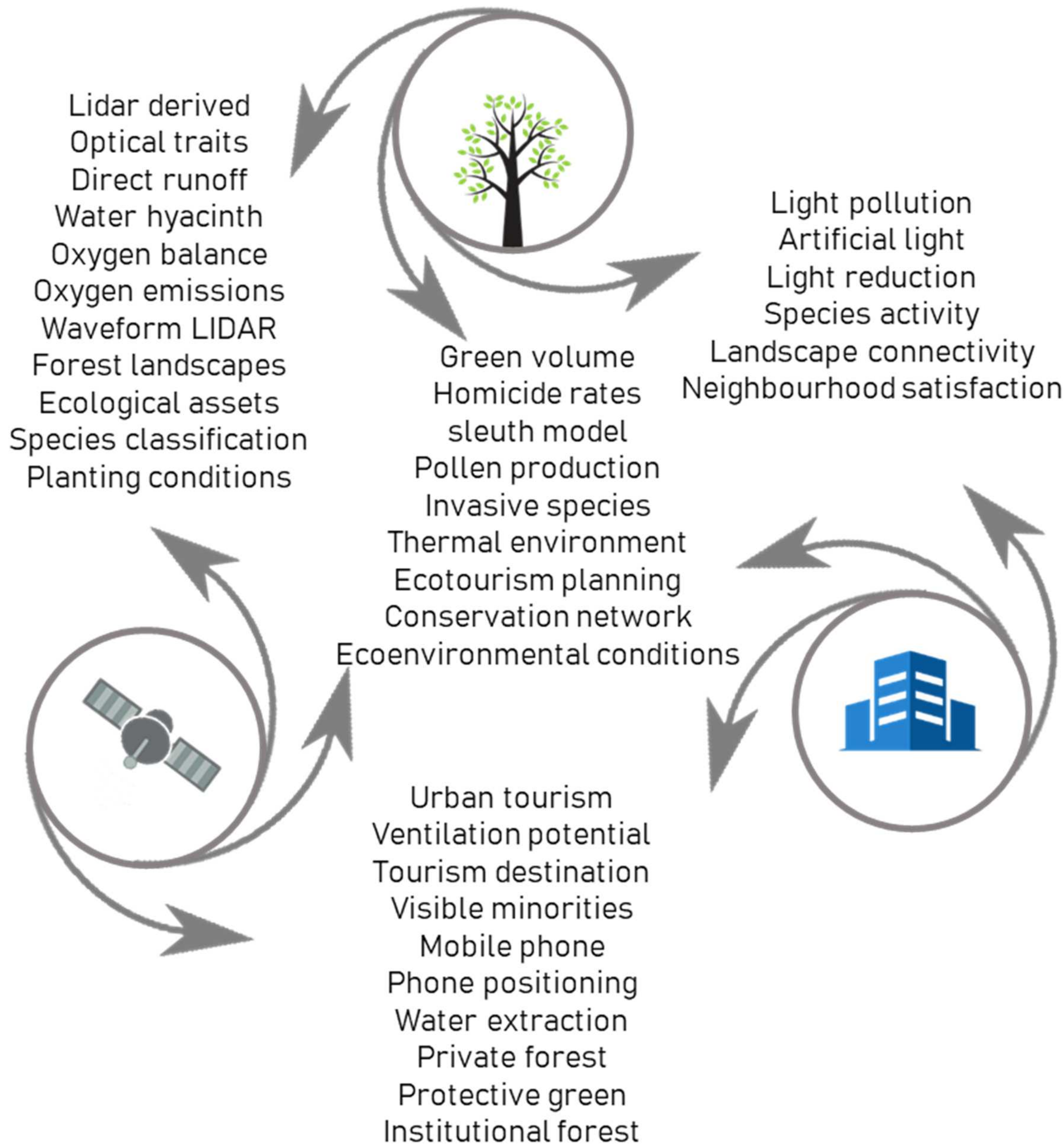

Fig. 5. Top-rated bigrams (= combination of two neighbouring words, for example 'ecosystem service') in the abstracts of the documents for each of the integration clusters in Fig. 4, using the term frequency–inverse document frequency (tf–idf) as indicator – a widely used statistical measure to portray the importance of a word in a document corpus. The differences in wording suggest a different thematic scope of the clusters.

The remote sensing and ecology cluster especially deals with ecological concepts like optical traits (Yu et al., 2018) and specific remote sensing recording techniques like LIDAR (Sasaki et al., 2016), ideally connecting the two fields by deriving very specific plant characteristics. In general, we can observe almost no overlap between the topics in the different clusters (only tourism is featured by more than one cluster).

3.3. Phases of the policy cycle

The selected studies cover all the six potential knowledge uses that we identified for remote sensing data along the policy cycle, but to a very different extent (Fig. 6). The vast majority of papers contributed primarily to the formation of the knowledge base inspired by research objectives, but with no direct application in policy design and assessment. The use that was the least tackled by the literature was 'participation', e.g. Locke et al. (2014) analysed the impact of ecosystem steward groups on the environmental condition in a city. The use of knowledge to support 'planning policies' was the third most studied group, e.g. the impact of urban densification on different income groups, deriving generalizable suggestions for green space planning (Lin et al., 2015). 'Planning actions' were mentioned in 8% of the papers, for instance in Teng et al. (2011), where the design of a green space network in a city for species conservation was developed. 'Management' was rarely mentioned, and was addressed in Katz and Batterman (2019), developing a management concept for urban greenspaces reducing plants with harmful pollen. 'Monitoring' was the second most analysed knowledge use, well represented by Landry and Pu (2010), assessing the impact of land development regulation on tree cover. Moreover, a host of studies used remote sensing for the monitoring of urbanisation, i.e. the physical growth of build-up land and the effects of these developments (see for example Li et al., 2018) measuring the changes in runoff related to urban growth).

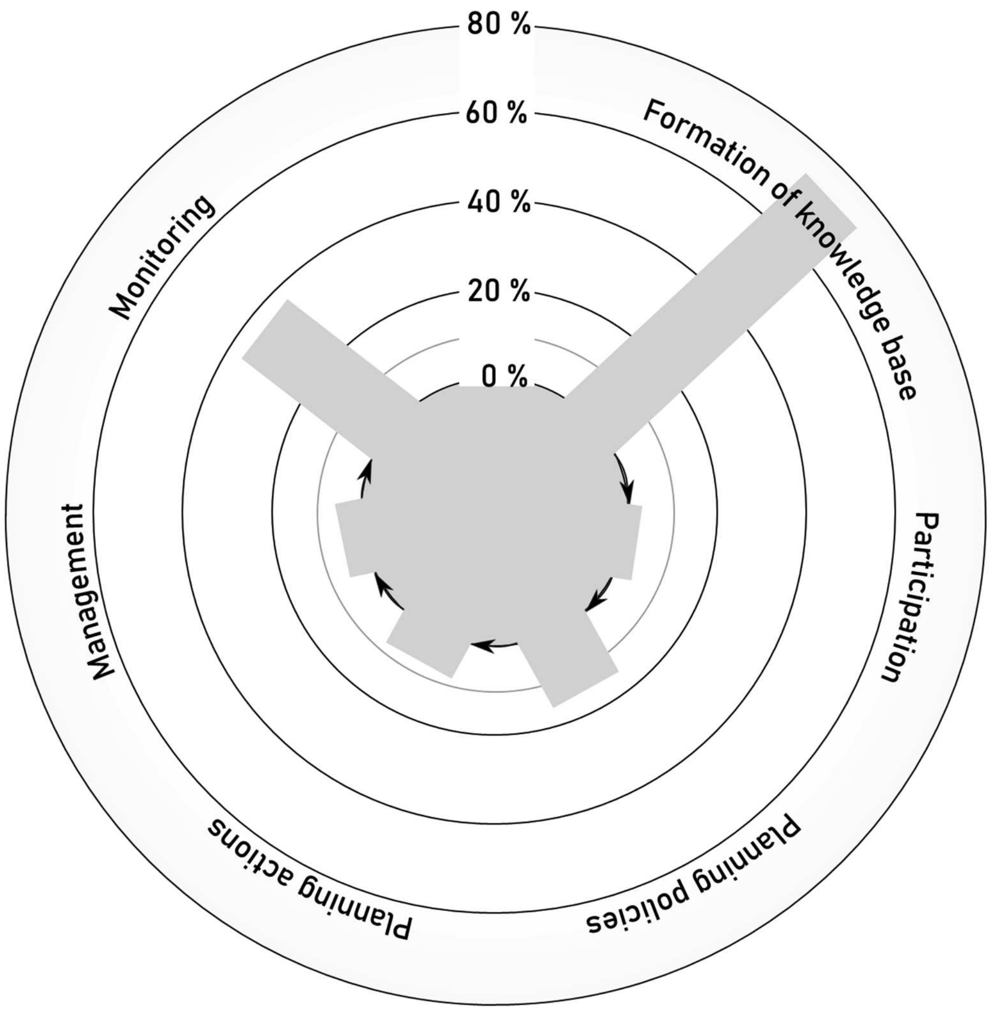

Fig. 6. Uses of knowledge with contributions from urban remote sensing to inform the policy cycle identified in the literature corpus.

3.4. Open science aspects

We evaluated four elements of accessibility and open science based on whether data, software and publication were based on open sources. Most of the reviewed studies used openly available non remote sensing data. These were followed by studies where none of the elements was openly available. The third most common type of studies was the one where only remote sensing data was openly available. None of the 186 reviewed articles was openly accessible in all of the four investigated elements of open science (Fig. 7).

Only 14% of articles were published open access (Fig. 7) and commercial software remains the most widely used software type. Especially widespread is the GIS (Geographic Information System) suite *ArcGIS* and the image processing software *ENVI*. Open software is dominated by *R* and *QGIS*. Own software was published once across the studies. Another reason why this is the lowest degree of accessibility is the fact that many method sections do not name the software they used.

Publicly available remote sensing data is frequently used, especially *Landsat* and *MODIS* data and their derived products distributed by the *USGS (United States Geological Survey)*. Additional data is mostly taken from official state sources, hence it is not necessarily available to the public or other scientists but to the authorities themselves. Own data was very rarely published (twice overall).

4. Discussion

4.1. Remote sensing in urban planning

The discipline of remote sensing, once developed as a political spy tool, has gradually evolved into a key source of environmental data for local to global analysis over the last 50 years, today representing one of the largest publicly accessible databases about our home planet and its cities (Wulder et al., 2019). Gradual technological progress regarding satellites, sensors, and computing structures on the ground, lead to quantitative as well as qualitative data increases (Zhu et al., 2019). This review set out to investigate how far this technological progress has permeated the scientific literature about urban planning and urban ecology, to derive suggestings for improving these connections.

Monitoring urban growth and its environmental impacts is a widespread objective in the reviewed literature corpus, showing the real potential of remote sensing in monitoring and steering one of the largest socio-economic and environmental changes in human history (Elmqvist et al., 2019). Due to regular image acquisitions, remote sensing is especially valuable to track temporal changes, thus potentially creating a neutral information source for assessing and balancing policies. Yu et al. (2012, p. 32) report about a successful case study, in which their: “planning has been adopted by the local government as [the] basis for making the future Urban Master Plan [and] a legally binding system of regulations […] was established”. Many of the analysed cities are located in developing countries where urban growth was

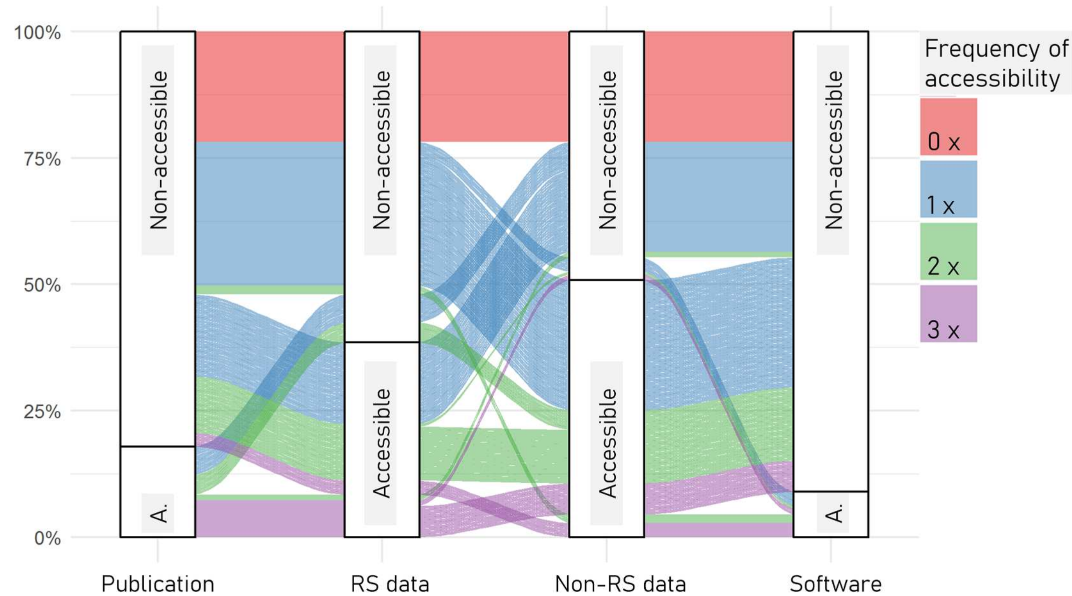

Fig. 7. Fluvial bar chart portraying the open accessibility of the four investigated elements of the studies, namely publications, remote sensing data (RS), non remote sensing data (Non-RS data), as well as the software used. Colouring of the flows represents how many of the four elements are accessible per paper. The majority offers accessibility in one domain, but none in all four.

fastest in the last decade. What is thereby missing almost entirely are stable and shrinking cities, also in need of careful and timely monitoring (Wolff & Wiechmann, 2018), and cities of the developing world where the highest urban growth rates are yet to come (UN, 2019b).

While we partly see highly interdisciplinary science, integrating views from different disciplines, finding answers and presenting analysis protocols of potentially high impact, we also very often see the opposite, with many studies designed and exploited one-dimensionally without reaching into the territories of neighbouring disciplines. As of now, urban remote sensing is still not meeting its full potential in terms of shaping urban land use policy, public information, and planning agendas. Theoretical and applied concepts like ES, landscape metrics, and GBI can play a key role in deriving meaningful information for planners and society from remote sensing data, thus contributing to steering a more environmentally sound urban development. A general issue is that few studies put their results into perspective, e.g. in a dense quarter of a medium sized city, what does a connectivity index of 0.14 mean? Presenting numbers without (suggestions of) interpretation can make them meaningless for the potential users in the planning community. Credibility and scientific soundness do not automatically make knowledge usable (Cash et al., 2003; Clark et al., 2016). As long as planning-relevant questions like ‘what is the problem?’, ‘what should be done where?’ or ‘what benefits will measure ‘xy’ have?’ are unresolved, adoption of the named measures will remain scarce. This is reflected in the fact that very few studies actually describe specific actions for management and interventions (two positive examples for this would be Yu et al., 2012; Katz & Batterman, 2019). This step of translating the findings into actionable knowledge would be very much needed for applied research aiming at directly affecting the new urban agenda that is anchored in the Sustainable Development Goals (SDG).

On the methodological side few investigations towards ecologically founded continuous indicators (see e.g. Wellmann et al., 2018) or the fruitful combination between continuous- and discrete indicators (see e.g. Haase et al., 2019; Kremer et al., 2018) can be found. Besides the widely used NDVI, individual patches or discrete classifications dominate, which on the one hand might be a good vehicle to communicate findings, but on the other hand can be simplistic as internal heterogeneity and boundary zones are omitted (Cortinovis & Geneletti, 2019; Lausch et al., 2015). The NDVI or visual interpretation are methods that do not grasp the full continuous information potential contained in remote sensing data, as for instance the NDVI only uses two of the potentially multiple bands. Furthermore, some method sections are incomplete in respect of not naming the software or data used undermining reproducibility and credibility. Generally, we see a lack of integrated method development aiming at diverse knowledge of planners, ecologists, and remote sensing experts.

The analysis of the urban heat island was one of the major topics of urban remote sensing science, mainly driven by Landsat data (see e.g. Andersson et al., 2020). Landsat’s 9 thermal resolution however will be coarser than its predecessor Landsat 7 which seems unfortunate for urban analysis while heatwaves are increasingly becoming of pronounced importance on a global scale (Scheuer et al., 2017). One potential revolution in urban remote sensing science could be the use of drones and local wireless sensor networks, as these systems gather very high resolution data at much less costs compared to an airplane campaign. The big potential (see e.g. Cabral et al., 2017) as of now is not being exploited as issues of conservation science (disturbance of intolerant species, Davy et al., 2017) or the law prohibit their usage, e.g. in many countries flying a drone above people or private property is forbidden. Therefore, as of today, the most promising step for overcoming the trade-off between high spatial resolution and high temporal resolution for adequately capturing the high spatio-temporal variability in cities, is the fusion of different sensors.

In the entangled Social-Ecological-Technological Systems of cities, enhancing the overall environmental performance (e.g. by maximising the provision of ecosystem services) is not enough, if it does not take into account the diverse perceptions and needs of people living in different realities. “Using the indicator to understand stakeholders’ perceptions of ecosystem services can assist [the planners] to plan multifunctional green spaces within local urban green infrastructure” (Lafortezza & Giannico, 2019, p. 96). Issues of justice also arise, e.g. because of densification. Lin et al. describe how densification “disproportionately affects communities with high socio-economic disadvantage” (Lin et al., 2015, p. 957), thus bringing the authors to the conclusion that “policies that aim to maintain public green spaces in lower socioeconomic communities and are designed to provide a wide array of ecosystem services may be necessary with urban densification” (p. 957). All these studies provide good examples of studies proving explicit knowledge on which authorities (and possibly the wider public) can act. If in independent hands combined with a good web-GIS visualisation, doubts can decline and a 'second' civic power emerges being able to work with remote sensing data too and monitor and check what (urban) governments are doing (Ellul et al., 2008). Remote sensing could thus contribute to the path towards transparent governance and power sharing.

We limited our search to English language peer reviewed journal articles, combining overarching terms from various scientific fields. This leads to two main limitations. First, planning documents, policy guidance and any other form of non-scientific literature is not included, meaning that the actual diffusion of remote sensing science and data into practice is not subject of this publication. Second, the selection of keywords leads to the situation where some scientific disciplines will be better represented than others, namely those that do not use conceptual terms like ecology or ecosystem services. Leaving out parts of our search string, we found out that this for instance true for the field of climatology (using the term 'heat island' as an example). Here, the difference between the number of papers published and those that are in our literature corpus was the largest. In addition, we searched for green infrastructure, meaning that while we have a substantial amount of hydrological paper there are more publications to be found applying ecological principles not primarily focussed on the green part. These are limitations to our study and we encourage more research in his direction.

The above mentioned limitations, the speed of the appearance of new publications, and the accompanying diversity of topics and number of journals in this specific review make it quite clear that regularly updated synthesis works and common databases are critically needed (Dicks et al., 2017). The entire database is therefore accessible at http://remotesensingforcities.org/wp/review-web-app/ and will be updated and maintained in the future. We call for authors to send us missing publications, together with filling out the form available at the website provided above.

4.2. Overcoming barriers: Three practical steps for the sciences

4.2.1. Open up: information barriers!

In the course of the study, we found several information barriers that need to be lifted (Lehmann et al., 2017) to reach higher levels of accessibility for applied remote sensing science in urban systems. Barriers could be identified throughout the scientific process, beginning with a lack of open access publications and a lack of uncommercial or open source software or data products used. The fact that so many publications are non open access but commercial software is widely used suggests that research groups or projects are underfunded in terms of publication fees or that the current pricing schemes of a number of journals might be too high (Vogel, 2011) and could therefore slow scientific progress and diffusion of developed methodologies.

Even though we generally see a lack of open science, the Landsat archive – open since 2009 – and the more recent European Copernicus program are lighthouse projects with open data-policies, representing two of the largest fully open access databases describing urban settlements on planet Earth (Wulder & Coops, 2014). The sole perspective on remote sensing data, however is not enough for applied urban remote sensing aiming for diffusion in the decision making process (Miguel et al., 2014). Similar progress needs to be achieved in the domains of non remote sensing data, publications, and software (Gallagher et al., 2020). For instance, commercial software, nowadays, can be often sufficiently replaced by open source counterparts and more and more initiatives of local governments are coming up to distribute geographical data openly. Such developments seem favourable for the pervasion of remote sensing in applied urban planning.

4.2.2. Integrate: across disciplines and space!

The differing views and approaches of the disciplines involved need to be brought together more strongly. Of the studies we analysed, only 12% integrated the three disciplines by e.g. citing literature, using methods or discussing the findings in light of these disciplines. Potentially, methods, terminology, training, and research cultures (Tobi & Kampen, 2018), are not yet aligned. Remote sensing experts have a strong knowledge and awareness towards data and computational methods. Ecologists are process driven and systems thinkers. Planning scientists in turn have the crucial knowledge about the problems cities around the world are facing and how changes can be made. This is a great simplification but we nevertheless hope to illustrate the differing strengths of the involved disciplines. In our opinion, if we manage to combine these approaches, we are one step closer to answer some problems of the 21st century with adequate ecological urban design (see e.g. Parris et al., 2018).

While we find many studies covering long time frames (see e.g. Wellmann et al., 2020), there are few spatially large-scale studies covering multiple cities in various conditions. We generally believe this city specific focus is very valuable, as cities severely differ one from another even in the same country or ecoregion, but more synthesis work is needed to test for the transferability of methods and results. In light of urbanisation being a global phenomenon, evidence across continents is valuable for understanding the earth system as a whole to steer higher-level policy decisions.

Concepts and approaches like the EBV's (Haase et al., 2018), the biotope area factor (Lakes & Kim, 2012), or the Vegetation-Impervious-Soil model (VIS, Ridd, 1995), which provide linkages between remote sensing and ecology or planning, are only used a few times. The Sustainable Development Goals by the UN also highlight a lack in indicators and initiative concerning urban remote sensing. While SDG 11 is prominent for cities and many of the desired goals formulated offer big potential for remote sensing contributions in the actual indicators there are no such hints or suggestions (UNDESA, n.d.). But in the scientific community there is great interest in achieving this (see e.g. Masó et al., 2020).

4.2.3. Go with the flow: the policy cycle!

Our results show that multiple phases of the policy cycle are rarely tackled with remote sensing data as many of the studies remain on a conceptual level, rarely providing recommendations for actions. Generally, the importance to give policy and planning guidance is acknowledged in the community, but actually doing it still lags behind. Typical for this is one or two sentence(s) at the end 'this is important for future management', which is not sufficient and in time seems like an alibi (see e.g Zhu et al., 2019 also commenting on this). Here a better framing of the authors taking issues of urban planning as a starting point and thereof explaining the importance of their undertaking concerning policy could greatly help. For instance, for the least tackled step 'participation', a highly accessible Digital Earth platform portraying ecological processes and planning processes and suggestions, allowing commenting and participating would be very desirable for single cities (e.g. Geo-Wiki by Fritz et al., 2012; UN biodiversity lab at https://www.unbiodiversitylab.org) allowing the public to openly evaluate scenarios and alternatives.

4.3. From distant observer to plan changer: Entry points for remote sensing into urban governance

In the section above, we recommend three specific steps for urban remote sensing science to better reach policy makers, stakeholders and also the wider public, promoting transdisciplinary research practices (Norström et al., 2020). Key for actual transformation of the environment is the integration of conceptual and technological progress into policy, thinking, and design (Geneletti, 2011). As ways for achieving this where not outlined in the reviewed literature we set out here to outline key entry points to integrate remote sensing in urban governance giving structural advice on data handling, capacity building and inclusion into existing legal frameworks.

4.3.1. 1st entry point: Urban data cubes (UDC)

We suggest to expand the GIS repositories that most cities have and that are commonly used as a basis for urban planning to Data Cubes (DC) on the city level. DC's can be built in ready to use cloud platforms like Google Earth Engine (Gorelick et al., 2017) or through software products like FORCE (Frantz, 2019). Such an Urban Data Cubes (UDC) could provide a seamless integration of data acquisition, storage, calculation and distribution of remote sensing data for a city. This can encompass aerial photography, but also pre-classified/computed products from satellites (e.g. from Sentinel 2) describing the spatio-temporal reality of urban functional processes, as well as commercial products (e.g. high-resolution satellite imagery) as buying it once for a wide range of beneficiaries will be cheaper. This would contribute to open UDCs consisting of analysis ready data layers but also information layers regarding various ecological processes and features such as cooling potential, connectivity, land use intensity, biodiversity, green volume and many more (Lehmann et al., 2020).

Centralising parts of these efforts via (national) remote sensing hubs could also be favourable. Centralised agencies could provide hosting capacities or other technological guidance on e.g. using the computing capabilities of cloud services like the Google Earth Engine. As such solutions scale with the problems and tasks (Gorelick et al., 2017), they are highly suited for a start-up setting and first products to be fed into the UDCs. In our set of papers, these techniques have not been used to their potential.

4.3.2. 2nd entry point: Capacity building

An effective science-policy interface (Ruckelshaus et al., 2015) must be established to ensure that the full potential of remote sensing innovation permeates real-life planning processes. This can be established through demand-oriented research, which develops proposals and projects together with municipalities or stakeholders. Thereby people working on the data meet people working on environmental assessments and both sides know of the others problems and capabilities so that every process can be met with the adequate information. Collecting capabilities for the urban environment, one foot in a local planning authority, one foot in science, meaning two hands and one whole person integrating across barriers (Norström et al., 2020).

Another way of involving non-governmental organizations and citizens is the creation of user-friendly web apps. Besides possibilities for interesting citizen science projects, this will build much needed trust. Existing initiatives aiming at capacity building towards a further diffusion of remote sensing (e.g. The Group on Earth Observations or Humanitarian OpenStreetMap) are encouraging.

In the economically least developed regions, where both urban population growth and climate change impacts are projected to be the strongest (Scheuer et al., 2017) and our review shows the biggest lack in remote sensing studies, the named entry points need to be applied with the highest urgency. More cooperation and training is needed, as many types of data and software are free and would be greatly helpful for cities with rather low monetary budgets.

4.3.3. 3rd entry point: Integrating remote sensing into strategic environmental assessments

The internalisation of new procedures into pre-existing formalities and governance structure should be favoured in contrast to creating new protocols (Geneletti, 2011). Even though we could not find any linkage between Strategic Environmental Assessments (SEA) and Environmental Impact Assessments (EIA) procedure and remote sensing in the reviewed literature, we see great potential of formalising the inclusion of remote sensing data and knowledge into these processes. SEA and EIA are legally binding in many countries and regions and are specifically aimed at supporting environmentally-aware policies, plans and projects by assessing the expected impacts during the planning and design stages and following-up on implementation (Sizo et al., 2016). If appropriately conducted, SEA and EIA often represent the easiest entry points for ecological concerns to enter the policy cycle, hence affect planning decisions. Protocols on data collection and analysis exists in contexts where SEA and EIA processes are mandatory, which could be enriched by a (further) integration of remote sensing data and methods. The latter could also contribute to shifting the scope of assessments from strictly environmental concerns to overall sustainability (Pope et al., 2017). Measuring the sustainability of urban systems taking into account of human and biophysical interactions is still a challenge, but recent research attempts demonstrate that knowledge from remote sensing at multiple scales, combined with a wide range of other spatial data, can play a key role in this endeavour (Stokes & Seto, 2019).

5. Conclusions

Remote sensing data is unquestionably one of the largest sources for environmental information of our time and its usage needs to be extended into areas where the majority of people live, namely cities. The view from above offers repeatable, independent, and cost effective ways for the digital (and smart) era to obtain relevant knowledge for social processes, ecological states, and technological innovations. In the literature that we reviewed, we found many examples where science showed the power of positively interfering in these deeply entangled Social-Ecological-Technological Systems. However, we also found many cases in which this large potential is not being tapped.

We see future avenues in promoting open science aspects and a deeper integration between disciplines leading to clearer statements about the outcomes and potential use of the research. Remote sensing has much potential to be combined with other methods of monitoring and assessment, and such combined approaches would also help to make remote sensing analysis more accessible to urban planners and decision-makers but also to environmental researchers working with more qualitative and social science approaches.

Remote sensing has the capabilities of transforming and improving many parts of urban governance. The outlined design for remote sensing information hubs, a better mainstreaming into policy frameworks and procedures and into initiatives in the (economically) least developed world would ensure a better, more ecologically founded urban planning. The potential, the data, and knowledge is available, but it is (to the extent we reviewed here) unconnected to a considerable degree. To set a systematic starting point for better integration of remote sensing into ecologically sound urban planning we release a web-app (http://remotesensingforcities.org/wp/review-web-app/) where new works will be continuously integrated both through new publications as well as through user submissions.

CRediT authorship contribution statement

Thilo Wellmann: Conceptualization, Methodology, Investigation, Validation, Data curation, Formal analysis, Visualization, Software (App Development), Writing - original draft. **Angela Lausch:** Investigation, Supervision, Writing - review & editing. **Erik Andersson:** Investigation, Supervision, Writing - review & editing. **Sonja Knapp:** Investigation, Writing - review & editing. **Chiara Cortinovis:** Investigation, Writing - review & editing. **Jessica Jache:** Investigation. **Sebastian Scheuer:** Software (App Development). **Peleg Kremer:** Investigation, Writing - review & editing. **André Mascarenhas:** Investigation, Writing - review & editing. **Roland Kraemer:** Investigation, Writing - review & editing. **Annegret Haase:** Investigation, Writing - review & editing. **Franz Schug:** Investigation, Writing - review & editing. **Dagmar Haase:** Conceptualization, Investigation, Supervision, Writing - review & editing.

Acknowledgments

Thilo Wellmann receives a scholarship by the Deutsche Bundesstiftung Umwelt – DBU (German Federal Environmental

Foundation). We furthermore wish to thank the CLEARING HOUSE (Collaborative Learning in Research, Information sharing and Governance on How Urban forest-based solutions support Sino-European urban futures) Horizon 2020 project (No 1290/2013) and the GreenCityLabHue Project (FKZ01LE1910A). We acknowledge further contributions by the ENABLE (Enabling Green and Blue Infrastructure Potential in Complex Social-Ecological Regions) BiodivERsA project, the Horizon 2020 innovation action CONNECTING (No730222-2), the Horizon 2020 program ERA-PLANET/GEOEssential project (689443) and the FORMAS project 'Nature-based solutions for urban challenges' (n. 2016-00324). Icons provided by Freepik.com.

Data availability

All data and information generated in this study will be publicly accessible via a web-app. The domain will be added after peer review.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2020.103921.

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