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The potential of volunteered geographic information to investigate peri-urbanization in the conservation zone of Mexico City

Katharina Heider · Juan Miguel Rodriguez Lopez · Jürgen Scheffran

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Abstract Due to the availability of Web 2.0 technologies, volunteered geographic information (VGI) is on the rise. This new type of data is available on many topics and on different scales. Thus, it has become interesting for research. This article deals with the collective potential of VGI and remote sensing to detect peri-urbanization in the conservation zone of Mexico City. On the one hand, remote sensing identifies horizontal urban expansion, and on the other hand, VGI of ecological complaints provides data about informal settlements. This enables the combination of top-down approaches (remote sensing) and bottom-up approaches (ecological complaints). Within the analysis, we identify areas of high urbanization as well as complaint densities and bring them together in a multi-scale analysis using Geographic Information Systems (GIS). Furthermore, we investigate the influence of settlement patterns and main roads on the peri-urbanization process in Mexico City using OpenStreetMap. Peri-urbanization is detected especially in the transition zone between the urban and rural (conservation) area and near main roads as well as settlements.

Keywords GIS · Hot spots · Informal settlements · Remote sensing · OpenStreetMap (OSM) · Multi-scale analysis

K. Heider (✉) · J. M. R. Lopez · J. Scheffran
Research Group Climate Change and Security (CLISEC), Institute of Geography, University of Hamburg, Grindelberg 5, 20144 Hamburg, Germany
e-mail: katharina.heider@uni-hamburg.de

Introduction

More than half of the world's population lives in urban areas and most of the urbanization happens in peripheral areas causing new patterns of centrality (Davis 2004; Gilbert and Jong 2015). Urban growth rates are high all over the world and urbanization is one of the main drivers for land use changes. Especially in developing countries, the growth rates are at their highest level and the accumulation of new informal settlements is common (Lombard 2014). Nowadays, especially the periphery of cities is affected by population growth and urbanization, which progresses further into small towns and rural areas (Aguilar and Ward 2003; Davis 2004; Su et al. 2014). The accumulation of informal settlements is advancing and characterized by its occurrence in peripheral areas, so-called peri-urbanization, and in contrast to suburbs by the housing of poorer inhabitants in precarious living conditions. Among others, rural-urban migration is an important driver of growth of cities, leading to a decreasing rural population and rural abandonment (Aguilar and Ward 2003; Augustijn-Beckers et al. 2011; Davis 2004; Grau and Aide 2008; Gray 2009; Naldi et al. 2015; Rodriguez Lopez et al. 2015), but likewise, urban-urban migration plays an important role (Davis 2004; Rodriguez Lopez et al. 2015). One example for high urbanization rates can be found in Mexico City. Although the city is one of the biggest in the world and has more than 8 million inhabitants in the urban area and more than 20 million inhabitants in the metropolitan region, including the neighboring state Mexico, urbanization rates are still high (Gilbert et al. 2016). The

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advance of the city into natural habitats causing land use changes and threatening biodiversity is a major challenge of this century. Since most of the population growth is predicted for urban areas and especially slums (Davis 2004), peri-urbanization needs further investigation and means of monitoring as well as an investigation of drivers.

In this study, we investigate the accumulation of informal settlements in the conservation zone of Mexico City. Besides locating informal settlements within the conservation zone, we focus on the influence of main roads and settlement patterns on the peri-urbanization process. Generating a more complete picture of urbanization and its possible drivers in the south of Mexico City is crucial for future urban planning. We combine remote sensing data with volunteered geographic information (VGI). For the integration of main roads and settlement patterns, we use the road network of OpenStreetMap (OSM), which was developed due to the contributions of many volunteers, representing a VGI project.

Thus, the main question of this study is the following: *Why does peri-urbanization occur in the conservation area of Mexico City?* More precisely, we investigate where informal settlements occur, how infrastructural patterns (main and residential roads) influence their accumulation, and whether the integration of VGI can enhance the accuracy of detecting informal settlements in Mexico City. VGI is combined with remote sensing techniques to increase accuracy and to integrate local perspectives and knowledge (Elwood et al. 2012). In this way, the bottom-up approach can be included into the remote sensing analysis.

The rural area in the south of Mexico City is rich in vegetation with diverse vegetation cover types like woodland, cropland, grassland, and forest. Linked to that are ecological services for the city that are provided by peri-urban regions and especially intact ecosystems and conservation land. These services include climate regulation, control of soil erosion, water filtration, and recreational use (Caro-Borrero et al. 2015; Mollá Ruíz-Gómez 2005; Saavedra et al. 2011; Su et al. 2014). Saavedra et al. (2011) identified roads in the conservation zone of Mexico City as a threat for the environment by causing fragmentation of habitats. However, roads also enable access to the city, which is crucial for people moving into new areas (Aguilar 2008). Ecological consequences of peri-urbanization are severe and cannot be ignored because greater impacts on the environment are expected more from urban land use than from the land use that is replaced (Aguilar 2008; Su et al. 2014).

Literature on informal settlements and slums has been emerging over the last years, specializing on several topics and varying methodologies. The literature can be classified into studies about the history, the detection of informal settlements, simulations, management of informal settlements, tourism, as well as ecological consequences (Dovey and King 2012; Dürr 2012; Gilbert et al. 2016; Lombard 2014; van Gelder et al. 2016; Wigle 2014). Aguilar (2008) investigates ecological impacts of informal settlements for the environment of Mexico City and the extent of the settlements using remote sensing techniques. Remote sensing is also used by numerous authors to locate informal settlements using very high spatial resolution to enable a differentiation between formal and informal settlements (Graesser et al. 2012; Jean et al. 2016; Owen and Wong 2013; Rodriguez Lopez et al. 2017a; Taubenböck and Kraff 2014). Problems arise concerning a correct classification in cases where typical characteristics decrease or in informal zones of low densities (Graesser et al. 2012). To augment the analysis, some authors combine remote sensing techniques with statistical data (Kit et al. 2013; Kontgis et al. 2014; Rodriguez Lopez et al. 2017a). Due to the limitations of statistical data for the conservation zone of Mexico City (Connolly 2009), a combination with another data source is beneficial.

In the following, we combine remote sensing data with VGI, a recently emerging type of data, which is mostly available free of charge and provides the possibility to integrate a local perspective following the bottom-up principle (Elwood et al. 2012). Due to the spontaneous contribution of individual users, VGI differentiates from traditional top-down techniques like remote sensing analyses. Because of the characteristics of VGI and its human contributors or sensors, it is from here on also called human sensing (Goodchild 2007). In our case, the VGI data consist of complaints about informal settlements in the conservation zone of Mexico City submitted by inhabitants. In a previous study, the authors found a negative relationship between the number of ecological complaints in a district and the unemployment rate (Rodriguez Lopez et al. 2017a). While two high spatial resolution RapidEye images provided by the RESA (RapidEye Science Archive) program enable the detection of urbanization between 2009 and 2014, VGI helps to integrate the local perspective of

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human sensors concerning violations against the conservation status and the accumulation of informal settlements, as well as potential conflicts. Combining both datasets enables an added benefit in detecting informal settlements, bypassing difficulties of differentiating between informal and formal settlements based on spatial characteristics detectable by remote sensing.

The paper is structured as follows: After the "Introduction" section, the study area will be presented in the second section including policies and ecological consequences concerning informal settlements in the conservation zone of Mexico City. In the third section, we introduce the data and methods used in this study to locate informal settlements and investigate accumulation patterns as well as the data's advantages and disadvantages followed by the description of the results. In the discussion, we interpret the results and identify limitations of the analysis. Finally, the conclusion sums up our findings, limitations, and suggestions for future policies and research.

Study area: the conservation zone in Mexico City

The conservation zone (CZ, *suelo de conservación* in Spanish) is located in the south of Mexico City (Fig. 1). The metropolitan region of the state of Mexico comprises 59 municipalities with 20 million inhabitants and including the surrounding states (Puebla, Hidalgo, Queretaro, and Morelos); the region has about 36 million inhabitants. High economic inequalities are characteristic of the fast urbanization in the past decades (Gilbert and Jong 2015; Gilbert et al. 2016). Population densities are higher in the north of Mexico City than in the south (INEGI 2012).

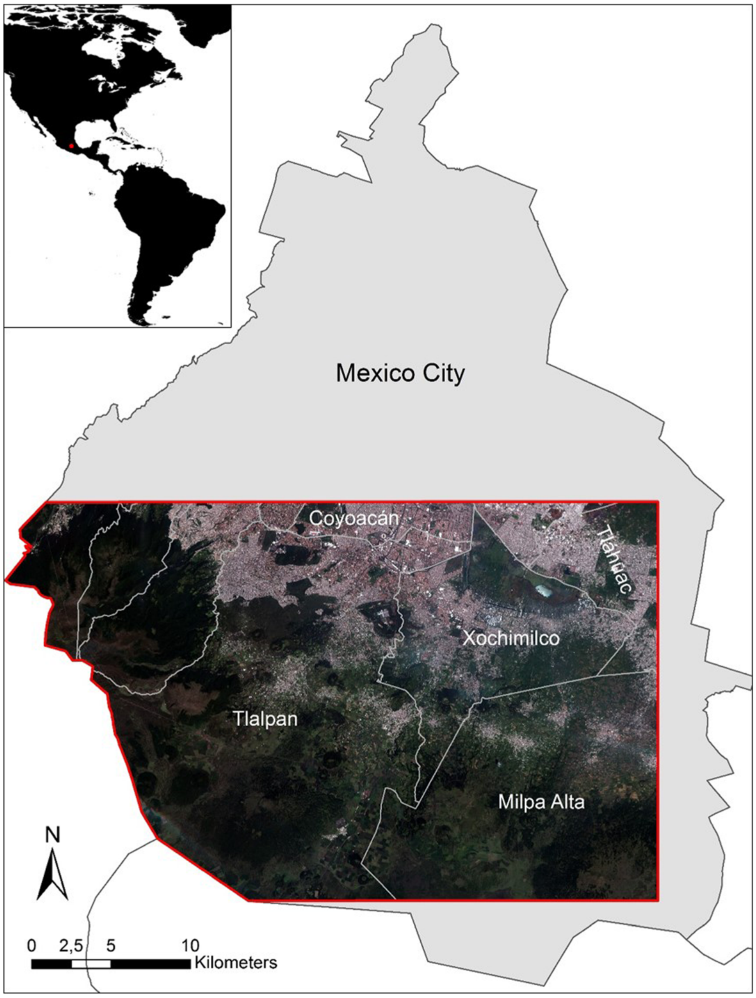

Fig. 1 Location map of the study area (red)

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Yet, there are lower growth rates in the historical city of Mexico City and higher growth rates in the periphery including the transition zone to the CZ (Aguilar 2008; Aguilar and Ward 2003; Connolly 2009).

The CZ was established in 1987 and a primary zoning was initialized. The starting point was the Urban Development Plan of the Federal District, which divided Mexico City into two parts: the urban part mainly to the north and the non-urban part mainly to the south. The non-urban zone was placed under the administration of the Secretariat for Environment of the Federal District with the aim to protect it against urban growth (Saavedra et al. 2011). The capital of Mexico was named Federal District of Mexico City until President Enrique Peña Nieto officially changed its name to Mexico City on January 29, 2016 (SEGOB 2016). Most of the CZ is located in seven subdistricts in the southern part of Mexico City, and two subzones were created: the transition zone between urban and rural area and the preservation zone with strict rules protecting the environment. Part of the strict rules is that new settlements are forbidden (Aguilar 2008). The preservation zone contains about 88,000 hectares of land, which is around 59% of Mexico City. The major part of the CZ is located in the delegations Milpa Alta (32.2%), Tlalpan (29.4%), and Xochimilco (11.9%) (Gobierno del 2012).

The CZ is the largest remaining green space in Mexico City and includes various property types as well as economic activities. Communal land represented about 62% of the total land in Mexico City, and ejidal land (community owned land designated for agricultural activities) accounted only for 14%. The rest of the land was private property (about 23%) or property of the government (Aguilar 2008; Bray 2013; Gobierno del 2012).

The conservation area is a hot spot of biodiversity. It contains less than 1% of the national territory but hosts 2% of the world's biodiversity and 11% of Mexico's flora and fauna (Gobierno del 2012; Saavedra et al. 2011). The environmental goods and services delivered by the CZ are a key factor for the well-being of Mexico City (Jujnovsky et al. 2012). These include the recharge of aquifers (about 60% of water used by the city), the forests' function as a carbon sink contributing to the mitigation of climate change, cultivation of agricultural products, and the recreational use of the conservation area for the city's population and tourists (Aguilar and Santos 2011; Gobierno del 2012). Additionally, the mountains of Chichinautzin and Las Cruces in the southwest of Mexico City provide high infiltration capacity of rainwater, the capture of pollutants and emissions, as well as the reduction of erosion because of soil protection by plant cover (Mollá Ruíz-Gómez 2005; Saavedra et al. 2011). Overall, a sustainable use of the CZ helps to provide a higher quality of life for the inhabitants of Mexico City (Aguilar and Santos 2011). Yet, the preservation is threatened by intense urbanization pressure (Aguilar 2008; Aguilar and Ward 2003; Aguilar and Santos 2011; Saavedra et al. 2011).

The evolution of peri-urbanization and consequences for the conservation zone

Due to the urbanization pressure and a lack of cheap housing, a high number of informal settlements have accumulated in the CZ (Aguilar 2008). There are different types of transition zones between rural and urban areas. They contain areas with uniform peri-urbanization as well as areas with small urban patches and open spaces between them. Furthermore, there are settlements following corridors, for example, roads or rivers (Aguilar 2008). In this article, we propose two different forms of measuring this influence: residential roads indicating the agglomeration of residents and main roads as proxy of the state decision.

Aguilar and Ward (2003) use the term peri-urbanization to describe the expansion of urban areas in many Latin American countries focusing on Mexico City and with special attention to informal settlements. The incorporation of rural areas and urban corridor developments is typical for forming urban subcenters (Aguilar and Ward 2003; Gilbert and Jong 2015). Mexico City is a well-known case of urban expansion and peri-urbanization.

The development of the settlements depends on the actors involved. A strict policy in the CZ is meant to protect the area against urbanization (Aguilar 2008). The present policy for the CZ consists of two main laws building the legal frame of human occupation in Mexico City: the General Program for Urban Development (Programa General de Desarrollo Urbano) and the Program for Ecological Planning (Programa General de Ordenamiento Ecológico del Distrito Federal) (Aguilar 2008; Mollá Ruíz-Gómez 2005; Wigle 2014). The Urban Development Plan regulates the urban land under the supervision of the Secretariat of Urban Development and Housing (SEDUVI), and the Program for Ecological Planning regulates the conservation land under the supervision of the Secretariat of the

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Environment (Wigle 2014). Both were passed in the year 2003. Nevertheless, the laws admit an ambiguous interpretation of the conservation area, encouraging the accumulation of informal human settlements. Thus, different procedures result from both laws (Aguilar 2008). Generally, residential use is prohibited in the CZ but it is legal in long existing rural towns, which results in overlaps of both regulations (Aguilar 2008; Aguilar and Santos 2011; Wigle 2014).

The delegations located in the conservation zone experience a higher growth rate than the city as a whole. In particular, the Áreas Geoestadísticas Básicas (AGEB), the smallest administrational entities, located in the CZ, showed high population growth rates of 3.6% between 1990 and 2000 (Aguilar 2008). Peri-urbanization takes place in an informal residential area (including so-called informal or irregular settlements) often with high densities and expanding over large areas. The increasing number of informal human settlements (IHS) in the periphery of Mexico City can be explained by a lack of affordable housing for the poor population in central areas. Yet, cheap land in the CZ is available. The land is often divided into parcels, which are illegally sold or rented. These areas are sometimes located at a large distance from urban cores, and they often lack even basic services (Gilbert and Jong 2015). These kinds of settlements have been accumulating since the twentieth century. Since then, there has been no successful policy addressing the needs of the poor, and thus the process has been steadily ongoing (Aguilar and Ward 2003; Wigle 2014). Connolly (2009) found that the formation of informal settlements, as well as formal urban housing, is not a smooth process; it can rather be characterized as cycles of expansion followed by cycles of densification of the settlements. Here, the network of residential roads is used to estimate the densification of settlements. Thus, one hypothesis of the study is the following: *The closer we are to existing settlements (indicated by residential roads), the more peri-urbanization occurs.*

In the 1970s, informal settlements were mostly built on flat ejidal land. However, in the last decades, peri-urbanization has expanded to risk-prone areas in the CZ. These areas are often unsuitable for urban development, which results in the destruction of environmentally sensitive areas (Aguilar and Santos 2011). Steep slopes, on the edges of ravines as well as land, which might be affected by landslides and floods or is forested and of high ecological value are used in the construction of settlements. The houses are mostly self-built and consist of permanent and disposable materials (Aguilar 2008; Mollá Ruíz-Gómez 2005).

Despite the Program for Ecological Planning, land use changes are happening in many areas of the conservation zone (Aguilar 2008; Aguilar and Guerrero 2013; Aguilar and Santos 2011; Aguilar and Ward 2003). People need cheap housing with access to the city and they gain additional income through deforestation and agriculture that leads to even more land use changes. Deforestation causes a decline in water and oxygen production. In addition, the role of the forest as a carbon sink loses importance due to a decline in sequestering capacity. Other reasons for land use changes in the conservation area are forest fires, poor agricultural practices, hunting, and soil erosion. These processes threaten the environment and the quality of life for everybody living in the capital (Hagene 2010; Saavedra et al. 2011).

Saavedra et al. (2011) studied threats for the CZ of Mexico City. Among others, they identified roads and the resulting fragmentation of habitats as a threat for the ecological values in the CZ. Depending on the type of road, they measured an individual area of influence. Additionally, Aguilar (2008) identifies the orientation of the road network as an important factor influencing urban expansion. The roads enable access from the CZ to the city and to jobs. Access to the city is a major motivation for the informal settlers to move to the CZ. Thus, another hypothesis is the following: *The closer we look to the main roads, the more peri-urbanization we find.*

Data and methods

To generate up-to-date information about the land cover, remote sensing is one of the most effective techniques available. Especially since the opening of the Landsat archive, costs for satellite imagery have been decreasing, enabling remote sensing analyses over long time periods (Woodcock et al. 2008; Wulder et al. 2012). However, a higher spatial resolution than that available with Landsat imagery is beneficial for a successful classification of land cover in cities but leads to higher costs for the images (Rodriguez Lopez et al. 2015). For a correct classification, it is important to consider phenological disparities or crop maturation within a year (Prenzel 2004). Change detections are often applied to detect

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urbanization using satellite or aerial imagery of different years (Prenzel 2004; Taubenböck et al. 2012). The detection of informal settlements is more complicated and can be a challenge due to difficulties differentiating between nature, agriculture, bare ground, and formal settlements. However, research shows that remote sensing is capable of detecting informal settlements (Graesser et al. 2012; Jean et al. 2016; Kit et al. 2013; Kontgis et al. 2014; Owen and Wong 2013; Taubenböck and Kraff 2014). Graesser et al. (2012) identified informal settlements in four cities because of their unique spatial characteristics like the heterogeneity of building materials and orientation of buildings, small building sizes, small streets, and proximity to hazardous areas. They used very high-resolution Quickbird imagery for a supervised classification and implemented decision parameters. Although the accuracy was up to 92%, they cited difficulties concerning the identification of formal areas with high densities as well as settlement commission errors of rugged terrain.

Image feature extraction is the key to settlement classification (Graesser et al. 2012). Thus, many studies follow a similar approach using remote sensing imagery and identifying characteristics to distinguish between informal and formal settlements, developing a combination of factors that make a differentiation possible (Owen and Wong 2013; Taubenböck and Kraff 2014). Due to the small size of buildings and streets with diameters below 1 m, a combination of different satellite imageries can be crucial to develop good results. Taubenböck and Kraff (2014) combined Landsat and Quickbird imagery with radar data. Another approach is to combine publicly available satellite imagery with machine learning by implementing convolutional neural networks (Jean et al. 2016) or to combine remote sensing data with statistical data (Kit et al. 2013; Kontgis et al. 2014). To not only detect informal settlements but also predict their expansion, slum models can be of interest (Augustijn-Beckers et al. 2011; Roy et al. 2014).

Overall, literature has shown that the research on informal settlements is of high topicality, especially considering population growth and migration into the cities. Although detection of informal settlements using remote sensing is possible, it is obvious that a high resolution of the images is often crucial or the combination of other data sources is necessary (Kontgis et al. 2014; Taubenböck and Kraff 2014). The computational effort is high when several to dozens of high-resolution images are processed and analyzed; moreover, the acquisition of high-resolution imagery is also a monetary investment, which restricts access and public use (Rothe 2017). In consequence, further research is needed and as some studies already have, a combination of remote sensing with another data source is beneficial when addressing the topic of informal settlements.

We use a combinational approach in this paper to develop new possibilities of detection and analysis of informal settlements. In this approach, we combine remote sensing data with two types of VGI. While a change detection of satellite imagery reveals urbanization patterns, VGI in the form of complaints about informal settlements enables the integration of local perspectives and helps to distinguish between urbanization and the accumulation of informal settlements. Furthermore, we include OSM data to analyze patterns of peri-urbanization. Before we explain the methods in more detail, VGI has to be discussed.

VGI describes georeferenced information and is generated through the voluntary contribution of individuals or groups. It is a subcategory of the more general user generated content (UGC) and thus a version of crowd sourcing in which members of the public produce information about the surface or near surface of the Earth. The information is then brought together in a database. The volunteering nature of this data type forms a contrast to traditional map production by authorities (Elwood et al. 2012; Goodchild 2007; Goodchild and Li 2012). Not long ago, official agencies were responsible for the creation of maps and the updating of geographic information. However, the progression of Web 2.0 technologies in the form of handheld GPS, in smartphones and cameras as well as in other portable devices, and an almost continuous Internet access combined with freely available GIS form the basis for crowd-sourced mapping. Examples are OSM, Google Maps, and Twitter (Kunze and Hecht 2015). VGI is distinct from traditional geographic information in several aspects. The content of information, technologies for acquisition, quality issues, as well as methods of usage are all different. As UGC does not rely on traditionally authoritative sources of information, VGI has no guarantee for a certain quality, which is the most severe disadvantage of usage (Elwood et al. 2012). It represents more a "wikification of GIS" (Boulos et al. 2011) due to its diversity on topics and scales as well as quality. Nevertheless, it provides broad opportunities for integration into research, augmentation of existing data, and a diversification of perspectives (Elwood et al.

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2012; Goodchild and Li 2012). For example, VGI promotes hybrid geographies by building a bridge between human and physical geography, spatial analysis, and social-critical approaches (Elwood et al. 2012). Despite the obvious quality issues of VGI, this technology has the potential for creating new insights in numerous topics throughout geography (Elwood et al. 2012).

An obvious advantage of VGI is its price. Because it works through voluntary participation, it is far cheaper than alternative data. The presence of free and open source software (FOSS) makes this possible (Elwood et al. 2012; Goodchild 2007; Goodchild and Li 2012). Furthermore, the shared information is up-to-date. It is often newer and more accurate than data from official sources because for the acquisition of official data, usually older technologies are used. There are high costs associated with updating official data or peer-reviewed information in specific topics (Giles 2005). Thus, in many cases, VGI has a better quality than official data. Considering new movements of fast news transfer around the world via microblogging, for example, VGI provides possibilities for frequent updates (Arsanjani et al. 2013; Boulos et al. 2011; Goodchild 2007; Goodchild and Li 2012). Especially, in situations when information updates within minutes are critical, VGI's advantages become clear. An example is the fire outbreaks in Santa Barbara: Citizens reported and updated within minutes, locations of fire, areas under evacuation, etc. before official information could be produced (Elwood et al. 2012). In this context, the value of VGI for perspectives on the local level emerges. Elwood et al. (2012) reviewed VGI projects and identified 76% to have a local extent. This perspective is most interesting for geographers as many events could be unnoticed by the media but appear as local activities in VGI (Goodchild 2007).

VGI is the product of human sensors. Humans are equipped with their five senses and are able to interpret local information. Furthermore, perceptions and concepts that are difficult to capture can be addressed in research using VGI. Web 2.0 technologies enable the generation and use of this information, based on the human sensor network (Elwood et al. 2012; Goodchild 2007).

In contrast to VGI, remote sensing techniques are prevalent for mapping purposes. Remote sensing is widely used by the authorities and researchers to produce maps and update information about the Earth's surface. Due to high temporal and spatial resolution of satellite imagery, it proves to be an effective tool for land use and land cover mapping. However, satellites are unable to detect many aspects that are traditional parts of maps, like place names and administrative boundaries as well as other points of interest (Elwood et al. 2012; Goodchild 2007). Yet, VGI is mostly freely available and can be used to complement traditional data sources. In consequence, a combination of remote sensing and VGI can help to compensate the shortcomings of each other. While remote sensing provides data from satellites or planes far above, VGI provides data from individual contributors on a local scale with local insights.

For the analysis, we use three databases: urbanization detected by RapidEye satellites, an ecological complaint database, and roads from OSM (see Fig. 2). The roads and complaints are VGI. For the detection of urbanization, we use two tiles of RapidEye 3A level products for two dates (Rodriguez Lopez et al. 2015). One scene is from November 2009 and one from August 2014. Rodriguez Lopez et al. (2015) conducted a change detection differentiating between natural and urban land cover. Now, we integrate the detected urbanization in the following analysis. The classes *non-urban 2009* and *urban 2014* (red) of RapidEye data which represents urbanization are shown in Fig. 2.

The complaint dataset was downloaded from the Procuraduría Ambiental y del Ordenamiento Territorial del D.F. (PAOT), a governmental entity that is responsible for reviewing and monitoring environmental and land use offenses. The complaints integrated in the analysis were submitted between 2002 and 2016. In contrast to the remote sensing images that were taken in 2009 and 2014, the complaint dataset extends over a longer period. This can be justified by the assumption that the complaint database represents another kind of data that is more heterogeneous. People need time to get used to the possibility of reporting. There might be people who submit a complaint immediately; others observe the event that they will complain about for a long time before submitting a complaint. Then, there are people who never complain. The database consists of about 24,000 complaints on various topics. The focus in this study lies on the category *suelo de conservacion* which stands for violations against the conservational requirements in the preservation zone. It consists of 1046 complaints in the study area which are specified here as environmental complaints and are submitted mostly because of irregular settlements. People can submit a complaint via Internet, telephone, or in person;

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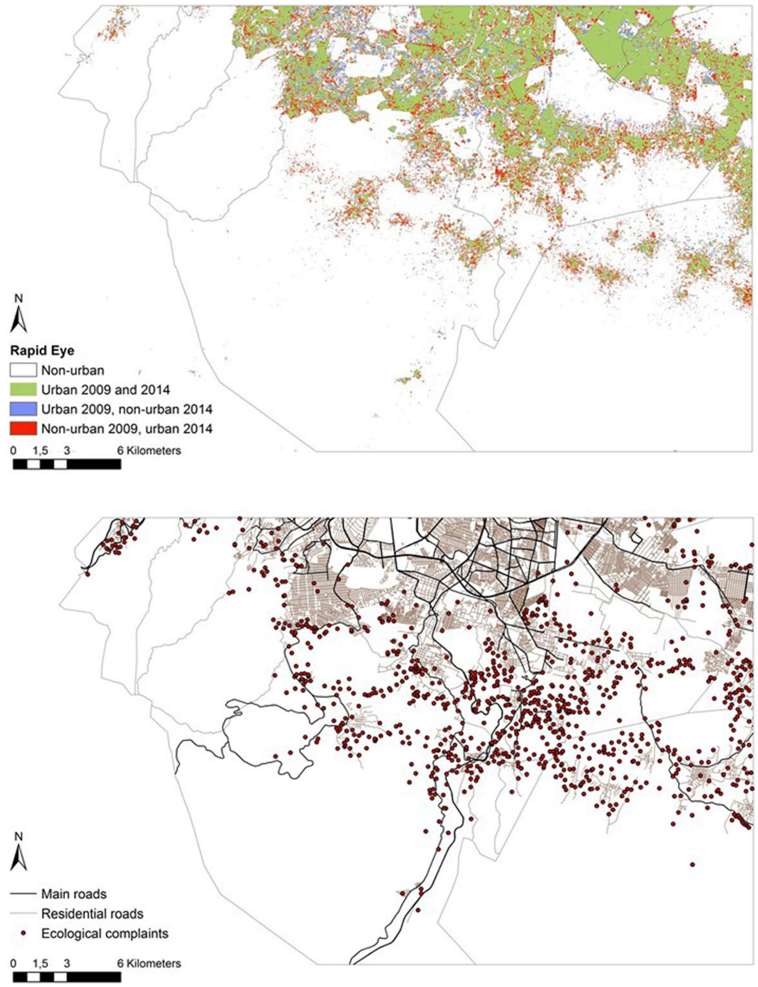

Fig. 2 Databases used for the GIS analysis. Above: urbanization detected by RapidEye imagery between 2009 and 2014 from the RESA program. Below: ecological complaints (PAOT), main and residential roads (OSM)

the complaint is then georeferenced with the location of the reported event. The complaint dataset helps to integrate local perspectives on peri-urbanization into the analysis. Someone who files a complaint feels disturbed by something. It represents the perception of a problem. Thus, the complaints can be seen as indicators of potential conflicts in neighborhoods.

While satellite imagery detects land use changes from non-urban to urban, the complaints help to identify the location where a land use change represents the construction of informal housing and a violation of environmental conservation as well as potential conflicts between natives and new settlers (Hagene 2010; Mollá Ruíz-Gómez 2005). Main and residential roads of the year 2015 were downloaded from the OSM provider Geofabrik (Geofabrik 2016). Residential roads are integrated to identify the phase of settlement formation with a focus on densification or expansion outside of consolidated settlements (Connolly 2009). Thus, the first hypothesis is the following: *New settlements accumulate near consolidated living areas and in consequence, ecological complaints and urbanization are located near residential roads*. Main roads are included to determine the importance of infrastructure and access to the city as a driver for peri-urbanization, as considered in the second hypothesis: *complaints and urbanization are more frequent near main roads*.

The analysis is conducted with ArcGIS 10.3. All data is projected in UTM Zone 14N. For further analyses, similar data types are beneficial. Here, vector data are the preferred type. The urbanization detected by remote sensing is in raster format. Every urbanization pixel is converted to a point. A visual comparison is conducted between the selected streets from OSM and the streets that can be identified on RapidEye satellite imagery. All

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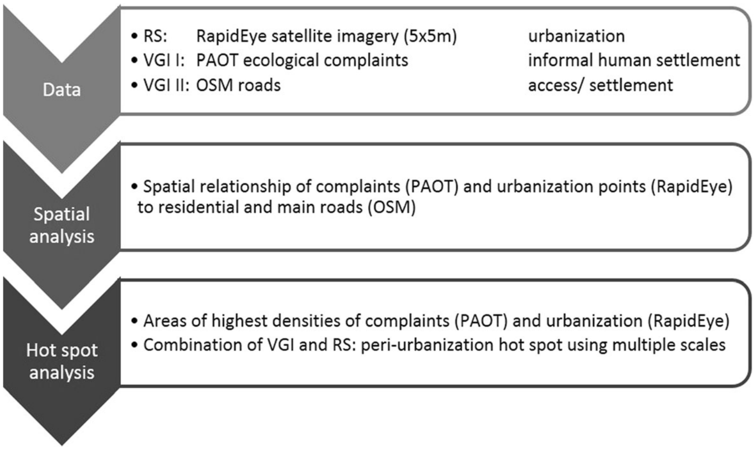

Fig. 3 Overview of GIS analysis: databases, spatial analysis, and hot spot analysis

data are clipped to the extent of the study area to minimize computing time.

Figure 3 gives an overview of data and methods. At first, we investigate the ecological complaints and the urbanization points separately. The integration of road networks helps to investigate the importance of infrastructure that provides access to the city. To investigate this topic, we integrate main roads in the analysis. For the category of main roads, we select the OSM categories: *motorway*, *primary*, *secondary streets*, and *trunk road*. Moreover, the integration of roads helps to identify settlement patterns. To address this topic, residential roads are used. For the category of residential roads, we select the OSM categories of *residential* and *living streets*. If settlements are accumulating within a distance of 50 m to residential roads in consolidated areas, the accumulation can be classified as densification (Connolly 2009; Saavedra et al. 2011). The distance of each point (ecological complaints or urbanization points) to the roads is identified, using the tool *near*, as part of the *proximity* toolset in ArcGIS.

In the next step, an approach combining VGI and remote sensing is applied. This approach helps to answer the research question: *Where do informal settlements occur?* Locations of high urbanization densities as well as high complaints densities have to be identified. The areas of high densities are called hot spots. To identify a hot spot, we use the tool *kernel density*, part of the *spatial analyst* in ArcGIS. We select a cell size of 100 m to locate hot spots accurately in the study area. The search radius determines the area in which the density is calculated. By reducing the search radius, hot spots can be located more exactly. By increasing the search radius, a more generalized pattern of hot spots is created.

Furthermore, the densities have to be classified. Here, a classification with four quantiles is applied. The top quantile with 75% of values below represents a hot spot. We apply these steps to the urbanization and complaint data. Afterwards, the urbanization hot spots and the complaint hot spots are overlaid to identify the areas with high densities (top quantile) of urbanization and at the same time high densities of ecological complaints. To create a map of multi-scale hot spots with a three-level search radius, the overlapping hot spots for the different search radii are overlaid. Then, we extract hot spots of complaints and urbanization for each search radius using the *spatial analyst* in ArcGIS. To create a layer of the urbanization and complaint hot spots overlaps (e.g., urbanization hot spot with a search radius of 500 m and complaint hot spot with a search radius of 500 m), we extract the overlaps using the tool *extract by mask*. This is repeated for the hot spots of 1000 and 2000 m.

While remote sensing detects urbanization from above, the ecological complaints represent people's perception of informal settlers and thus violations against preservation requirements on the local scale. By combining urbanization and ecological complaints, peri-urban areas can be located more accurately. In the following, we take a closer look at these areas. After the identification of "common" or "overlapping" hot spot areas, we overlay the smallest administrative entities (AGEB) of Mexico City to see the extent of the multi-scale hot spots with different search radii in comparison to the administrative borders. Afterwards, we investigate the percentage of urbanization points and ecological complaints within the smallest administrative entities (AGEB). The *intersect* tool or the *select by location*

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mode of ArcGIS enables this. If settlements accumulate within AGEB limits, the settlement is located within the influence zone of the Urban Development Plan (Aguilar 2008).

In the following, the accessibility of the hot spots of peri-urbanization is assessed. Therefore, we compare the location of the entire road network of the study (OSM roads dataset from 2015) with the extent of the identified peri-urban multi-scale hot spots.

Results

In this section, we first describe the results of the distance analysis between roads and complaints, followed by the results of the hot spot analysis. In Fig. 4, the histogram shows the distances of the ecological complaints to the main roads. The gray bars indicate the frequency of each distance class from 100 to > 3000 m, and the black line represents the cumulated frequency in percent. As we expect in the first hypothesis, the histogram shows a trend of decreasing frequency the higher the distance from the main roads. More ecological complaints are found near the main roads, and with increasing distance, the number of ecological complaints decreases.

Figure 5 shows a histogram of the distances of the ecological complaints to the residential roads. The gray bars indicate the frequency of ecological complaints with the appropriate distance to the residential roads. The cumulated frequency in percent is shown in black. Distance classes from 100 to > 1000 m are chosen. The histogram illustrates a decreasing frequency of ecological complaints with increasing distance to the residential roads. Thus, most frequent are ecological complaints with less than 100 m to the residential roads. About 400 complaints are located less than 100 m from a residential road. That represents c. 40% of the complaints. About 25% of the complaints are found less than 50 m from residential roads. These complaints indicate an accumulation of informal settlements as densification of existing settlements. With increasing distance of the complaints from the residential roads, the frequency of complaints is decreasing.

In the next step, we present the hot spots of ecological complaints and urbanization (Fig. 6). The ecological complaints (human sensing) are in the left column and the urbanization densities (remote sensing) are in the right column. To apply a multi-scale analysis, the search radius is set at 500, 1000, and 2000 m. While a search radius of 500 m represents a specification of patterns, where complaints about informal settlements (left) and urbanization (right) can be located more accurately, the search radius of 2000 m shows a generalization of the urbanization and complaint hot spots, which illustrates a rough pattern of urbanization and complaints occurrence. The densities in the top quantile are higher when the search radius is small and the areas of complaints and urbanization are located more precisely. The category Q 0.75 presents the top quantile with 75% of density values below (dark blue). Here, we consider the top quantile as a hot spot. Comparing the hot spots of complaints and urbanization, the urbanization hot spot has a greater extent than the hot spot of ecological complaints. Not every urban change is the

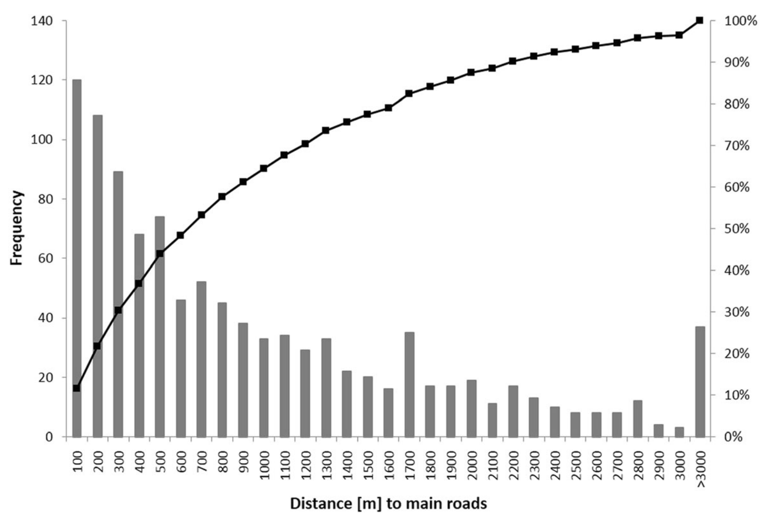

Fig. 4 Histogram of distances (m) of each ecological complaint (PAOT) to the nearest main road (OSM). The frequency is illustrated in gray; the cumulated frequency (%) is in black

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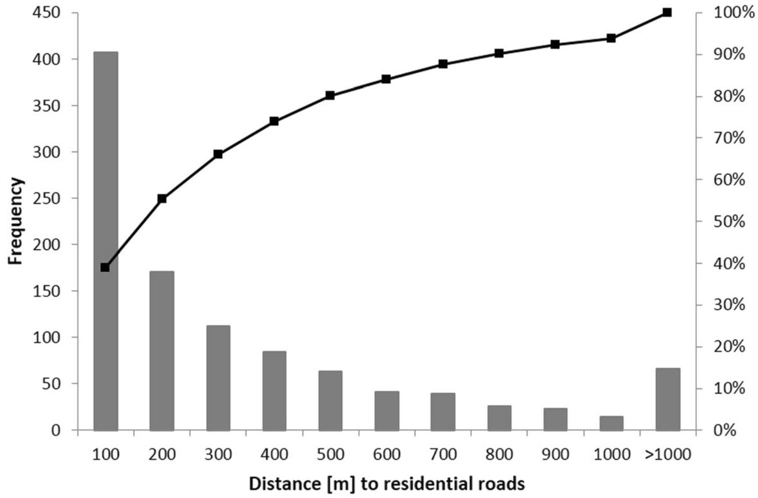

Fig. 5 Histogram of distances (m) of each ecological complaint (PAOT) to the nearest residential road (OSM). The frequency is illustrated in gray; cumulated frequency (%) is in black

accumulation of informal settlements, and people do not complain about every informal settlement (Rodriguez Lopez et al. 2017a). Furthermore, the urbanization hot spot is located in the north of the study area where population densities are higher. In contrast, the complaint hot spot is located near the border of the CZ and thus in the area where city and countryside blend. Comparing the maps of the complaint hot spot with different search radii, the major cluster in the center is mainly located in the south of Xochimilco in the frontier of the CZ, especially the core of the generalized hot spot with a search radius of 2000 m.

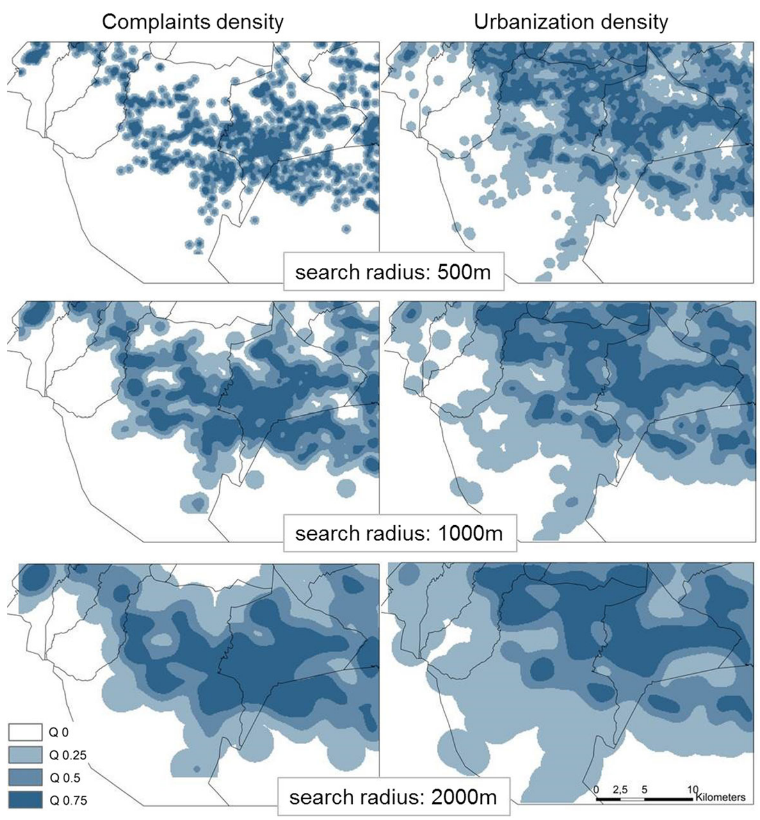

Fig. 6 Overview of ecological complaint hot spots (PAOT) and urbanization hot spots (RapidEye 5 × 5 m imagery). The search radius is changed between 500, 1000, and 2000 m with a cell size of 100 m in each case. Q 0.75 is the top quantile that we consider as hot spot

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Figure 7 illustrates the construction of the multi-scale hot spots. It is based on the overlap between ecological complaint hot spots and urbanization hot spots in different scales. These common hot spots are illustrated in dark blue. In these maps, no differentiation is made between the colors for human or remote sensing hot spots which are both illustrated in bright blue. We consider the overlapping areas (dark blue) as hot spots of peri-urbanization. Figure 7 shows at the top right side the overlap with a search radius of 500 m. At the top left side, the overlap with a search radius of 1000 m, and on the bottom left side, the overlap with a search radius of 2000 m are shown (from specification to generalization). By combining the hot spots with different search radii, multi-scale hot spots are created, illustrated below in the lower right map. Dark red represents the hot spot with a search radius of 500 m, medium red represents 1000 m and light red 2000 m. Due to the occurrence of high urbanization densities and high densities of complaints, the overlaps are very likely to locate informal settlements. This area is also considered to have a high conflict potential between native settlers and newcomers (Hagene 2010). The main accumulation of the overlapping area is located in Xochimilco. Yet, Tlalpan, as well as Milpa Alta, hosts huge overlapping clusters of complaints and urbanization hot spots.

In Fig. 8, the administrative boundary (AGEB) is added to the multi-scale hot spots. The frontiers of the CZ are approximated with the extent of the AGEBs (SEDUVI 2009) which represent the extent of the Urban Development Plan. An informal settlement within the area of the Urban Development Plan is more likely to be legalized. It is striking that the red areas are located near the limits of AGEB. In many cases, the hot spot exceeds the AGEB area intruding into the CZ. In particular, the hot spot of complaints extends outside the area of the smallest administrative area (see Fig. 6). Moreover, we analyze the ecological complaint dataset and the urbanization dataset separately for their location within or outside of AGEB boundaries. The major part of both datasets lies within AGEB boundaries. Seven hundred and thirty-six of 1046 complaints are located within AGEB limits, which correspond to 70.36%. An even bigger part of 80.55% of urbanization takes place within the AGEB boundaries.

Figure 9 illustrates the overlap of the multi-scale hot spots of urbanization and ecological complaints with the entire OSM road network using all available roads of the

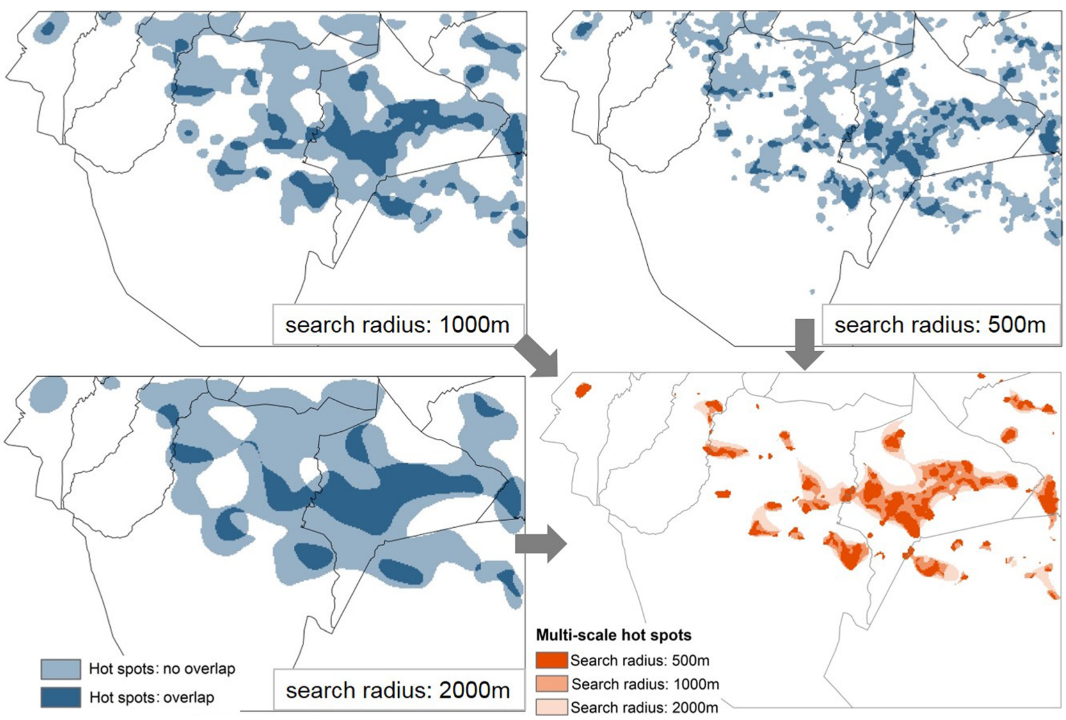

Fig. 7 Combining different scales from the hot spot overlaps of ecological complaints (PAOT) and urbanization pixels (RapidEye) to multi-scale hot spots

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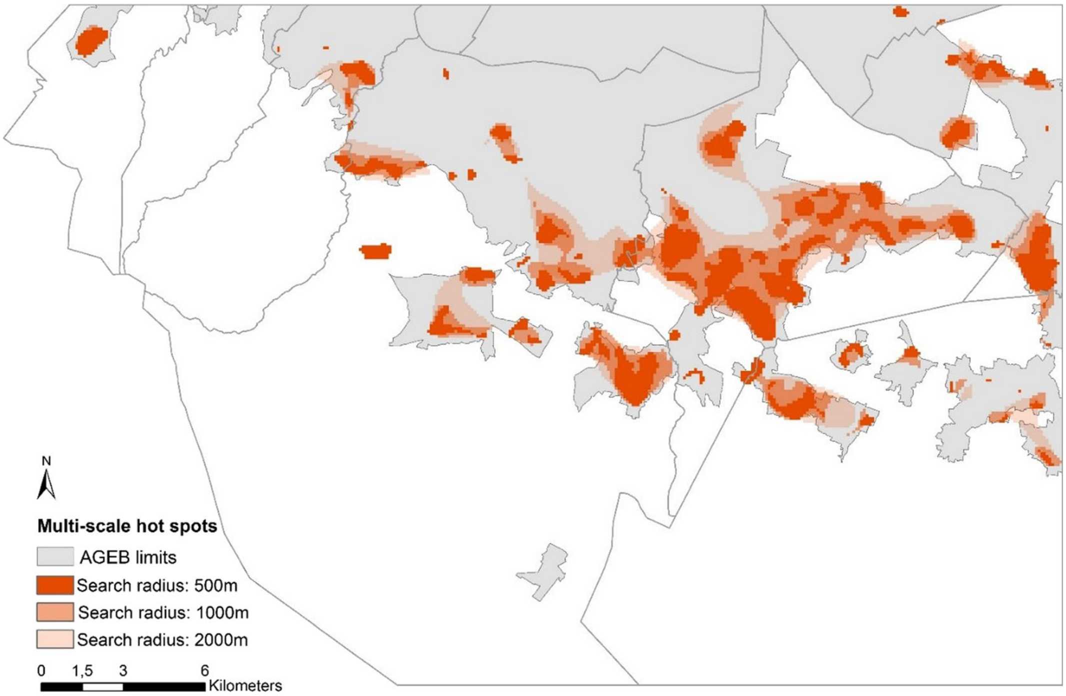

Fig. 8 Multi-scale hot spots (overlap of ecological complaints (PAOT) and urbanization hot spot (RapidEye)) with search radii of 500, 1000, and 2000 m overlaid with AGEB limits. AGEB limits illustrate the influence zone of the Urban Development Plan

OSM 2015 dataset (illustrated in brown). It is striking that roads connect the hot spots. For the hot spots of 1000 m (medium red) and 2000 m radius (light red), no peri-urbanization hot spot without road connection can

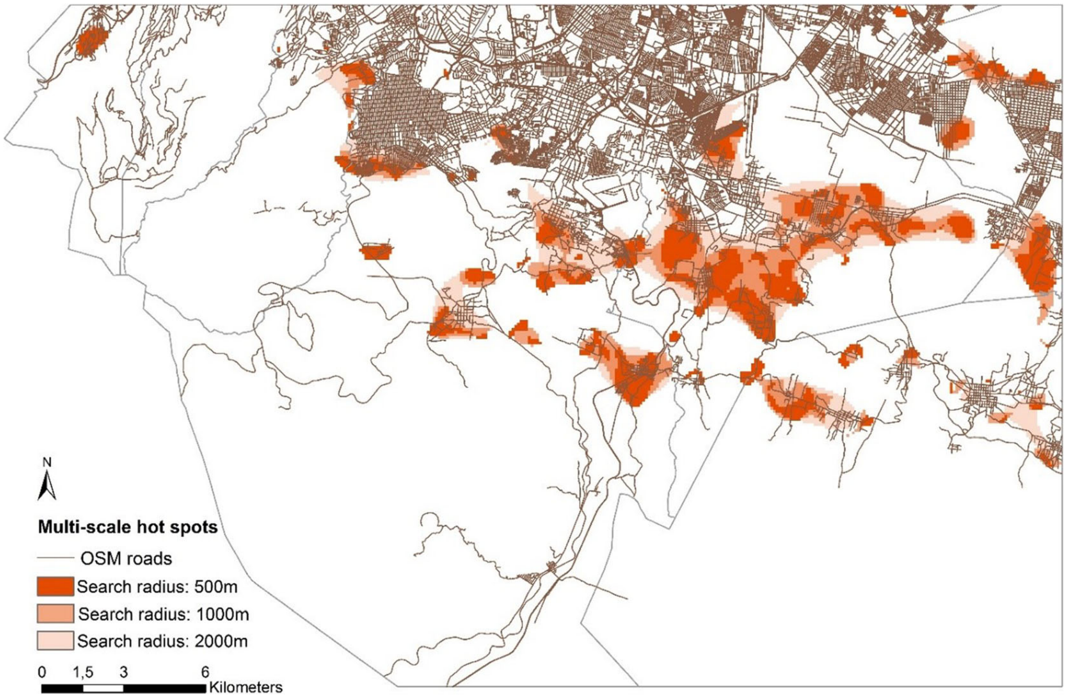

Fig. 9 OSM roads with overlaid multi-scale hot spots (from PAOT and RapidEye 5 × 5 m imagery)

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be seen. The hot spots are often located around residential roads, recognizable because of their regular rectangular pattern, but the extent of the hot spot exceeds the area of residential roads. The hot spots are located around main roads but also road types that are not included in the category of main roads in this study. Looking at the hot spot with a search radius of 500 m (dark red), a similar pattern can be recognized. Here, the peri-urbanization hot spots are smaller and have a higher density. Nevertheless, the connectivity of the hot spots remains. Roads intersect not all hot spots but a large portion. Using a multi-scale analysis enables the detection of generalized as well as specified peri-urbanization patterns.

Discussion

Combining remote sensing and VGI helps to compensate the shortcomings of each data source. This is especially the case for satellite imagery and ecological complaints as we have shown in this analysis. Yet, remote sensing and human sensing are not considered to be detecting the same phenomenon here. While remote sensing detects urbanization, human sensing helps to locate places where regulations against ecological conservation are violated.

Remote sensing analysis is a reliable tool applied in science to detect changes on the Earth's surface and a lot of satellite data are freely available or becoming cheaper. Remote sensing data have a vast range of spatial, spectral, and temporal resolutions although there are generally two major tradeoffs: the higher the spatial resolution, the lower the spatial coverage and the smaller the coverage the lower the frequency of images. However, high-resolution data is expensive which restricts access for public use, and a remote sensing analysis always captures information using a top-down approach without consideration of local perspectives (Prenzel 2004; Rodriguez Lopez et al. 2017b; Rothe 2017).

On the contrary, VGI is cheap and created through the power of crowd sourcing (Elwood et al. 2012; Goodchild 2007; Goodchild and Li 2012). Especially, the complaint dataset enables the integration of local perspectives using a bottom-up approach (Elwood et al. 2012). Human sensors generate the data while at the same time including individual perceptions of violations against the conservation status of the CZ (Elwood et al. 2012; Goodchild 2007). This dataset is probably not complete (Arsanjani et al. 2013) and might have errors, but due to the contribution of many, clusters of contribution (Giles 2005; Goodchild and Li 2012) can balance errors of some. Quality is definitely an issue here. Rodriguez Lopez et al. (2017a) found that the occurrence of complaints (in the PAOT complaint dataset) is associated more with the unemployment rate than with the population density in the study region. The use of remote sensing helps to address these shortcomings by including urbanization. For the investigation of peri-urbanization, a combination of remotely detected urbanization and a crowd sourced complaint dataset is the preferred way to augment accuracy.

The integration of the ecological complaint dataset provides insights on different levels. On the one hand, it helps to locate hot spots of human informal settlements more accurately in combination with the urbanization detected by remote sensing. Furthermore, we compare the location of urbanization pixels and complaints in their spatial relation to roads. The complaints show a different pattern, which extends more to the south into the CZ, but they also have a higher distance from main as well as residential roads. On the other hand, the complaint dataset gives indication of areas with a high potential for conflicts between native inhabitants and newcomers as mentioned in field studies (Hagene 2010). Through the complaints, a person's perception becomes visible. Since a person who complains about informal settlers is likely to be not satisfied with the new neighbors, the risk of conflicts increases. Thus, the peri-urbanization hot spots identify areas with high conflict potential. For an identification of possible conflict zones without considering the urbanization, the complaint hot spots can be used. These hot spots expand more to the south than the urbanization hot spots and lie in the area where urban and rural areas blend (see Fig. 6). This is the area especially affected by future urbanization around the world (Davis 2004).

Like the complaints, the road data are created by a VGI project. The quality of OSM data is heterogeneous. Cities are considered more accurate in the OSM data and with an increasing distance from agglomerations and a decreasing population density, the quality is likely to decrease (Kunze and Hecht 2015). Thus, we compared roads visible on the satellite imagery used (RapidEye) with selected OSM roads for the analyses. Aside from population density, socioeconomic factors are also identified as influencing OSM data (Haklay et al. 2010). Richer areas are likely to be more complete in VGI than

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poorer and marginalized areas (Haklay et al. 2010; Rodriguez Lopez et al. 2017a).

Roads are identified as pull factors for peri-urbanization and as a threat for the ecosystem (Saavedra et al. 2011). Peri-urbanization and land use changes tend to follow the roads (Schneibel et al. 2013) and settlement patterns. Thus, further provision of infrastructure for areas worthy of nature protection could endanger these ecosystems. Clear regulations that need to be monitored and enforced are needed to prevent a “tragedy of the commons” in the CZ (Hardin 1968; Ostrom et al. 1999). Furthermore, we found that the extent of the Urban Development Plan, represented by the AGEB district limits, might be an influence factor for peri-urbanization. A reason might be that informal settlements located in the influence zone of the Urban Development Plan are more likely to be legalized (Aguilar and Santos 2011). However, a sustainable solution can only be reached if alternative living space is available for the urban poor. It has to be considered that about 60% of residents in Mexico City do not earn enough to buy or rent housing through the formal housing market and the high importance of accessibility was neglected in social programs of the past (Wigle 2014; Connolly 2009).

Neglected factors of peri-urbanization in this analysis include other drivers like social dynamics of poverty, public transport systems, and biological diversity. However, the integration remains open for future research. Furthermore, the applicability of our study to other research areas is limited by the availability of VGI.

Conclusion

In this study, it has been shown that two different data sources of VGI and remote sensing work well together to address the question of why and where peri-urbanization occurs in the conservation area of Mexico City. Peri-urbanization hot spots were located, and some drivers of the process were investigated. We argue that a higher accuracy in the detection of informal settlements can be reached if multiple data sources are used, especially in areas where remote sensing techniques reach their limits, like in rugged terrain or if the density of informal settlements is low and both apply to the south of Mexico City. Applying a multi-scale analysis enables precise and generalized detection. The ecological complaint dataset (VGI) helps to integrate local perspectives of processes happening in the study area. OSM data is another VGI project integrated in the analysis and helps to investigate patterns of peri-urbanization as well as drivers. The use of OSM road data is especially important in areas where official data are lacking.

We identified peri-urbanization hot spots as areas where high densities of urbanization and high densities of complaints come together. Peri-urbanization is mainly found in the transition zone between urban and rural area on the frontiers of the CZ. In particular, high densities of ecological complaints indicating informal settlements are located more to the south than urbanization, which is to a higher extent happening in already urbanized areas with higher population densities.

This research has shown that access to the city is likely to be a major factor. Therefore, no solution for peri-urbanization can be found without meeting the needs of the poor. As long as no affordable living space for the poor is available, informal settlements will continue to grow. Regarding urban planning, we argue that peri-urbanization hot spots occur chiefly close to main roads that enable access to the city or near existing settlements represented by residential roads. Therefore, building social housing far away from the city and from jobs without proper public transportation will not solve the problem. Other requirements that are important for the conservation of ecological goods and services in the CZ in the future include clear regulations for urbanization that need to be monitored and enforced. Focusing on the processes of rural-urban migration, the consequences for rural areas also have to be further investigated, considering smart pathways to cope with decreasing population in these areas.

The findings and methodologies of this study can be applied to many other regions of the world, especially in the “Global South” where urbanization pressure and a lack of affordable living space for the urban poor converge. A limitation might be the availability of VGI, but this is still a growing field, which is likely to bring major changes to the geographical data landscape. In the last years, the number of projects generating VGI has increased and thus the number of people using it as an alternative to officially produced geographic data. Due to the free availability, the availability on multiple scales and topics as well as the strong growth of this kind of data it has become more interesting for research.

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References

Aguilar, A. G. (2008). Peri-urbanization, illegal settlements and environmental impact in Mexico City. *Cities, 25*(3), 133–145.

Aguilar, A. G., & Guerrero, F. L. (2013). Poverty in peripheral informal settlements in Mexico City: the case of Magdalena Contreras, Federal District. *Tijdschrift voor Economische en Sociale Geografie, 104*(3), 359–378.

Aguilar, A. G., & Santos, C. (2011). Informal settlements' needs and environmental conservation in Mexico City: an unsolved challenge for land-use policy. *Land Use Policy, 28*(4), 649–662.

Aguilar, A. G., & Ward, P. M. (2003). Globalization, regional development, and mega-city expansion in Latin America: analyzing Mexico City's peri-urban hinterland. *Cities, 20*(1), 3–21.

Arsanjani, J. J., Helbich, M., Bakillah, M., Hagenauer, J., & Zipf, A. (2013). Toward mapping land-use patterns from volunteered geographic information. *International Journal of Geographical Information Science, 27*(12), 2264–2278.

Augustijn-Beckers, E., Flacke, J., & Retsios, B. (2011). Simulating informal settlement growth in Dar es Salaam, Tanzania: an agent-based housing model. *Computers, Environment and Urban Systems, 35*(2), 93–103.

Boulos, M. N. K., Resch, B., Crowley, D. N., Breslin, J. G., Sohn, G., Burtner, R., et al. (2011). Crowdsourcing, citizen sensing and sensor web technologies for public and environmental health surveillance and crisis management: trends, OGC standards and application examples. *International Journal of Health Geographics, 10*(67), 1–29.

Bray, D. B. (2013). When the state supplies the commons: origins, changes, and design of Mexico's common property regime. *Journal of Latin American Geography, 12*(1), 33–55.

Caro-Borrero, A., Corbera, E., Neitzel, K. C., & Almeida-Leñero, L. (2015). "We are the city lungs": payments for ecosystem services in the outskirts of Mexico City. *Land Use Policy, 43*, 138–148.

Connolly, P. (2009). Observing the evolution of irregular settlements: Mexico City's colonias populares, 1990 to 2005. *International Development Planning Review, 31*(1), 1–35.

Davis, M. (2004). Planet of slums: urban involution and the informal proletariat. *New Left Review, 26*, 5–34.

Dovey, K., & King, R. (2012). Informal urbanism and the taste for slums. *Tourism Geographies, 14*(2), 275–293.

Dürr, E. (2012). Urban poverty, spatial representation and mobility: touring a slum in Mexico. *International Journal of Urban and Regional Research, 36*(4), 706–724.

Elwood, S., Goodchild, M. F., & Sui, D. Z. (2012). Researching volunteered geographic information: spatial data, geographic research, and new social practice. *Annals of the Association of American Geographers, 102*(3), 571–590.

van Gelder, J.-L., Cravino, M. C., & Ostuni, F. (2016). Housing informality in Buenos Aires: past, present and future? *Urban Studies, 53*(9), 1958–1975.

Geofabrik (2016). OpenStreetMap data extracts. http://download.geofabrik.de. Accessed 25 August 2017.

Gilbert, L., & Jong, F. (2015). Entanglements of periphery and informality in Mexico City. *International Journal of Urban and Regional Research, 39*(3), 518–532.

Gilbert, L., Hhosla, P., & Jong, F. (2016). Precarization and Urban Growth in Metropolitan Mexico City. Espacialidades. *Revista de temas contemporáneos sobre lugares, política y cultura 6*(2), 5–32.

Giles, J. (2005). Internet encyclopaedias go head to head. *Nature, 438*(7070), 900–901.

Gobierno del, D. F. (2012). *Atlas geográfico del suelo de conservación del Distrito Federal*. México: Secretaría del Medio Ambiente, Procuraduría Ambiental y del Ordenamiento Territorial del Distrito Federal.

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal, 69*(4), 211–221.

Goodchild, M. F., & Li, L. (2012). Assuring the quality of volunteered geographic information. *Spatial Statistics, 1*, 110–120.

Graesser, J., Cheriyadat, A., Vatsavai, R. R., Chandola, V., Long, J., & Bright, E. (2012). Image based characterization of formal and informal neighborhoods in an urban landscape. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5*(4), 1164–1176.

Grau, H. R., & Aide, M. (2008). Globalization and land-use transitions in Latin America. *Ecology and Society 13*(2), 16.

Gray, C. L. (2009). Rural out-migration and smallholder agriculture in the southern Ecuadorian Andes. *Population and Environment, 30*(4–5), 193–217.

Hagene, T. (2010). Everyday political practices, democracy and the environment in a native village in Mexico City. *Political Geography, 29*(4), 209–219.

Haklay, M., Basiouka, S., Antoniou, V., & Ather, A. (2010). How many volunteers does it take to map an area well? The validity of Linus' law to volunteered geographic information. *The Cartographic Journal, 47*(4), 315–322.

Hardin, G. (1968). The tragedy of the commons. *Science, 162*, 1243–1248.

INEGI (2012). Estadísticas Censales a Escalas Geoelectorales. Principales Resultados del Censo de Población y Vivienda 2010, http://www.inegi.org.mx/est/contenidos/proyectos/ccpv/cpv2010/iter_2010.aspx. Accessed 25 September 2017.

Jean, N., Burke, M., Xie, M., Davis, W. M., Lobell, D. B., & Ermon, S. (2016). Combining satellite imagery and machine learning to predict poverty. *Science, 353*(6301), 790–794.

Jujnovsky, J., González-Martínez, T. M., Cantoral-Uriza, E. A., & Almeida-Leñero, L. (2012). Assessment of water supply as an ecosystem service in a rural-urban watershed in southwestern Mexico City. *Environmental Management, 49*(3), 690–702.

Kit, O., Lüdeke, M., & Reckien, D. (2013). Defining the bull's eye: satellite imagery-assisted slum population assessment in Hyderabad, India. *Urban Geography, 34*(3), 413–424.

Kontgis, C., Schneider, A., Fox, J., Saksena, S., Spencer, J. H., & Castrence, M. (2014). Monitoring peri-urbanization in the greater Ho Chi Minh City metropolitan area. *Applied Geography, 53*, 377–388.

المنارة للاستشارات
www.manaraa.c

Kunze, C., & Hecht, R. (2015). Semantic enrichment of building data with volunteered geographic information to improve mappings of dwelling units and population. *Computers, Environment and Urban Systems, 53*, 4–18.

Lombard, M. (2014). Constructing ordinary places. Place-making in urban informal settlements in Mexico. *Progress in Planning, 94*, 1–53.

Mollá Ruíz-Gómez, M. (2005). El crecimiento de los asentamientos irregulares en áreas protegidas. La delegación Tlalpan. *Investigaciones Geograficas, Boletín del Instituto de Geografía, UNAM, 60*, 83–109.

Naldi, L., Nilsson, P., Westlund, H., & Wixe, S. (2015). What is smart rural development? *Journal of Rural Studies, 40*, 90–101.

Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B., & Policansky, D. (1999). Revisiting the commons: local lessons, global challenges. *Science, 284*, 278–282.

Owen, K. K., & Wong, D. W. (2013). An approach to differentiate informal settlements using spectral, texture, geomorphology and road accessibility metrics. *Applied Geography, 38*, 107–118.

Prenzel, B. (2004). Remote sensing-based quantification of land-cover and land-use change for planning. *Progress in Planning, 61*(4), 281–299.

Rodriguez Lopez, J. M., Rosso, P., Scheffran, J., Delgado Ramos, G. C. (2015). Remote sensing of sustainable rural-urban land use in Mexico City: a qualitative analysis for reliability and validity. *Interdisciplina*, 3 (7),321–342

Rodriguez Lopez, J. M., Heider, K., & Scheffran, J. (2017a). Frontiers of urbanization: identifying and explaining urbanization hot spots in the south of Mexico City using human and remote sensing. *Applied Geography, 79*, 1–10.

Rodriguez Lopez, J. M., Heider, K., & Scheffran, J. (2017b). Human and remote sensing data to investigate the frontiers of urbanization in the south of Mexico City. *Data in Brief, 11*, 5–11.

Rothe, D. (2017). Seeing like a satellite: remote sensing and the ontological politics of environmental security. *Security Dialogue, 48*(4), 334–353.

Roy, D., Lees, M. H., Palavalli, B., Pfeffer, K., & Sloot, M. P. A. (2014). The emergence of slums: a contemporary view on simulation models. *Environmental Modelling & Software, 59*, 76–90.

Saavedra, Z., Ojeda Revah, L., & López Barrera, F. (2011). Identification of threatened areas of environmental value in the Conservation Area of Mexico City, and setting priorities for their protection. *Investigaciones Geográficas, Boletín del Instituto de Geografía, UNAM, 74*, 19–34.

Schneibel, A., Stellmes, M., Revermann, R., Finckh, M., Röder, A., & Hill, J. (2013). Agricultural expansion during post-civil war period in southern Angola based on bi-temporal Landsat data. *Biodiversity & Ecology, 5*, 311–319.

SEDUVI (2009). CIUDADMX. http://ciudadmx.df.gob.mx:8080/seduvi/. Accessed 20 August 2017.

SEGOB (2016). Diario Oficial de la Federación 29/01/2016. http://dof.gob.mx/nota_detalle.php?codigo=5424043&fecha=29/01/2016. Accessed 02 February 2018.

Su, S., Wang, Y., Luo, F., Mai, G., & Pu, J. (2014). Peri-urban vegetated landscape pattern changes in relation to socioeconomic development. *Ecological Indicators, 46*, 477–486.

Taubenböck, H., & Kraff, N. J. (2014). The physical face of slums: a structural comparison of slums in Mumbai, India, based on remotely sensed data. *Journal of Housing and the Built Environment, 29*(1), 15–38.

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A., & Dech, S. (2012). Monitoring urbanization in mega cities from space. *Remote Sensing of Environment, 117*, 162–176.

Wigle, J. (2014). The 'graying' of 'green' zones: spatial governance and irregular settlement in Xochimilco, Mexico City. *International Journal of Urban and Regional Research, 38*(2), 573–589.

Woodcock, C. E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S. N., Helder, D., Helmer, E., Nemani, R., Oreopoulos, L., Schott, J., Thenkabail, P. S., Vermote, E. F., Vogelmann, J., Wulder, M. A., & Wynne, R. (2008). Free access to Landsat imagery. *Science, 320*(5879), 1011.

Wulder, M. A., Masek, J. G., Cohen, W. B., Loveland, T. R., & Woodcock, C. E. (2012). Opening the archive: how free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment, 122*, 2–10.

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