frontiers in Environmental Science

ORIGINAL RESEARCH
published: 26 September 2019
doi: 10.3389/fenvs.2019.00144

Evaluating Socio-Ecological Interactions for the Management of Protected Urban Green Spaces

Luis Zambrano[1]*, Zenón Cano-Santana[2], Ana Wegier[3], Denise Arroyo-Lambaer[3], J. Jaime Zúñiga-Vega[4], Antonio Suárez[5], César Rafael Bouchain[6], Fernando Gual Sill[7], Julio Campo[8], Pilar Ortega-Larrocea[9], Alejandra Fonseca[1,10], Alejandra G. Ramos[1,11], Heli Coronel-Arellano[1], Manuel Bonilla-Rodríguez[2], Alicia Castillo[12], Marcela Negrete-González[1], Gonzalo A. Ramírez-Cruz[4], Javier Pérez-López[3] and Brenda González Calderón[3]

[1] Laboratorio de Restauración Ecológica, Instituto de Biología, Universidad Nacional Autónoma de México, Mexico City, Mexico, [2] Laboratorio de Interacciones y Procesos Ecológicos, Facultad de Ciencias, Universidad Nacional Autónoma de México, Mexico City, Mexico, [3] Laboratorio de Genética de la Conservación, Jardín Botánico, Instituto de Biología, Universidad Nacional Autónoma de México, Mexico City, Mexico, [4] Laboratorio de Ecología Evolutiva y Demografía Animal, Facultad de Ciencias, Universidad Nacional Autónoma de México, Mexico City, Mexico, [5] Laboratorio de Movilidad e Infraestructura Verde, Arquitectura del Paisaje, Facultad de Arquitectura, Universidad Nacional Autónoma de México, Mexico City, Mexico, [6] Economía Aplicada, Instituto de Investigaciones Económicas, Universidad Nacional Autónoma de México, Mexico City, Mexico, [7] Etología, Fauna Silvestre y Animales de Laboratorio, Facultad de Ciencias, Universidad Nacional Autónoma de México, Mexico City, Mexico, [8] Laboratorio de Biogeoquímica Terrestre y Clima, Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City, Mexico, [9] Laboratorio de Microcosmos Bioedáfico, Instituto de Geología, Universidad Nacional Autónoma de México, Mexico City, Mexico, [10] Coordinación Universitaria para la Sustentabilidad, Universidad Nacional Autónoma de México, Mexico City, Mexico, [11] Facultad de Ciencias, Universidad Autónoma de Baja California, Ensenada, Mexico, [12] Laboratorio de Sociología y Comunicación, Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Morelia, Mexico

OPEN ACCESS

Edited by:
*Hallie Eakin,
Arizona State University, United States*

Reviewed by:
*Gulnihal Ozbay,
Delaware State University, United States
Payam Aminpour,
Michigan State University, United States*

***Correspondence:**
*Luis Zambrano
zambrano@ib.unam.mx*

Specialty section:
This article was submitted to Environmental Health, a section of the journal Frontiers in Environmental Science

Received: 20 March 2019
Accepted: 11 September 2019
Published: 26 September 2019

Citation:
Zambrano L, Cano-Santana Z, Wegier A, Arroyo-Lambaer D, Zúñiga-Vega JJ, Suárez A, Bouchain CR, Gual Sill F, Campo J, Ortega-Larrocea P, Fonseca A, Ramos AG, Coronel-Arellano H, Bonilla-Rodríguez M, Castillo A, Negrete-González M, Ramírez-Cruz GA, Pérez-López J and González Calderón B (2019) Evaluating Socio-Ecological Interactions for the Management of Protected Urban Green Spaces. Front. Environ. Sci. 7:144. doi: 10.3389/fenvs.2019.00144

Protected urban green spaces (PUGS) are exposed to numerous disturbances and threats since they are immersed in highly dynamic socio-ecological systems. PUGS in highly urbanized cities require particular conservation strategies. Here, we propose an approach for PUGS management which integrates three components: (i) scientific knowledge (monitoring/restoration), (ii) community interaction with the environment, and (iii) management decision. Based on the perception of stakeholders, we searched for evidence that these components are well-integrated in PUGS management and decision-making. The intersection of these components should produce a solid management program, provided that the obtained multidisciplinary knowledge meets the needs of information required by the community and decision makers. We tested this in a small PUGS located within Mexico City at the National Autonomous University of Mexico campus that holds the Ecological Reserve of Pedregal de San Ángel. Through a participatory approach we elicited mental models and represented group beliefs using Fuzzy Cognitive Mapping (FCM). This, in turn, produced evidence of effective integration of the three components in terms of management and decision-making. Our findings provide insight into the actors' perceptions and concerns and suggest that the interactions among the three components, although important, are not self-generated and must be constructed. The findings also suggest that one of the management problems is the mismatch between scientific knowledge and conservation programs.

It is paramount to include generated knowledge into management and monitoring programs. The complexity of the PUGS requires an active collaboration among actors and monitoring the development of management strategies using the three components while taking the conservation goals into account.

Keywords: cities, Mexico City, UNAM main campus, urban conservation, socio-ecological system, Ecological Reserve of Pedregal de San Ángel, community perception, fuzzy cognitive map

INTRODUCTION

In most cities urban green spaces (UGS) are subject to urbanization pressures and ecological disturbances (Ernstson et al., 2010), such as the reduction of green areas, the introduction of invasive species, increased pollution, and soil compaction in pathways (Alberti et al., 2003; Andersson, 2006; Yang et al., 2017). The establishment of protected urban green spaces (PUGS) can reduce urban pressures upon these areas if they are properly managed. However, devising effective management programs for PUGS is a challenge in highly dynamic and populated areas. Outside of cities, the management of natural protected areas is based on multidisciplinary scientific information that generates tasks to increase the efficacy of conservation strategies. This strategy is focused on simultaneously maintaining ecological processes and the activities carried out by local people in rural communities such as forestry, gathering, hunting, harvesting, or cropping (e.g., Kharel, 1997).

Human and nature interactions are integrated systems in which people interact with natural components (Liu et al., 2007), thus, the resources used by humans are embedded in complex social-ecological systems (SESs) which are composed of multiple subsystems and internal variables at different levels (Ostrom, 2009). Due to intense interactions with humans, PUGS in urban areas with complex socio-ecological dynamics must generate new management strategies. For example, restoration projects in rural regions are normally controlled by few people who have minimal contact with local settlers (Mangun et al., 2009; Davenport et al., 2010). In cities, restoration programs such as the eradication of exotics—plant or animal—may be misunderstood by numerous citizens who are in daily contact with those protected areas (Leong et al., 2009). This may culminate in protests against eradication measures (e.g., Gaertner et al., 2016; Novoa et al., 2018), and ultimately reduce program achievements (e.g., Madden and McQuinn, 2014). In addition, there is an increase in the number of people who are adopting pets, especially dogs and cats near PUGS (e.g., Sepúlveda et al., 2014; Paschoal et al., 2016). Exotic pets like fish, turtles, and frogs are also being released into PUGS (e.g., Taniguchi et al., 2017), which can generate human health issues and harm native biodiversity.

Land is one of the critical limiting resources in cities for both society and nature (Lambin et al., 2001). The large influence of UGS in urban ecosystems is based on the amount of land they occupy within cities (Xu et al., 2016). Parklands in New York City cover 21% of the area, containing 85% of the flora diversity (Schewenius et al., 2014), while in Chandirgah they extend over a third of the city's surface (Chaudhry and Tewari, 2010; Shen and Fitriaty, 2018). This land occupies a key role in ecological processes such as biodiversity maintenance and ecosystem services (Aronson et al., 2017; Sirakaya et al., 2018). The PUGS often undergo fragmentation, which in turn modifies ecological/evolutive interactions as well as provision of ecosystem services (Tian et al., 2011; Mitchell et al., 2015a,b). Fragmentation not only modifies ecological dynamics but also change social interactions in the neighborhood of green spaces (Hansen and DeFries, 2007). Therefore, to increase conservation success, management practices in PUGS should pay attention to the socio-ecological interactions generated in and around PUGS.

An assessment of the factors and interactions comprising each component is critical to evaluate PUGS management, which may vary from areas to areas. We studied a small PUGS, the Ecological Reserve of Pedregal de San Ángel (REPSA, as it stands in Spanish; hereafter it might be also referred as "Reserve"), situated in the National Autonomous University of Mexico main campus, Mexico City. We analyze PUGS management based on three components that have been traditionally used to manage protected areas: (i) scientific knowledge (monitoring/restoration), (ii) community interaction with the environment, and (iii) management decisions (**Figure 1**).

In order to answer the research questions "Is there evidence that these components are well-integrated in REPSA decision-making, according to stakeholder perceptions?" and "Is the intersection of the three components enough to create a solid foundation for management of any green space within this university?" we described the characteristics of the three components in this PUGS, elicited mental models and represented group beliefs (including students, academics, and administrators) using Fuzzy Cognitive Mapping (FCM) (Kosko, 1986; Gray et al., 2014). We evaluated the connections among these components based on activities, perceptions, and ecological variables within the university campus. The intersection should be critical since both decision makers and those who generate the scientific information come from the same community. Then, the FCM will show that the key concepts for the solid management of the REPSA will fall exclusively in the intersection of the three components.

STUDY SITE

In the middle of the last century, the Federal Government bought 723 ha of lava field far away from the city center and gave it to the National Autonomous University of Mexico (Morales-Schechinger and García-Jiménez, 2008). The land lies within a xerophytic and thornshrub ecosystem established over volcanic material generated from the eruption of a monogenetic volcano (Xitle) in 280 ± 35 BCE, which covered roughly 70 km^2 in the

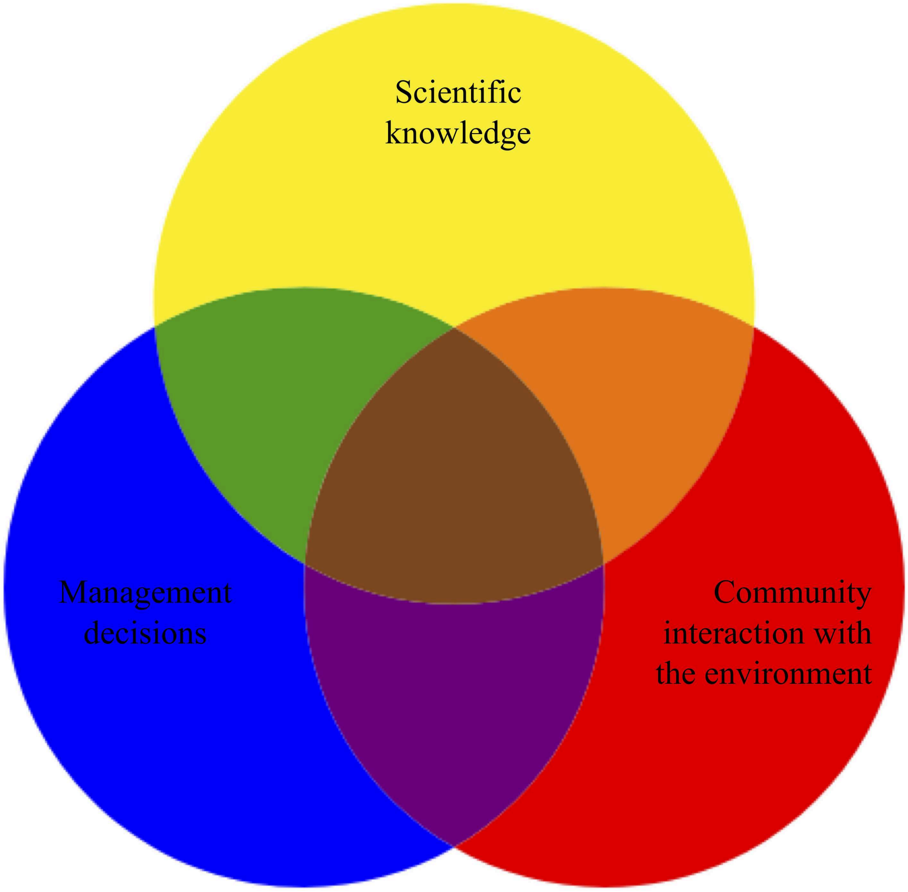

FIGURE 1 | PUGS management using the three components. The intersection of the three circles is in which elements of a proper management should arise.

south of Mexico City (Siebe, 2009), which is known as Pedregal de San Ángel (hereafter will be also referred as "Pedregal"). It generates diverse habitats, depending on the flow and cooling conditions, resulting in a heterogeneous interstitial matrix. It has a high gradient of light and temperature within few meters, allowing only xerophytic species of plants to survive (Rzedowski, 1954; Peralta-Higuera and Prado-Molina, 2009).

The University moved its main campus in 1953 to this land in an attempt to generate a development pole at the south of the city, but occupied only 178 ha of the total area (Zambrano and Cano-Santana, 2016). Soon afterwards, regional urbanization spread along the area outside of the University, reducing the lava field ecosystem. The University had development plans that would urbanize the rest of the lava field landscape (Morales-Schechinger and García-Jiménez, 2008), threatening the geoheritage of this ecosystem and a large number of species.

Academics and students mobilized to protect this area and the university authorities established a protected 124 ha area within the campus in 1983, naming it Ecological Reserve of Pedregal de San Ángel (REPSA) (García-Barrios, 2014). During the past three decades, the Reserve has been expanded and now occupies a third of the campus area (237 ha). Scattered along the campus there are also 40 ha of non-protected patches of original ecosystem. It comprises a complex basaltic volcanic field that is the base for a large biodiversity of pioneer plants and animals (Cano-Santana et al., 2008). The REPSA is now home to 1,849 native and 317 exotic species (REPSA, 2017). As other PUGS, this area is inserted in an urban matrix and provides ecosystem services such as high-water infiltrations to the city and flood regulation (Vargas, 1984; Delgado et al., 1998; Nava-López et al., 2009; Palacio-Prieto and Guilbaud, 2015).

THE THREE COMPONENTS APPROACH

First Component: Scientific Knowledge

The constant generation of scientific information of a protected space is essential since most parts of ecosystem interactions can be explained by long term ecological monitoring (Brown et al., 2001) and ecological restoration programs, which give information about ecosystem processes. Long-term ecological data provide baselines for evaluating environmental change (Rustad et al., 2007), help to detect and evaluate changes in ecosystem structure and function, and help to distinguish the ecosystem's response to changes in environmental trends from those responses to changes in the intensity and frequency of episodic events (e.g., by drought or wildfires).

Two examples are understanding fire causes or eutrophication trends due to pollution accumulation within a reserve (Welch, 1998; Radeloff et al., 2010), and understanding the interaction among species in different areas. Information on native and exotic species is critical to understand the ecosystem functioning in an urban space. For example, understanding ecological interactions such as competition or predation is critical for management (MacKenzie et al., 2004). Monitoring represents a challenge but provides reliable estimates of demographic and population variables (Yoccoz et al., 2001; Nichols and Williams, 2006). Recent methodological advances, such as occupancy models, allow demographic estimations with simple observation of presences and apparent absences of species and should be implemented in long-term monitoring programs (Buckland et al., 2015; MacKenzie, 2018). Ecological monitoring studies in the REPSA have revealed that occupancy of exotic species occupancy may have both negative and positive effects on native species (Ramírez-Cruz et al., 2018, 2019). Likewise, the analysis of genetic erosion (e.g., de Oliveira and Martins, 2002; Moodley et al., 2017) of the species is necessary given the small PUGS size where populations are intended to continue their evolutionary processes (Sherwin and Moritz, 2000; Moritz, 2002). Factors that maintain diversity should also be considered, like plants with their pollinators, seed dispersers, and other ecological interactions (Tylianakis et al., 2010; Jordano, 2016).

Restoration ecology programs are equally important to the monitoring of PUGS and therefore need to be included in management programs. The first restoration program developed in the REPSA was the reduction of the *Eucalyptus* spp. populations, initially introduced in the campus when it was under construction in 1951 (Segura-Burciaga and Meave, 2001; Cano-Santana et al., 2006; Antonio-Garcés et al., 2009; Estañol-Tecuatl and Cano-Santana, 2017). A current restoration program, which aims to restructure the original trophic dynamics of local wildlife (Kagata and Ohgushi, 2006), comprises two significant actions: (i) the restoration of wildlife populations by the eradication of feral dogs and cats (Zambrano et al., 2016), and (ii) the population re-establishment of gray foxes (*Urocyon cinereoargenteus*) which were presumed to have been extirpated from the REPSA (Hortelano-Moncada et al., 2009) until an individual was photographed in 2017 by Y. Glebskiy (see López, 2017).

Scientific information is critical for a biological understanding of the system, but also, for creating strategies to ensure that current and future generations enjoy an ecosystem and its services (Faith et al., 2010). Therein lies the importance of the interface between generating scientific information and the other two components (i.e., community interaction with the environment and management decisions); it provides the knowledge that authorities and the community require along with information on community-nature interactions needed for management.

Second Component: Community Interaction With the Environment

The university community's perceptions regarding the green spaces on campus have changed, particularly the perception of the REPSA being either a problem or a solution. This has modified the position of stakeholders (authorities, students, and workers) toward these green spaces. In the early stages (1951–1983), only aesthetics aspects were valued for campus management. Most of the community was essentially unaware of the natural area (Morales-Schechinger and García-Jiménez, 2008; García-Barrios, 2014). In a more recent study from 2014, a poll showed that <30% of students and academics knew the type of ecosystem in the campus (Pérez-Escobedo, 2014). Nevertheless, in recent years there has been a change in perception about what it means to have this ecosystem amidst buildings and avenues.

In order to understand this second component based on the conflict between urban land use and conservation at the university, different perspectives (other than those used for the traditional biodiversity conservation studies) have been employed. For example, social cartography is one tool that has been applied on specific areas of the campus to uncover collective ideas of urban nature (Amin, 2007; James, 2015). Cartography studies helped to evaluate if the university community is willing to balance conservation vs. infrastructure needs, without compromising social cohesion. In this sense, the environmental game theory approach (Dinar et al., 2008) has been also implemented as a tool to represent and manage the conflicts arising from the interaction of the various REPSA stakeholders (researchers, students, administrative workers, authorities, and citizens in general), whose acts are guided by their own interests (Kreps, 1990). The third employed tool is participatory modeling through FCM (e.g., Gray et al., 2015). There are many experts in several disciplines, focusing on specific species, processes and knowledge of history, working within or closely-related with the REPSA (academics, students, and administrators) whose perceptions and knowledge are important to capture, integrate, and facilitate the decision-making related to the management of the Reserve (Gray et al., 2012).

Because each stakeholder of this particular socio-ecological system plays a fundamental role and has different perceptions, a clear communication and close interaction between the community and the decision-makers are critical. Frequently, plans to change the infrastructure are communicated late by the authorities. This shows opposite interests among stakeholders and induces difficulties in each stage of the process. The result in the long term turns out exhausting to each part of the community. Nevertheless, the authorities of the REPSA have a role only in cases when a project is carried out on the Reserve land. For the rest of the projects (even in those that affect the Reserve) they do not have decision capacities. A constant interaction of the second component with the other two is relevant as it can potentially contribute to the social-environmental dynamics. This is a basic relation for the establishment of programs and actions that effectively allow the transfer of valuable information to the community, and thereby increases the chances of better management.

Third Component: Management Decisions

Urbanization of the campus since 1953 has increased according to the development projects of each Dean and the economical capacities of the country. Historically, for the first few years, no consideration was given to landscaping from an architectural point of view (Morales-Schechinger and García-Jiménez, 2008; García-Barrios, 2014). Since the PUGS was established, a series of conflicts between the community and the campus authorities have surfaced. The result is a campus with fragmented and scattered areas, some of them well-planned, while others seem poorly-planned (Zambrano et al., in press). Even though there is a protected area, the green space is divided by buildings, roads, and fences, therefore, the ecosystem is highly fragmented with biotic communities poorly connected.

The REPSA had a difficult start as a PUGS since it resulted from a dispute between university authorities, had limited planning to urbanize the total area in a short period of time, and students and academics promoted the protection of the native ecosystem (García-Barrios, 2014). This generated confrontations for decades, and surprisingly the result has been an increment on the protected space on the campus and the strengthening and institutionalization of the office in charge of its protection (Carrillo-Trueba, 1995; Zambrano and Cano-Santana, 2016). Volunteer programs, political gatherings and social mobilizations to stop the destruction of the remaining native ecosystem in the Pedregal areas, and the institutional work based on the people in charge of the Reserve have helped to save it from destruction (Carrillo-Trueba, 1995; García-Barrios, 2014).

Nowadays, the campus is facing a new challenge since the university needs to grow to meet the demand for education in the country. The remaining space is highly reduced and, hence, the opportunities to increase the infrastructure are severely limited. Similar to other universities, such as Oxford or Cambridge in the UK (NIC, 2018), a university needs to increase its facilities without affecting its landscape or monuments. With these challenges in mind it is necessary to ask if it is possible to manage a PUGS under this type of pressure. The information generated on each of the parts is crucial to guide management decisions. Consequently, the integration of the three components (scientific knowledge, community interaction with the environment and management decisions) may provide the building blocks for the authorities and decision-makers to define actions for the university and the reserve.

Assessment of the Three Components

Typically, knowledge is generated by different and very specific disciplines; collaborators work together and produce information within each one of the three components explained above. Once the information is available, selection, and organization processes are carried out to develop Reserve management plans that could facilitate decision making regarding its management.

Therefore, it is expected that the intersection between the three components should lead to the proper management of a PUGS. That is, the union between all of the disciplines is crucial to generate effective management regarding the Reserve. This should be particularly true in a PUGS within a university able to generate scientific knowledge needed immediately by academics in constant communication with the authorities and the community.

METHODS

Participatory Approach and Group Fuzzy Cognitive Map Building

Integrating knowledge through participatory modeling has been a successful approach although it can present several challenges (Gray et al., 2012). Through participatory workshops it is plausible to elicit the perception of different sectors of stakeholders. In order to know, communicate and graphically capture the perception of an individual or group of individuals who are part of a socio-ecological system several techniques have been developed, one of which is the mental model. A mental model obtained through the FCM approach (see Kosko, 1986) can be defined as internal representations or beliefs of the external world (Jones et al., 2011; Gray et al., 2012). FMC is a useful tool for understanding the community's knowledge about the university campus and its implications for the REPSA management since it has a bottom-up approach and can integrate in a standardized format several levels of knowledge from individual to community as well as expert knowledge (Gray et al., 2015). After building the FCM, results are analyzed by an interdisciplinary group. The ideas, and perceptions of different actors are merged through an in-depth discussion, which in turn contributes toward better decision-making related to scientific monitoring and restoration, and improvement of the interaction university community—nature and urbanization decisions. The analysis evaluated whether the concepts of the FCM and its interactions fit into the three components (i) scientific knowledge (monitoring/restoration), (ii) community interaction with the environment, and (iii) management decisions.

In order to further understand the factors driving management strategies for PUGS, we applied a participatory approach through which the perceptions of different actors and their social and ecological relationships with this PUGS were elicited and used to prove the integration of the three components. A participatory workshop was conducted in 2018 with 25 members of the university community to discuss the main concerns, management plans, and decision making around the university campus and REPSA protection and conservation. The group of participants was formed by students, academics, and administrators working at the university in different areas of expertise (e.g., conservation biologists, ecologists, restoration specialists, architects, urban planners, veterinarians, and administrators) and collaborating closely with projects related to the REPSA. Specifically, the students (40%) were mostly part of the Postgraduate Program of Biological Sciences although a few undergraduate students also participated. The academics (36%) were from several research institutes such as Biology and Ecology Institutes as well as the Architectural, Sciences, and Veterinarian and Zootechnics Faculties, whose research activities have been focused for several years on the REPSA. In addition, some of the academics from the Sciences Faculty and Architecture Faculty were working on topics related to campus mobility. Finally, the administrators (24%) were part of the Executive Secretariat of the Ecological Reserve of Pedregal de San Ángel (SEREPSA, as it stands in Spanish) which is in charge of the liaison between the Technical Committee and several academic entities, as well as with the university community and society. The percentage of members of each one of these particular sectors was similar to prevent as much as possible specific group bias.

The participatory workshop consisted of several activities (see **Supplementary Material 1** for more details) to build a collaborative model (e.g., Voinov et al., 2018; Cholewicki et al., 2019): (i) construction of a rich picture, or a drawing to illustrate a specific situation (in groups of five people). Since the RESPA is immersed in the campus and what is happening might affect or have influence on the decisions made at the Reserve level, the participants were asked to discuss and to make a sketch based on the question *What do you think are the main problems on the campus and their implications for the Reserve conservation?* Drawing a rich picture provides an understanding process of the central idea, and it is plausible to identify multiple viewpoints as all of the participants intervene; (ii) explanation of the rich picture and collection of the concepts that will be the building blocks of the FCM. In this activity the participants exposed to each other the drawings; concurrently a facilitator was writing on paper cards all of the words and concepts mentioned by the participants; (iii) building a group FCM where the paper cards with the concepts were connected through causal relations. For example, a concept may have a direct influence on another and/or others by increasing or decreasing them. The participants were asked to connect the concepts and to establish the relations among them through positive and/or negative arrows. Here the role of the facilitators was critical to guarantee a mental model that reflected the perceptions of all of the participants through a large discussion and promoting consensus; and finally, (iv) weighting of the FCM concepts, which provides an individual weight of the most relevant components and their relative importance in the model according to each one of the participants. For this activity, the same number of stickers were given to the participants who were asked to put the stickers on what they believe were the most important concepts of the map. Each sticker had a value of one point, and the participants made a freewill to use their points in one or several relevant concepts.

This exercise triggers the communication between parties that need to communicate in a systematic way and to synthesize the community perception of REPSA, the urban green areas, and the urban context. The mental model generated is a first interdisciplinary product to evaluate the management of this PUGS. The result obtained is dynamic and therefore can be used to analyze changes in the perception of the problems of the university campus, to evaluate conservation strategies based on management, population growth, and public safety.

Fuzzy Cognitive Map Analysis

By employing the specialized software Mental Modeler (www.mentalmodeler.org; Gray et al., 2013) and Cytoscape 3.4.0 (Shannon et al., 2003) the mental model generated during the workshop was digitized, visualized and analyzed. The model is visualized as a network in which concepts are connected through positive or negative edges. These programs were also employed to compute the network structure statistics, including number of concepts, type of concept (driver, ordinary, receiver) number of connections, connections per concept (number of connections divided by number of concepts), and the calculation of measures such as density or an index of connectivity determined by dividing the number of connections present by the maximum number of possible connections (Hage and Harary, 1983; Özesmi and Özesmi, 2004), and complexity score calculated as the ratio of receiver concepts to driver concepts (Özesmi and Özesmi, 2004; Gray et al., 2014). In addition, in Cytoscape 3.4.0 a Hierarchical Layout algorithm was applied to the network to help visualize the flow of information from the base to the top concepts.

In order to deeper analyze the concepts and their relations, all of the concepts were assigned to categories regarding the three components as follows: A = scientific knowledge (monitoring/restoration), B = community interaction with the environment, and C = management decisions. Since some of the concepts fell into two or the three categories, the subcategories *A-B*, *A-C*, *B-C*, and *A-B-C* were also included. For instance, concepts that potentially corresponded to both the *A* and *B* categories were included into the *A-B* subcategory. Thus, some concepts were exclusive to a category or fell into two or more categories. The concepts assignment was conducted as part of a group activity that included the complete interdisciplinary work team, who discussed the categorization of concepts and reached a consensus. Finally, the concepts were color coded to be visualized according to the categories (see **Figure 1**) in the hierarchical network. Likewise, the weighting score was visualized as black dots for the corresponding concepts.

RESULTS

The participatory workshop was successful in terms of attendance and participation of members of the university community. Through several activities conducted during the workshop (described in the **Supplementary Material 1**), a FCM representing the participant community's perception was created. This model was the first interdisciplinary product developed by the research project team to evaluate the management of the REPSA.

The FCM developed from the workshop was moderately complex (**Table 1**) as it consists of 45 concepts and 85 connections, whereas the connections per concept (calculated by the ratio connections/concepts) was of 1.88, the density of 0.042, and complexity (ratio of receiver concepts/driver concepts) was of 0.875. Through the hierarchical arrangement of the network a total of 14 hierarchical levels were observed (**Figure 2**) as well as the flow of information which goes from the bottom to the top of the network, and in the same flow, three types of concepts or nodes were recognized: the drivers or those affecting other concepts, the ordinary ones which are affecting and at the

TABLE 1 | Summary statistics of the network.

Metrics	Value
Total concepts	45
Total connections	85
Density	0.043
Connections per concept	1.889
Number of driver concepts	8
Number of receiver concepts	7
Number of ordinary concepts	30
Total positive connections	44
Total negative connections	41
Number of weighted concepts	17
Complexity score	0.875

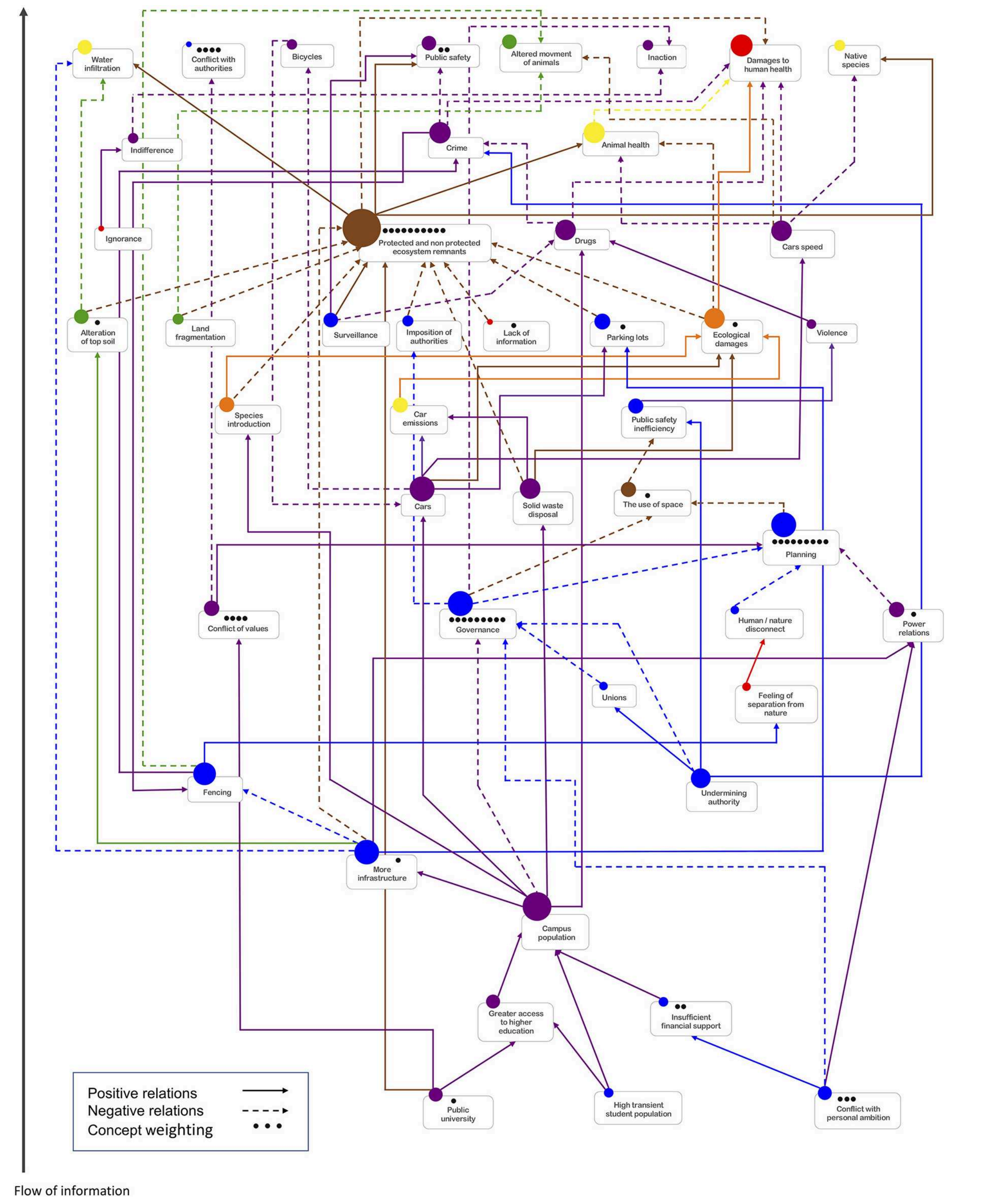

FIGURE 2 | FCM depicting the community's perception. The color of the concepts corresponds to the different categories established: *A* in yellow, *B* in red, *C* in blue, whereas the subcategories *A-B*, *A-C*, *B-C*, and *A-B-C* are in orange, green, purple, and brown, respectively. Likewise, the size of the nodes is consistent with the centrality, hence, bigger nodes have more connections with other nodes, while the smallest nodes contain one edge only. The small black circles next to the concepts indicate the weighting scores, that is, the sum of the points given by each participant to those concepts considered of high relevance for the system. The concepts are connected through causal relations that are positives (solid lines) or negatives (dotted lines). The black arrow to the left depicts the flow of information from the base to the top concepts.

same time are influenced by other concepts, and the receivers not having influence on others only being influenced by others (Özesmi and Özesmi, 2004) (**Figure 2**; for more detail on the meaning of concepts see **Supplementary Material 2**).

With regard to the category allocation, 30 out of the 45 concepts are contained within the category *C* (15 concepts) and the subcategory *B-C* (15 concepts; see **Table 2** and **Figure 3**). The categories *A* and *B* contain four concepts each, whereas

TABLE 2 | Concepts location and characteristics.

Concepts	Network level	Centrality	Input	Output	Weighting score	Component*
Protected and non-protected ecosystem remnants	12	16	11	5	10	A,B,C
Campus population	3	9	3	6	7	B,C
Governance	7	8	4	4	9	C
More infrastructure	4	7	1	6	1	C
Cars	9	7	2	5	–	B,C
Ecological damages	11	7	4	3	1	A,B
Crime	13	6	3	3	–	B,C
Damages to human health	14	6	6	–	–	B
Cars speed	12	5	1	4	–	B,C
Fencing	5	5	2	3	–	C
Drugs	12	5	3	2	–	B,C
Planning	8	5	4	1	9	C
Undermining authority	5	4	–	4	–	C
Solid waste disposal	9	4	1	3	–	B,C
Animal health	13	4	3	1	–	A
Surveillance	11	3	–	3	–	C
Conflict with personal ambition	1	3	–	3	3	C
Public university	1	3	–	3	1	B,C
Alteration of top soil	11	3	1	2	1	A,C
Species introduction	10	3	1	2	–	A,B
Conflict of values	7	3	1	2	4	B,C
The use of space	9	3	2	1	1	A,B,C
Security inefficiency	10	3	2	1	–	C
Power relations	7	3	2	1	1	B,C
Parking lots	11	3	2	1	1	C
Car emissions	10	3	2	1	–	A
Greater access to higher education	2	3	2	1	–	B,C
Public safety	14	3	3	–	2	B,C
Altered movement of animals	14	3	3	–	–	A,C
Water infiltration	14	3	3	–	–	A
Land fragmentation	11	2	–	2	–	A,C
High transcent student population	1	2	–	2	–	C
Indifference	13	2	1	1	–	B,C
Imposition of authorities	11	2	1	1	–	C
Unions	6	2	1	1	–	C
Violence	11	2	1	1	–	B,C
Human/nature disconnect	7	2	1	1	–	C
Feeling of separation from nature	6	2	1	1	–	B
Insufficient financial support	2	2	1	1	2	C
Bicycles	14	2	1	1	–	B,C
Inaction	14	2	2	–	–	B,C
Native species	14	2	2	–	–	A
Lack of information	11	1	–	1	1	B
Ignorance	12	1	–	1	–	B
Conflict with authorities	14	1	1	–	4	C

**Components A, scientific knowledge (monitoring/restoration), B, community interaction with the environment, and C, management decisions.*

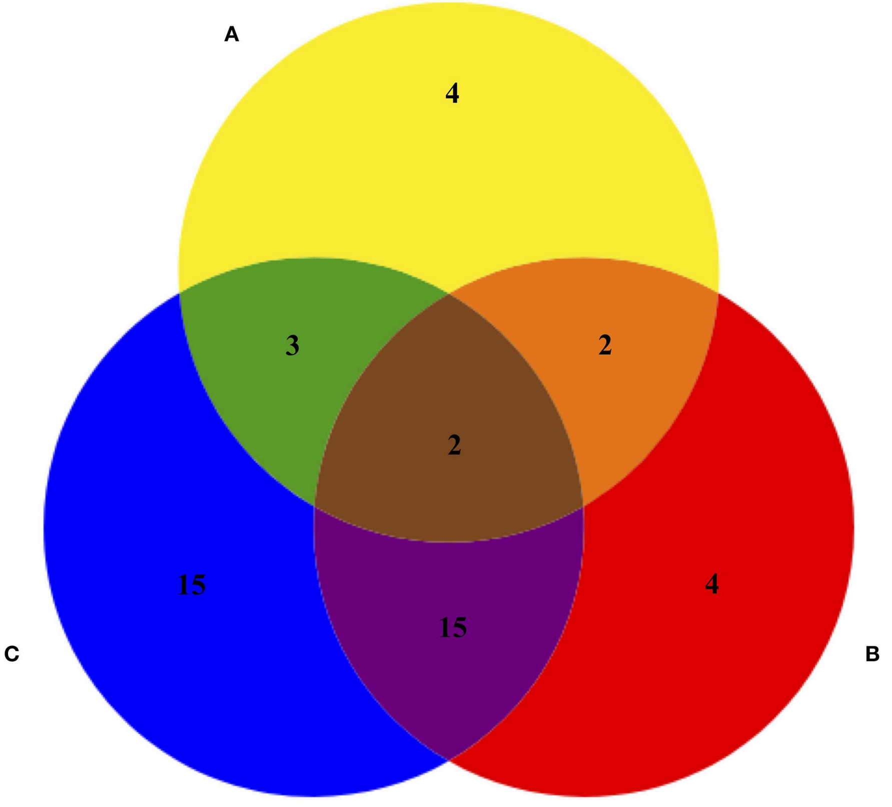

FIGURE 3 | Total number of concepts per component (see **Figure 1**) and the number of concepts within each of the intersections. Yellow circle represents Scientific knowledge, Blue circle represents Management decisions, and Red circle represent Community interaction with the environment.

A-B and *A-C* contain two and three concepts, respectively. The intersection of the three components, the subcategory *A-B-C*, comprises only two concepts, one of these (*Protected and non-protected ecosystem remnant*) presented the highest centrality, however, it is not related with any management action. Category *C* and subcategory *B-C* not only have the highest number of concepts, also, the first seven hierarchical levels of the FCM (**Figure 2**) presented concepts corresponding to these categories only. It is not until the eighth level where a component from the subcategory *A-B-C* (*The use of space*) appears. From the ninth to the fourteenth levels all categories are present. **Figure 4** depicts the centrality for each one of the concepts contained in the categories and subcategories. The polygons are shaped according to the number of concepts per category and subcategory and their centrality. Thus, one of the concepts of subcategory *A-B-C* (*Protected and non-protected ecosystem remnant*) presents the highest centrality while the lowest are for two concepts within category *B* and one of category *C*.

The category *C* is highly connected to almost all of the categories (**Figure 5**), while the category *A* has the lowest percentage of connections (both the number of edges incoming to and outgoing from a node). From the total number of connections (coming in and going out of the nodes), the category *C* and subcategory *B-C* corresponded to 74–89% and 55–60%, respectively. Private relations of a category, that is, those connecting concepts within the same category or subcategory are depicted in brown, and as shown in **Figure 5** a considerable number of such private relations are presented in categories *C* and *B-C*.

The concepts with the highest centrality were *Protected and non-protected ecosystem remnants, Campus population, Governance, More infrastructure, Cars, and Ecological damages* (**Table 2** and **Figure 4**). *Undermining authority, Conflict with personal ambition, Surveillance, Public university, High transient student population, Land fragmentation, Ignorance* and *Lack of information* are the driver concepts, that is, components that influence others. On the other hand, *Damages to human health, Altered movement of animals, Water infiltration, Public safety, Inaction, Native species, and Conflict with authorities* are receiver concepts or those that are affected by others (**Table 1**). The concepts at the end of the discussion of the participatory workshop were weighted up individually (see **Supplementary Material 1**) and the highest score was for the concepts *Protected and non-protected ecosystem remnants* (with 10 points), *Governance* and *Planning* (nine points each) (**Figure 2**). At least for the concepts *Protected and non-protected ecosystem remnants* and *Governance* the highest centrality and the highest weighted score were consistent.

DISCUSSION

The analysis tests three components —scientific knowledge, community interaction with the environment, and managements

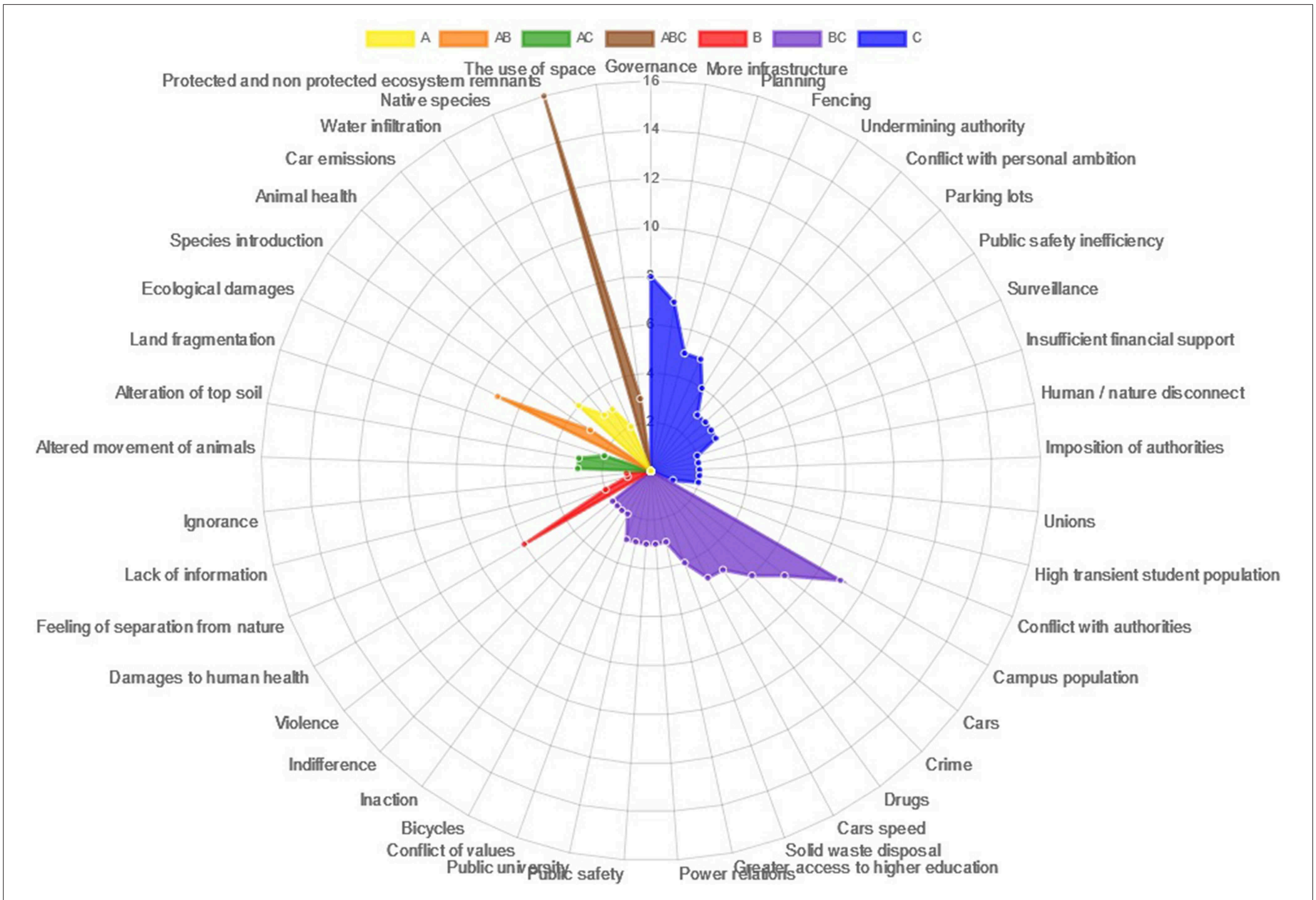

FIGURE 4 | Number of connections for each one of the network components per categories.

decisions—and provides insight into the community perceptions and conflicts between the university campus and the REPSA. There is a prioritization to solve problems in the Reserve, focusing mostly in urban threats. The first seven levels of the network (bottom to top, see **Figure 2**) highlight the urbanization pressure within the campus; showing a society that expects constant growth of the public university. In second place, the main problems are those variables that directly affect the REPSA. The discussion that took place during the participatory workshop and building of FCM revealed that assistants view the campus as being under constant urban pressure; an increase in infrastructure and student population represents a severe threat to the protection of green spaces.

Since the participatory workshop was conducted with similar percentage of participants from each sector (students 40%, academics 36%, and administrators 24%), the power was balanced to hold discussion and dialogue (Barnaud and van Paassen, 2013). Participants were free to express their opinion within the workshop, and the power relations were shown in the mental model. The model—and the moment when it is being built—is unique for the community as it represents a relevant learning experience for participants and detonates the processes of reflection within the group. Nonetheless, participants and executors might validate and use the information in very different ways because each one of the participants has, starting at the same mental model, a particular analysis according to individual interests and concerns. Planning formulas (another of the more weighted concepts), can help absorb complications and disputes if conducted with a long-term vision under a proper institutionalization and balance of power to reduce short term individual actions (e.g., Puchet-Anyul, 2010; Puchet-Anyul et al., 2013).

Several methodologies have been developed to meet different needs in participatory approaches (Voinov et al., 2016), thus, results might be different based on the methodology employed (Jordan et al., 2018). We used FCM to represent a group mental model, nonetheless, as this approach takes a large-scale view of the world (Giabbanelli et al., 2017) methodological limitations dealing with the complexity of a particular problem are recognized (Jordan et al., 2018). In contrast, Agent Based Modeling, with a micro-level view technique (each entity or agent is represented) can be adopted and used in combination with FCM (e.g., Giabbanelli et al., 2017) to obtain an accurate socio-ecological interaction model. As for our study, we found that

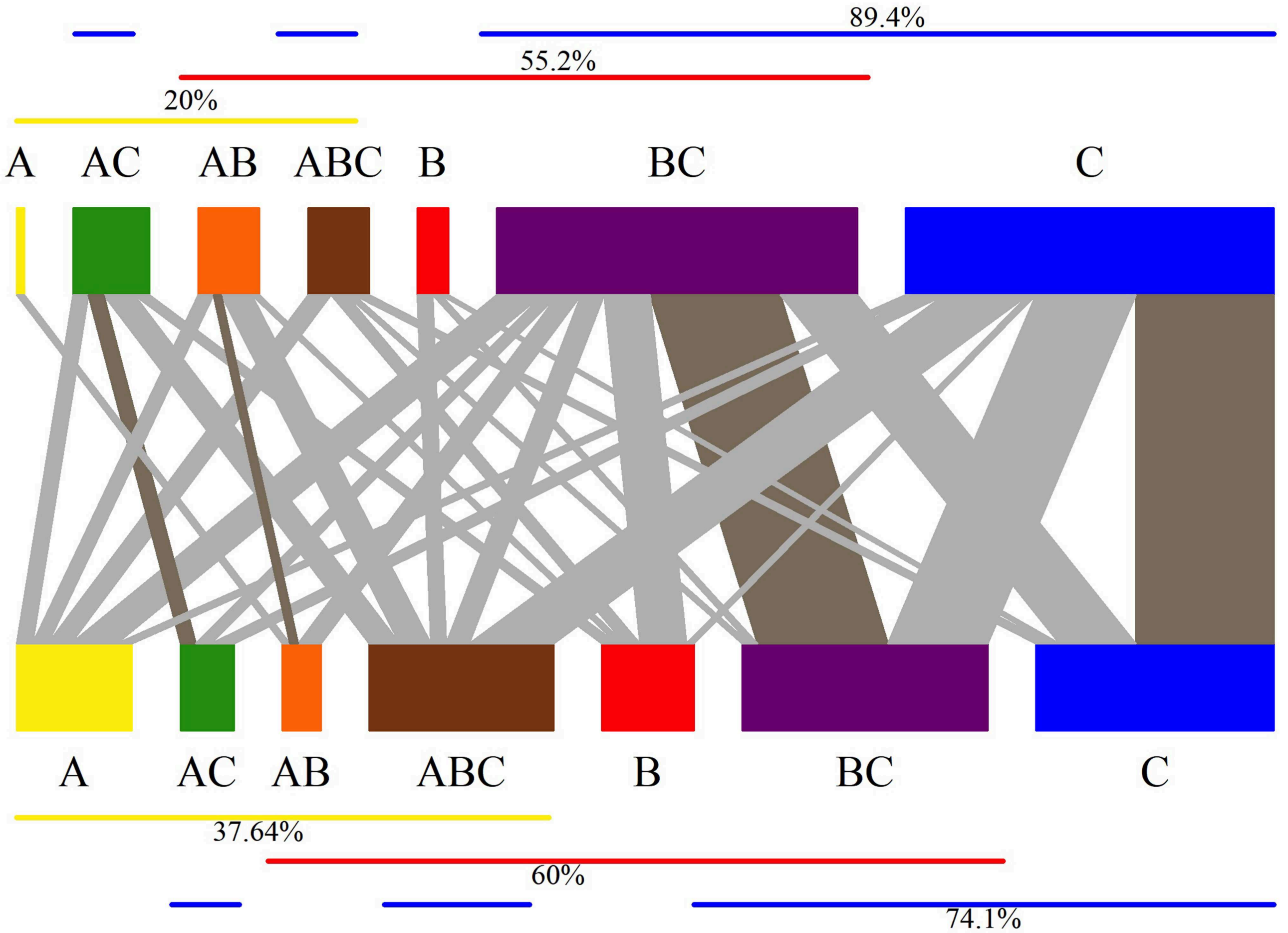

FIGURE 5 | Proportion of connections within and between categories. Darker lines correspond to unique connections or those linking components from the same category.

the FCM approach was useful to evaluate areas where conflicts around the reserve and the university campus occur.

When the concepts of the FCM were classified within the three components, surprisingly there were only two that fell in the intersection: *Protected and non-protected ecosystem remnants* and *The use of space.* The first one, with the greatest centrality, would support our central idea that the intersection of the three components is essential. Nevertheless, this concept does not have any management implication as it only refers to the conserved area. Likewise, REPSA benefits (such as ecosystem services) are not displayed here or in the rest of the model.

The FCM suggests that some reasons why this interaction is reduced are: (i) the lack of feedback links among actors, and (ii) a mismatch between conservation objectives and actual projects generated to preserve the Reserve. The absence of a concept related to scientific generation and the presence of concepts such as *Ignorance*, *Indifference*, *Imposition of authorities*, and *Conflicts with authorities* suggest a lack of feedback on the most important interaction between knowledge generation and management decision.

The lack of links among actors is partially based on the poor communication regarding the importance of the ecosystem services and the biodiversity inhabiting PUGS. Other factors related to the perception of the local community, including academics working on its ecological understanding and authorities that are responsible for the protection of these urban ecosystems, seem to be relevant in the decision process. The mismatch arises from the low number of connections that the ecological scientific knowledge component (Category *A*) has in the FCM. Even at the university, this lack of inclusion of current scientific knowledge in management and conservation programs is as common as in the rest of urban societies (Kim and Byrne, 2006). Some projects fail partially because they are justified under a particular research interest instead of management needs. Also mono-disciplinary scientific research is unable to solve problems in socio-ecological systems for these require interdisciplinarity and transdisciplinarity (Lélé and Norgaard, 2006; MacMynowski, 2007). The lack of feedback loops may generate a spiral of apparently impossible-to-solve conflicts, as well as discontent and general discomfort across sectors coupled with discomfort that falls on individuals rather than institutions.

These conditions can be seen in several examples in REPSA. A first example that shows the lack of feedback links was the elimination of the *Eucalyptus* populations in the Reserve, which generated a series of expressions of disapproval and protests against deforestation by the community. The weak feedback links came from the authorities since a communication channel did not exist to explain the ecological damages being caused by the presence of exotic flora (Segura-Burciaga and Martínez-Ramos, 1994; Segura-Burciaga, 2009). There was no explanation of the importance of their removal or the positive environmental outcomes that accompanied such actions (Segura-Burciaga and Meave, 2001; Antonio-Garcés et al., 2009). The response to these eradication programs by groups of the society is clearly in defense of eucalyptus. Same problem applies to a more recent feral dog eradication program.

Weak feedback links can be seen in a second example based on the efforts made by the academic community to generate information that contributes to educational programs or strategies that promote that the whole community understands and supports the protection of lava relicts surrounded by buildings and roads. The adoption and restoration of a remnant lava field by the Geosciences community called "Geopedregal" (González et al., 2016) succeeded in promoting the conservation and geo-heritage identity, but only at the local community level, and this effort is not acknowledged for larger decisions regarding land use on the campus or for receiving long-term support.

Likewise, the complexity of the misinformation cannot be solved only with informative programs. It is necessary to create a web of connections between components *A* and *C*. There is abundant scientific information produced under robust analysis that can be easily accessed by the community; however, none of it is used in the decisions regarding new constructions, placing fences, and gardening. The application of scientific knowledge requires additional work that facilitates the understanding of authorities to make informed decisions.

One of the examples of the mismatch is based on the monitoring program of several species that provided relevant knowledge on how these species use the reserve, as well as their population and seasonal dynamics (Ramírez-Cruz et al., 2018, 2019). This includes ecological interactions among species and the diverse impacts of humans. These efforts have to be continued to understand ecological interactions in the long-term. Nevertheless, constant monitoring is not considered by funded programs of the Reserve.

Other examples show the mismatch between conservation objectives and the projects in REPSA. There is a social cartography study that aims to understand the time spent by the inhabitants within an area, where these are distributed, and their environment. Results are visualized by mapping territory use by individuals (Fox, 1998; Vaughan, 2018). This information is valuable to decide the land use of the campus and the importance of green spaces and the Pedregal ecosystem, but it is not used for management. This constantly happens when decisions are made without considering the scientific information about land conservation, the genetic diversity, species richness, and the ecological interactions in the long-term. Both projects are part of the responsibilities of the authorities and could be used to evaluate the efficiency of actions taken on *A*, *B*, *C*, and their intersections, but are not used in any of the management programs.

PUGS can be seen as a common resource having different dynamics for their management. An approach for proper management is based on the community's appropriation of the area, thus ensuring that the whole community will protect it (Ostrom, 1990; Matson et al., 2016). In this situation, it is paramount that the community is informed with clear mechanisms of decision and that most members reach an agreement. Decisions must be based on the integration of the new information generated by the community itself (Cook, 2008). Our results suggest this is not happening partly because the scientists should improve the communication strategies (Raymond et al., 2010; Safford and Brown, 2019), monitoring the adequate integration in the conservation programs. Nonetheless, reverting this situation is possible. The constant cooperation and learning between researchers—an important condition to develop innovative research— is key for an organization (Buanes and Jentoft, 2009), an idea that is entirely applicable to PUGS management. Systematic monitoring of the long-term effects of invasive species, acid rain and atmospheric deposition of residues, and species prioritization for conservation plans (Arponen, 2012; Lindenmayer et al., 2015; Wright et al., 2018) must be properly communicated to generate a reaction from different actors. Likewise, the assessment of the ecosystem services provided by the REPSA should be made public. Profitable management of the Reserve depends on the active engagement of several actors as well as a supportive university governance.

Importantly, the model revealed that the REPSA management is only focused on administrative activities. Technical profiles only focus on solving management and administrative problems, without time, or funds to generate or apply academic information for management. Nonetheless, the mismatch can be solved by taking actions directed to specific fields, that is, actions directed to well-localized high-pressure points, for example *More infrastructure* near the base of the FCM and *Governance* in the middle of it (see **Figure 2**). By changing the negative edges to positive ones, the structure of the network will modify the whole FCM by establishing priority actions related to management based on scientific knowledge. This would possibly improve the system's internal management and sustainability.

To modify the interactions based on the FCM, a variable that must be included should be the institutionalization of the reserve management. Even though the reserve operates under specific guidelines that are part of the internal regulations of the Technical Committee of the Ecological Reserve of Pedregal de San Ángel (Gaceta UNAM, 2006), it lacks institutionalization processes for scientific knowledge. There is no liaison group or committee that functions as organizer and facilitator with capacities of linking the great amount of scientific information accumulated about social-ecological systems to the operational groups as well as to other researchers and the general public (Castillo et al., 2018).

The intersection of the three components only had the two concepts *Protected and non-protected ecosystem remnants* and *The use of space*), the first one was highly connected but it does not imply management or applied scientific knowledge. In this particular case, our assumption about the intersection does not apply because the interaction is not naturally given, and even in this university community these interactions do not guarantee the management and conservation goals. Further studies that aim to accomplish this will be developed within the REPSA.

The complexity of the protected urban green spaces in terms of their dynamics within the city requires to actively build the collaboration among actors to reinforce the three components (scientific knowledge, community interaction with the environment, and management decisions).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

LZ, ZC-S, and AC participated in the design of the project. LZ coordinated the study. AW and DA-L participated in the design of the participatory workshop and the analyses of the mental model. LZ, AW, and DA-L wrote the manuscript. The rest of the authors attended the workshop, included relevant information within their areas of expertise, and reviewed the manuscript.

FUNDING

This work was financially supported by the Dirección General de Asuntos del Personal Académico—Universidad Nacional Autónoma de México through the project PAPIIT IV200117 Eco-social analysis of an urban reserve for sustainability on the main campus of the National Autonomous University of Mexico.

ACKNOWLEDGMENTS

We are grateful with the Consejo Nacional de Ciencia y Tecnología (CONACYT) as scholarships were granted to MB-R (scholarship 629340), MN-G (scholarship 853751), GR-C (scholarship 270133), JP-L (scholarship 609346), BG (scholarship 479502) to conduct postgraduate studies. We would like to thank to the Programa de Posgrado en Ciencias Biológicas, UNAM. We also thank the REPSA technicians to attend to the workshop and Merly Yaridi Fábila, the postdoctoral researchers DA-L, AF, AR, HC-A, and whose scholarships were granted by the PAPIIT project IV200117. Iván Castellanos Vargas offered technical support.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00144/full#supplementary-material

REFERENCES

Alberti, M., Marzluff, J. M., Shulenberger, E., Bradley, G., Ryan, C., and Zumbrunnen, C. (2003). Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. *Bioscience* 53, 1169–1179. doi: 10.1641/0006-3568(2003)053[1169:IHIEOA]2.0.CO;2

Amin, A. (2007). Re-thinking the urban social. *City* 11, 100–114. doi: 10.1080/13604810701200961

Andersson, E. (2006). Urban landscapes and sustainable cities. *Ecol. Soc.* 11:34. doi: 10.5751/ES-01639-110134

Antonio-Garcés, J., Peña, M., Cano-Santana, Z., Villeda, M., and Orozco-Segovia, A. (2009). "Cambios en la estructura de la vegetación derivados de acciones de restauración ecológica en las Zonas de Amortiguamiento Biológicas y Vivero Alto," in *Biodiversidad del Ecosistema del Pedregal de San Ángel*, eds A. Lot and Z. Cano-Santana (México City: UNAM), 465–481.

Aronson, M. F., Lepczyk, C. A., Evans, K. L., Goddard, M. A., Lerman, S. B., MacIvor, J. S., et al. (2017). Biodiversity in the city: key challenges for urban green space management. *Front. Ecol. Environ.* 15, 189–196. doi: 10.1002/fee.1480

Arponen, A. (2012). Prioritizing species for conservation planning. *Biodivers. Conserv.* 21, 875–893. doi: 10.1007/s10531-012-0242-1

Barnaud, C., and van Paassen, A. (2013). Equity, power games, and legitimacy: dilemmas of participatory natural resource management. *Ecol. Soc.* 18:art21. doi: 10.5751/ES-05459-180221

Brown, J. H., Whitham, T. G., Morgan Ernest, S. K., and Gehring, C. A. (2001). Complex species interactions and the dynamics of ecological systems: long-term experiments. *Science* 293, 643–650. doi: 10.1126/science.293.5530.643

Buanes, A., and Jentoft, S. (2009). Building bridges: institutional perspectives on interdisciplinarity. *Futures* 41, 446–454. doi: 10.1016/j.futures.2009.01.010

Buckland, S. T., Rexstad, E. A., Marques, T. A., and Oedekoven, C. S. (2015). *Distance Sampling: Methods and Applications*. New York, NY: Springer. doi: 10.1007/978-3-319-19219-2

Cano-Santana, Z., Castillo-Argüero, S., Martínez-Orea, Y., and Juárez-Orozco, S. (2008). Análisis de la riqueza vegetal y el valor de conservación de tres áreas incorporadas a la Reserva Ecológica del Pedregal de San Ángel, D.F. (México). *Bol. Soc. Bot. Méx.* 82, 1–14. doi: 10.17129/botsci.1777

Cano-Santana, Z., Pisanty, I., Segura, S., Mendoza-Hernández, P. E., León-Rico, R., Soberón, J., et al. (2006). "Ecología, conservación, restauración y manejo de las áreas naturales y protegidas del pedregal del Xitle," in *Manejo, Conservación y Restauración de Recursos Naturales en México*, eds K. Oyama and A. Castillo (Mexico City: UNAM/Siglo XXI), 203–226.

Carrillo-Trueba, C. (1995). *El Pedregal de San Ángel*. Mexico City: UNAM.

Castillo, A., Vega-Rivera, J. H., Pérez-Escobedo, M., Romo-Díaz, G., López-Carapia, G., and Ayala-Orozco, B. (2018). Linking social-ecological knowledge with rural communities in Mexico: lessons and challenges toward sustainability. *Ecosphere* 9:e02470. doi: 10.1002/ecs2.2470

Chaudhry, P., and Tewari, V. P. (2010). Managing urban parks and gardens in developing countries: a case from a City. *Int. J. Leis. Tour. Mark.* 1, 248–256. doi: 10.1504/IJLTM.2010.029588

Cholewicki, J., Popovich, J. M., Aminpour, P., Gray, S. A., Lee, A. S., and Hodges, P. W. (2019). Development of a collaborative model of low back pain: report from the 2017 NASS consensus meeting. *Spine J.* 19, 1029–1040. doi: 10.1016/j.spinee.2018.11.014

Cook, W. K. (2008). Integrating research and action: a systematic review of community-based participatory research to address health disparities in environmental and occupational health in the USA. *J. Epidemiol. Commun. Health* 62, 668–676. doi: 10.1136/jech.2007.067645

Davenport, M. A., Bridges, C. A., Mangun, J. C., Carver, A. D., Williard, K. W. J., and Jones, E. O. (2010). Building local community commitment to wetlands restoration: a case study of the Cache River Wetlands in Southern Illinois, USA. *Environ. Manage.* 45, 711–722. doi: 10.1007/s00267-010-9446-x

de Oliveira, L., and Martins, E. R. (2002). A quantitative assessment of genetic erosion in ipecac (Psychotria ipecacuanha). *Genet. Resour. Crop Evolu.* 49, 607–617. doi: 10.1023/A:1021275006915

Delgado, H., Molinero, R., Cervantes, P., Nieto-Obregon, J., Lozano-Santacruz, R., Macías González, H., et al. (1998). Geology of Xitle volcano in southern Mexico City - A 2000-year-old monogenetic volcano in an urban area. *Rev. Mex. Ciencias Geológicas* 15, 115–131.

Dinar, A., Albiac, J., and Sánchez-Soriano, J. (2008). *Game Theory and Policy Making in Natural Resources and the Environment*. London: Routledge. doi: 10.4324/9780203932018

Ernstson, H., van der Leeuw, S. E., Redman, C. L., Meffert, D. J., Davis, G., Alfsen, C., et al. (2010). Urban transitions: on urban resilience and human-dominated ecosystems. *Ambio* 39, 531–545. doi: 10.1007/s13280-010-0081-9

Estañol-Tecuatl, F., and Cano-Santana, Z. (2017). Recovery of basalt substrate for xeric scrub restoration in a lava field in Mexico City. *Ecol. Restor.* 35, 41–51. doi: 10.3368/er.35.1.41

Faith, D. P., Magallón, S., Hendry, A. P., Conti, E., Yahara, T., and Donoghue, M. J. (2010). Evosystem services: an evolutionary perspective on the links between biodiversity and human well-being. *Curr. Opin. Environ. Sustain.* 2, 66–74. doi: 10.1016/j.cosust.2010.04.002

Fox, J. (1998). Mapping the commons: the social context of spacial information technologies. *Common Prop. Resour. Dig.* 45, 1–4.

Gaceta UNAM (2006). *Reglamento interno del Comité Técnico de la Reserva Ecológica del Pedregal de San Ángel de Ciudad Universitaria.* 14 (2006).

Gaertner, M., Larson, B. M. H., Irlich, U. M., Holmes, P. M., Stafford, L., van Wilgen, B. W., et al. (2016). Managing invasive species in cities: a framework from Cape Town, South Africa. *Landsc. Urban Plan.* 151, 1–9. doi: 10.1016/j.landurbplan.2016.03.010

García-Barrios, R. (2014). El origen de la reserva ecológica de la UNAM en CU: historia de un conflicto patrimonial y ambiental. *Cult. y Represent. Soc.* 9, 177–226.

Giabbanelli, P. J., Gray, S. A., and Aminpour, P. (2017). Combining fuzzy cognitive maps with agent-based modeling: frameworks and pitfalls of a powerful hybrid modeling approach to understand human-environment interactions. *Environ. Model. Softw.* 95, 320–325. doi: 10.1016/j.envsoft.2017.06.040

González, R., Estrada, M., Orellana, A., Bueno, I., and Segura, S. (2016). *Saving Islands Within a City*. Available online at: https://it.cornell.edu/ (accessed March 17, 2019).

Gray, S., Chan, A., Clark, D., and Jordan, R. (2012). Modeling the integration of stakeholder knowledge in social-ecological decision-making: benefits and limitations to knowledge diversity. *Ecol. Modell.* 229, 88–96. doi: 10.1016/j.ecolmodel.2011.09.011

Gray, S., Zanre, E., and Gray, S. R. J. (2014). "Fuzzy cognitive maps as representations of mental models and group beliefs," in *Fuzzy Cognitive Maps for Applied Sciences and Engineering*, ed. E. I. Papageorgiou (Berlin; Heidelberg: Springer), 29–48. doi: 10.1007/978-3-642-39739-4_2

Gray, S. A., Gray, S., Cox, L. J., and Henly-Shepard, S. (2013). "Mental modeler: a fuzzy-logic cognitive mapping modeling tool for adaptive environmental management," in *2013 46th Hawaii International Conference on System Sciences* (Wailea, HI), 965–973. doi: 10.1109/HICSS.2013.399

Gray, S. A., Gray, S., de Kok, J. L., Helfgott, A. E. R., O'Dwyer, B., Jordan, R., et al. (2015). Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. *Ecol. Soc.* 20:art11. doi: 10.5751/ES-07396-200211

Hage, P., and Harary, F. (1983). *Structural Models in Anthropology*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511659843

Hansen, A. J., and DeFries, R. (2007). Ecological mechanisms linking protected areas to surrounding lands. *Ecol. Appl.* 17, 974–988. doi: 10.1890/05-1098

Hortelano-Moncada, Y., Cervantes, F. A., and Trejo-Ortiz, A. (2009). Mamíferos silvestres de la Reserva Ecológica del Pedregal de San Ángel en Ciudad Universitaria, Universidad Nacional Autónoma de México, México, D. F. *Rev. Mex. Biodivers.* 80, 507–520.

James, P. (2015). *Urban Sustainability in Theory and Practice*. London: Routledge. doi: 10.4324/9781315765747

Jones, N. A., Ross, H., Lynam, T., Perez, P., and Leitch, A. (2011). Mental models: an interdisciplinary synthesis of theory and methods. *Ecol. Soc.* 16:46. doi: 10.5751/ES-03802-160146

Jordan, R., Gray, S., Zellner, M., Glynn, P. D., Voinov, A., Hedelin, B., et al. (2018). Twelve questions for the participatory modeling community. *Earth's Future* 6, 1046–1057. doi: 10.1029/2018EF000841

Jordano, P. (2016). Chasing ecological interactions. *PLoS Biol.* 14:e1002559. doi: 10.1371/journal.pbio.1002559

Kagata, H., and Ohgushi, T. (2006). Bottom-up trophic cascades and material transfer in terrestrial food webs. *Ecol. Res.* 21, 26–34. doi: 10.1007/s11284-005-0124-z

Kharel, F. R. (1997). Agricultural crop and livestock depredation by wildlife in Langtang National Park, Nepal. *Mt. Res. Dev.* 17, 127–134. doi: 10.2307/3673827

Kim, K. C., and Byrne, L. B. (2006). Biodiversity loss and the taxonomic bottleneck: emerging biodiversity science. *Ecol. Res.* 21, 794–810. doi: 10.1007/s11284-006-0035-7

Kosko, B. (1986). Fuzzy cognitive maps. *Int. J. Man. Mach. Stud.* 24, 65–75. doi: 10.1016/S0020-7373(86)80040-2

Kreps, D. M. (1990). *Game Theory and Economic Modelling*. Oxford: Oxford University Press. doi: 10.1093/0198283814.001.0001

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., et al. (2001). The causes of land-use and land-cover change: moving beyond the myths. *Glob. Environ. Chang.* 11, 261–269. doi: 10.1016/S0959-3780(01)00007-3

Lélé, S., and Norgaard, R. B. (2006). Practicing interdisciplinarity. *Bioscience* 55, 967–975. doi: 10.1641/0006-3568(2005)055[0967:PI]2.0.CO;2

Leong, K. M., Forester, J. F., and Decker, D. J. (2009). Moving public participation beyond compliance: uncommon approaches to finding common ground. *George Wright Forum* 26, 23–39. Available online at: https://www.jstor.org/stable/43598116

Lindenmayer, D. B., Wood, J., MacGregor, C., Buckley, Y. M., Dexter, N., Fortescue, M., et al. (2015). A long-term experimental case study of the ecological effectiveness and cost effectiveness of invasive plant management in achieving conservation goals: bitou bush control in Booderee National Park in Eastern Australia. *PLoS ONE.* 10:e0128482. doi: 10.1371/journal.pone.0128482

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., et al. (2007). Complexity of coupled human and natural systems. *Science* 317, 1513–1516. doi: 10.1126/science.1144004

López, P. (2017). *Reaparece la zorra gris en la reserva del Pedregal, tras 13 años.* Gac. UNAM 4889, 9.

MacKenzie, D. I. (2018). *Occupancy Estimation and Modeling: Inferring Patterns and Dynamics of Species Occurrence*. Burlington, MA: Elsevier/Academic Press.

MacKenzie, D. I., Bailey, L. L., and Nichols, J. D. (2004). Investigating species co-occurrence patterns when species are detected imperfectly. *J. Anim. Ecol.* 73, 546–555. doi: 10.1111/j.0021-8790.2004.00828.x

MacMynowski, D. P. (2007). Pausing at the brink of interdisciplinarity: power and knowledge at the meeting of social and biophysical science. *Ecol. Soc.* 12:20. doi: 10.5751/ES-02009-120120

Madden, F., and McQuinn, B. (2014). Conservation's blind spot: the case for conflict transformation in wildlife conservation. *Biol. Conserv.* 178, 97–106. doi: 10.1016/j.biocon.2014.07.015

Mangun, J. C., Degia, C. A., and Davenport, M. A. (2009). Neighbors yet strangers: local people's awareness of Cypress Creek National Wildlife Refuge, Southern Illinois, USA. *Soc. Nat. Resour.* 22, 295–307. doi: 10.1080/08941920801981931

Matson, P., Clark, W. C., and Andersson, K. (2016). *Pursuing Sustainability: A Guide to the Science and Practice*. Princeton University Press, Princeton, NJ.

Mitchell, M. G. E., Bennett, E. M., and Gonzalez, A. (2015a). Strong and nonlinear effects of fragmentation on ecosystem service provision at multiple scales. *Environ. Res. Lett.* 10:094014. doi: 10.1088/1748-9326/10/9/094014

Mitchell, M. G. E., Suarez-Castro, A. F., Martinez-Harms, M., Maron, M., McAlpine, C., Gaston, K. J., et al. (2015b). Reframing landscape fragmentation's effects on ecosystem services. *Trends Ecol. Evol.* 30, 190–198. doi: 10.1016/j.tree.2015.09.002

Moodley, Y., Russo, I. R. M., Dalton, D. L., Kotzé, A., Muya, S., Haubensak, P., et al. (2017). Extinctions, genetic erosion and conservation options for the black rhinoceros (Diceros bicornis). *Sci. Rep.* 7:41417. doi: 10.1038/srep41417

Morales-Schechinger, C., and García-Jiménez, S. (2008). "Mexico City and University City: a story of struggle for autonomy through land," in *Global Universities and Urban Development*, eds W. Wiewel and D. C. Perry (Cambridge, MD: Rutledge), 119–154.

Moritz, C. (2002). Strategies to Protect Biological Diversity and the Evolutionary Processes That Sustain It. *Syst Biol* 51, 238–254. doi: 10.1080/10635150252899752

Nava-López, M., Jujnovsky, J., Salinas-Galicia, R., Álvarez-Sánchez, J., and Almeida-Leñero, L. (2009). "Servicios ecosistémicos," in *Biodiversidad del Pedregal de San Ángel*, eds A. Lot and Z. Cano-Santana (Mexico City: UNAM), 51–60.

NIC (2018). *Final Report*: *Cambridge*, *Milton Keynes and Oxford Future Planning Options Project*. London.

Nichols, J. D., and Williams, B. K. (2006). Monitoring for conservation. *Trends Ecol. Evol.* 21, 668–673. doi: 10.1016/j.tree.2006.08.007

Novoa, A., Shackleton, R., Canavan, S., Cybèle, C., Davies, S. J., Dehnen-Schmutz, K., et al. (2018). A framework for engaging stakeholders on the management of alien species. *J. Environ. Manage.* 205, 286–297. doi: 10.1016/j.jenvman.2017.09.059

Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511807763

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. doi: 10.1126/science.1172133

Özesmi, U., and Özesmi, S. L. (2004). Ecological models based on people's knowledge: A multi-step fuzzy cognitive mapping approach. *Ecol. Modell.* 176, 43–64. doi: 10.1016/j.ecolmodel.2003.10.027

Palacio-Prieto, J. L., and Guilbaud, M.-N. (2015). Patrimonio natural de la Reserva Ecológica del Pedregal de San Ángel y áreas cercanas: sitios de interés geológico y geomorfológico al sur de la Cuenca de México. *Bol. Soc. Geol. Mex.* 67, 227–244. doi: 10.18268/BSGM2015v67n2a7

Paschoal, A. M. O., Massara, R. L., Bailey, L. L., Kendall, W. L., Doherty, P. F., Hirsch, A., et al. (2016). Use of Atlantic Forest protected areas by free-ranging dogs: estimating abundance and persistence of use. *Ecosphere* 7:e01480. doi: 10.1002/ecs2.1480

Peralta-Higuera, A., and Prado-Molina, J. (2009). "Los límites y la cartografía," in *Biodiversidad del Pedregal de San Ángel*, eds A. Lot and Z. Cano-Santana (Mexico City: UNAM), 27–42.

Pérez-Escobedo, M. (2014). *Estudio de Percepciones Ambientales de la REPSA*. Reporte interno para la SEREPSA. Mexico City: UNAM.

Puchet-Anyul, M. (2010). *Evaluación del Desempeño del Foro Consultivo Científico y Tecnológico (2002 – 2009)*. Mexico City: Foro Consultivo Científico y Tecnológico.

Puchet-Anyul, M., Casalet, M., Jorge, E., Antonio, L., Stezano, F., Daniel, Z., et al. (2013). *Propuestas Para Contribuir al Diseño del PECiTI 2012-2037. Gobierno y Gobernanza de la CTI*. Mexico City: Foro Consultivo Científico.

Radeloff, V. C., Stewart, S. I., Hawbaker, T. J., Gimmi, U., Pidgeon, A. M., Flather, C. H., et al. (2010). Housing growth in and near United States protected areas limits their conservation value. *Proc. Natl. Acad. Sci. U.S.A.* 107, 940–945. doi: 10.1073/pnas.0911131107

Ramírez-Cruz, G. A., Mendoza-Hernández, P. E., Solano-Zavaleta, I., and Zúñiga-Vega, J. J. (2018). How widespread are nonnative species? estimating habitat occupancy in an ecological reserve within a megacity. *Nat. Areas J.* 38, 68–87. doi: 10.3375/043.038.0108

Ramírez-Cruz, G. A., Solano-Zavaleta, I., Mendoza-Hernández, P. E., Méndez-Janovitz, M., Suárez-Rodríguez, M., and Zúñiga-Vega, J. J. (2019). This town ain't big enough for both of us…or is it? Spatial co-occurrence between exotic and native species in an urban reserve. *PLoS ONE* 14:e0211050. doi: 10.1371/journal.pone.0211050

Raymond, C. M., Fazey, I., Reed, M. S., Stringer, L. C., Robinson, G. M., and Evely, A. C. (2010). Integrating local and scientific knowledge for environmental management. *J. Environ. Manage.* 91, 1766–1777. doi: 10.1016/j.jenvman.2010.03.023

REPSA (2017). *Reserva Ecológica del Pedregal de San Ángel. Lista de Especies la Reserva Ecológica del Pedregal San Ángel*. Available online at: http://www.repsa.unam.mx/index.php/objetivos/caracteristicas/biodiversidad/listado-de-especies (accessed February 1, 2019).

Rustad, L., Mitchell, M. J., Lovett, G. M., Burns, D. A., Shanley, J. B., Driscoll, C. T., et al. (2007). Who needs environmental monitoring? *Front. Ecol. Environ.* 5, 253–260. doi: 10.1890/1540-9295(2007)5[253:WNEM]2.0.CO;2

Rzedowski, J. (1954). "Vegetación del pedregal de San Ángel Distrito Federal México," in *Reserva Ecológica "El Pedregal de San Ángel": Ecología, Historia Natural y Manejo* (1994), ed A. Rojo (Mexico City: UNAM), 9–66.

Safford, H., and Brown, A. (2019). Communicating science to policymakers: six strategies for success. *Nature* 572, 681–682. doi: 10.1038/d41586-019-02372-3

Schewenius, M., McPhearson, T., and Elmqvist, T. (2014). Opportunities for increasing resilience and sustainability of urban social-ecological systems: insights from the URBES and the cities and biodiversity outlook projects. *Ambio* 43, 434–444. doi: 10.1007/s13280-014-0505-z

Segura-Burciaga, S. (2009). "Introducción de especies: la invasión y el control de Eucalyptus resinifera," in *Biodiversidad del Pedregal de San Ángel*, eds A. Lot and Z. Cano-Santana (Mexico City: UNAM), 533–538.

Segura-Burciaga, S., and Meave, J. (2001). "Effect of the removal of individuals of the exotic species Eucalyptus aff. resinifera Sm. on the floristic composition of a protected xerophytic shrubland in southern Mexico City," in *Plant Invasions: Species Ecology and Ecosystem Management*, eds G. Brundu, J. Brock, I. Camarda, L. Child, and M. Wade (Leiden: Backhuys Publishers), 319–330.

Segura-Burciaga, S. G., and Martínez-Ramos, M. (1994). "La introducción de especies a comunidades naturales: ei caso de Eucalyptus resinifera Smith. (Myrtaceae) en la reserva 'EI Pedregal' de San Ángel," in *Reserva Ecológica "El Pedregal de San Ángel": Ecología, Historia Natural y Manejo* (1994), ed A. Rojo (Mexico City: UNAM), 177–186.

Sepúlveda, M. A., Singer, R. S., Silva-Rodríguez, E., Stowhas, P., and Pelican, K. (2014). Domestic dogs in rural communities around protected areas: conservation problem or conflict solution? *PLoS ONE.* 9:e86152. doi: 10.1371/journal.pone.0086152

Shannon, P., Markiel, A., Ozier, O., Baliga, N. S., Wang, J. T., Ramage, D., et al. (2003). Cytoscape: a software environment for integrated models of biomolecular interaction networks. *Genome Res.* 13, 2498–2504. doi: 10.1101/gr.1239303

Shen, Z., and Fitriaty, P. (2018). "Overview: Green city planning and practices in Asian cities," in *Green City Planning and Practices in Asian Cities*, eds Z. Shen, L. Huang, K. Peng, and J. Pai (Cham: Springer), 1–16. doi: 10.1007/978-3-319-70025-0_1

Sherwin, W., and Moritz, C. (2000). "Managing and monitoring genetic erosion," in *Genetics, Demography, and Viability of Fragmented Populations*, eds A. G. Young and G. M. Clarke (Cambridge: Cambridge University Press), 438.

Siebe, C. (2009). "La erupción del volcán Xitle y las lavas del Pedregal hace 1670 +/- 35 años AP y sus implicaciones," in *Biodiversidad del Pedregal de San Ángel*, eds A. Lot and Z. Cano-Santana (Mexico City: UNAM, Reserva Ecológica del Pedregal de San Ángel and Coordinación de la Investigación Científica), 43–49.

Sirakaya, A., Cliquet, A., and Harris, J. (2018). Ecosystem services in cities: towards the international legal protection of ecosystem services in urban environments. *Ecosyst. Serv.* 29, 205–212. doi: 10.1016/j.ecoser.2017.01.001

Taniguchi, M., Lovich, J. E., Mine, K., Ueno, S., Kamezaki, N., and Yeo, D. (2017). Unusual population attributes of invasive red-eared slider turtles (*Trachemys scripta elegans*) in Japan: do they have a performance advantage? *Aquat. Invasions* 12, 97–108. doi: 10.3391/ai.2017.12.1.10

Tian, Y., Jim, C. Y., Tao, Y., and Shi, T. (2011). Landscape ecological assessment of green space fragmentation in Hong Kong. *Urban For. Urban Green.* 10, 79–86. doi: 10.1016/j.ufug.2010.11.002

Tylianakis, J. M., Laliberté, E., Nielsen, A., and Bascompte, J. (2010). Conservation of species interaction networks. *Biol. Conserv.* 143, 2270–2279. doi: 10.1016/j.biocon.2009.12.004

Vargas, F. (1984). *Parques Nacionales de México y Reservas Equivalentes. Pasado, Presente y Futuro. Colección: Grandes Problemas Nacionales. Serie: Los Bosques de México*. Mexico City: Instituto de Investigaciones Económicas, UNAM.

Vaughan, L. (2018). *Mapping Society*. London: UCL Press. doi: 10.2307/j.ctv550dcj

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P. D., Bommel, P., et al. (2018). Tools and methods in participatory modeling: selecting the right tool for the job. *Environ. Model. Softw.* 109, 232–255. doi: 10.1016/j.envsoft.2018.08.028

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., et al. (2016). Modelling with stakeholders—next generation. *Environ. Model. Softw.* 77, 196–220. doi: 10.1016/j.envsoft.2015.11.016

Welch, D. (1998). Air issues and ecosystem protection, a Canadian National Parks Perspective. *Environ. Monit. Assess.* 49, 251–262. doi: 10.1023/A:1005842825220

Wright, L. P., Zhang, L., Cheng, I., Aherne, J., and Wentworth, G. R. (2018). Impacts and effects indicators of atmospheric deposition of major pollutants to various ecosystems-a review. *Aerosol. Air Qual. Res.* 18, 1953–1992. doi: 10.4209/aaqr.2018.03.0107

Xu, L., You, H., Li, D., and Yu, K. (2016). Urban green spaces, their spatial pattern, and ecosystem service value: the case of Beijing. *Habitat. Int.* 56, 84–95. doi: 10.1016/j.habitatint.2016.04.005

Yang, J., Sun, J., Ge, Q., and Li, X. (2017). Assessing the impacts of urbanization-associated green space on urban land surface temperature: a case study of Dalian, China. *Urban For. Urban Green.* 22, 1–10. doi: 10.1016/j.ufug.2017.01.002

Yoccoz, N. G., Nichols, J. D., and Boulinier, T. (2001). Monitoring of biological diversity in space and time. *Trends Ecol. Evol.* 16, 446–453. doi: 10.1016/S0169-5347(01)02205-4

Zambrano, L., Aronson, M. F. J., and Fernandez, T. (in press). The consequences of landscape fragmentation on socio-ecological processes in a rapidly developing city. *Front. Environ. Sci.*

Zambrano, L., and Cano-Santana, Z. (2016). *Historias que Brotan de las Rocas. Experiencias sobre el Pedregal de San Ángel y su Reserva Ecológica.* Mexico City: UNAM/CONABIO.

Zambrano, L., Rodríguez-Palacios, S., Pérez-Escobedo, M., Gil-Alarcón, G., Camarena, P., and Lot, A. (2016). *Ecológica del Pedregal de San Ángel: Atlas de Riesgos*. Mexico City: Secretaría Ejecutiva de la Reserva Ecológica del Pedregal de San Ángel, UNAM.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.