INDICATORS FOR THE MEASUREMENT AND MONITORING OF BIODIVERCITIES

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Measuring the status and trends of biodiversity and ecosystem services is critical to understand whether a city is adequately managed to protect various ecological and social processes. For example, indicators of biophysical aspects, referring to the size of vegetation patches and their degree of connectivity, are necessary to assess the viability of wildlife populations within the urban matrix (Litteral & Wu, 2012; Yang et al., 2021). A BiodiverCity, however, should not only be characterized by its capacity to provide favorable conditions for the preservation of different living organisms. It should also promote better relationships between citizens and nature and inspire new ventures and technologies that take advantage of ecosystem services at local and regional scales (Gaston et al., 2013; Wang et al., 2019). Therefore, measuring and monitoring a BiodiverCity is a task that requires models that address the city as a complex and dynamic socio-ecological system. These models are composed of multiple indicators, chosen depending on the type of pressures, impacts and management actions to be understood and evaluated (Figure 1). Likewise, indicators should be associated with clear targets and verifiable outputs included in monitoring plans (Mori et al., 2015; Mori & Yamashita, 2015; Pierce et al., 2020).

THE CHALLENGE OF MEASURING A BIODIVERCITY

Defining indicators in the framework of BiodiverCities represents a challenge both for those who generate information and those responsible for formulating policies related to the sustainable use of biodiversity and ecosystem services in urban areas. These challenges may be related to aspects such as the implementation of methodologies to acquire and update information in a cost-effective way, the definition of a measurement scale (Goddard et al., 2010), and the integration of biodiversity into social and economic goals (Kohsaka et al., 2013; Pierce et al. 2020). It is also important to keep in mind that urban areas are heterogeneous and host multiple actors associated with different institutions and management levels, which have diverse visions regarding the use of nature (Goddard et al., 2010). Thus, obtaining indicators that reflect the multiple perspectives of urban stakeholders is a primary task for effective monitoring in a BiodiverCity (Uchiyama & Kohsaka, 2020).

In addition to promoting conservation opportunities, a BiodiverCity must also be able to provide a wide range of ecosystem services that facilitate relationships between social groups and the exchange of goods at regional scales. A key concept is "social sustainability" (Kimpton, 2017), which addresses place attachment, social cohesion, collective efficacy, and social norms and sanctions. These dimensions can be translated into indicators aimed at measuring whether a city enables, among other aspects, sustainable economic growth and citizen participation. Additionally, due to the diversity of social groups, indicators should be applied considering the values, visions, and motivations that different sectors of society have about nature (Pereira et al., 2020; Soma et al., 2018).

Recently, the concept of Nature-based Solutions (NbS) has been used to identify benefits that bring together the interests of multiple stakeholders on social, cultural, environmental, and economic issues (Kabisch et al., 2016; Raymond et al., 2017). NbSs can lay the groundwork for engaging cities in meeting global goals in the face of biodiversity loss, climate change, or equity by paying attention to the types of targets and indicators considered relevant, practical, and measurable. In this sense, identifying these solutions can help define indicators to measure the benefits derived from the recovery or rehabilitation of ecosystem functions and biodiversity to make them meaningful for different population groups (Xie & Bulkeley, 2020).

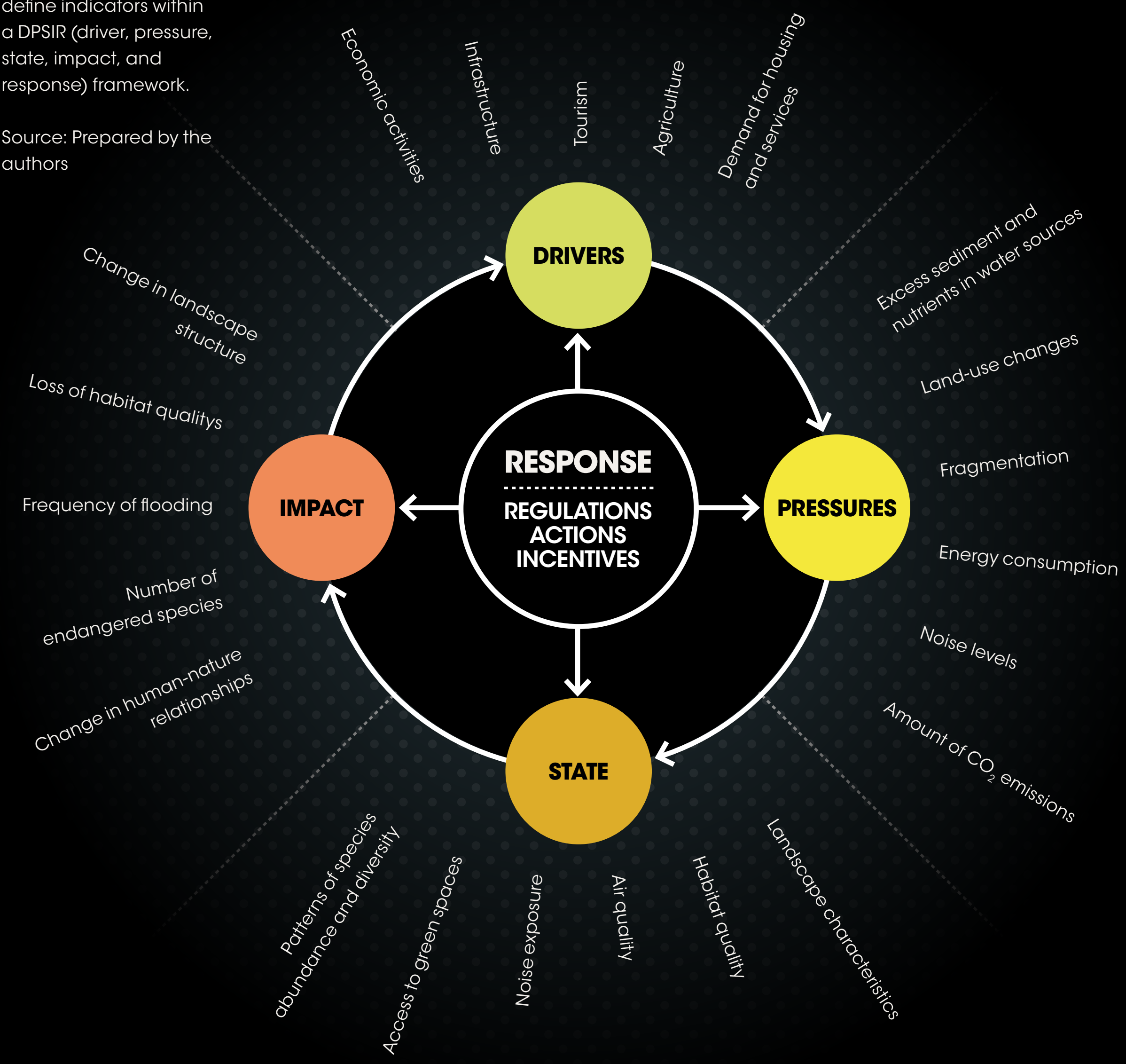
Despite the challenges of measuring and monitoring biodiversity, there are several opportunities to generate quality information that facilitates the use of indicators in urban environments. For example, new advances in the development of remote sensors and databases have enabled access to relevant information on urban biodiversity trends (Dobbs et al., 2017; Goddard et al., 2021). In addition, cities have become ideal locations for community science projects (Li et al., 2019; Callaghan et al., 2020), as well as for developing indicators that integrate biophysical, social, and economic aspects (Alam et al., 2016; Chan et al., 2021; Pierce et al., 2020; Wang et al., 2019). These indicators offer a more inclusive vision of sustainable cities, which considers biodiversity conservation and its relationship with the well-being of citizens.

TOWARDS A BIODIVERCITY ASSESSMENT AND MONITORING MODEL

An essential step in monitoring a BiodiverCity is to identify a comprehensive set of indicators that represent the state of biodiversity in a study system, as well as the type of pressures and actions that lead to its loss and transformation. The driver-pressure-state-impact-response (DPSIR) model (Figure 1) can be very useful for distinguishing between these different types of indicators (Hughes & Chan, 2021; Maxim et al., 2009). This model helps to identify the social and economic drivers that pressure the urban environment, generating a change in the state of its biodiversity and ecosystem services. Changes in

Figure 1. Examples of aspects considered to define indicators within a DPSIR (driver, pressure, state, impact, and response) framework.

Source: Prepared by the authors



Actions
Vegetation restoration, establishment of protected areas, maintenance of gardens and green spaces.

Incentives
Housing subsidies, payments for environmental services, economic incentives for biodiversity protection.

Regulations
Territorial management plans.

the states of biodiversity are, in turn, reflected in impacts on human health, ecosystem functioning, urban infrastructure, and the economy.

Frameworks such as DPSIR facilitate environmental monitoring by categorizing different problems along a cause-effect chain (Qu et al., 2020). In addition, they allow the design of evaluations and the identification of actions and policies aimed at solving each problem through adaptive management. The DPSIR model has been adapted to include specific aspects such as ecosystem-based management (EBM) (EBM-DPSER) (Kelble et al., 2013) or to be linked to ecosystem services and social benefits (Atkins et al., 2011; Nassl & Löffler, 2015). It is recommended to consult Patrício et al. (2016) and Nassl & Löffler (2015) to become familiar with other extensions of the DPSIR model and understand further advantages and limitations.

Within the DPSIR framework, the following types of indicators can be identified (Figure 1, Table 1):

- *Driver indicators:* describe social, demographic, and economic developments in societies that lead to changes in production and consumption levels, thereby putting pressure on the environment.
- *Pressure indicators:* describe pressures exerted by society on natural resources, which are manifested in changes in the environmental conditions of a system.
- *Condition indicators:* describe the quantity and quality of physical, chemical, biological, and socioeconomic attributes in a given area.
- *Impact indicators* describe changes in the state of the environment resulting from specific pressures. Impact indicators focus on changes in the state of environmental attributes that may influence biodiversity and ecosystem services.
- *Response indicators:* describe the responses of different groups of citizens and decision-makers to prevent, compensate, improve or adapt to changes in the state of the environment.

INDICATORS AND CAUSAL NETWORK MODELS

The implementation of different types of DPSIR indicators in urban areas requires identifying various citizen groups and their motivations for promoting the conservation and use of urban biodiversity. Motivations include preserving local biodiversity, maintaining urban-regional connectivity, fostering relationships between people and nature, and conserving areas that favor ecosystem services (Dearborn & Kark, 2010; Shanahan et al., 2018). Monitoring these objectives requires complementary indicators that consider different values, drivers of consumption and management strategies. By using complementary indicators, it is possible to identify a baseline to compare drivers, pressures and management opportunities that involve different stakeholders.

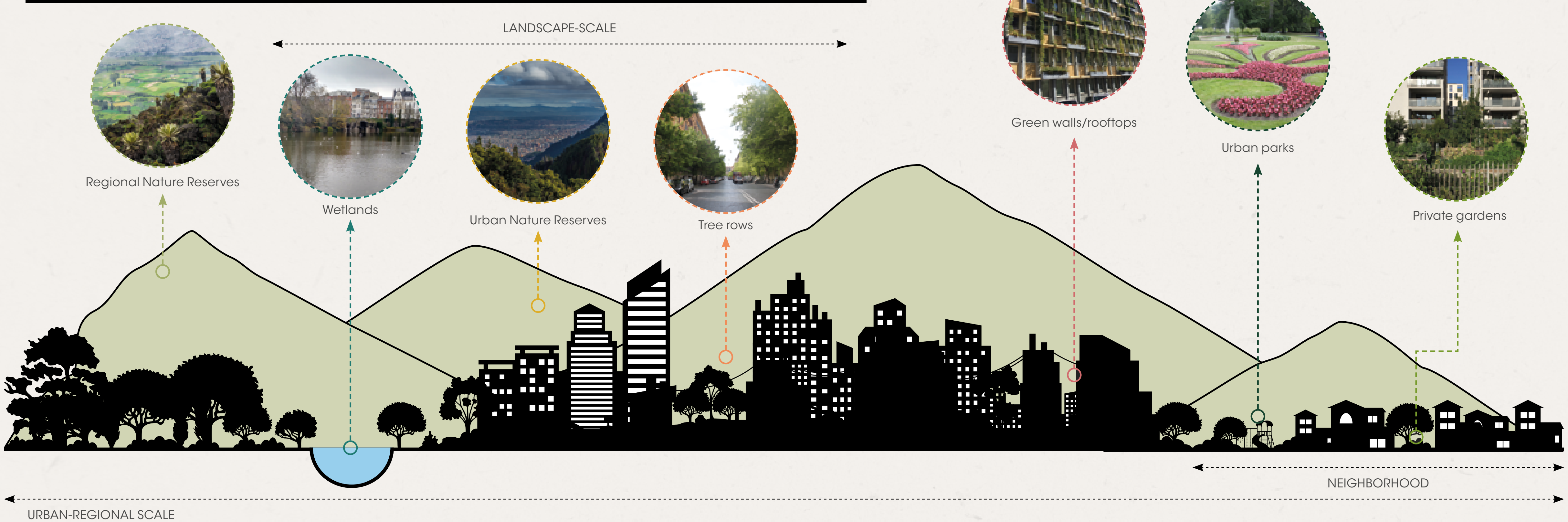
To establish a rigorous management and monitoring framework, it is crucial to understand that the relationships between drivers, pressures, states, impacts, and responses are synergistic (Patrício et al. 2016). Cause-effect relationships where a state is linked to a single pressure and action are uncommon. For example, the state of a wildlife population within the urban matrix is influenced by multiple pressures such as noise generation, land-use changes, and fragmentation processes, among others (Lepczyk et al., 2017; Yang et al., 2021). In turn, each pressure originates from a wide range of drivers related to the demand for housing, transportation, and recreation in areas surrounding green and blue spaces. These drivers can modify people's behaviors and thus promote both positive and negative responses to the shape, size, and spatial configuration of species habitats within the urban matrix (Goddard et al., 2010). In this sense, monitoring a BiodiverCity depends not only on measuring physical and biological attributes but also how these attributes relate to demographic and socioeconomic indicators (e.g., population density, occupancy rates, etc.) that reflect the pressures and actions of human populations on environment.

Given the complexity associated with the relationships between social actors and biodiversity, new conceptual frameworks have been proposed to move from a causal chain to a causal network (Hou et al., 2014; Niemeijer & De Groot, 2008). These include combining DPSIR frameworks with models that highlight the interdependence of four key dimensions of sustainability: environmental, economic, social, and political (Maxim et al., 2009; Spangenberg et al., 2009). These approaches go beyond linear causality by allowing descriptions of different levels of interaction at the societal level (Nassl & Löffler, 2015). Moreover, they enable the assessment of DPSIR components, considering that a network of related ecosystem services contributes to human well-being (Alam et al., 2016; Nassl & Löffler, 2015). For example, native vegetation relicts in urban parks fulfill multiple functions and services, such as providing habitat for wildlife species, carbon sequestration, temperature regulation, water cycle maintenance, and cultural and recreational services. Each of these services has different beneficiaries with different values and governance systems. Causal network approaches attempt to integrate this complexity through social-ecological interactions, where impacts and responses reflect the link between nature and society (Nassl & Löffler 2015). A key challenge consists on conducting quantitative analyses that integrate these models with urban areas' biodiversity monitoring.

HIERARCHICAL SRUCTURES AND SPATIAL SCALES

The hierarchical structure of residential landscapes affecting biodiversity and the provision of ecosystem services is a challenge for the management and monitoring of a BiodiverCity. Hierarchical structure means that the urban environment can be conceptualized as a set of nested spatial units. (Norton et al., 2016; Uchida et al., 2021). These units are temporally dynamic, can be defined according to the study system, and are managed by different types of citizens. For example, an individual garden constitutes the scale at which citizens manage vegetation on their private property. Still, the size and configuration of different interconnected gardens and parks are controlled by urban planners, housing developers, and local authorities. The definition

Figure 2. A BiodiverCity is heterogeneous and hosts different types of green and blue spaces.
Photos: Juan Sebastián Hincapié, Érika Peñuela and María Angélica Mejía.



of hierarchical structures has been successfully used in applications such as habitat quality assessment of urban landscapes (Goddard et al., 2010), research to understand socioeconomic drivers (Pickett & Cadenasso, 2006), and the study of biogeochemical processes in urban ecosystems (Zhang et al., 2013).

In addition to recognizing a hierarchical structure, the definition of urban indicators also requires assessing the heterogeneity of green and blue spaces in cities. A BiodiverCity promotes the existence of multiple types of green and blue spaces that facilitate biodiversity conservation and the provision of ecosystem services (Garrard et al., 2018; Goddard et al., 2010); these spaces include public parks, strips of trees on roads, wetlands, and private gardens, among others (Figure 2). Urban green and blue spaces are incredibly heterogeneous, satisfying the provision of different ecosystem services depending on their physical characteristics (e.g., size, vertical vegetation structure, degree of fragmentation), their accessibility, and the presence of amenities (Dade et al., 2020). This heterogeneity acts differentially on biotic communities and the social needs of human societies (Lepczyk et al., 2017; Wood et al., 2018). For example, parks with high forest cover and more significant vegetation heterogeneity are generally associated with activities based on contact with nature (Bjerke et al., 2006; Shanahan et al., 2015). Similarly, large and linear parks are associated with a greater diversity of cultural and recreational amenities (Brown et al., 2014).

Green and blue spaces are also immersed in a heterogeneous matrix - dominated by human activities - so it is essential to define their identity and the spatial and social context surrounding them. A specific garden or park can promote or affect species conservation, depending on attributes such as vegetation structure, the availability of particular habitats (such as ponds), and the presence of domestic species that put wildlife at risk (Garrard et al., 2018). However, the effectiveness of these spaces in protecting viable wildlife populations will depend on other landscape attributes; such as the size of patches and their degree of isolation or the density of built infrastructure, which influences the permeability of the urban matrix (Burkman & Gardiner, 2014, Spotswood et al., 2021; Uchida et al., 2021; Yang et al., 2021). This permeability promotes or hinders the movement of species and individuals through the urban landscape and depends on factors such as the presence of vegetation corridors, essential habitat patches (e.g., wetlands), and the proportion of built environments (Beninde et al., 2015).

Spatial context also affects the type of human-nature relationships, which depend not only on physical features such as patches of natural vegetation and open areas. Other aspects such as proximity, accessibility, and perceived safety are also important (Kimpton 2017). For example, roads and trails that connect parks to residential areas can increase the likelihood of people accessing nature and gaining recreational and health benefits (Mitchell et al., 2015; Takano et al., 2002). In addition, there is an increasing recognition of ecological footprints in cities that extend beyond their boundaries, spanning regional and global scales, where cities have significant impacts and dependencies (Figure 2) (Hughes & Chan, 2021). This means that management decisions regarding zoning and governance in the surrounding landscape impact people's ability to interact not only with resources at local scales (Goddard et al., 2010), but also with systems that are interconnected across regions.

Understanding the relationships across spatial scales is thus a fundamental aspect of defining indicators to monitor nature within and beyond the city. As processes occurring at local and regional scales are considered, the plurality of perspectives that influence the development of joint goals and visions increases. Therefore, indicators must use a multiscale approach that facilitates communication among various stakeholders in the use and management of biodiversity at local, landscape, and regional scales. Because the type of interactions among stakeholders acting at multiple scales can be highly diverse, indicators should also be interdisciplinary; they should not be limited to including contributions from biology and ecology but also those from architecture, engineering, and the social and economic sciences.

GLOBAL INDICATORS FOR A BIODIVERCITY

Different indices and global initiatives can be applied in the measurement and monitoring of a BiodiverCity. An index refers to a group of indicators that allow the aggregation of multiple aspects into a single value. For example, the Human Development Index (HDI) has been used to measure the development of countries by integrating three factors: life expectancy, level of education, and gross domestic product (GDP) per capita. Specifically, one of the most widely used indices for measuring urban biodiversity is the City Sustainability Index (CSI), which integrates environmental, economic, and social indicators (Table 1). This index measures pressures, impacts, states, and responses at both local scales (e.g., parks, wetlands, and neighborhoods) and at scales beyond the city's geographic boundaries. Another index with an integrative approach is the City Biodiversity Index (CBI), or Singapore index (Chan et al., 2021), which can be included in the CSI.

The Singapore index is divided into three components to measure urban biodiversity. The first refers to biodiversity within the city, and it includes indicators such as the proportion of natural city areas or the change in the number of vascular plant species. The second refers to the ecosystem services obtained from urban biodiversity. Associated indicators include water quantity regulation or the proportion of tree cover. Finally, the third component addresses the governance and management of biodiversity and it includes indicators related to education, budget invested in biodiversity, and community support. Examples of governance indicators include the budget allocated to biodiversity or policies and incentives for green infrastructure (Chan et al., 2021) (Table 1).

To standardize the application of different indices, the International Organization for Standardization (ISO) created the technical committee on sustainable cities and communities in 2012. This committee was formed under the Global City Indicators Facility (GCIF), which seeks to contribute to the development of requirements, frameworks, techniques, and tools to achieve sustainable development objectives in urban and rural areas. The ISO standard, its pilots, and other similar initiatives - such as the "Red de Ciudades Cómo Vamos" in Colombia (RCCV, 2021) - focus mainly on social and governance aspects, while urban biodiversity aspects are in the background. Although other local initiatives focus on biophysical elements like urban tree management (SIGAU, 2021), their implementation is still in development. Numerous academic studies have been conducted on urban biodiversity monitoring, with particular emphasis on biophysical aspects and focal species (Beninde et al., 2015; Burkman & Gardiner, 2014; Carvajal et al., 2020; Spotswood et al., 2021; Villaseñor et al., 2020,). However, social and economic issues in biodiversity are less studied. This duality in approaching urban monitoring is a challenge that must be addressed to adequately understand the relationships between biodiversity conservation and human well-being in a BiodiverCity.

FROM DATA TO INDICATOR

Data and indicators are related entities but have their own characteristics. An indicator allows communicating the state of one or multiple variables through arithmetic ratios of data that have been measured directly or estimated by different methods. Thus, the feasibility of calculating indicators in BiodiverCities also depends on the institutional and technical capacity to collect biophysical, socioeconomic, and ecosystem services data. Data can be acquired through numerous sources, including primary biodiversity data platforms, community science programs, and local government public documents that house key information on economic and governance issues. In addition, land-use planning policies and other instruments can generate opportunities to collect data needed to calculate indicators. This is because planning tools consider existing institutional resources (e.g., financial resources, human talent, physical resources, and infrastructure for data collection) that help diagnose the potential for applying indicators in the medium and long term.

An example of the existing planning instruments that can help to define indicators in urban areas is the concept of Main Ecological Structure (MES) used in Colombia (Andrade et al. 2014). The MES is an instrument that seeks to incorporate biodiversity and ecosystem services criteria in territorial planning; it is based on a network of interconnected green spaces that contribute to the protection of biodiversity, the maintenance of ecological processes, and the provision of ecosystem services. Although MES has been defined mainly at the regional scale, it can also be represented at urban and local (e.g. wetlands) levels. Thus, there is a multiscale nature within MES that can help with its implementation at different hierarchical levels, from the garden to the urban-regional scale. The MES concept is based on the recognition of an unifying axis composed by a series of elements that interact at different spatial and temporal scales. Axes are defined depending on the regional context. For example, an unifying axis can be the urban and rural water network (Humboldt Institute & municipality of Envigado, 2018) since it is assu-

Table 1. Examples of indicators for the different components that comprise a BiodiverCity.

TYPE OF INDICATOR	COMPONENT	INDICATORS
DRIVER	SOCIOECONOMIC	Population growth rate (%)
		GDP growth rate (%)
		Urbanization rate (%)
PRESSURE	SOCIOECONOMIC	Population density (inhabitants/km^2)
		Unemployment rate
	BIOPHYSICAL	Amount of CO_2 emissions
		Amount of solid waste generated
		Relationship between expansion areas and population growth
		Greenhouse gas emissions (tons per capita)
STATE	BIOPHYSICAL	Metrics of landscape structure (composition and configuration): average size of vegetation patches, isolation of patches, proportion of land cover types.
		Blue-green area structural connectivity indices (size, distance, proportion)
		Indicator of resistance to species movement (e.g. proportion of built-up and blue-green areas)
		Average vegetation strata diversity
		Atmospheric concentration of Hg
		Atmospheric concentration of PM10
		Indicator of microclimatic regulation: heat islands vs. green-blue areas ratio.
	SOCIOECONOMIC	Proximity and accessibility to green spaces
		Square meters of space in public recreational facilities
		Percentage of population with sewage collection, potable water, sewage treatment, and drinking water
		Percentage of untreated wastewater
		Percentage of solid waste disposed in landfills

med that the provision of water service is the basis for sustaining both human communities and biodiversity. Thus, providing water requires green and blue spaces capable of supporting resilient ecosystems and the urban infrastructure that allows access to water for all citizens (Oral et al., 2020). In this sense, monitoring the water network requires recognition of the intrinsic heterogeneity of urban spaces through biophysical indicators (such as the diversity of key species) and socioeconomic indicators (such as the total volume of water used to produce goods and services consumed by the community) (Van Leeuwen et al., 2012).

The definition of a unifying axis also allows to diagnose specific pressures, actions, impacts, and responses, depending on the measurement objective and the type of space being analyzed. The axis of the MES is composed of diverse spaces that can serve, among others, as core biodiversity protection areas, corridors, sustainable use areas, or buffer zones. Although indicators such as the percentage of area loss due to infrastructure construction can be applied to all components of the MES, explicit recognition of the different types of spaces allows prioritization and implementation of actions that require differentiated management and monitoring. For example, monitoring conservation sites for water provision requires indicators that reflect the status of critical ecosystems and the amount of area protected and physicochemical parameters that reflect ecosystem health. By incorporating indicators differentiated by space within the MES, it is possible to identify functional attributes with explicit social value (Andrade et al., 2014).

Several challenges exist for the application of indicators within a BiodiverCity. Although there are multiple indicators of the functionality of green and blue spaces in terms of connectivity, biodiversity, or accessibility of the population to recreational and cultural services (Table 1), in most cases, institutional capacities are limited to ensure a continuous updating of information (Wilkinson et al., 2013). Including citizens in data collection and guaranteeing free access to information will be fundamental for more robust monitoring. In addition, new technologies from robotics and autonomous systems (e.g., drones and remote sensors) have revolutionized how environmental data is detected, collected, analyzed, and manipulated (Goddard et al., 2021), even though there are challenges related to the cost of implementing these technologies and their effect on attributes of biodiversity and urban ecosystems. Implementing these technologies, strengthening institutional capacities, and using multidisciplinary approaches to understand the diversity of human-nature interactions, are significant challenges for establishing protocols to monitor urban areas at different spatial and temporal scales.

TYPE OF INDICATOR	COMPONENT	INDICATORS
IMPACT	BIOPHYSICAL	Change in species richness and abundance Change in the number of endangered species Change in the proportion of native species of focus group species (birds, arthropods, plants) Proportion of invasive species Water footprint
	SOCIOECONOMIC	Congestion cost (distance to city center) Public satisfaction Sense of security and sovereignty; health
RESPONSE	BIOPHYSICAL	Number of protected areas Number of ecological corridors or networks against fragmentation Percentage of habitat area restored Water quantity regulation
	SOCIOECONOMIC	Research centers or groups related to knowledge and innovation for urban biodiversity issues Budget used for biodiversity protection Number of biodiversity conservation and restoration projects initiated by the city per year Number of local groups supporting restoration processes Percentage of urban protection soils included in land use plans Status of green and blue space management plans in the city Biodiversity-related responses to climate change Policy and incentives for green infrastructure as Nature-based Solutions

Table adapted using examples from City Biodiversity Index (Chan et al., 2021), City Sustainability Index (Mori & Yamashita, 2015), Worldbank (Worldbank, 2021), urban environmental quality indices (Cerquera-Losada et al., 2019) and CITYkeys (Bosch et al., 2017).

KEY MESSAGES

➔ **An effective monitoring framework considers urban spaces as causal networks.** that recognize the complexity of synergistic interactions between drivers, pressures, states, impacts, and responses. These interactions also consider the diversity of relationships that exist between nature and society.

➔ **The indices should reflect the hierarchical structure and spatial heterogeneity of urban environments.** Because cities are highly heterogeneous environments, the design of indices should encourage collaboration among actors with different views and values. Understanding how these actors relate to each other at multiple spatial and temporal scales is essential for defining indicators to monitor nature inside and outside the city.

➔ **Citizen science is fundamental to generating essential information and connecting people with nature.** BiodiverCities should take advantage of opportunities to develop citizen science projects engaging people in information generation and decision-making. These projects should be supported by a robust institutional framework and new technological advances that enable effective biodiversity and ecosystem services monitoring.